SINGLE PHOTON WORKSHOP 2017

July 31 – August 4, 2017

Boulder, Colorado

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Single Photon Workshop 2017

Welcome to the Single Photon Workshop 2017. SPW2017 is the eighth installment in a series of international workshops on single-photon generation and detection technology and applications. Cutting-edge single-photon technologies are vital to many applications such as quantum cryptography, quantum information processing, quantum imaging, quantum metrology, astrophysics, nuclear physics and biology.

We are proud to host SPW 2017, which is intended to bring together a broad range of scientists, engineers and newcomers in the field of single-photon generation and detection for fundamental science and applications. Researchers from universities, industry, and government will present their latest developments in single-photon devices and methods with a view toward improved performance and new application areas. It will be an exciting opportunity for those interested in single-photon technologies to learn about the state-of-the-art and to foster continuing partnerships with others seeking to advance the capabilities of such technologies.

Thank you for your participation and we are all looking forward to an excellent workshop.

The organizing committee

ABOUT NIST BOULDER

A world leader in the physical sciences and precision measurement for more than 60 years, NIST Boulder Laboratories provide research, measurements, technology, tools, data, and services that enable innovation and improve the quality of our lives.

NIST Boulder develops and supplies measurement tools, test methods, and scientific data that businesses need to invent, innovate, and produce high-quality products for electronics, communications, optics, nanotechnology, public safety, biosciences, forensics, defense, and environmental applications.

NIST Boulder makes possible many commonplace technologies—such as accurate wristwatches and GPS navigation systems, advanced communications networks, DVD players, safe laser surgery, and reliable gas pipelines.

NIST Boulder generates spin-off companies and jobs and provides industry, academia, and other federal agencies with cutting-edge technologies. Commercial products influenced by NIST Boulder-pioneered technologies include closed captioning and chip-scale atomic clocks. NIST technologies used by other labs include frequency combs, quantum sensors, laser power meters, single-photon detectors, and magnetometers.

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Ivo Degiovanni (INRIM - Italy)
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Warren Grice (Oak Ridge National Lab - USA)
Stefan Kück (PTB - Germany)
Alan Migdall (NIST - USA)
Alberto Tosi (Politechnico di Milano - Italy)
Harald Weinfurter (Ludwig-Maximilians-Universität München - Germany)
Hugo Zbinden (University of Geneva - Switzerland)

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Josh Bienfang (NIST-Gaithersburg)
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SPW 2017 Sponsors

Gold Sponsors

OEC OptoElectronic Components

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CQT Centre for Quantum Technologies

Single Quantum Excellence in photon detection

qutools

HPD High Precision Devices, Inc.

IDQ From Vision to Technology

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O E C
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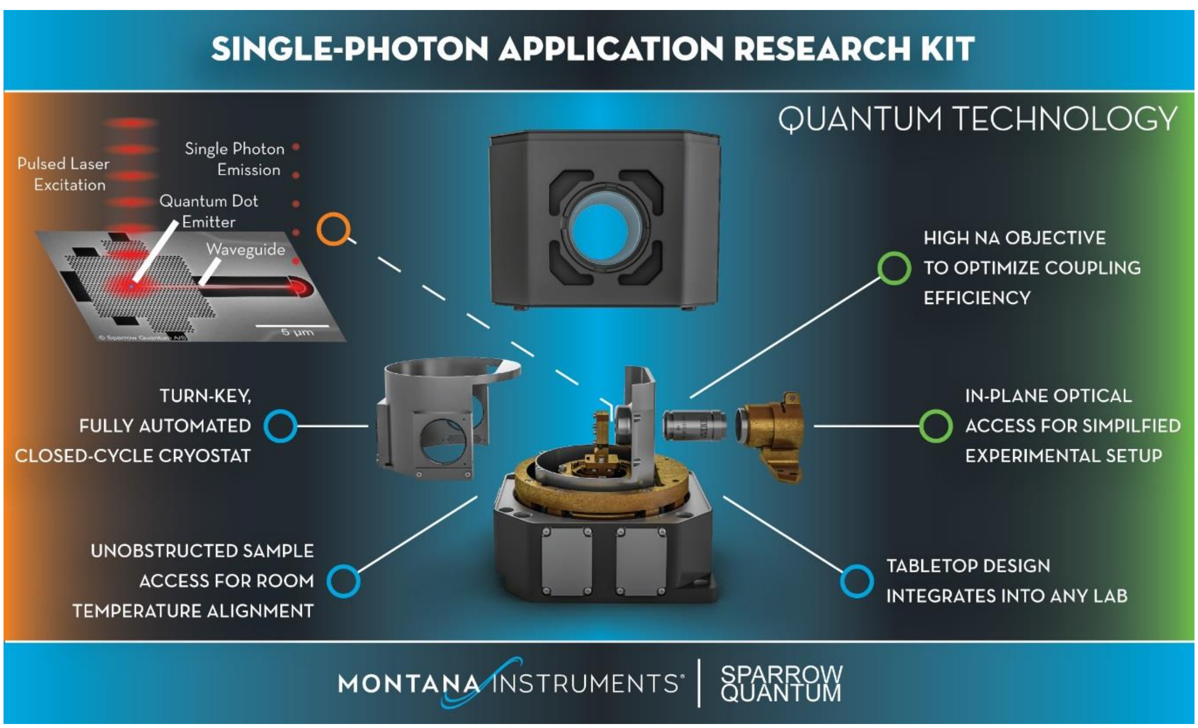
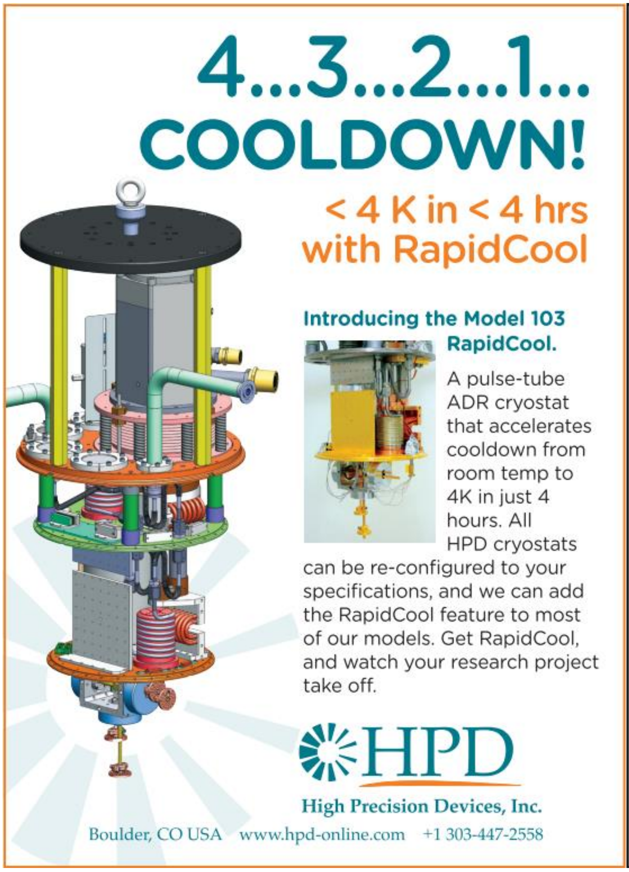
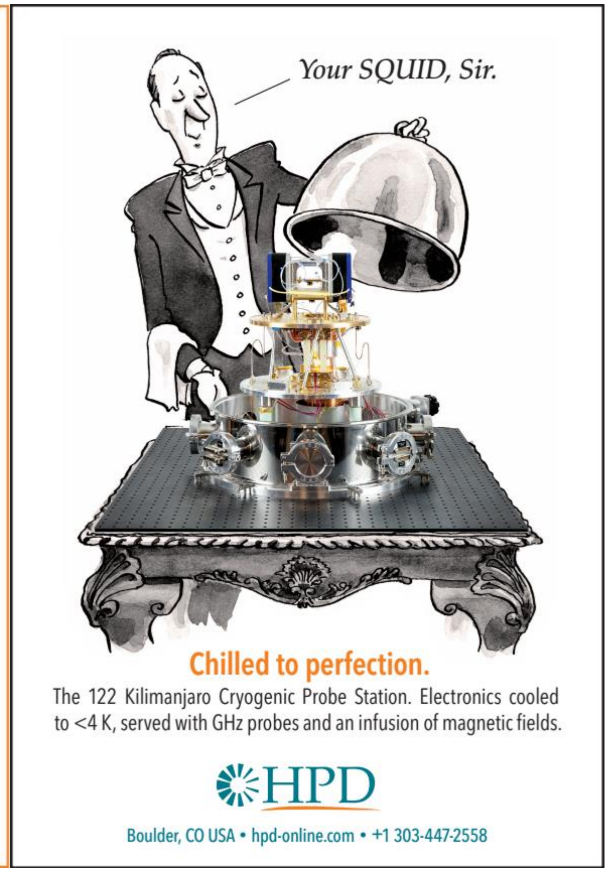
Photon Counting Detectors
Picosecond Event Timers
SuperConducting Nanowires
Entangled Photon Source


SINGLE-PHOTON APPLICATION RESEARCH KIT
QUANTUM TECHNOLOGY
Pulsed Laser Excitation
Single Photon Emission
Quantum Dot Emitter
Waveguide
5 µm
HIGH NA OBJECTIVE TO OPTIMIZE COUPLING EFFICIENCY
TURN-KEY, FULLY AUTOMATED CLOSED-CYCLE CRYOSTAT
IN-PLANE OPTICAL ACCESS FOR SIMPLIFIED EXPERIMENTAL SETUP
UNOBSTRUCTED SAMPLE ACCESS FOR ROOM TEMPERATURE ALIGNMENT
TABLETOP DESIGN INTEGRATES INTO ANY LAB
MONTANA INSTRUMENTS
SPARROW QUANTUM


4...3...2...1...
COOLDOWN!
< 4 K in < 4 hrs with RapidCool
Introducing the Model 103 RapidCool.
A pulse-tube ADR cryostat that accelerates cooldown from room temp to 4K in just 4 hours. All HPD cryostats can be re-configured to your specifications, and we can add the RapidCool feature to most of our models. Get RapidCool, and watch your research project take off.
HPD
High Precision Devices, Inc.
Boulder, CO USA www.hpd-online.com +1 303-447-2558


Your SQUID, Sir.
Chilled to perfection.
The 122 Kilimanjaro Cryogenic Probe Station. Electronics cooled to <4 K, served with GHz probes and an infusion of magnetic fields.
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SPW 2017 General Information

Wireless access

Access wireless service on the CU campus by selecting **UCB Guest Wireless** from your available Wi-Fi network options and accepting the terms and conditions upon opening your web browser. You will be prompted to re-accept these terms and conditions periodically.

If you encounter difficulty accessing the Internet, call 303-735-HELP (4357) or email help@colorado.edu for assistance during their business hours.

Check firewalls or security settings on your computer that could possibly complicate accessing the campus Wi-Fi system before you arrive.

Important Phone Numbers

Emergency:

Campus and Off-Campus Emergencies	911
CU Police Department (On-Campus, Non-Emergency)	303-492-6666
City of Boulder Police Department (Non-Emergency)	303-441-3333
Boulder Community Hospital	303-415-7000
4747 Arapahoe Ave, Boulder, CO 80303	

Important Addresses

WORKSHOP LOCATION

Glenn Miller Ballroom
University Memorial Center (UMC), University of Colorado Boulder
1669 Euclid Avenue (corner of Broadway and Euclid)
Boulder, CO 80309

CONFERENCE DINNER LOCATION

Rayback Collective
2775 Valmont Rd
Boulder, CO 80304

NIST LAB TOURS LOCATION

Main Auditorium
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305

Best Student Poster Award

The SPW 2017 committee has organized a sponsored 'Best Student Poster Award'. If you are a student and presenting a poster, you should sign up for the best student poster award, if you have not already done so. All eligible and signed-up posters are marked with a read sticker next to the poster number. If you are eligible you can still get a red sticker at the registration desk. However, please do so before the poster session starts.

sponsored by: MPD MICRO PHOTON DEVICES

Food and Social Program

WORKSHOP RECEPTION

The workshop reception will be hosted on Monday July 31st 2017 along with the poster session from 16:45 to 19:15. Light snacks will be served and a cash bar will be available for purchase of drinks.

WORKSHOP DINNER

Join us Wednesday evening for a casual dinner at the Rayback Collective. Come sample the best of the Boulder craft beer scene (wine and cider also available), and food from some of the best local food trucks. Drinks and food are *not included* in the registration fee. Since the dinner is self-pay, there is no need to sign up prior to the event. Families and significant others are encouraged to join us. We have organized buses leaving the UMC (University Memorial Center, where the talks are held) at 18:00 to transport workshop attendees to the Rayback. Bus pickups back to the UMC are scheduled for 20:30, 21:00 and 21:30.

LUNCHES AND COFFEE BREAKS

Lunches are on your own. There are two main lunch options on the CU campus: the UMC (University Memorial Center, where the talks are held) and C4C (Center for Community) offer buffet-style lunches. If you purchased the meal plan during registration, your lunches will be at the UMC or C4C. If you did not purchase the meal plan, you can still eat at the UMC or C4C for $12+tax (credit or debit card only, no cash). Through the CU housing registration page you can sign up for the “Commuter Meal Package” only, following the instructions. The cost is $43.30 for four lunches (Monday through Friday).

The University Hill neighborhood (“The Hill” for short), across Broadway from the UMC, also has many restaurants. See the maps and “Places to Eat” section below for more detail. Coffee breaks are held in the vendor area of the UMC. Light refreshments and snacks will be served at each coffee break.

Workshop Satellite Meetings

SHORT LECTURE COURSE

Tuesday August 1 2017, 19:00 – 21:30
location: UMC Aspen Room

SPW2017 will host a short satellite meeting lecture course on "Single-photon metrology and its application to quantum technologies" on Tuesday evening. Participation in this course is encouraged for all attendees, especially students and recent graduates. Refreshments and light snacks will be provided. There is no fee for this course, which is sponsored by EMPIR project 14IND05 MIQC2, and coordinated by the National Physical Laboratory (NPL), the Istituto Nazionale di Ricerca Metrologica (INRiM) and the organizing committee of SPW2017.

Please note that the number of attendees is limited. Therefore, ensure that you sign up for the short course beforehand on the sign-up sheet at the registration desk.

NIST LAB TOURS

Friday, August 4 2017, 8:00 – 13:00
location: Main Auditorium, NIST, 325 Broadway, Boulder, CO, 80020

On Friday, August 4, we are offering lab tours at our NIST Boulder facility. For registered lab tour attendees, a bus pickup is arranged for 8:00 at the UMC (University Memorial Center, where the talks are held). We will serve a sponsored lunch for all lab tour attendees on the NIST campus at 12:00 and a mid-morning coffee break. The return bus to the UMC is scheduled for 13:00.

Only those who signed up for the tour at the time of registration will be able to attend. Unfortunately, we cannot offer a last-minute waiting list, since all attendees need to be registered with our security office in advance. (Note that sign up for the NIST lab tours occurred during the registration process, and was limited to 75 participants. If you were not asked during registration whether you would like to participate in the NIST lab tours, then the lab tours were already filled up.)

SINGLE PHOTON RADIOMETRY AND DISCUSSION FORUM ON FEW PHOTON METROLOGY

Friday, August 4 2017, 13:00 – 15:30
location: NIST, room 1-1107

The TG11 "Single Photon Radiometry" and TG7 "Discussion Forum on Few Photon Metrology" is organizing a joint meeting during SPW 2017. The discussion forum will address:

- Progress report and discussion of the Si SPAD comparison [TG11]
- Update the schedule plan of the Si SPAD comparison [TG11]
- Planning of the future InGaAs SPAD comparison [TG11]
- Update the technical issues in the few photon metrology field [TG7]
- Needs for publication of technical guidance [TG7]

Because the forum is held on the NIST campus, prior registration with the NIST security office is required. To sign up for the meeting, contact Stefan Kück (Stefan.Kueck@ptb.de) or Dong-Hoon Lee (dh.lee@kriss.re.kr).

Local information

ABOUT BOULDER

Located right against the eastern foothills of the Rocky Mountains and at an altitude of 1,655 m (5,430 ft), Boulder is a famous gateway to exploring the natural beauty of the centennial state of Colorado. Only 30 km (18 miles) away lies the continental divide with many peaks above 4,000 m (13,100 ft). Rocky Mountain National Park with its beauty and wildlife is only about a one hour drive away. Of course, the first settlers in 1858 were stunned by the beauty of the surrounding area, but also because of gold finds in the nearby mountains, evidence of which can still be seen today in many ghost towns.

CLIMATE

Boulder is located about one mile above sea level and has a semi-arid climate with low humidity. Average highs in early August are 30°C (85°F) and lows are 15°C (60°F). During a typical summer day, it can get quite warm while in direct sunlight. For prolonged exposure, especially at higher elevations, be sure to bring sunscreen or other sun protection. Afternoon thunderstorms are common and lightning can be a serious threat, especially at higher elevations. To lessen the risk, hiking or other activities above tree line (about 3,500 m (11,500 ft)) should be started in the early morning and completed by noon. Because of the high elevation and dry climate, it is advisable to drink plenty of water.

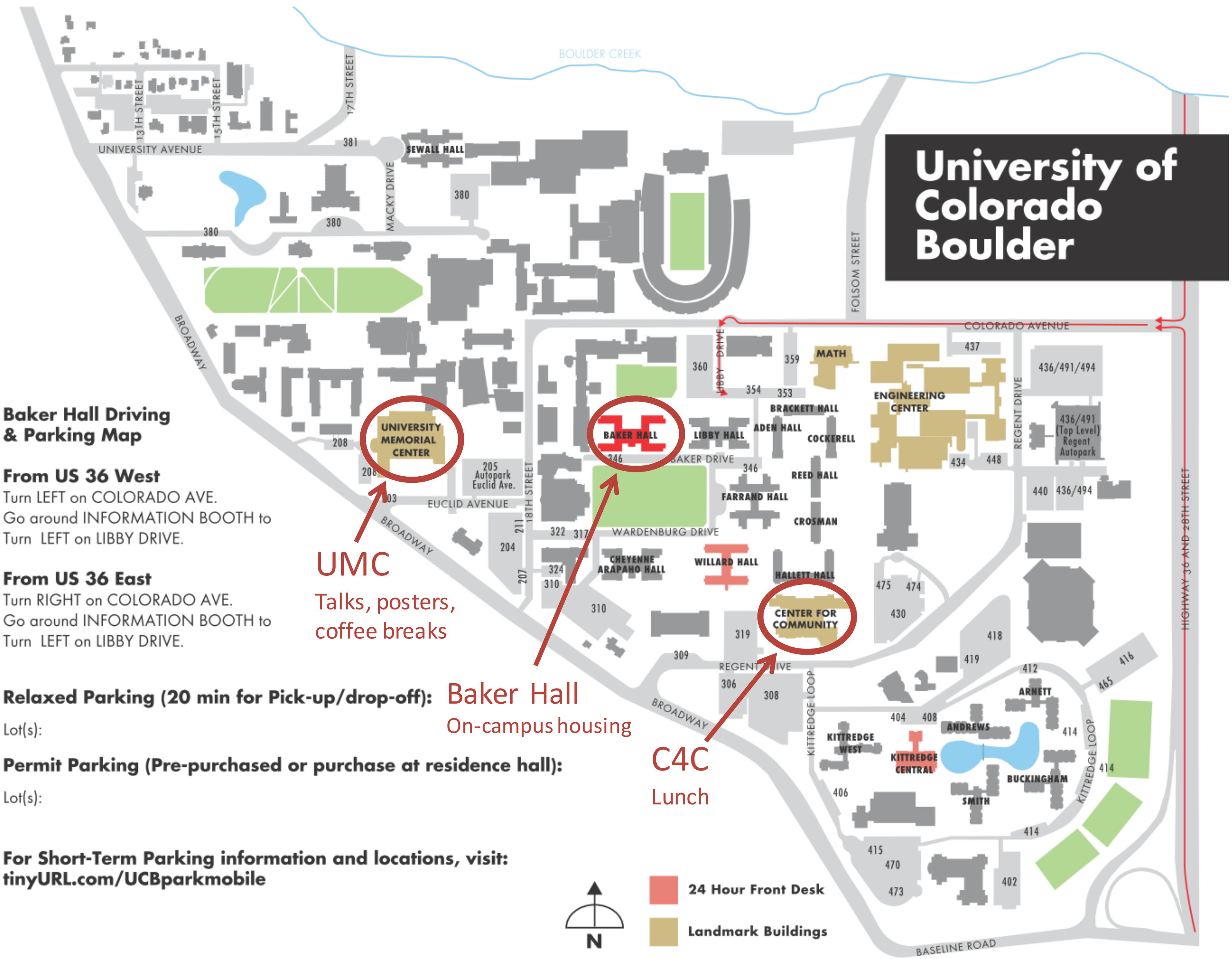
WHAT TO DO

Many tourists like to explore the Pearl Street walking mall with lots of shops, restaurants and street performers. Located close to the mountains, Boulder is famous for its plethora of outdoor activities. From hiking and biking to whitewater kayaking and rock climbing, there are many ways to explore the natural habitat. For more urban pursuits, Denver is just 50 km (30 miles) away.

BIKE SHARE

For the full Boulder experience, consider the Boulder B-Cycle bike sharing program. For only $11, you can purchase a month-long membership that allows unlimited 30-minute rides. (This should be plenty of time to reach most restaurants in Boulder from the UMC or any of the hotels.) There are stations within a short walk of all the hotels and the on-campus housing, and one right next to the conference venue. Just remember to cancel your membership once you depart Boulder to avoid being charged for the next month.

MAPS



Baker Hall Driving & Parking Map

From US 36 West
Turn LEFT on COLORADO AVE.
Go around INFORMATION BOOTH to
Turn LEFT on LIBBY DRIVE.

From US 36 East
Turn RIGHT on COLORADO AVE.
Go around INFORMATION BOOTH to
Turn LEFT on LIBBY DRIVE.

Relaxed Parking (20 min for Pick-up/drop-off):

Lot(s):

Permit Parking (Pre-purchased or purchase at residence hall):

Lot(s):

For Short-Term Parking information and locations, visit: tinyURL.com/UCBparkmobile

UNIVERSITY MEMORIAL CENTER (UMC)

Location of talks, poster sessions, short course and coffee breaks Monday-Thursday. Alferd Packer Restaurant & Grill is also located in the UMC, and is the closest option for a quick lunch. If you signed up for a commuter meal package, this is one place to go for your lunch.

CENTER FOR COMMUNITY (C4C)

Large, on-campus cafeteria, known for good food. Located a short walk from the UMC, this is a place to grab lunch if you are signed up for the commuter meal package. An all-you-can eat buffet, this place has something for everyone, from sushi to salad and sandwiches to burgers. Even if you didn’t pre-purchase the meal plan, you can pay on site with credit card or debit card (no cash): $12 + tax for lunch.

BAKER HALL

On-campus housing.

ORIENTATION

From most places in Boulder, the nearest mountains will be to your west. Broadway and 28th St are the main north-south streets running on either side of campus. Major east-west streets include Baseline, Arapahoe, Canyon and Pearl.

PUBLIC TRANSPORTATION

The UMC (University Memorial Center, where the talks are held) is well served by the public bus system, which is run by RTD. **Fares must be paid in cash as you board the bus, and no change is given.** Transfers are valid for 3 hours and can be used on your return trip; ask for a transfer when you board.

The SKIP and DASH buses run north and south along Broadway, providing frequent service to NIST and downtown Boulder's Pearl Street Mall. The HOP line provides service between the CU campus, Pearl Street, and the 29th Street Mall. Local bus fare for any of these three routes is $2.60 per ride. Local daily passes can be purchased when you board for $5.20.

The FF1 (all stops) and FF2 (express) buses also pick up along Broadway and travel between downtown Boulder and downtown Denver. The fare is $4.50 each way.

The AB1 bus runs along Broadway and goes directly to the Denver International Airport (DEN) for $9.00 each way.

More information is available at www.rtd-denver.com. There are also several phone apps with real-time bus arrival information. Search for "RTD" wherever you purchase apps.

PLACES TO EAT

Boulder is a food town, with restaurants scattered throughout its neighborhoods. Many are clumped in the areas listed below. For specific recommendations, ask a local—everyone's got a favorite or two they rave about!

UNIVERSITY MEMORIAL CENTER (UMC)

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THE HILL

This is the closest set of restaurants to the UMC, with an emphasis on cheap, quick lunch options, skewed toward the student lunch crowd.

PEARL STREET MALL

This pedestrian mall at the heart of downtown Boulder contains the highest concentration of restaurants, with more fine dining spots than other neighborhoods.

29TH STREET MALL

The Twenty Ninth Street mall has a number of shops and restaurants, with the latter skewed more towards fast food and fast casual dining. In addition, there are many restaurants on or near Arapahoe Ave, especially near Folsom and 28th Streets.

Program Overview & Summary

MONDAY: JULY 31, 2017

8:00	Registration open[1]
8:50	*Welcome*
9:10	**Metrology I**
10:20	*Coffee Break*
10:50	**Applications I**
12:00	*Lunch*
13:30	**Detectors I**
15:00	*Coffee Break*
15:30	**Integration I**
16:45	**Reception & Poster Session**
19:15	*End*

TUESDAY: AUGUST 1, 2017

8:30	**Applications II**
10:00	*Coffee Break*
10:30	**Metrology II**
12:00	*Lunch*
13:20	*Exhibit-Only Time*
14:20	**Sources I**
15:10	*Coffee Break*
15:40	**Sources II**
17:10	*End*
19:00- 21:30	**Short lecture course**[4] *Single-photon metrology and its application to quantum technologies*

WEDNESDAY: AUGUST 2, 2017

8:30	**Detectors II**
10:00	*Coffee Break*
10:30	**Applications III**
12:00	*Lunch*
13:40	**Integration II**
14:30	*Group Picture, Coffee Break & Exhibit-Only time*
15:40	**Metrology III**
17:20	*End*
18:00 – 21:00	**Conference Dinner, Boulder Casual:** *Food Trucks & Craft Beer*

THURSDAY: AUGUST 3, 2017

8:30	**Quantum Measurements**
10:00	*Coffee Break*
10:30	**Imaging**
12:00	*Lunch*
13:30	**Sources III**
15:00	*Coffee Break*
15:30	**Detectors III**
17:00	*Closing remarks*

FRIDAY: AUGUST 4, 2017

8:00	**NIST lab tours pickup at UMC**[4]
9:15	*Welcome*
9:30	**Lab tours**[4]
12:00	*Lunch*[2]
13:00- 15:30	*Single Photon Radiometry and Discussion Forum on Few Photon Metrology*[3,4]

[1]The registration desk will be open throughout the workshop from 8:00 – 17:00.

[2]We will have buses back to the UMC for attendees leaving after lunch

[3]We will have buses back to the UMC for attendees attending the Single Photon Radiometry Forum

[4]Prior sign-up required. See "Workshop Satellite Meetings" section for more detail.

Monday: July 31, 2017

8:00	Registration open	
8:50	Thomas Gerrits Marla Dowell	*Welcome*
Metrology I		Alan Migdall
9:10	Carl Williams (Invited) *NIST-Gaithersburg*	*A Federal Perspective on Single Photon Metrology and Technology*
9:40	Ingmar Müller *PTB-Berlin*	*Bilateral Comparison of Calibration Methods for Photon-Counting Detection Efficiency between NIST and PTB using Superconducting Nano-wire Single Photon Detectors*
10:00	Christopher Chunnilall *NPL*	*Metrology for characterizing single photon technologies*
10:20	**Coffee break**	
Applications I		John Lehman
10:50	Alipasha Vaziri (Invited) *Rockefeller University*	*Visual Perception at the threshold*
11:20	Jeff Shainline *NIST-Boulder*	*Photonic signaling and superconducting detectors for large-scale neuromorphic computing*
11:40	Matt Shaw *JPL*	*Superconducting nanowire single photon detectors for deep space optical communication*
12:00	**Lunch**	
Detectors I		Marty Stevens
13:30	Robert Hadfield (Invited) *University of Glasgow*	*Infrared single-photon detection with superconducting nanowires*
14:00	Gabrielle Bulgarini *Single Quantum*	*Single-photon detection with near unity efficiency, ultra-high detection rates, and ultra-high time resolution*
14:20	Boris Korzh *JPL*	*Single photon detection with a system temporal resolution below 10 ps*
14:40	Prasana Ravindran *UMass-Amherst*	*Active Quenching of Superconducting Nanowire Single Photon Detectors*
15:00	**Coffee break**	***Sponsored by: Sumitomo Cryogenics of America***
Integration I		Rich Mirin
15:30	Hong Tang (Invited) *Yale University*	*Photon pair generation and detection on silicon chips*
16:00	Cale Gentry *University of Colorado*	*Single-chip source of photon pairs with integrated pump rejection*
16:20	Evan Meyer-Scott *University of Paderborn*	*A plug & play single photon source with high heralding efficiency, and application to purity-efficiency tradeoff under spectral filtering*
16:45-19:15	Reception & Poster Session	

Tuesday: August 1, 2017

Applications II		Chris Chunnilall
8:30	Andrew Shields (Invited) *Toshiba-Cambridge*	*A Universal Transmitter for Quantum Communications*
9:00	Morgan Weston *Griffith University*	*Heralded quantum steering over a high-loss quantum channel*
9:20	Catherine Lee *MIT*	*High-dimensional quantum state transfer over deployed fiber*
9:40	Christoph Simon *University of Calgary*	*Single photons for quantum networks, macroscopic quantum effects, and neuroscience*
10:00	**Coffee break**	***Sponsored by:*** Photon Spot
Metrology II		Malcom White
10:30	Stefan Kück (Invited) *PTB-Braunschweig*	*Single-photon sources and detectors for quantum radiometry*
11:00	Glenn Solomon *NIST/JQI*	*Simultaneous, full characterization of a single-photon state*
11:20	Vaigu Aigar *VTT*	*Experimental demonstration of a predictable single photon source with variable photon flux*
11:40	Beatrice Rodiek *PTB-Braunschweig*	*Metrological realization of an absolute single-photon source based on a nitrogen-vacancy center in nanodiamond*
12:00	**Lunch**	
13:20	Exhibit-Only Time	
Sources I		Krister Shalm
14:20	Jelena Vuckovic (Invited) *Stanford University*	*Quantum Light Generation with Quantum Dot - Cavity QED systems*
14:50	Carlos Antón *CNRS*	*Efficient single photon sources in the solid-state*
15:10	**Coffee break**	
Sources II		Krister Shalm
15:40	Lorenzo De Santis *CNRS*	*Single-photon Fock-state filtering with an artificial atom*
16:00	Maria Chekhova (Invited) *Max-Planck Institute*	*Towards photon triplet generation through a direct cubic nonlinear effect*
16:30	Mike Reimer *University of Waterloo*	*New nanoscale source of bright entangled photon pairs*
16:50	Gregor Weihs *University of Innsbruck*	*Three Photons – Efficient and Interfering*
19:00- 21:30	***Short lecture course*** 'Single-photon metrology and its application to quantum technologies' Course organized by the European Metrology Program for Innovation and Research project 'Optical metrology for quantum-enhanced secure telecommunication (14IND05)'	

Wednesday: August 2, 2017

Detectors II		Varun Verma
8:30	Karl Berggren (Invited) *MIT*	*Transmission-Line Superconducting Nanowire Single-Photon Detectors: Imagers and Coincidence Counters*
9:00	Félix Bussières *University of Geneva*	*Amorphous MoSi SNSPDs with a low time jitter and a high detection efficiency*
9:20	Daniel Slichter *NIST-Boulder*	*UV-sensitive SNSPDs for integration in an ion trap quantum processor*
9:40	Zhaohui Li *E China Normal Univ*	*Multi-beam laser imaging with 100-channel single-photon detector*
10:00	**Coffee break**	***Sponsored by:*** Becker & Hickl, BostonElectronics
Applications III		Oliver Slattery
10:30	Hugo Zbinden (Invited) *University of Geneva*	*Quantum-enabled applications*
11:00	Peter Bierhorst *NIST-Boulder*	*Device-Independent Random Number Generation with Photons*
11:20	Ivo Degiovanni *INRIM*	*Inferring the fairness of a quantum coin with a single (detected) toss*
11:40	Aitor Villar *National U of Singapore*	*Photons in space: a demonstration and a roadmap for satellite QKD*
12:00	**Lunch**	
Integration II		Thomas Gerrits
13:40	Dirk Englund (Invited) *MIT*	*Large Scale Photonic Integrated Circuits for Quantum Information Science and Machine Learning*
14:10	Sonia Buckley *NIST-Boulder*	*Low-temperature waveguide coupled Si LEDs and superconducting nanowire detectors*
14:30	**Group Picture, Coffee break & Exhibit-Only time**	
Metrology III		Ingmar Müller
15:40	Sergey Polyakov *NIST-Gaithersburg*	*Characterizing single-photon detectors within a second-order model and beyond*
16:00	Hugo Ferretti *University of Toronto*	*Beating Rayleigh's Curse Using SPLICE*
16:20	Jean-Philippe MacLean *University of Waterloo*	*Experimental observation of ultrafast biphoton correlations with energy-time entanglement*
16:40	Animesh Datta *University of Warwick*	*New aspects of quantum-optical sensing: multiple parameters & covertness*
17:00	Ivan Burenkov *NIST/JQI*	*Quantum Coherent Spectrometer: frequency discrimination below the standard quantum limit*
18:00	Conference Dinner, Boulder Casual: Food Trucks and Craft Beer	

Thursday: August 3, 2017

Quantum Measurements		Omar Magana-Loaiza
8:30	Andrew White (Invited) *University of Queensland*	*Manifold single photons and their many uses*
9:00	Geoff Pryde *Griffith University*	*Unconditional shot noise limit violation in photonic quantum metrology*
9:20	Alex Jones *University of Oxford*	*Many-photon distinguishability and unambiguous characterization of multiport interferometers*
9:40	Michael Mazurek *University of Waterloo*	*Quantum-free state and measurement tomography*
10:00	**Coffee break**	***Sponsored by:*** PicoQuant
Imaging		Sae Woo Nam
10:30	Eric Fossum (Invited) *Dartmouth College*	*Photon-Number-Resolving Quanta Image Sensor*
11:00	Joshua Rapp *Boston University*	*Unmixing Signal and Noise for Photon-Efficient Active Imaging*
11:20	Davide Portaluppi *Politecnico di Milano*	*Monolithic CMOS SPAD array with gating, timing electronics and photon-coincidence detection for 3D-ranging*
11:40	Richard Younger *MIT-Lincoln Labs*	*Crosstalk Elimination in Infrared Geiger-mode Avalanche Photodiode Arrays*
12:00	**Lunch**	
Sources III		Alessandro Farsi
13:30	John Rarity (invited) *University of Bristol*	*Spins and photons*
14:00	Fumihiro Kaneda *University of Illinois*	*Memory-assisted time multiplexing for efficient multi-photon generation*
14:20	Morgan Mastrovich *University of Waterloo*	*Spectral manipulation of entangled photons with an upconversion time lens*
14:40	Till Weinhold *University of Queensland*	*Sub-Megahertz Linewidth Single Photon Source Suitable for Quantum Memories*
15:00	**Coffee break**	
Detectors III		Joshua Bienfang
15:30	Seth Bank (Invited) *University of Texas*	*Emerging Semiconductor Single Photon Counters*
16:00	Bernicy Fong *Excelitas Technologies*	*Transit time, timing jitter and time walk in SLiK APD – measurement and implication for single photon counting applications*
16:20	Alberto Gola *FBK, Trento*	*Overview of Silicon Photomultipliers Developed at FBK*
16:40	Hesong Xu *FBK, Trento*	*Detecting entangled photons using CMOS SPAD arrays*
17:00	Closing remarks	

Friday: August 4, 2017 NIST Lab Tours

8:00	NIST lab tours pickup at UMC		
9:15	Welcome		
9:30	Lab Tours		
12:00	**Lunch**	***Sponsored by:***	Quantum Opus
13:00-15:30	CCPR WG-SP TG 11 Stefan Kück (*PTB*) and Dong-Hoon Lee (*KRISS*)	*Single Photon Radiometry and Discussion Forum on Few Photon Metrology*	

Monday, July 31 2017

Metrology I

9:10 – 10:20

Session Chair: Alan Migdall

9:10 ***INVITED***	Carl Williams *NIST-Gaithersburg*	***A Federal Perspective on Single Photon Metrology and Technology***
9:40	Ingmar Müller *PTB-Berlin*	***Bilateral Comparison of Calibration Methods for Photon-Counting Detection Efficiency between NIST and PTB using Superconducting Nano-wire Single Photon Detectors***
10:00	Christopher Chunnilall *NPL*	***Metrology for characterizing single photon technologies***

A Federal Perspective on Single Photon Metrology and Technology

Carl J. Williams[1]
[1]*Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899-8400, USA*

This talk will provide a NIST centric view of the United States governments interest in quantum information science with a specific focus on single photon metrology and its relevance to quantum based measurements, the potential redefinition of the candela, and future technologies. The talk will begin with a high-level overview of the ongoing activities within the United States government to coordinate quantum information science. The talk will then turn towards single photon sources and detectors and how they enable everything from the redefinition of the candela to physically guaranteed sources of random numbers. It will conclude with exploring ongoing and future metrological applications followed by some hypothetical conjectures of future technological applications.

Bilateral Comparison of Calibration Methods for Photon-Counting Detection Efficiency between NIST and PTB using Superconducting Nano-wire Single Photon Detectors

I. Mueller[1], R.D. Horansky[2], R.M. Klein[1], J.H. Lehman[2], S.W. Nam[2], I. Vayshenker[2], L. Werner[1], and M. White[2]

[1] *Physikalisch-Technische Bundesanstalt, Berlin, Germany*

[2] *National Institute of Standards and Technology, Boulder, Co, USA*

Three different calibration methods for fiber-coupled single photon detectors that are traceable to cryogenic radiometers of NIST and PTB have been compared. The results agree within their uncertainties. However, fiber connection and coupling issues were found to have a dominant influence on the calibration result and are excluded from the uncertainties that are related to the calibration methods.

Several radiometric calibration methods for single photon detectors, traceable to the International System of Units, have been described [1-7]. In recent years the achievable relative standard uncertainties were improved. For free-space detectors uncertainties as low as 0.16~\% have been reported. For fiber-coupled single photon detectors radiometric calibrations with approximately 2~\% relative standard uncertainty have been shown [5]. However, in order to become a mature and well standardized technology, the equivalence of the different calibration methods has to be shown. In this sense, the verification of repeatability, consistency and accuracy of every radiometric calibration method is crucial for the development of customer-available quantum radiometry. Here, three different calibration techniques have been compared using superconducting nano-wire detectors (SNSPDs) as transfer standards. Two methods are traceable to a cryogenic radiometer of NIST, namely the direct-substitution method [9] and the calibrated-attenuator method [1]. The third calibration method is traceable to a cryogenic radiometer of PTB and uses the unique properties of synchrotron radiation [5,8].

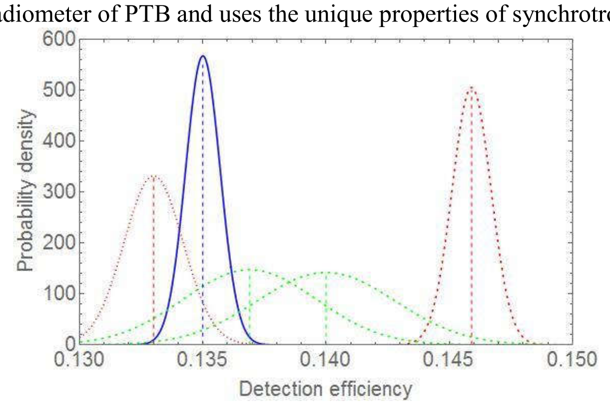

Fig 1. Measured detection efficiency of a commercial superconducting nano-wire single photon detector at approximately 1550 nm. The detection efficiencies were obtained by means of the calibrated attenuator method (blue curve) at 1547 nm, direct-substitution method (red curves) at 1547 nm, and the synchrotron method (green curves) at 1552 nm.

The varying fiber-connector losses, however, turned out to have a dominant influence on the calibration. While this problem can be easily overcome by fiber splicing this is not always possible when a customer detector is calibrated and, hence, fiber connector losses remain an issue. Superconducting nano-wire detectors proved to be close to ideal transfer standards as they combine high detection efficiency, low dark count rates, can be operated in free running mode and achieve maximum count rates up to 100 MHz and higher. The polarization dependence of the detection of most SNSPD systems may be a liability, but the control of the polarization states is necessary in any case to minimize the influence of polarization dependent losses. In this talk I will discuss the results and uncertainty budgets of the different techniques.

References

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Metrology for characterizing single-photon technologies

Christopher Chunnilall[1]
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Abstract. Physical characterisation is important in assessing the security claims of practical QKD systems. NPL has developed techniques to perform single-photon metrology of the quantum-optical layer in such systems. This is presently being applied to hardware developed and implemented by the UK Quantum Communications Hub. This work points to standardized measures to verify the claimed performance of quantum optical technologies.

Quantum key distribution (QKD) systems and quantum random number generators (QRNGs) are two of the most commercially-advanced quantum optical technologies operating in the single-photon regime. Ensuring and demonstrating the security of the keys distributed by QKD systems is essential to assure a spectrum of interested parties such as procurement, security and compliance specialists within a service provider, as well as end customers.

The UK Quantum Technology Hub for Quantum Communications [1] **is** a partnership of UK academic researchers, private sector companies and public sector bodies that aims to deliver quantum encryption systems for a range of users in real-world applications. NPL's role within this program is to develop accurate single-photon measurement techniques and instrumentation for calibrating the hardware. This capability will contribute to establishing an assurance process for quantum communications in the UK. Alongside this, NPL contributes to the development of relevant industrial standards via the Industry Specification Group on QKD of the European Telecommunication Standards Institute (ETSI ISG-QKD) [2], and a pan-European effort to develop metrology for QKD [3].

In earlier work, we performed traceable characterization of the transmitter ('Alice') and receiver ('Bob') modules of weak-laser-pulse BB84 QKD systems, which operated at clock rates up to 1 GHz over optical fibre in the 1550 nm telecommunications band. This capability is now being extended to address on-chip components and transmitters which can implement BB84, COW and DPS protocols at clock rates above 1 GHz [4]; furthermore, it is being developed to cater for metrology of short-range free-space devices in the visible wavelength range, as well as for optical fibre systems which are being installed on the UK Quantum Network.

For accurate metrology, the relevant instrumentation is synchronized to the QKD transmitter pulse or the detector gate with low jitter (< 10 ps r.m.s.). Transmitter properties that can be measured include the mean photon number(s), temporal bandwidth and jitter of the single-photon pulses, as well as their spectral content which may provide distinguishing information that can be utilised by an eavesdropper. Measures for receivers include the dark count probability, after-pulse probability and detection efficiency of the single-photon detectors within. The spectral and temporal distinguishability of the single-photon detectors can also be measured.

Instrumentation and techniques for various metrics will be described; these will be illustrated by way of measurements on several optical components use in QKD systems. This work will continue to inform standardisation initiatives.

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Monday, July 31 2017

Applications I

10:50 – 12:00

Session Chair: John Lehman

10:50 ***INVITED***	Alipasha Vaziri *Rockefeller University*	***Visual Perception at the threshold***
11:20	Jeff Shainline *NIST-Boulder*	***Photonic signaling and superconducting detectors for large-scale neuromorphic computing***
11:40	Matt Shaw *JPL*	***Superconducting nanowire single photon detectors for deep space optical communication***

Visual Perception at the threshold

Alipasha Vaziri
Laboratory of Neurotechnology and Biophysics, Kavli Neural Systems Institute
The Rockefeller University, New York, NY, United States

Optical technologies have been transformative for our current understanding of structure and function of neuronal circuits underlying behavior and are in many cases the limiting factors for pushing our understanding of the brain forward.
In vision science despite of investigations for over seventy years, the absolute limits of human vision have remained unclear. Rod cells have been shown to respond to individual photons, yet whether this information is processed by the brain and is accessible on the behavioral level has remained a fundamental open question. We have recently been able to show that humans can report a single photon incident on the eye with an above chance probability [1]. This was achieved by combining a two-alterative forced choice psychophysics procedure with a single photon source base on Type-I Spontaneous Parametric Down-Conversion (SPDC), a tool that allows to eliminate the irreducible variability of photon numbers in previous experiments. Furthermore, we found that the probability for reporting a single photon is modulated by the presence of an earlier photon. Our results and other applications of this tool may open up fundamentally new avenues for investigating yet undiscovered retinal pathways using quantum technologies and may find applications in fundamental tests of quantum mechanics using human observers.

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Photonic signaling and superconducting detectors for large-scale neuromorphic computing

Jeffrey M. Shainline[1], Sonia M. Buckley[1], Adam N. McCaughan[1], Jeffrey Chiles[1], Richard P. Mirin[1], and Sae Woo Nam[1]

[1] *National Institute of Standards and Technology, Boulder, Colorado, USA*

Advanced neuromorphic systems require massive interconnectivity, extreme energy efficiency, and complex signaling mechanisms. Here we propose an integrated optoelectronic platform utilizing superconducting electronics with photonic signaling to enable neuromorphic computing beyond the scale of the human brain.

In neuromorphic systems, information is encoded in a temporal sequence of pulses. Neurons in the brain make thousands of connections in order to identify a large number of patterns in pulse trains. This method of information encoding is energy efficient, resilient to noise, and has high bandwidth. However, such massive connectivity places severe demands on interconnectivity in neuromorphic hardware. Light is an excellent candidate for massive interconnectivity between artificial neurons due to its non-interacting, bosonic nature. In an integrated-photonic environment, fanout can be implemented without an *RC* penalty. In addition, communication with photons provides access to degrees of freedom such as frequency, polarization, and mode order which can be used for information encoding.

To achieve neuromorphic systems on the scale of the human brain, 10^{11} neurons are required. Any hardware platform hoping to operate at this scale must utilize devices with extreme energy efficiency. Yet many integrated photonic detectors draw power in the steady state and require large input power to operate with a useful signal-to-noise ratio. However, superconducting-nanowire single-photon detectors (SNSPDs) are capable of detecting single quanta of light with greater than 90% efficiency. These detectors can be easily integrated with room-temperature-deposited nanophotonic waveguides in a scalable process [1]. The use of superconductors leads to energy efficiency both by minimizing static power dissipation as well as by enabling few-photon signals. We are therefore motivated to pursue neuromorphic systems combining superconducting electronics with photonic signaling to achieve massive connectivity with extreme energy efficiency [2].

The basic neuronal device of the superconducting optoelectronic platform combines an an array of SNSPDs in parallel with a light-emitting diode (LED). The LED must be compact to minimize capacitance, and should be integrated with a nanophotonic waveguide. Hybrid III-V emitters or point defects in silicon can be used for this purpose. The signals from upstream neurons must be collected and combined on the SNSPD receiver array.

A principal advantage of photonic signaling is the potential to achieve massive fanout and routing without incurring *RC* parasitics and power penalties. Two important devices make this fanout and routing possible: directional couplers and waveguide crossings. To create one-to-many directional couplers, deposited photonic planes can be independently patterned, leading to devices that couple light both laterally and vertically. This can be done with either amorphous silicon or silicon nitride [1]. A device utilizing three waveguiding planes can split light from a central waveguide to nine output ports. Coupling a neuron to roughly 700 downstream neurons appears feasible with these devices, and to accomplish this, three such one-to-nine splitters can be cascaded. Synaptic weights can be modified using mechanically mobile waveguides or electronic means based on Josephson circuitry.

Multi-plane photonic couplers are useful for massive fanout, but if one wishes to utilize a small number of waveguiding planes (on the order of 10), intra-plane waveguide crossings [3] are still required for routing. Such waveguide crossings have been implemented with 0.02 dB/crossing, leading to the potential for massive connectivity between photonic neurons.

The fanout, routing, and complex signaling operations required by neuromorphic computers are greatly facilitated by the physics of light. It is sensible to base a neuromorphic architecture around photonic signals. Having made this decision, superconducting electronics offer excellent performance for both detecting photons and biasing the circuitry with minimal steady-state power dissipation. A platform combining superconductors and light appears promising for implementing large-scale neuromorphic computing with massive connectivity and extreme energy efficiency. Estimates comparing the proposed hardware platform to a human brain show that with the same number of neurons (10^{11}) and 700 independent connections per neuron, the hardware presented here may achieve an order of magnitude improvement in synaptic events per second per watt.

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Superconducting nanowire single photon detectors for deep space optical communication

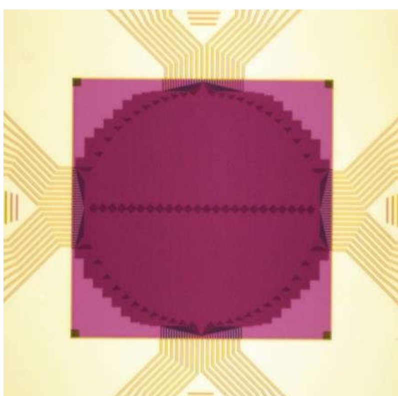
J. Allmaras[1], F. Marsili[2], A. Beyer[2], R. Briggs[2], A. Velasco[2], and M. Shaw[2]

[1]*Applied Physics, California Institute of Technology, Pasadena CA 91125 USA*

[2]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109 USA*

The Deep Space Optical Communication (DSOC) project is a NASA-funded technology demonstration mission which will represent the first true bidirectional optical communication experiment from deep space [1]. With a flight transmitter on the PSYCHE spacecraft and a downlink receiver at the 200-inch Palomar telescope, the DSOC system is designed to support downlink data rates of 0.2 to over 200 Mbps at ranges of 0.1 to 2 astronomical units. We report on the development of a 64-pixel tungsten silicide superconducting nanowire single photon detector (SNSPD) array with a 320 µm diameter active area which is suitable for the DSOC ground receiver. We are targeting a free-space coupled device with >50% system detection efficiency at 1550 nm, 100 ps time resolution, gigacount-per-second saturation rates, and background-limited false count rates below 1 Mcps, with negligible crosstalk and afterpulsing.

SNSPDs are the highest performance single-photon detectors available in the infrared, with unmatched efficiency, saturation rates, false count rates, and time resolution. SNSPDs have previously been fielded in ground terminals for the Lunar Laser Communication Demonstration [1,2] and are widely used in quantum optics experiments. Based on single-pixel fiber-coupled WSi SNSPDs developed collaboratively at JPL and NIST [3], we have developed a 64-pixel WSi SNSPD array suitable for use in the ground receiver for the DSOC project. To efficiently couple the focal plane array to the 5-meter telescope aperture in the presence of atmospheric disturbance and to accommodate fast beam centroiding, we have developed a free-space coupled 320-µm diameter focal plane array divided into four spatial quadrants, with 16 co-wound nanowires per quadrant. The WSi nanowires are embedded in a front-side illuminated quarter-wave optical stack to enhance absorption. In this presentation, we share the most recent results on SNSPD array development for the DSOC project, as well as provide an overview of the DSOC project and the design of the ground receiver.



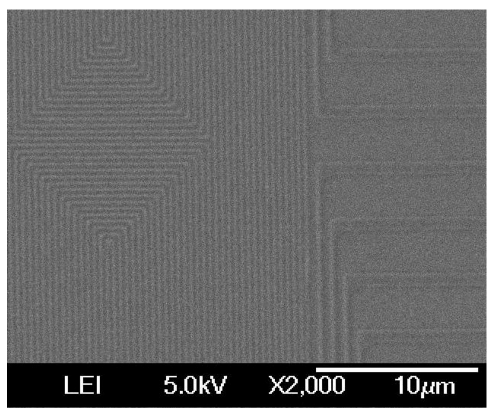


Figure 1. (Left) Optical microscope image of a prototype 64-pixel SNSPD array. The round active area has a diameter of 320 µm, all of which is photosensitive. (Right) A scanning electron microscope image showing the co-wound meandering nanowire structure. Each quadrant of the focal plane array contains 16 meandering nanowire sensor elements.

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Monday, July 31 2017

Detectors I

13:30 – 15:00

Session Chair: Marty Stevens

13:30 *INVITED*	Robert Hadfield *University of Glasgow*	***Infrared single-photon detection with superconducting nanowires***
14:00	Gabrielle Bulgarini *Single Quantum*	***Single-photon detection with near unity efficiency, ultra-high detection rates, and ultra-high time resolution***
14:20	Boris Korzh *JPL*	***Single photon detection with a system temporal resolution below 10 ps***
14:40	Prasana Ravindran *UMass-Amherst*	***Active Quenching of Superconducting Nanowire Single Photon Detectors***

Infrared single-photon detection with superconducting nanowires

R. H. Hadfield, R. M. Heath, N. R. Gemmell, A. Casaburi

School of Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom

Abstract. Single photon detectors based on superconducting nanowires have emerged as a highly promising alternative for single-photon detection [1]. These devices offer single photon sensitivity from visible to mid infrared wavelengths with high efficiency, low dark counts and tens of picoseconds timing resolution. Major avenues of development include scale up from single pixel SNSPDs to large area arrays, integration with optical waveguides and nanoantennas [2,3]. At the University of Glasgow, Scotland, we are employing novel superconducting materials and advanced nanofabrication techniques to realize these designs [figure 1 (a),(b)]. We are using a suite of advanced characterization tools, including low temperature photoresponse mapping to characterize these devices from near to mid infrared wavelengths. In tandem our group is addressing the challenge of practical device operation at cryogenic temperatures. We have recently partnered with STFC Rutherford Appleton Laboratory to realize a miniaturized 4 K cooling platform for SNSPDs [figure 1 (c)]. In collaboration with UK and international partners we are deploying SNSPDs in a wide range of advanced photon counting applications. Recent examples implementations include quantum communication networks [4], on-chip quantum information processing [5], single photon remote sensing [6] and singlet oxygen luminescence dosimetry for photodynamic therapy in the treatment of cancer [7].

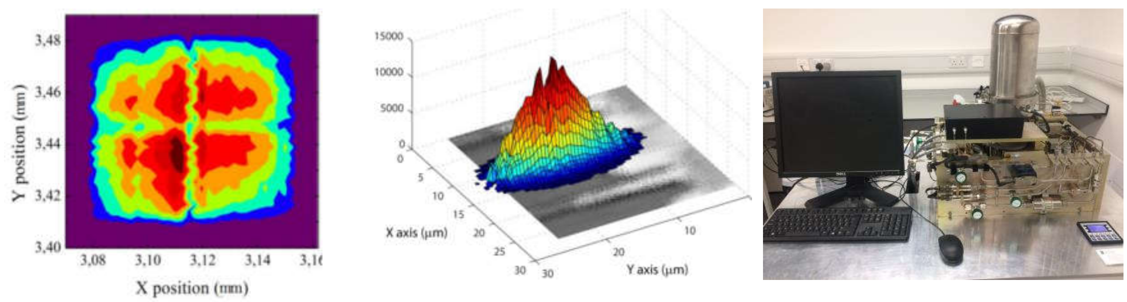

Fig 1. SNSPD development at the University of Glasgow (a) photoresponse map of 60 µm x 60 µm area four-pixel SNSPD array with peak detection efficiency >40%. (b) waveguide integrated SNSPD (c) miniaturized 4 K cooler for SNSPDs

Acknowledgements

We acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC) including the UK Quantum Technology Hub in quantum enhanced imaging (QuantIC) and the European Research Council (ERC) through a Consolidator Grant award (IRIS 648604).

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Single-photon detection with near unity efficiency, ultra-high detection rates, and ultra-high time resolution

Iman Esmaeil Zadeh[1] , Johannes W.N. Los[1], Ronan B.M. Gourgues[1], Violette Steinmetz[1], Sergiy M. Dobrovolskiy[1], G. Bulgarini[1],* Val Zwiller[2] and Sander N. Dorenbos[1]

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Abstract

Single-photon detectors with high efficiency, high time resolution, low dark counts and high photon detection-rates are indispensable elements of quantum optics experiments. Combining all performances in a single device has been a long time challenge. Here, we demonstrate a broadband detector with an efficiency higher than 92%, over 150 MHz photon detection-rate and dark counts below 130 Hz operated in a conventional Gifford-McMahon cryostat. Furthermore, using our custom made cryogenic amplifiers and optimized detector, we reach record low jitter below 10 ps. Remarkably, high time resolution and high efficiency are obtained simultaneously.

We present superconducting single photon detectors fabricated from NbTiN film, with a thickness of 8.4nm, on top of gold mirrors. The nanowire width is 50 nm and the filling factor is optimized to 0.44. SEM and optical pictures of a device are shown in Figure 1(a). For the wavelength of 1310nm, the efficiency curve saturates at 92.3 ± 4.2 %. The efficiency of SNPDs at their maximum detection-rate can be influenced not only by their recovery time constant (defined as the ratio of the kinetic inductance of the SNSPD to the readout impedance) but also by the charging and discharging of the readout capacitance. To improve the high detection-rate performance of our detectors, we used a resistive network between the detectors and the readout capacitor, similarly to [1]. As a result, a count rate up to 150 MHz is reached together with high efficiency. Moreover, we demonstrate by using cryogenic amplification integrated within the cryostat a record timing jitter below 10 ps.

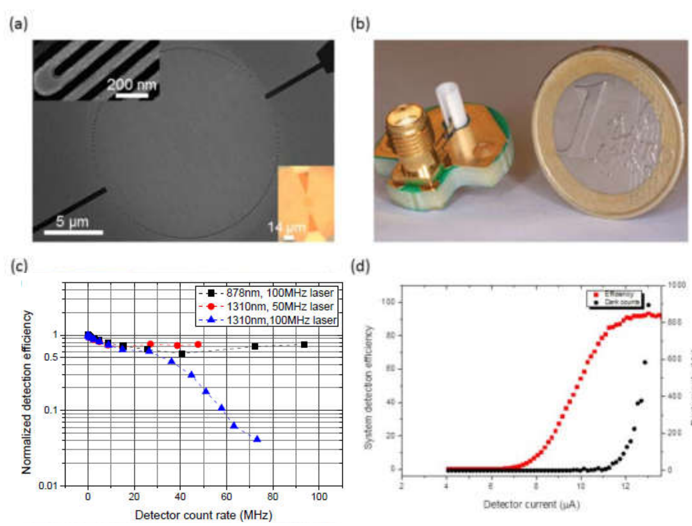

Figure.1 (a) An SEM image of a fabricated SNSPD. (b) A typical detector mount, the chips are fixed in FC mating sleeve. (c) Efficiency versus detection-rate under pulsed excitations for different count rates. (d) The efficiency curve of the studied detector. The detector reaches >92% system detection efficiency in the telecom range.

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Single photon detection with a system temporal resolution below 10 ps

Boris Korzh[1], Qing-Yuan Zhao[2], Garrison Crouch[1], Andrew E. Dane[2], Peter Day[1], Simone Frasca[1], Emma Wollman[1], Karl K. Berggren[2] and Matthew Shaw[1]

[1]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*

[2]*Massachusetts Institute of Technology, Cambridge, MA, USA*

Detecting the arrival time of single photons is a critical requirement of many applications such as optical communication, biological imaging, spectroscopy, laser ranging, astronomical observation as well as quantum communication and information processing. Among the various single photon detector technologies, superconducting nanowire single photon detectors (SNSPDs) have demonstrated the lowest temporal resolution of 18 ps [1-2]. Despite the relative maturity of the SNSPD technology, the origin of the temporal jitter, which characterizes the uncertainty in the arrival time of the photon, is a topic of ongoing research.

Recently, we took an important step forward by demonstrating that superconducting nanowires act like a high impedance transmission line with velocities of just a few percent of the speed of light in vacuum [3-4]. Since SNSPDs form a long meandering nanowire, this leads to a delay of the readout signal, which depends on the position of the photon absorption. This effect is referred to as the geometric jitter, and it can become the dominant effect, especially for large area devices. The second contribution is known as the noise jitter, arising due to a finite slew rate of the readout signal and the presence of electrical noise. This can be reduced by fabricating SNSPDs with an increased switching current or reducing the noise of the readout electronics. Finally, the detection mechanism of the SNSPD will introduce an intrinsic jitter contribution. To date, the two former effects have been the dominant contributions, making it impossible to study the intrinsic jitter.

We have reduced the noise contribution by using a broadband cryogenic amplifier with a noise temperature of 9 K, whilst the geometric jitter has been reduced by fabricating NbN devices with very short nanowire sections. The combination of these developments has yielded a system temporal jitter of 6.3 ps (Fig. 1a), which is a factor 3 lower than the previous record [1]. The bias current dependence of the jitter, Fig. 1b, reveals a scaling which cannot be explained by the noise jitter variations alone, indicating that we are probing the intrinsic jitter of the nanowires, for the first time. By studying different nanowire geometries, we are able to investigate devices with and without the saturation of the detection efficiency and the effect this has on the timing jitter, which has been an open question in the community. Our results demonstrate that SNSPDs have not reached their maximum potential in terms of temporal resolution and we have taken an important step towards understanding the origin of this characteristic. This work also opens up a new tool in the study of the detection mechanism, since it gives access to information regarding the early stages of the hotspot formation. Work is ongoing to reduce the noise contribution to the jitter even further in order to understand the fundamental limits.

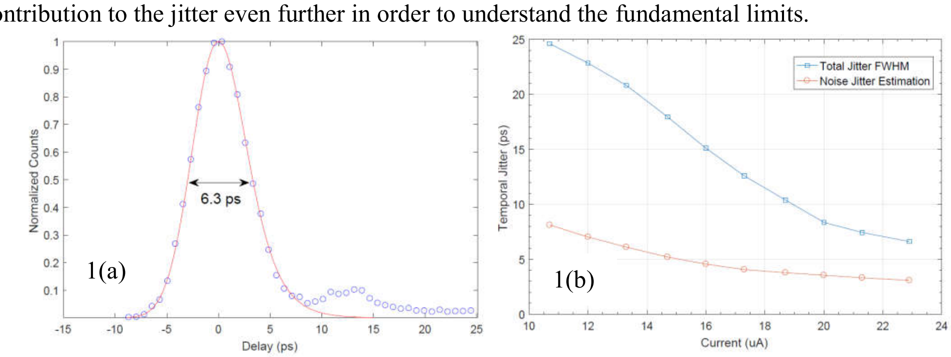

Fig 1. (a) System instrument response function demonstrating a full-width at half-maximum value of 6.3 ps. (b) Bias current dependence of the system jitter as well as the noise jitter contribution in the system.

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Active Quenching of Superconducting Nanowire Single Photon Detectors

P. Ravindran and J. C. Bardin

University of Massachusetts Amherst, Amherst, MA 01003, USA

While superconducting nanowire single photon detectors (SNSPDs) have received significant attention due to their excellent timing resolution, low jitter, low dark count rates, and high detection efficiency, limited research has focused on the optimization of bias and readout schemes for these devices. Today, SNSPDs are universally biased using a passive quenching scheme. In such an approach, the bias current is shunted through a resistive load while the device returns to the superconducting state, resulting in a voltage pulse with an approximate amplitude of $I_B R_L$, where I_B is the nanowire bias current and R_L is the load resistance. To maximize the amplitude of this pulse and to minimize the reset time, one would want to maximize the load resistance [1]. However, the maximum resistance that may be employed is ultimately limited by the thermal time constant of the device, as too short of an electrical time constant ($\tau_e = L_K/R_L$, where L_K is the kinetic inductance) results in a latching behavior, where the nanowire settles with a self-heating hot spot and the bias must be cycled to reset the device to the superconducting state [2]. Typically, this maximum resistance is over an order of magnitude smaller than the peak value of the normal domain resistance (R_N), meaning that the realized voltage swings are significantly smaller than what could be achieved if an open-circuit load could be driven. Improving these swings could improve jitter performance and reduce system complexity.

Here, we present an active quenching scheme in which the SNSPD is terminated in a high-impedance load and the bias current is cycled after a detection event is sensed. The basic architecture that we have implemented is shown in Fig. 1(a). The SNSPD is biased through a resistive current source, and the voltage across the SNSPD is sensed using an on-chip comparator. Once this voltage exceeds a defined threshold, a reset signal is generated and the current through the nanowire is abruptly shut off. Finally, after a time delay, the current is turned back on with a defined profile. Not shown in Fig. 1(a) is an optional de-Q resistor that can be switched into the circuit to reduce ringing during the re-biasing operation. The circuit was designed using a co-simulation that incorporated our own custom Verilog-A SNSPD models. In our SiGe BiCMOS implementation, resistors R_1 and R_2 as well as the recovery delay (D_1) and a de-Q resistor (not shown) are all digitally programmable using a serial programming interface. A photograph of the die as well as the device directly bonded to an SNSPD appears in Fig. 1(b). The circuit has been measured and the core electronics consume just 100 µW. Example detection waveforms appear in Fig. 1(c). During this presentation, detailed design considerations and measurement results will be shown.

Acknowledgement: We thank H. Tang and R. Cheng for providing SNSPD devices. This work was partially supported by NSF grant CCCS-1351744, ONR grant N00014-15-1-2417, and DARPA grant W911NF-16-2-0151.

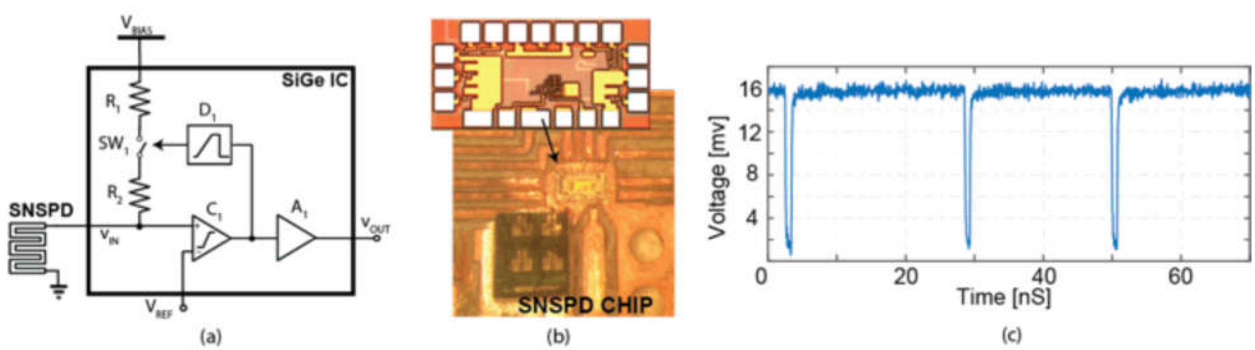

Figure 1: (a) Block diagram of proposed approach, (b) photograph of SiGe IC (top) and SiGe IC directly bonded to SNSPD chip, and (c) measured detection waveform V_{OUT} for a detector at 2.8 Kelvin.

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Integration I

15:30 – 16:40

Session Chair: Rich Mirin

15:30 ***INVITED***	Hong Tang *Yale University*	***Photon pair generation and detection on silicon chips***
16:00	Cale Gentry *University of Colorado*	***Single-chip source of photon pairs with integrated pump rejection***
16:20	Evan Meyer-Scott *University of Paderborn*	***A plug & play single photon source with high heralding efficiency, and application to purity-efficiency tradeoff under spectral filtering***

Photon pair generation and detection on silicon chips

Hong Tang

[1]*Department of Electrical Engineering, Yale University, New Haven, CT 06520*

Quantum photonic chips, which integrate quantum light sources alongside active and passive optical elements, as well as single photon detectors, show great potential for photonic quantum information processing and quantum technology. Mature semiconductor nanofabrication processes allow for scaling such photonic integrated circuits to on-chip networks of increasing complexity. Second order nonlinear materials are the method of choice for generating photonic quantum states in the overwhelming part of linear optic experiments using bulk components but integration with waveguide circuitry on a nanophotonic chip proved to be challenging.

Here we demonstrate such an on-chip parametric down-conversion source of photon pairs based on second order nonlinearity in an Aluminum nitride microring resonator. We show the potential of our source for quantum information processing by measuring high-visibility antibunching of heralded single photons with nearly ideal state purity. Our down conversion source operates with high brightness and low noise, yielding pairs of correlated photons at MHz-rates with high coincidence-to-accidental ratio. The generated photon pairs are spectrally far separated from the pump field, providing good potential for realizing sufficient on-chip filtering and monolithic integration of quantum light sources, waveguide circuits and single photon detectors.

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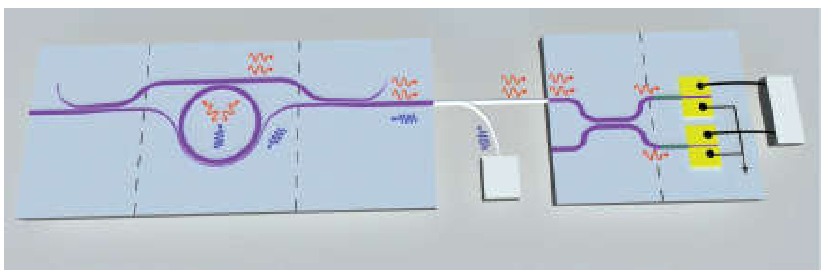

Fig 1. Schematic illustration of an on-chip photon pair source based on a $\chi(2)$ nonlinearity connected to superconducting single photon detectors (SSPD) on another chip. Higher energy pump photons (visible wavelengths) are coupled into a microring resonator and the generated lower energy photon pairs (IR wavelengths) are randomly split on the detector chip for coincidence measurements with integrated SSPDs.

References

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Single-chip source of photon pairs with integrated pump rejection

Cale M. Gentry[1], Omar S. Magaña-Loaiza[2], Mark T. Wade[1], Fabio Pavanello[1], Thomas Gerrits[2], Sen Lin[3], Jeffrey M. Shainline[2], Shellee D. Dyer[2], Sae Woo Nam[2], Richard P. Mirin[2], and Miloš A. Popović[1,4]

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[2]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado, 80305, USA*

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[4]*Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA*

We demonstrate the first quantum correlations of photon pairs from an integrated source with pump rejection implemented entirely on the same chip. Fabricated in a commercial 45nm CMOS microelectronics process, the spontaneous four-wave mixing source and pump filter span chip areas of approximately 1500 μm^2 and 3500 μm^2, respectively, demonstrating the feasibility of implementing thousands of sources on a single 10 mm^2 chip.

While photon pair sources based on bulk optical components have been the subject of in-depth study and have demonstrated high efficiency, indistinguishability, and purity, their size has inherently limited their scalability to systems requiring less than approximately 10 sources. Recent proposals of quantum photonic technologies such as multiplexed on-demand single photon sources [1], boson sampling [2], and linear optical quantum computing [3] suggest a need for systems with large numbers of photon pair sources. This has led to increased interest in the development of microscale quantum photonic sources and circuits on silicon chips which take advantage of the high yield and scalability of the fabrication processes pioneered by the CMOS microelectronics industry [4,5]. While sources, reconfigurable circuits, and single photon detectors have all been demonstrated on-chip, ultra-high extinction filters to reject the strong classical pump have remained elusive due to pump light indirectly scattering through the mostly transparent chips to the output fiber. To avoid this scattered light, on-chip ultra-high rejection filters have, until now, required cascaded filtering stages on multiple separate chips [6-8]. By integrating a silicon microring-based spontaneous four-wave mixing source with four cascaded 2nd-order filters [see Fig 1(a)] on a single CMOS chip, we demonstrate on-chip pump rejection greater than 95dB [see Fig 1(b)]. Scattered pump light is mitigated by absorptive metal and dielectric density fill surrounding the photonic devices, as well as by the complete removal of the silicon handle wafer. With only an off-chip 50%-50% splitter to probabilistically separate the signal and idler photons, we measure coincidences-to-accidentals ratios (CARs) above 3 with detected pair rates near 400 coincidences per second [see Fig 1(c)]. In addition, with a wide band pass filter to remove parasitic spontaneous Raman generated light (but *not* any residual pump), the measured CARs increased to greater than 12 and demonstrated a visibility in time-energy entanglement of 81.3% [see Fig. 1(d)].

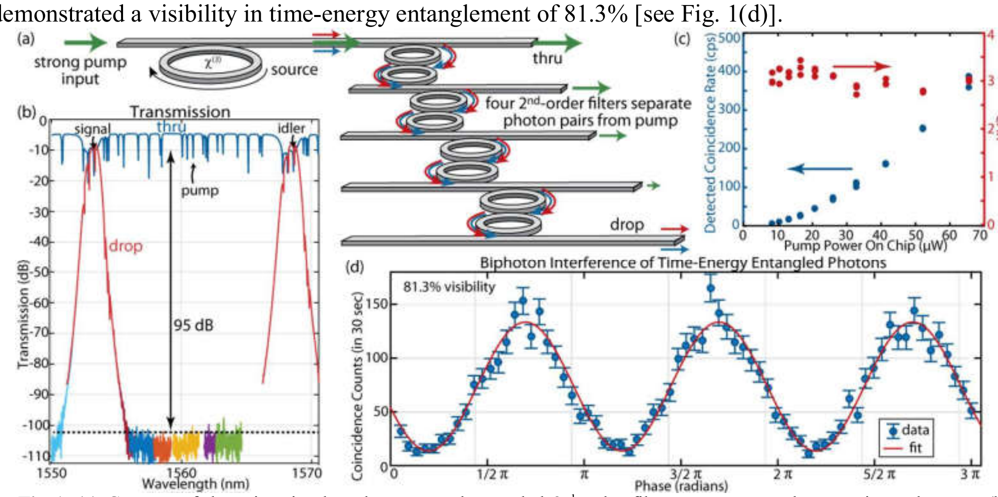

Fig 1. (a) Concept of the microring-based source and cascaded 2nd-order filters to separate photon pairs and pump. (b) Transmission spectra demonstrating >95dB extinction. (c) Detected coincidence rates and CARs with no off-chip filtering. (d) Biphoton interference through a Franson interferometer displaying time-energy entanglement with a visibility of 81.3%.

References

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A plug & play single photon source with high heralding efficiency, and application to purity-efficiency tradeoff under spectral filtering

Evan Meyer-Scott, Nicola Montaut, Johannes Tiedau, Linda Sansoni, Harald Herrmann, Raimund Ricken, Viktor Quiring, Tim J. Bartley, and Christine Silberhorn

Integrated Quantum Optics, Department of Physics, University of Paderborn, Warburger Straße 100, 33098 Paderborn, Germany

We report on a fully fiber-coupled heralded single photon source with 46% raw heralding efficiency [1]. The source (Fig. 1a) is based on type-II parametric down-conversion in a periodically-poled lithium niobate waveguide, producing degenerate photon pairs at 1558 nm. The photons exit the waveguide via a fiber-optic pigtail with ~80% coupling efficiency, are split in a fiber polarization beamsplitter, and pass through a pair of isolators for pump suppression. The signal photon additionally passes a dense wave-division multiplexing filter, heralding the idler photon with the highest efficiency achieved to date in an alignment-free source. Many previous attempts at packaging single photon sources have resulted in sharply reduced performance [2], but by filtering just the heralding arm the heralding efficiency is limited only by optical losses, which we keep low by careful selection and coupling of components.

However, when both photons are tightly filtered, for example to increase the spectral purity for multiphoton interference, this high efficiency is no longer possible [3]. We use our source to probe this fundamental tradeoff, finding that as filters (Fig. 1b) are narrowed to increase the spectral purity of the individual signal and idler photons, the signal and idler heralding efficiencies necessarily decrease (Fig. 1c) [4]. We also find fundamental limits to these quantities common to standard down-conversion sources, and discuss the source engineering needed to avoid this problem. This purity-efficiency tradeoff under spectral filtering is of immediate importance as many groups are now scaling up multi-photon and multi-source experiments and cannot afford the reduced efficiency caused by this effect.

Our heralded single-photon source is ideal for applications in quantum communication, networking, and information processing where hands-off operation is desired without sacrificing laboratory-scale performance. For applications requiring multiphoton interference, however, our work highlights the need to properly tailor the photon generation process to the application rather than rely on filtering after photon generation.

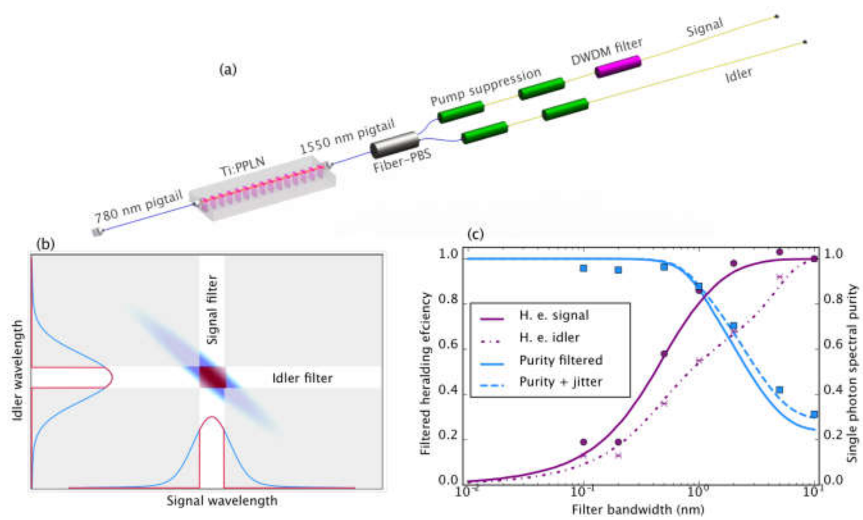

Fig 1. (a) Fiber-coupled single photon source with high heralding efficiency. Arbitrary spectral filters are then added in place of the DWDM filter to probe the tradeoff between heralding efficiency and spectral purity. (b) Spectral filtering of correlated two-photon joint spectrum. (c) Theoretical (curves) and experimental (points) tradeoff between heralding efficiency and spectral purity of the reduced heralded single-photon state.

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Monday, July 31 2017

Reception and Poster Session

16:45 – 19:15

The poster session will be held in the east UMC ballroom during the workshop reception. We have arranged for the posters to be up for the duration of the whole workshop to encourage further discussions beyond the actual poster session.

There will be a sponsored 'Best Student Poster Award'. If you are a student and presenting the poster, please sign up for the best student poster award if you have not already done so. All eligible and signed-up posters are marked with a red sticker next to the poster number. If you are eligible you can still get a red sticker at the registration desk. However, please do so before the poster session starts.

POSTERS

101	Marco Lopez	***Metrological characterization of a single-photon source based on a deterministic quantum dot microlens***
103	Alessandro Fedrizzi	***Pure downconversion photons through sub-coherence length domain engineering***
104	Alejandro Mattar	***Device-independent quantum key distribution with single-photon sources***
105	Carlos Anton	***Light-matter interfacing with quantum dots: a polarization tomography approach***
107	Tim Bartley	***Towards integrated superconducting detectors on lithium niobate waveguides***
108	Bingcheng Du	***Free space optical communication employing multi-plexing single photon detection***
109	Maria Bondani	***Photon-number-resolving detectors: an enabling technology for quantum state engineering***
111	Jens Breffke	***Sub-20ps IRF Width from Hybrid Detectors, Superconducting NbN Detectors, and MCP-PMTs***
112	Jens Breffke	***Wide-Field Photon Counting Imaging with bh SPC-150N System and Photek FGN 392-1000 Detector***
113	Ivan Burenkov	***Software solution for complete statistical mode structure analysis of mesoscopic states of light***
114	Daniel Jones	***Characterization of detector efficiencies with a high intensity source of entangled photon pairs in the presence of Raman noise***
115	Ivo Degiovanni	***Metrology for Quantum-Cryptography: the Coordinated European Effort***

117	Lorenzo De Santis	***Overcomplete quantum tomography of a spatially encoded 2-photon NOON state***
118	Dong-Hong Lee	***Detection Efficiency Measurement of Single Photon Detectors from 250 nm to 1000 nm***
119	Eric Gansen	***Decomposition of the 1/f Noise in QDOGFET Single-Photon Detectors***
120	Hui Zhou	***Ghost imaging based on superconducting nanowire single-photon detector at the wavelength of 1.5 microns***
121	Amir Jafari-Salim	***Integrated SNSPD with on-chip SFQ readout and time stamping***
122	Jin-Shi Xu	***Observation of the optimal form of quantum state-independent contextuality***
123	Kyle Major	***Single Molecule Dynamics with Variable Dephasing for Molecular Single-Photon Sources***
124	Sang-Min Lee	***Disturbance-free measurement and experimental test of CHSH inequality***
125	Svetlana Lukishova	***Nanophotonic advances for room-temperature single-photon sources***
126	Nicola Massari	***A QRNG system based on the oversampling principle***
127	Ingmar Muller	***An Absolute few-Photon Detector based on a Predictable Quantum Efficient Photodiode and a Switched Integrator Current Amplifier***
128	Natalie Mujica-Schwahn	***Position dependence of W-TES photon counting capabilities***
129	Anna Mukhtarova	***Fabrication of the Superconducting-Nanowire Single-Photon Detector with Low Polarization Sensitivity***
130	Jianwei Lee	***Photon number and timing resolution of a near-infrared continuous-wave source with a transition edge sensor***
131	Ronan Gourgues	***Toward the integration of photonic device with nanocrystal and superconducting nanowires:***
134	Simone Ferrari	***Hot-spot relaxation time current dependence in NbN waveguide-integrated superconducting nanowire single-photon detectors***
135	Dong-Hoon Lee	***Single Photon Source based on Silicon Vacancy in Nano-Diamond at KRISS***
136	Andreas Suss	***Towards CMOS compatible, fully depleted single-photon detection using avalanche multiplication***
137	Jerzy Szuniewicz	***Second order phase holograms without coherence between the sources***
138	Mitchell Thornton	***Single Photon Quantum State Oscillator***
140	Michael Wahl	***Ultra-fast time-correlated single photon counting system for rapid fluorescence lifetime imaging***
141	Xingsheng Xu	***Integrated single photon source based on SU8 waveguide with colloidal quantum dots***
143	Fabio Acerbi	***An integrated emitter-detector quantum random number generator based on a silicon photomultiplier and a single photon avalanche diode***

144	Malcom White	***Optical Fibre Power Meter Calibration for use in Determining the Efficiency of Single Photon NIR Nanowire Detectors***
146	Soeren Wengerowsky	***Quantum Communications Network Based on Polarization Entanglement at Telecom Wavelength***
147	Dale Durand	***Photon Statistics of Electroluminescence from Suspended Carbon Nanotube Field Effect Transistors***
148	Misael Caloz	***Optically probing the detection mechanism in a molybdenum silicide superconducting nanowire single-photon detector***
149	Jeff Shainline	***Superconducting single-photon detectors integrated with multitudinous photonic devices***
151	Alexander Otterpohl	***Tunable quantum light from a crystalline whispering gallery mode resonator***
152	Alessandro Farsi	***Interference between Different Colors in Single- and Bi-Photon States***
153	Alessandro Farsi	***Picosecond-Resolution Time-Lens for Single Photons***
154	Gregory Lafyatis	***Using an effective-medium approach for designing superconducting nanowire single-photon detectors***
155	Chris Chunnilall	***Studies of single-photon emission from hexagonal boron nitride***
156	Geiland Porrovecchio	***Absolute calibration of single-photon detectors using a multi-element transmission-trap attenuator and switched integrator amplifier***
157	Oliver Slattery	***Towards the Integration of Single Photon Source and Cesium Based Quantum Memory***
158	Taimur Islam	***High-Rate Quantum Key Distribution using Time-bin Qudits***
159	Aye Win	***Quantum state tomography by photon-number-resolving measurements***
160	Ivo Straka	***Quantum non-Gaussian light: a compass for experimental Fock states***
161	Rebecca Holmes	***Testing the limits of human vision with quantum states of light***
163	Davide Tamborini	***Improvement of Diffuse Correlation Spectroscopy sensitivity to brain through Time-Correlated Single-Photon Counting technique***
164	Adriana Lita	***Molybdenum Silicide Thin Film Optimization for High Efficiency Superconducting Nanowire Single-Photon Detectors***
165	Kathryn Nicolich	***Temperature Dependence of the Kinetic Inductance in a WSi Superconducting Nanowire Single-Photon Detector***
166	Michelle Victora	***Digital Delay Optical Quantum Memory***
167	Kristina Meier	***Characterization of a waveguide SPDC source for nondegenerate polarization entanglement***
169	Thomas Parker	***Frequency Multiplexed Single-Photon Sources***
170	Josef Blazej	***Photon counting detector with sub-picosecond passive stabilization of detection delay***
171	Clinton Cahall	***Cryogenic Amplifiers for a Superconducting Nanowire Single Photon Detector System***

172	Devin Smith	***Bragg cavities enhanced narrowband four wave-mixing sources in UV-written silica***
173	Rajveer Nehra	***Heisenberg-limited quantum interferometry with photon-subtracted twin beams***
174	Adam McCaughan	***SNSPD integrators for neuromorphic applications***
175	Adriana Lita	***Spatial Mapping of Optical Transition Edge Sensors Response***
176	Abijith Kowligy	***Progress toward high-efficiency single-photon-level interactions in crystalline microresonators***
177	Chaitali Joshi	***A frequency multiplexed heralded single-photon source***
178	Salih Yanikgonul	***Towards a Waveguide-based Single Photon Detector for Integrated Quantum Photonics Platforms***
179	Camden Ertley	***Photon Counting Microchannel Plate Imaging Sensors***
180	Weijie Guo	***Counting Near Infrared Photons with Microwave Kinetic Inductance Detectors***
181	Alberto Tosi	***Gating techniques for InGaAs/InP and silicon SPADs***
182	Emna Amri	***Temporal jitter in free-running InGaAs/InP Single-Photon Avalanche Detectors***
183	Thomas Gerrits	***Progress on Single Photon Detector Efficiency Calibrations at NIST***
184	Robert Kirkwood	***Single-photon avalanche detectors- their characterisation and use in measuring single-photon pulses***

Tuesday, August 1 2017

Applications II

8:30 – 10:00

Session Chair: Chris Chunnilall

8:30 ***INVITED***	Andrew Shields *Toshiba-Cambridge*	***A Universal Transmitter for Quantum Communications***
9:00	Morgan Weston *Griffith University*	***Heralded quantum steering over a high-loss quantum channel***
9:20	Catherine Lee *MIT*	***High-dimensional quantum state transfer over deployed fiber***
9:40	Christoph Simon *University of Calgary*	***Single photons for quantum networks, macroscopic quantum effects, and neuroscience***

A Universal Transmitter for Quantum Communications

George Roberts, Marco Lucamarini, James Dynes, Bernd Frohlich, Zhiliang Yuan and Andrew Shields
Toshiba Research Europe Ltd, Cambridge, UK.

Abstract: We propose optical injection locking as a method to encode the phase of qubits generated by a gain switched laser diode and demonstrate its application to several protocols for quantum key distribution. The technique enables greatly simplified systems with improved stability and performance.

Phase encoding is one of the most robust methods for transmitting qubits over long distances. Typically it involves sending weak coherent pulses from an attenuated laser diode through an unbalanced Mach Zehnder interferometer that uses a phase modulator in one arm to encode a phase difference between the two output pulses. The qubit state can be read-out by measuring the interference after a matched interferometer at the receiver.

Here we demonstrate an alternative method, employing direct phase modulation of the source. It involves using a second quasi-continuous (*master*) laser diode, to manipulate the coherence and phase of the output (*slave*) pulsed laser diode. Applying small modulations to the drive voltage of the master laser allows different qubit states to be encoded as a phase difference between pulse pairs from the slave. We show this method allows record low half-wave voltages, V_{π}= 0.35V, compatible with CMOS drive voltages. Furthermore driving the master below the lasing threshold breaks the coherence between successive pulse pairs, as required for the security of many quantum key distribution protocols.

We demonstrate that this technique can be used to realize a flexible, universal transmitter for quantum key distribution that can be electrically programmed for different protocols, including *BB84*, *Distributed Phase Shift* and *Coherent One Way*. We characterize the performance of each and discuss the prospects for realizing greatly simplified and improved devices for quantum communications.

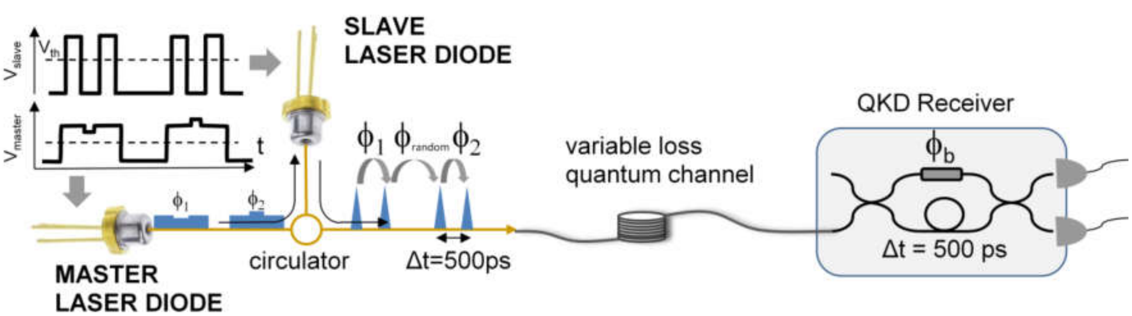

Fig 1. Schematic of the universal QKD transmitter. Light from a master laser diode is used to control and manipulate the phase difference between successive pulses from a slave laser diode. The modulation patterns are relevant to the BB84 protocol.

Heralded quantum steering over a high-loss quantum channel

Morgan M. Weston[1], Sergei Slussarenko[1], Helen M. Chrzanowski[1,2], Sabine Wollmann[1] and Geoff J. Pryde[1]
[1]*Centre for Quantum Dynamics & cqc2t.org , Griffith University, Brisbane, 4111, Australia*
[2]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK*

Entanglement is the key resource for many long-range quantum information tasks, such as secure communication, networking quantum computers, and remote processing of quantum information. As the characteristic trait of quantum mechanics, it is also important for testing quantum physics over long distances or in different reference frames. Robust verification of remote shared entanglement is highly sought after, as it permits these fundamental tests and protocols, such as device-independent quantum key distribution. However, distributing and rigorously verifying entanglement over long distances is presently technologically intractable as optical fiber and atmospheric or diffraction losses reduce the transmission efficiency below a required threshold, opening up the "detection loophole". To overcome this challenge, we design and experimentally demonstrate an event-ready scheme which verifies entanglement in the presence of at least 14.8 ± 0.1 dB of added channel loss, equivalent to approximately 80 km of telecommunication fiber [1].

The gold standard for complete verification is a violation of a Bell inequality with all loopholes closed, which has been experimentally demonstrated in low-loss schemes. An alternative approach that we employ is quantum steering, which is an asymmetric protocol that provides enhanced loss tolerance with the additional assumption that one party is trusted. The aim of the protocol is that an untrusted party, Alice, needs to convince a trusted party, Bob, that she can steer his measurement outcomes for any measurement choice from a pre-defined set n of Bob's measurement settings. In the loss-tolerant quantum steering protocol [2] Alice is prevented from exploiting the fair-sampling assumption to cheat, by Bob requiring her to announce a measurement a certain fraction of the trials (Alice's heralding efficiency), from which he constructs a secure steering inequality. This protocol was previously used to demonstrate quantum steering over 1 km of optical fiber [2], however in the case of higher-loss (say, 10s to 100s of km of optical fiber) Alice's heralding efficiency is reduced further, preventing her from violating the inequality.

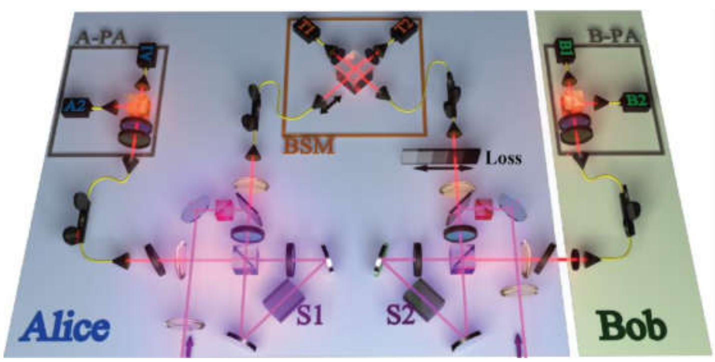

Fig 1. The experimental scheme for the heralded quantum steering protocol: The two polarization-entangled spontaneous parametric down conversion sources are labelled S1 and S2, the entanglement swapping step is implemented by a Bell state measurement (BSM). The untrusted party Alice and trusted party Bob measure the polarization of their photons with their corresponding polarization analyzer (PA). The lossy channel is simulated with neutral density filters.

Our new heralded quantum steering protocol relies on entanglement swapping to herald the presence of a photon in Alice's arm after the lossy channel [1]. This additional step allows Alice to maintain a high effective heralding efficiency and complete the quantum steering protocol with the detection loophole closed. To implement the scheme, we use two polarization-entangled photon sources, featuring high heralding efficiencies, state fidelities, and purity [3] and superconducting nanowire photon detectors [4]. We achieved entanglement swapping with a high singlet-state fidelity of $(91 \pm 3)\%$ while maintaining an effective heralding efficiency of up to (47 ± 2) %, resulting in a steering inequality violation of two standard deviations with 14.8 ± 0.1 dB of additional channel loss. The results achieved are a considerable step towards the implementation of secure quantum communication, and represents a single step quantum relay, a crucial component for future quantum repeaters.

References
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High-dimensional quantum state transfer over deployed fiber

Catherine Lee,[1,2] Darius Bunandar,[1] P. Ben Dixon,[2] Matthew E. Grein,[2]
Mark L. Stevens,[2] Scott A. Hamilton,[2] and Dirk Englund[1]

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[2] *Lincoln Laboratory, Massachusetts Institute of Technology; Lexington, MA 02421, USA*

High-dimensionally encoded quantum states can provide significant advantages over binary-encoded states in applications such as quantum metrology and quantum communication. We report on three high-dimensional experiments in a 43-km deployed fiber testbed: prepare-and-measure quantum key distribution (QKD), entanglement-based QKD, and quantum steering.

We report on experiments using high-dimensional photonic states to boost quantum communication rates in a 43-km deployed-fiber testbed, illustrated in Fig. 1(a). The three experiments are based on high-dimensional time-energy encoding, in which the conjugate measurement bases of photon arrival time and photon energy (or frequency) are implemented by selectively applying normal and anomalous group-velocity dispersion (GVD). The first two experiments are the prepare-and-measure (P&M) and entanglement-based (EB) implementations of the hjigh-dimensional dispersive-optics quantum key distribution (DO-QKD) protocol [1]. The two implementations are theoretically equivalent, indicating that they share the same levels of proven security, but practically, they differ in terms of attainable secret-key rates and compatibility with other quantum networking elements.

P&M transmitters, as shown in Fig. 1(b), allow for high state generation rates, and the high-dimensional alphabet size can be easily adjusted to maximize the secret-key rate for a given channel/receiver (see Fig. 1(d)). We have demonstrated P&M DO-QKD locally in the lab and over the deployed-fiber testbed, and the high-dimensional encoding demonstrates a secret-key rate advantage over binary encoding in the presence of receiver saturation [2].

Despite the challenges of producing entangled-photon pairs at high rates, only EB QKD is compatible with future quantum repeaters for long-distance communication or with device-independent protocols that reduce the assumptions required for security. We have demonstrated DO-QKD using high-dimensional time-energy entanglement in the deployed-fiber testbed, as depicted in Fig. 1(c-d), with a secure information advantage over binary encoding per detected photon coincidence.

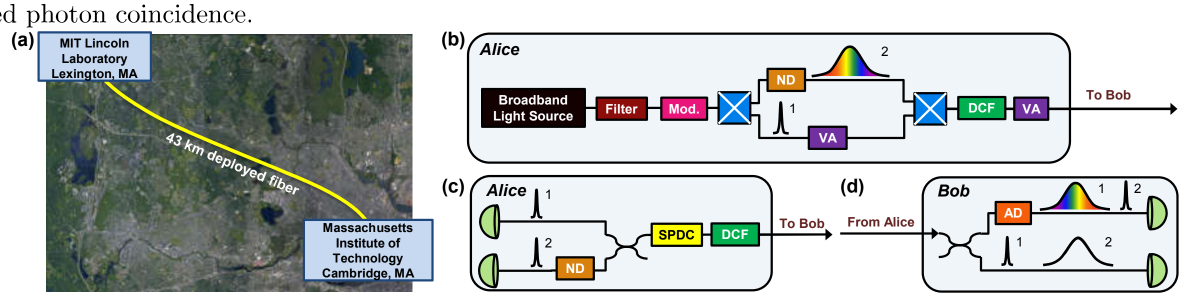

FIG. 1. (a) Map of deployed-fiber testbed. (b) Prepare-and-measure transmitter. Mod.: electro-optic modulator; ND: normal GVD; VA: variable attenuator; DCF: dispersion-compensating fiber. (c) Entanglement-based transmitter. SPDC: spontaneous parametric downconversion source. (d) Receiver. AD: anamolous GVD.

In the third experiment, we use the time and frequency measurements of EB DO-QKD to observe violations of a high-dimensional EPR steering inequality [3]. By multiplexing the entangled photons with an active loop that stabilizes propagation time, optical phase, and polarization over the deployed fiber [4], we demonstrate that the steerability (and thus, entanglement) of the biphoton state is preserved in the presence of the stabilization system.

The three experiments include the first deployed-fiber tests of high-dimensional QKD (both P&M and EB) and also demonstrate the potential for metropolitan-area quantum networking with high-dimensional quantum states.

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Single photons for quantum networks, macroscopic quantum effects, and neuroscience

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I will describe our work towards the non-destructive detection of photonic qubits for quantum networks, on the demonstration of entanglement between many large atomic ensembles in a solid based on single-photon absorption, and on the possible existence of optical communication channels in the brain.

Global quantum networks with quantum repeaters, satellite links, and non-destructive photonic qubit detection: The first quantum communication satellite was recently launched in China. It is a low-earth orbit satellite carrying a source of entangled photon pairs. I will describe a proposal [1] how such satellites could be used as part of a relatively simple quantum repeater architecture to create entanglement over global distances. A key element of the proposed architecture is the non-destructive detection of photonic qubits, and I will describe two proposals [2,3] and a proof-of-principle experiment [2] for realizing such non-destructive detection with rare-earth ion doped crystals, which is attractive from the point of view of integration with quantum memories.

Entanglement between many large atomic ensembles in a solid [4]: I will describe a recent experiment in which we created a multi-partite entangled state by storing a single photon in a crystal that contained many large atomic ensembles with distinct resonance frequencies. The photon was re-emitted at a well-defined time due to an interference effect analogous to multi-slit diffraction. We derived a lower bound for the number of entangled ensembles based on the contrast of the interference and the single-photon character of the input, and we experimentally demonstrated entanglement between over two hundred ensembles, each containing a billion atoms. These results are the first demonstration of entanglement between many macroscopic systems in a solid.

The possible existence of optical communication channels in the brain [5]: It is well established that neurons can emit photons, which prompts the question whether these biophotons could serve as signals between neurons, in addition to the well-known electro-chemical signals. For such communication to be targeted, the photons would need to travel in waveguides. We showed, based on detailed theoretical modeling, that myelinated axons could serve as photonic waveguides, taking into account realistic optical imperfections, and we proposed experiments to test this hypothesis. Our results also raise the question whether photons could mediate long-range quantum entanglement in the brain.

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Metrology II

10:30 – 12:00

Session Chair: Malcom White

10:30 *INVITED*	Stefan Kück *PTB-Braunschweig*	***Single-photon sources and detectors for quantum radiometry***
11:00	Glenn Solomon *NIST/JQI*	***Simultaneous, full characterization of a single-photon state***
11:20	Vaigu Aigar *VTT*	***Experimental demonstration of a predictable single photon source with variable photon flux***
11:40	Beatrice Rodiek *PTB-Braunschweig*	***Metrological realization of an absolute single-photon source based on a nitrogen-vacancy center in nanodiamond***

Single-photon sources and detectors for quantum radiometry

Stefan Kück
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In this presentation, an overview of the single-photon sources and detectors with respect to their application in quantum radiometry is given.

Single-photon sources and detectors have a wide field of applications, ranging from almost pure research fields like quantum optics, quantum computing and quantum metrology over areas entering the market like quantum key distribution and quantum-enhanced optical measurements to already established applications, see e.g. the operation of single-photon detectors in biology and astronomy. Quantum radiometry (or photon-based radiometry) is defined as the science of measurement of radiation by counting (single) photons. Recently, due to the existing and expected applications, this metrology research area has gained increasing interest in a number of national metrology institutes.

In this presentation, an overview of the current activities in the field of quantum radiometry is given. This concerns the realization of different types of single-photon sources, absolutely characterized single-photon sources and the current activities towards the development of standard single-photon sources. Different types of detectors and their characterization, e.g. by use of different radiation sources (single-photon sources as well as attenuated laser and LED radiation sources), will be reported on. Special emphasis is on the current situation concerning standardization.

Simultaneous, full characterization of a single-photon state

G. S. Solomon[1], S. V. Polykov[2], T. Thomay[1] O. Gazzano[1], E. Goldschmidt[1,3], V. Loo[1], and T. Huber[1]

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Abstract. The single-photon character of a light source can be characterized by the multiphoton suppression and the indistinguishability, usually using multiple measurements. We demonstrate an efficient scheme to simultaneously measure this single photon character using two number-resolving detectors, here simulated by four single-photon detectors.

As single-photon sources become more mature and are used more often in quantum information, communications and measurement applications, the details of their characterization become more important. Single-photon-like light is often characterized by the device's photon flux—its brightness, and two quantum properties: the suppression of multiply-photon components and the photon indistinguishability. While it is desirable to obtain these quantities from a single measurement, currently two or more measurements are used.

Here we simultaneously determine the brightness, the suppression of multi-photon content, the indistinguishability, and the statistical distribution of Fock states to third order for a quantum light source [1]. For demonstration purposes, we use the light emitted from a single InAs quantum dot in a planar microcavity; however, the measurement is not source specific. The measurement uses a pair of two-photon ($n = 2$) number-resolving detectors, and the output is a set of cross-correlation and auto-correlations, as shown in Fig. 1. Using a Fisher-information analysis, we show that the new method extracts more information per experimental trial than a conventional measurement for all input states, and is particularly more efficient for statistical mixtures of photon states. Furthermore, $n \geq 3$ number-resolving detectors provide no additional advantage in the single-photon characterization. Thus, using this n=2, number- resolving detector scheme will provide new advantages in a variety of quantum optics measurements and system characterization.

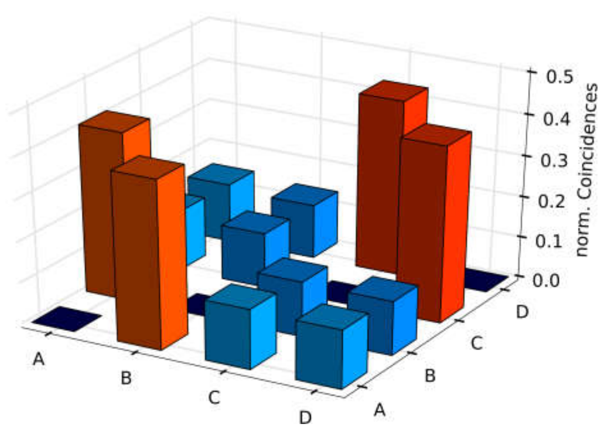

Fig 1. Second-order characterization of quantum light; here from a single quantum dot source. Normalized conditional detector counts are plotted for the four detectors at j = 0. These four detectors are configured to simulate two n=2 number-resolving detectors. Correlated detections on AD, AC, BC, BD (blue) represent cross-correlations. Correlations of the type AB and CD (red) are autocorrelations.

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Experimental demonstration of a predictable single photon source with variable photon flux

Aigar Vaigu[1,2], Geiland Porrovecchio[3], Xiao-Liu Chu[4,5], Sarah Lindner[6], Marek Smid[3], Albert Manninen[1], Christoph Becher[6], Vahid Sandoghdar[4], Stephan Götzinger[4,5] and Erkki Ikonen[1,2]

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Quantum information technology has been the major driving force for the development of single emitter single-photon sources (SPSs) [1, 2] with prominent applications in quantum key distribution, all-optical quantum computation and quantum simulations.

We demonstrate a method [3] that allows us to realise an SI-traceable single-photon source (SPS) based on a silicon vacancy centre in nanodiamond [4], which is optically excited by a pulsed laser (Fig 1 a). Our method takes advantage of a very sensitive analog-mode photodetector comprising of a low-noise 3×3 mm silicon photodiode in conjunction with a custom made switched integrator amplifier [5]. At the excitation rate of 70 MHz, the source delivers a photon flux large enough to be measured by the low optical flux detector (LOFD) (Fig 1 b). The directly measured photon flux constitutes an absolute reference. A measurement of the SPS's absolute optical power with this detector eliminates the need for a precise knowledge of the SPS characteristics.

By changing the pump laser repetition rate, the photon flux of the SPS can be tuned in a controlled way. This gives us a direct way of linking conventional optical power levels, measurable with specifically designed analog-mode detectors, down to low photon flux levels needed for single-photon detectors (Fig 2). The advantage of our method of changing the pump laser repetition rate is that it does not require precise knowledge of the source efficiency, but the source is calibrated by the analog-mode detector and can then be used at the reduced repetition rate for detector responsivity characterizations at the few-photon level.

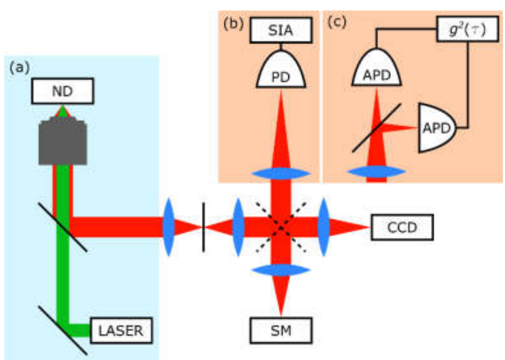

Fig 1. Experimental setup. (a) The pumping of nanodiamonds (ND) at 685 nm and ND fluorescence emission at λ=725 nm. (b) The LOFD setup for the absolute flux measurement of single photons (c) The HBT setup to measure the second-order correlation function $g^2(\tau)$. PD - SI photodiode, SIA - amplifier electronics, APD - avalanche photodiode, SM - spectrometer, CCD - camera.

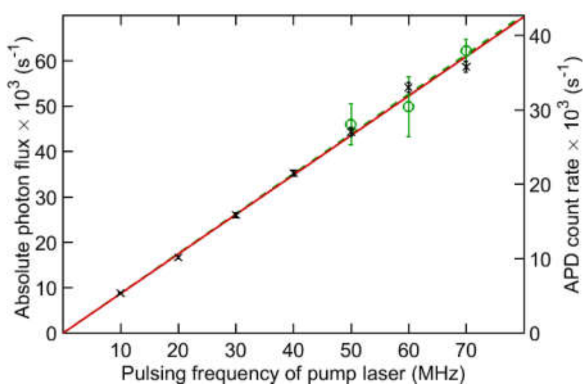

Fig 2. Photon flux as a function of the pump laser repetition frequency. Both, the measurement with an absolutely calibrated silicon photodetector (circle symbols, left vertical scale) and the avalanche photodiode (APD) count rates (cross symbols, right vertical scale) are shown and fitted with a straight line passing through the origin.

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Metrological realization of an absolute single-photon source based on a nitrogen-vacancy center in nanodiamond

Beatrice Rodiek[1], Marco López[1], Helmuth Hofer[1] and Stefan Kück[1]

[1]*Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany*

Single-photon sources are of large interest in several research fields in quantum optics and metrology, e.g. in quantum key distribution, quantum computing, and quantum-enhanced optical measurements [1,2,3]. Furthermore, a bright and pure single-photon source is also needed in radiometry as a standard source for the efficiency calibration of single-photon detectors as well as a link to the classical radiometry [4,5]. Thus, single-photon detectors can easily be compared to analogue detectors which are traced to a primary standard [6].

We present the metrological realization of an absolute single-photon source based on a nitrogen-vacancy (NV-) center in nanodiamond [7], which is developed at PTB. The source is absolutely calibrated to the national standards via an unbroken traceability chain in terms of its absolute spectral photon flux per wavelength and absolute spectral radiant flux per wavelength at room temperature. The absolute photon flux is measured with a low noise silicon photodiode traceable to the cryogenic radiometer and the spectral distribution was determined by using a calibrated spectroradiometer. The single-photon emission is tunable in the range from 55 fW to 75 fW, which corresponds to 190,000 photons per second and 260,000 photons per second, respectively. The purity of its single-photon emission is determined by the 2nd order autocorrelation function which is as low as 0.10 for a single-photon emission of 190,000 photons per second (Figure 1a). Furthermore, the absolute spectral photon flux per wavelength and its standard uncertainty is obtained (Figure 1b).

At the conference, we will present further details and results of the metrological realization of a nitrogen-vacancy center based single-photon source, its uncertainty budget and its emission characteristics.

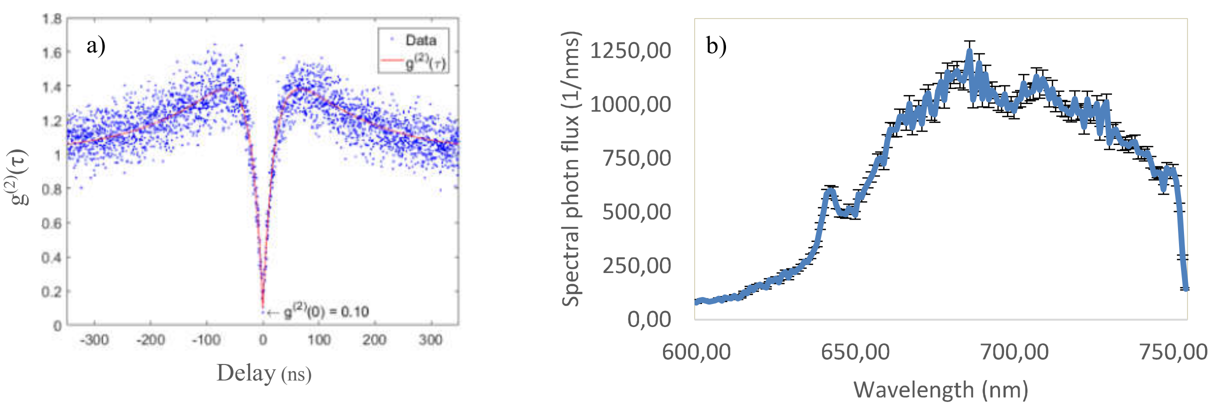

Fig 1. a) Second order autocorrelation function. b) Absolute spectral photon flux per wavelength of the single-photon source. Error bars: standard measurement uncertainty.

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Tuesday, August 1 2017

Sources I

14:20 – 15:10

Session Chair: Krister Shalm

14:20 ***INVITED***	Jelena Vuckovic *Stanford University*	***Quantum Light Generation with Quantum Dot - Cavity QED systems***
14:50	Carlos Antón *CNRS*	***Efficient single photon sources in the solid-state***

Quantum Light Generation with Quantum Dot - Cavity QED systems

Jelena Vuckovic, Kai Mueller, Kevin Fischer, Constantin Dory, Tomas Sarmiento, Konstantinos Lagoudakis, Yousif Kelaita

[1]*Stanford University, Stanford, California, USA*

Single InAs quantum dots embedded in high quality, small volume GaAs photonic crystal cavities have been used as a platform to probe interesting regimes of light-matter interaction and to implement a variety of devices for quantum technologies, including sources of quantum states of light.

Of particular interest is a strong coupling regime of cavity quantum electrodynamics (QED), where coupling strength between a single quantum emitter (quantum dot) and the cavity field exceeds loss rates of the system. In this regime, an anharmonic ladder of energy eigenstates occurs, which are entangled states between light and matter. We have shown that by resonant excitation of such eigenstates using a tunable laser, one can generate quantum states of light – from single photon states to photon bundles. This generation is achieved in the regimes of photon blockade and photon tunneling, which are direct consequence of the dressed states ladder anharmonicity. We have also shown that the generation of such quantum light – single photons in particular – can be done with high efficiency and indistinguishability.

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2. Kai Müller, Kevin A. Fischer, Constantin Dory, Tomas Sarmiento, Konstantinos G.Lagoudakis, Armand Rundquist, Yousif Kelaita, Jelena Vuckovic, "Self-homodyne enabled generation of indistinguishable photons," *Optica,* vol. 3, 931-936 (2016)
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Efficient single photon sources in the solid-state

N. Somaschi[1], V. Giesz[1], L. De Santis[1,2], J. C. Loredo[3], C. Antón[1], J. Demory[1], C. Gómez[1], G. Coppola[1], I. Sagnes[1], N. D. Lanzillotti-Kimura[1], A. Lemaitre[1], A. Auffeves[4,5], A. G. White[3], L. Lanco[1,6] and P. Senellart[1,7]

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Single photons are foreseen as elementary qubits to carry and manipulate the quantum information. The development of quantum photonic networks relies on the technological capabilities to fabricate efficient sources of quantum light [1]. The scalability of this photonic technology depends critically in the ability of the sources to provide light pulses delivering photons (i) one by one (characterized by the single-photon purity, measured through the $g^{(2)}(0)$), (ii) in a pure quantum state or indistinguishable (measured by the mean-wave packet overlap obtained from a HOM visibility) (iii) in a deterministic way (i.e. with probability 1 that each pulse contains photon). The latter property being very sensitive to any optical loss, we define the brightness as the probability that a pulse does contain a single photon. This metrics allows comparing various technologies..

We fabricate efficient single photon sources by deterministically coupling a semiconductor quantum dot in an electrically-controlled pillar microcavity [2,3]. Under resonant excitation we measure near-unity indistinguishability of 0.9956±0.0045 between single photons successively emitted 2.2 ns apart, and we measure a single photon purity of $g^{(2)}(0)$=0.0028±0.0012. The measured probability to obtain a single photon per pulse (brightness) before the first collection lens is 0.154±0.015. This makes such sources one order of magnitude brighter than a parametric down conversion source of the same purity [3]. Moreover, the pillar mode profile allows very efficient (>60%) coupling of the photons into an optical fiber [4].

Many applications require multi-photon states, encoded either in orthogonal temporal modes or orthogonal spatial modes. This requires the generated photons to be highly indistinguishable even if emitted by the quantum dot at long time delays. This is why we have tested the photon indistinguishability as function of their temporal delay, observing up to 0.0878±0.016 for two photons delayed by 463 ns. Given the short lifetime of the single photons (~100 ps), this implies that the sources can generate streams of more than 300 highly indistinguishable single photons.

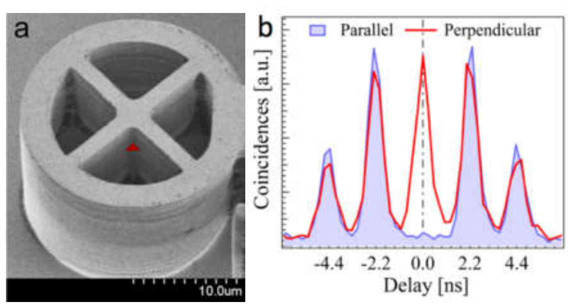

Fig 1. a. Microscope image of the device under study: a single QD is deterministically placed at the center of a micropillar cavity. **b.** Indistinguishability curves for two identical photons (parallel polarization, filled curve) and artificially distinguishable photons (perpendicular polarization, red curve). The fluorescence is obtained under resonant excitation.

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Sources II

15:40 – 17:10

Session Chair: Krister Shalm

15:40	Lorenzo De Santis *CNRS*	***Single-photon Fock-state filtering with an artificial atom***
16:00 ***INVITED***	Maria Chekhova *Max-Planck Institute*	***Towards photon triplet generation through a direct cubic nonlinear effect***
16:30	Mike Reimer *University of Waterloo*	***New nanoscale source of bright entangled photon pairs***
16:50	Gregor Weihs *University of Innsbruck*	***Three Photons – Efficient and Interfering***

Single-photon Fock-state filtering with an artificial atom

L. De Santis[1], C. Antón[1], B. Reznychenko[2], N. Somaschi[1], G. Coppola[1], J. Senellart[1], C. Gómez[1], A. Lemître[1], I. Sagnes[1], A. G. White[3], L. Lanco[1], A. Auffeves[2] and P. Senellart[1]*

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[2]CEA/CNRS/UJF joint team "Nanophysics and Semiconductors", Institut Néel, Université Grenoble-Alpes & CNRS, Grenoble, France
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Abstract: We demonstrate that a quantum dot-micropillar cavity system can perform as a single-photon Fock state filter. When sending coherent light pulses on the device, we observe an optical nonlinearity at the sub-photon scale and 80% single-photons in the reflected light intensity.

One of the major roadblocks to scale optical quantum technologies is the probabilistic operation of quantum optical gates that are based on the coalescence of two indistinguishable photons. A way around this problem is to make use of the single-photon sensitivity of an atomic transition when the atom interacts with only a single mode of the optical field (one dimensional atom case [1]). In such situation, each photon sent on the device interacts with the atom: the first photon is reflected and the second one is transmitted, realizing a deterministic photon router. Such possibility has been explored with artificial atoms in the form of semiconductor quantum dots, yet in the continuous-wave regime or with strong post-selection to compensate for the inefficient coupling between the incident light and the device optical mode.

In this work, we demonstrate the single-photon filtering by a quantum dot deterministically coupled to a micropillar cavity, performing as a quasi-ideal one dimensional atom [2], see scheme in Fig. 1(a). The device is probed with a pulsed laser and we collect the total reflected signal in the same spatial mode and polarization. As shown in Fig. 1(b), the system presents a nonlinearity threshold for an average incident photon number as low as ~0.3. The $g^{(2)}(0)$ measure of the reflected light evidences that it is mostly constituted by single-photons (80% single-photons of the total output intensity, see Fig. 1(c)) and that the multi-photon component of the field is efficiently suppressed. Three-photon correlation measurements of the reflected signal have been performed to evidence the non-poissonian statistics of the output photons [3].

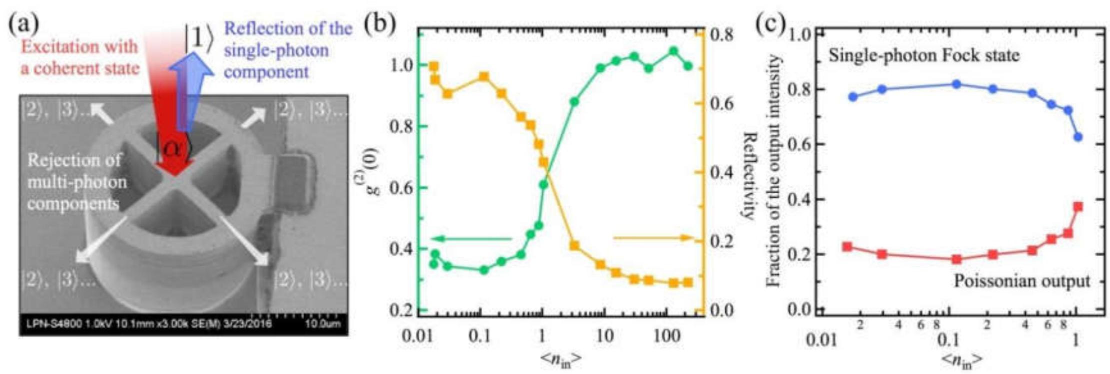

Fig 1. (a) Sketch of the working principle of the Fock state filter, $|\alpha\rangle$ represents the input laser coherent state with average photons per pulse $\langle n_{in}\rangle$ (see red arrow), the QD-cavity system scatters back mostly $|1\rangle$ Fock states (blue arrow), filtering out other multi-photon states (white arrows). (b) $g^{(2)}(0)$ (green circles, left axis) and nonlinear reflectivity curve (orange squares, right axis) as function of $\langle n_{in}\rangle$, which represents the average photon number per pulse of the poissonian input. (c) Fraction from the total output intensity of single-photons (blue circles) and poissonian output (red squares) as function of $\langle n_{in}\rangle$.

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Towards photon triplet generation through a direct cubic nonlinear effect

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Abstract. The possibility of generating photon triplets through a direct decay of pump photons in a cubic nonlinear medium is discussed. First results towards this goal obtained with nonlinear crystals and photonic-crystal fibers are presented.

Generation of nonclassical states of light has always been one of the major tasks of quantum optics. Among few-photon states, only single-photon and two-photon ones are now routinely produced in laboratories, by using, respectively, single-photon emitters and spontaneous parametric down-conversion (SPDC) or spontaneous four-wave mixing (SFWM). Going beyond this state of the art and obtaining three-photon states is far more difficult. Although photon triplets have been produced in several experiments using cascaded nonlinear effects and postselection, the direct decay of pump photons into triplets through cubic nonlinearity, usually referred to as third-order parametric down-conversion (TOPDC), has not been achieved yet. At the same time, this third-order nonlinear effect, unlike its second-order analogue SPDC, leads to the generation of a non-Gaussian state without any postselection [1]. Together with the possibility of heralded generation of photon pairs, this fundamental property makes TOPDC extremely interesting.

As possible media for the realization of TOPDC, we consider photonic crystal fibers and nonlinear crystals. The former offer a large interaction length together with the high energy confinement in the core, while the latter provide an easy way to satisfy the phase matching through birefringence.

The difficulty in using optical fibers for producing photon triplets is that the phase matching can be only realized through inter-modal dispersion. This kind of interaction suffers from rather low overlap between the phase-matched modes and has therefore low efficiency. To overcome this difficulty, we have designed and manufactured a novel type of hybrid fibre [2] where the pump radiation at 532 nm and the triplet radiation at 1596 nm will be guided through different mechanisms: a photonic bandgap in the first case and a step index in the second one. The phase matching has been tested through experiments with third-harmonic generation, which is reverse to TOPDC [2].

Alternatively, we consider using gas-filled kagome-type photonic-crystal fibers filled with noble gas. This system allows for tuning the phase matching by varying the gas pressure, which has been also demonstrated in experiments on the third harmonic generation [3].

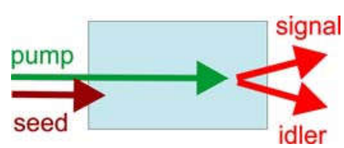

Fig 1. Seeded generation of photon triplets in calcite, with the seeding beam collinear to the pump beam. The two unseeded photons of the triplet are emitted along a cone, similar to non-collinear type-I SPDC.

In nonlinear crystals, the main problem is a short interaction length, leading to rather modest estimates for the rates of photon triplet generation. Here, our first step is using an input beam seeding the emission of one of the three photons under non-degenerate phase matching. This configuration leads to a source of photon pairs, which has some similarity with FWM in the sense that the pair production rate scales as a product of the pump and the seed powers. At the same time, seeding the emission of one of the three down-converted photons allows one to study the three-photon amplitude of the triplet state similar to how it is done in the stimulated emission tomography of SPDC [4].

First experiments on TOPDC with noncollinear e->eoo phase matching in calcite (Fig. 1) and seeding collinearly with the pump beam show a measurable rate of pair generation.

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New nanoscale source of bright entangled photon pairs

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[4]*Applied Physics Department, Royal Institute of Technology, Stockholm, Sweden*

The on-demand generation of bright entangled photon pairs is an essential resource in quantum optics and communication and in emerging quantum technologies such as sensing. However, a quantum light source combining both high entanglement fidelity and on-demand bright emission has proven elusive with current leading photon technologies. In this work we present a new bright nanoscale source of strongly entangled photon pairs generated with a quantum dot in a nanowire waveguide [1, 2]. The quantum dot guarantees highly entangled photon pairs are produced on-demand, while the shape of the nanowire waveguide with a taper towards the tip allows both photons of the entangled pair to be efficiently collected. As a result, we detect photon pair rates that are more than two orders of magnitude brighter than a bare quantum dot without a photonic nanostructure, while reaching entanglement fidelities close to 90 %. These results will be put in perspective with respect to state-of-the-art entangled photon sources with the viewpoint of going beyond in the future towards near-unity fidelity and efficiency. This nanowire-based photonic structure is the first bright quantum dot source of entangled photon pairs capable of violating Bell`s inequalities, opening up future experiments in quantum optics and developments in quantum repeaters for long-distance quantum communication, and is a new resource for on-chip photonic circuits [3].

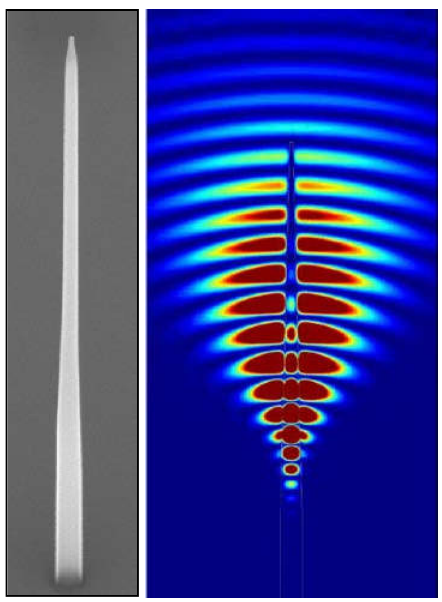

Fig 1. Left panel: SEM image of nanoscale source of bright entangled photons based on a quantum dot in a tapered nanowire waveguide. The nanowire waveguide diameter at the base is ~ 250 nm with a tapered shape towards the tip. Right panel: Simulation of quantum dot in a tapered nanowire waveguide demonstrating the highly directional Gaussian emission.

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Three Photons – Efficient and Interfering

Gregor Weihs[1], Sascha Agne[2], Dan Dalacu[3], Deny R. Hamel[4], Tobias Huber[5], Thomas Jennewein[2], Jeongwan Jin[2], Thomas Kauten[1], Milad Khoshnegar[6], Brahim Lounis[7], Hamed Majedi[6], Evan Meyer-Scott[8], Philip Poole[3], Ana Predojević[9], Maximilian Prilmüller[1], Kevin J. Resch[2], Jeff Z. Salvail[2], Philippe Tamarat[7]

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Producing advanced quantum states of light is a priority in quantum information technologies. While remarkable progress has been made on single photons and photon pairs, multipartite correlated photon states are usually produced in purely optical systems by postselection or cascading, with extremely low efficiency and exponentially poor scaling. Multipartite states enable improved tests of the quantum mechanics foundations as well as implementations of complex quantum optical networks and protocols. It would be favorable to generate these states directly using solid-state systems, for better scaling, simpler handling, and the promise of reversible transfer of quantum information between stationary and flying qubits.

In our work [1], we have shown that quantum dots in nanowires are extremely efficient sources of single photons and entangled photon pairs. Most recently, we used ground states of two optically active coupled InAsP quantum dot insertions in an InP nanowire to directly produce photon triplets. The formation of a triexciton leads to a triple cascade recombination (see figure) and sequential emission of three photons with measurable correlations. This source surpasses the rates of all earlier reported sources, in spite of the moderate efficiency of our detectors. Our structure and data represent a breakthrough towards implementing multipartite photon entanglement and multi-qubit readout schemes in solid state devices, suitable for integrated quantum information processing.

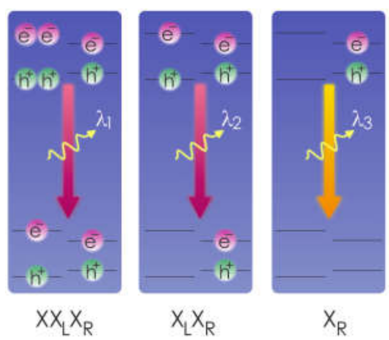

Fig 1. A triple cascade from an indirect triexciton via an indirect biexciton and an exciton to the ground states produces three photons in three different modes, with a strong triplet count above any Poissonian background.

In particular we will show how this compares to a cascaded spontaneous parametric down-conversion source and present the demonstration of genuine three-photon interference using the latter. In a three-photon Franson interferometer we were able to show high visibility three-fold fringes, while the single and two-photon data does not exhibit any modulation.

These two experiments open new ways towards multiphoton sources and multiphoton interferometry. They also indicate what needs to be improved and developed to go towards applications in quantum technologies.

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Tuesday, August 1 2017

Short lecture course

19:00 – 21:30

19:00	Thomas Gerrits *NIST-Boulder*	***Properties of single-photon detectors***
19:20	Alan Migdall *NIST-Gaithersburg*	***Present records and fundamental limits to single photon detection***
19:40	Ivo Degiovanni *INRIM*	***Characterization of single-photon detectors***
20:00	***Break***	
20:30	Stefan Kück *PTB-Braunschweig*	***Properties of single-photon sources***
20:50	Sergey Polyakov *NIST-Gaithersburg*	***Characterization of single-photon sources***
21:10	Chris Chunnilall *NPL*	***Examples of single-photon metrology applied to QKD***

Detectors II

8:30 – 10:00

Session Chair: Varun Verma

8:30 *INVITED*	Karl Berggren *MIT*	***Transmission-Line Superconducting Nanowire Single-Photon Detectors: Imagers and Coincidence Counters***
9:00	Félix Bussières *University of Geneva*	***Amorphous MoSi SNSPDs with a low time jitter and a high detection efficiency***
9:20	Daniel Slichter *NIST-Boulder*	***UV-sensitive SNSPDs for integration in an ion trap quantum processor***
9:40	Zhaohui Li *E China Normal Univ*	***Multi-beam laser imaging with 100-channel single-photon detector***

Transmission-Line Superconducting Nanowire Single-Photon Detectors: Imagers and Coincidence Counters

K. K. Berggren, A. E. Dane, A. McCaughan, E. Toomey, Q.-Y. Zhao, D. Zhu

[1]*Affiliation: Massachusetts Institute of Technology, Cambridge, USA*

Superconducting Nanowire Single-Photon Detectors (SNSPDs) have long been thought of as lumped-element detectors in which a voltage pulse is triggered by the arrival of a single photon. In recent years, innovative architectures that enable photon-number resolution or amplified signal strength were developed, but these elements were based on similar whole-device responses to an incident photon. Arrayed architectures were developed that enhanced the capabilities of the detectors, but these approached also treated the detectors as lumped elements.

We discuss here recent developments in which we have learned to treat the device as a distributed, rather than lumped, element, and we show that the distributed behavior of the nanowire permits an array of new functions including time-resolved imaging as well as coincidence counting.

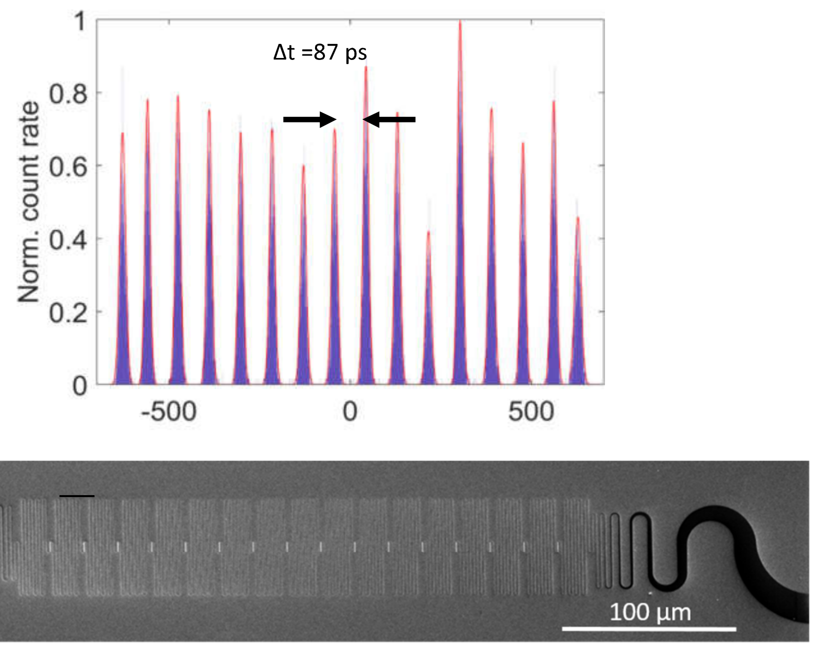

Fig 1. Top: Count rate vs. time difference between amplifiers at the two ends of distributed nanowire for a 16-channel nanowire readout. Bottom: Scanning-electron micrograph of 16 nanowire detectors with intervening delay lines integrated into a microstrip waveguide. This configuration enables not only spatial and temporal photon-arrival resolution, but also enables photon-coincidence counting.

Amorphous MoSi SNSPDs with a low time jitter and a high detection efficiency

Misael Caloz,[1] Boris Korzh,[1] Claire Autebert,[1] Nuala Timoney,[1] Matthieu Perrenoud,[1] Markus Weiss,[2] Christian Schönenberger,[2] Richard J. Warburton,[2] Hugo Zbinden,[1] and Félix Bussières[1,3]

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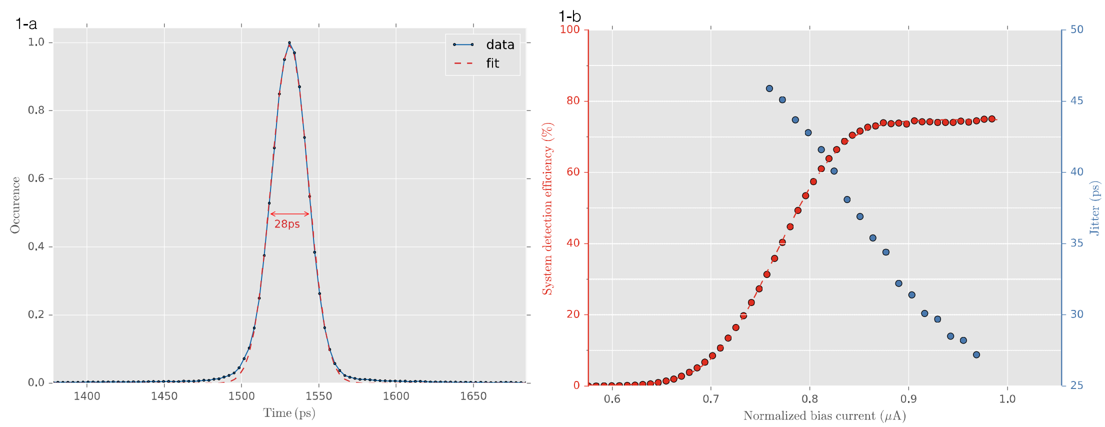
[2] *Department of Physics, University of Basel, CH-4056 Basel, Switzerland*
[3] *ID Quantique, CH-1227 Carouge, Switzerland*

Superconducting nanowire single-photon detectors (SNSPDs) are a key technology for optical quantum information processing [1]. Their low dark count rate, fast response time, small jitter, and high system detection efficiency (SDE) favours their use in various demanding quantum optics applications such as high-speed or long-distance quantum key distribution, quantum networking, device-independent quantum information processing and deep-space optical communication. One recent advance in the SNSPD field has been the introduction of amorphous superconductors such as tungsten silicide (WSi), molybdenum silicide (MoSi) and molybdenum germanium (MoGe). SNSPDs based on these materials currently have the highest reported detection efficiencies (93% with WSi [3]), as well as a high fabrication yield, favouring their use in complex structures such as detectors arrays. One limitation is that they typically operate at lower bias currents, in particular with nanowire geometries that lead to a saturated detection efficiency (a plateau). As a result, high-efficiency amorphous SNSPDs reported so far have a higher detection jitter, because the latter is essentially limited by the electronic noise of the amplification chain. Some previously reported values are 150 ps with 93% detection efficiency with WSi [3], and 76 ps with 87% detection efficiency for MoSi [4].

Obtaining a low jitter and a high detection efficiency requires finding an appropriate nanowire geometry in order to maximise the critical current while keeping a plateau, as well as the use of an optical stack to maximise absorption. In this talk we will report on high-efficiency SNSPDs based on amorphous MoSi exhibiting time jitters lower than 30 ps. For this we fabricated and characterised a series of devices with varying nanowire widths and fill factors. Fig. 1-a shows a jitter histogram for one device having a full-with at half maximum value of 28 ps at a temperature of 0.8 K. The corresponding detection efficiency curve is shown on Fig. 1-b; this device reaches a 75% detection efficiency with a clear detection plateau. Another device with a larger fill factor resulted in a detection efficiency of 85% with a jitter of 40 ps. The influence of the nanowire and meander geometries on the jitter and efficiency will be discussed.



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UV-sensitive SNSPDs for integration in an ion trap quantum processor

D. H. Slichter[1], V. B. Verma[2], D. Leibfried[1], R. P. Mirin[2], S. W. Nam[2], and D. J Wineland[1]

[1] *Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO USA*

[2] *Applied Physics Division, National Institute of Standards and Technology, Boulder, CO USA*

Superconducting nanowire single photon detectors (SNSPDs) are a versatile class of photon-counting detectors exhibiting near-unity detection efficiencies, fast response times, low timing jitter, and very low dark counts over a broad range of wavelengths. Recent advances demonstrating SNSPDs made from amorphous superconducting materials such as MoSi have enabled device fabrication without lattice-matched substrates [1], making it easier to integrate SNSPDs with other technologies. Our work focuses on integrating SNSPDs with surface-electrode rf ion traps, which are microfabricated devices for trapping atomic ions in vacuum; trapped atomic ions are an important technology for quantum information processing applications. Readout of the quantum state of a trapped ion qubit is accomplished by counting ultraviolet fluorescence photons emitted by the ion, and we propose using SNSPDs integrated directly into an ion trap chip for this task. This application may provide qubit state detection without any intermediate optics, which can be a crucial advantage for scaling to larger ion traps, but also presents several challenges for successful SNSPD operation, including the presence of large rf voltages near the SNSPD and the requirement of operation at temperatures near 4 K.

We present an overview of the work in [2]. We demonstrate stand-alone SNSPDs with 76(4) % system detection efficiency (SDE) at a wavelength of 315 nm and an operating temperature of 3.2 K, with a background count rate (BCR) below 1 count per second at saturated detection efficiency. This performance represents a factor of two increase in SDE and a reduction by two orders of magnitude in BCR relative to the best commercially available photomultiplier tube (PMT) detectors at this wavelength.

As proof of principle for our scheme of trap-integrated detectors, we fabricate MoSi SNSPDs integrated into test ion trap structures and measure their performance at 3.8 K in the presence of realistic rf trapping fields, produced by driving the rf electrode at 46 MHz with a peak-to peak amplitude of 50 V. The presence of rf degrades the maximum SDE, but not the BCR, of the trap-integrated detector. We present a simple model explaining these features, and demonstrate a maximum SDE with rf which is only 9 % lower than the maximum SDE without rf.

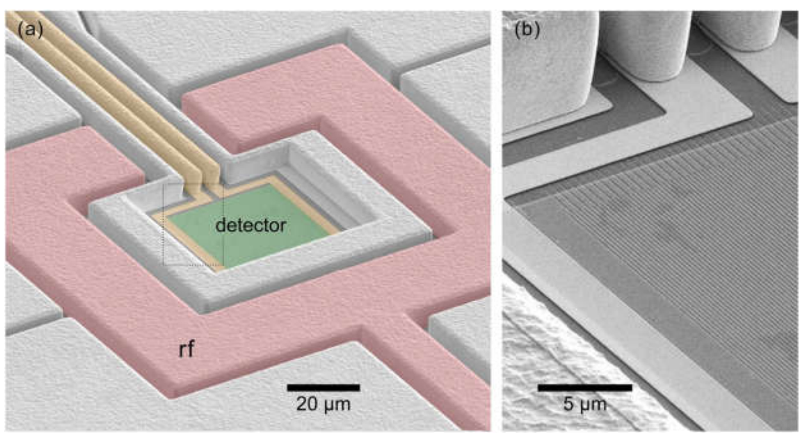

Fig 1. Panel (a) shows a test ion trap structure with integrated SNSPD (green). The SNSPD leads are shown in yellow, while the trap rf electrode is in red. When driven with a radio frequency potential (50 V peak-to-peak at 46 MHz), the rf electrode creates a three-dimensional pseudopotential well suitable for trapping a ^{9}Be+ ion 48 μm above the center of the detector. Panel (b) is a magnified view of the region in the dotted rectangle in (a), showing the meandered nanowire.

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Multi-beam laser imaging with 100-channel single-photon detector

Zhaohui Li, E Wu, Bingcheng Du, Heping Zeng and Guang Wu

State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China

Abstract. We demonstrated a multi-beam photon-counting laser imaging system based on a 100-channel single-photon detector. The three-dimensional image of the remote targets could be rebuilt quickly with the 100 beams and the time-of-flight measurement,

Light detection and ranging (Lidar) is a remote sensing technique, which detects the distance and the other information by illuminating the target with a laser [1]. The breakthrough of the measurement distance and the detecting rate is the research focus of Lidar [2]. The measurement can be improved to the quantum limit through the techniques of single-photon detection and time-correlated single-photon counting (TCSPC), which increase the range of the Lidar greatly [3]. On the other hand, with more laser beams in use, the Lidar system can rapid scan the target, which provides an important method for increasing the detecting rate.

Here we combined the two techniques of photon-counting and multi-beam, and developed a multi-beam photon-counting Lidar system. A pulsed laser source at 532 nm was applied in this system. With a diffractive optical element (DOE) beam-divider in use, the laser beam was divided into 100 beams in a linear array. At the receiving port, a home-built 100-channel single-photon detector was utilized to detect the reflected photons from the targets. Finally, long-distance high-speed three-dimension laser imaging was realized in the experiment.

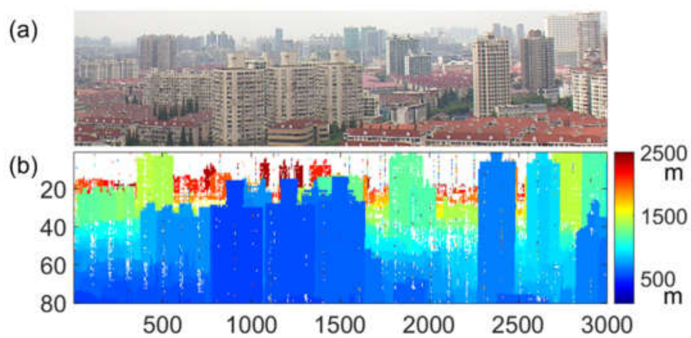

Fig 1. (a) Real photo of the target buildings, (b) the image of the buildings in vision rebuilt by Lidar.

Figure 1 shows the real photo of the buildings and the depth image obtained by the multi-beam photon-counting Lidar system in comparison. Figure 1(a) shows the real photo of the buildings taken in day time, in which these buildings at different distance are distinguished distinctly. The image of 80×30 acquisitions (80×3000 pixels) acquired by the Lidar system is shown in Fig. 1(b), in which the different colors refer to the different distance of the target buildings corresponding to the color bar. In Fig. 1 (b), the tall buildings in the real photo could be rebuilt and recognized easily. The maximum measurement distance of the system could be more than 2.5 km with an average distance precision of 26mm, while the average reflected photons number was only 0.0065 per pulse.

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Wednesday, August 2 2017

Applications III

10:30 – 12:00

Session Chair: Oliver Slattery

10:30 ***INVITED***	Hugo Zbinden *University of Geneva*	***Quantum-enabled applications***
11:00	Peter Bierhorst *NIST-Boulder*	***Device-Independent Random Number Generation with Photons***
11:20	Ivo Degiovanni *INRIM*	***Inferring the fairness of a quantum coin with a single (detected) toss***
11:40	Aitor Villar *National U of Singapore*	***Photons in space: a demonstration and a roadmap for satellite QKD***

Quantum Enabled Applications

Hugo Zbinden[1]
[1] *Université de Genève, GAP-Optique, Chemin de Pinchat 22, CH-1211 Genève 4, Switzerland*

It is interesting to note that limitations imposed by the quantum theory like the Heisenberg uncertainty principle or the non-cloning theorem lead to interesting applications like QKD or in metrology. In this talk, I will show that shot noise can be exploited in many ways. A first application, which is not surprising, is the use of shot noise for random number generation. Indeed, noise in modern cameras is heavily dominated by shot noise, so random numbers of quantum origin can be extracted from virtually any picture. Interestingly, this inevitable shot noise allow us also to achieve steganography in a provably secure way. Steganography may eventually be the only way of private communications in countries under a totalitarian regime. Finally and most importantly, the study of the entropy related to shot noise allows us also to design a new compression algorithm for pictures, which allows at a the same time high compression factors and neglectable (and quantifiable) information loss. This is of huge importance in many application with an exploiting number of high resolution pictures.

Device-Independent Random Number Generation with Photons

Peter Bierhorst[1], Scott Glancy[1], Emanuel Knill[1]
[1] NIST-Boulder, USA

It is possible to use a Bell nonlocality experiment to generate random numbers in a device-independent fashion: The output randomness can be trusted without having to assume a detailed model of the experimental devices being used. Intuitively, this is because any device that can consistently violate a Bell inequality necessarily must be generating entangled quantum states which will have some irreducible randomness. The amount of randomness can be quantified by measuring the size of the Bell violation.

A loophole-free Bell experiment can certify output randomness with the smallest possible set of assumptions. In particular, photonic loophole-free Bell tests [1,2] can be used to generate randomness [3], but since the per-trial violation is small, novel methods were required to effectively certify and extract the randomness. Here, we review the experiment and analysis of [1,3] and provide a general outline for implementing device-independent randomness generation with a photonic experiment.

In our experiment [1], a source generates nonmaximally entangled pairs of photons via spontaneous parametric downconversion. The two photons travel through fiber optic cables to two respective measurement stations that are space-like separated for the duration of each experimental trial. At each station, a random number generator governs polarization rotators that implement one of two possible measurement settings prior to detection or nondetection of an arriving photon. For our experiment, we employed a novel entanglement source and superconducting nanowire single-photon detectors to achieve a system efficiency of roughly 75 % for collection, transmission, and detection of the photons. This significantly exceeds the 66.7 % efficiency required to observe violation in a loophole-free Bell test (which does not allow postselection).

A Bell experiment employs a Bell function that assigns a numerical score to each possible outcome of an experimental trial. The Bell function, when applied to the observed outcomes, quantifies the amount of randomness in the data. To successfully account for low per-trial violations in photonic experiments, we construct a Bell function that is closely tailored to the expected experimental distribution. In [3], training data was used for this purpose, but a sufficiently accurate theoretical model could also be used. Because no experiment is perfectly stable, we describe an adaptive Bell function that can change during run time in response to changes in the experiment.

After the data is collected, the protocol may abort if the accumulated Bell score signals that the data contains little or no certifiable randomness. Conditioned on not aborting, the experimental data is certified to contain randomness. Classical post-processing with an extractor function is then employed to process the raw output data into a short, near-uniformly distributed output string.

The protocol consumes randomness to govern the polarization rotators, and the classical post-processing also requires a small random seed input. Considering this, two paradigms under which such a protocol is useful are: 1) “Public to private” randomness, in which the input randomness can be public so long as it is assumed to be random with respect to the experimental devices, and the output randomness can be trusted to be private. 2) “Randomness expansion,” in which the input randomness is assumed fully private and the amount of private output randomness exceeds the size of the input. The second paradigm requires additional strategies to minimize the amount of input randomness which may be feasible to implement soon with existing technology.

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Inferring the fairness of a quantum coin with a single (detected) toss

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Measurements are the very basis of Physics, especially in Quantum Mechanics, where they assume even a very fundamental role. Apart from usual projective measurements, causing the wave function collapse into an eigenstate of the measured operator, in Quantum Mechanics other kinds of measurement are possible, some of them featuring remarkable properties.

An example of these are Weak Measurements [1-3], realised for the first time in [4-6] and used for addressing fundamental questions [7-13], and as a very promising tool for Quantum Metrology [6,14-19].

One of the most intriguing properties of Weak Measurements, since they rarely lead to wave function collapse, is allowing to gather simultaneous information on non-commuting observables [20,21], impossible with the standard (projective) measurement protocols.

A second example, which will be discussed in detailed within this talk, is provided by Protective Measurements [22,23], a newly realized technique able to extract information regarding the expectation value of an observable even by measuring a single (protected) particle.

A generalisation of the protective measurement approach leads to a novel quantum measurement paradigm (named hereby Genetic Quantum Measurement) exploiting a genetic-like approach to measurement that mimics the evolution-inspired processes of mutation, crossover and selection, typical of genetic evolution, that inspired also the concept of genetic algorithm in computer science. This paradigm can be also seen as a special kind of quantum random walk [24].

Genetic Quantum Measurements are composed of a sequence of steps consisting of an interaction-interference stage followed by a selective (i.e. projective) measurement. For a reasonable number of interactions and for specific interaction strength, this protocol outperforms, in terms of uncertainty reduction, the conventional projector-based quantum measurements (even when they represent the optimal measurement, i.e. the one saturating the quantum Cramer-Rao bound). Specifically, a detection of just a single photon (the quantum coin is realized by the polarisation state of the single photon) for a sufficient number of steps will provide complete information about the fairness of the initial state preparation.

For these reasons, the Genetic Quantum Measurement approach appears to be an intriguing technique that may have far-reaching implications on the area of quantum measurement, therefore being of the utmost interest for all quantum technologies and, in particular, for quantum metrology and quantum-enhanced measurement.

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Photons in space: a demonstration and a roadmap for satellite QKD

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Significant efforts are being expended to enable Quantum Key Distribution (QKD) over global distances [1,2,3]. In this framework, we propose to use entanglement-based QKD with satellites equipped with optical links. We are working on a programme called SPEQS (Small Photon Entangling Quantum System) focused on building space-ready light sources with the strongest photon correlation possible, capable of operating in small satellites and eventually enabling QKD communications from space.

The programme use an iterative approach. Three generations of devices are envisioned. First, ***SPEQS-CS*** (Correlated Source) is built around a single β-Barium Borate (BBO) crystal. This source provides polarisation-correlated photon pairs. Its purpose is to demonstrate essential supporting technology such as polarisation rotators based on liquid crystal devices, single-photon detectors and the electronics package to measure the quantum state. This is already demonstrated onboard the *Galassia* cubesat and the results are reported in [4].

SPEQS-1 comprises an entangled source based on a collinear non-degenerate type-I SPDC emission. The source is implemented via a crossed-crystal configuration using a pair of BBOs whose optical axis are rotated at 90 degrees with respect to each other. The goal is to demonstrate polarisation entanglement in space by generating the two-photon state shown in Fig. 1.

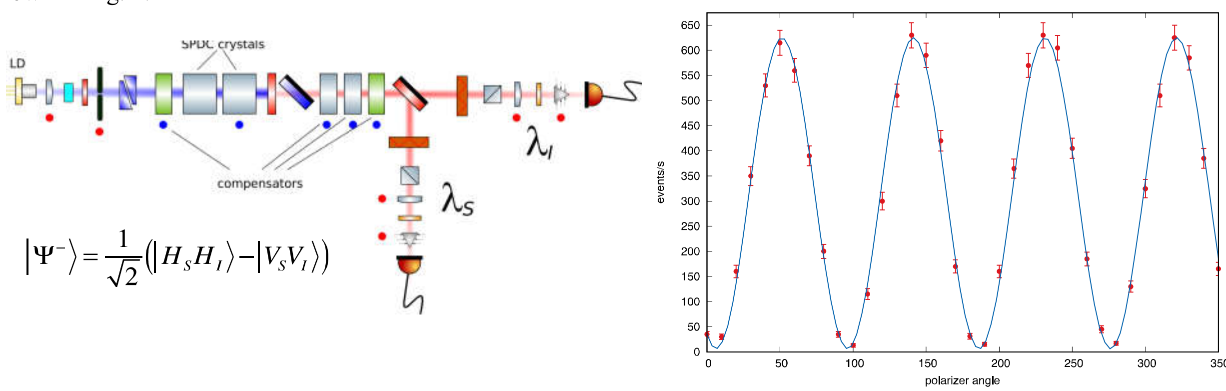

Fig 1. (Left) SPEQS-2 layout. Removing components with red spots will show SPEQS-1. Additionally removing components with blue spots depicts SPEQS-CS. (Right) Polarisation entanglement measurement on the |Ψ⁻⟩ state generated in SPEQS-1 and 2. |Ψ⁻⟩ is the only state that allows fidelity measurements with a single polarisation analyser.

SPEQS-2 is an enhanced version of SPEQS-1. It has the same crystal geometry but is targeted for improved brightness (pairs/s/mW) and efficiency (coincidences-to-singles ratio). Here, due to the emission-opening angle nature of the SPDC process, numerical simulations of the effect of larger collection angles in entanglement quality via a ray-tracing model (Fig. 2) are used to analyse the trade-off between brightness and entanglement quality.

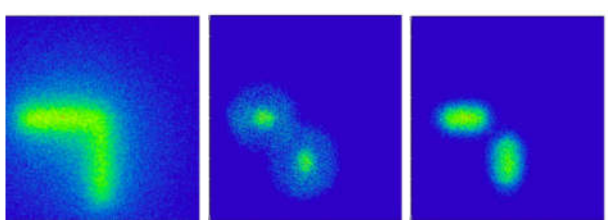

Fig 2. Ray-tracing simulation of SPDC photons in a crossed-crystal configuration. (Left) shows the total SPDC emission. The central (right) picture shows SPDC emission effectively coupled into a single mode fiber using an achromatic (aspheric) lens. Different angular distributions account for different arrival times of the SPDC photons, making them distinguishability in time, thus decreasing entanglement quality.

The demonstration of these compact, robust, small-footprint sources will be beneficial not only for moving platforms such as satellites, spacecrafts or drones, but also for environments like data centers, where fiber-based QKD is employed.

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Wednesday, August 2 2017

Integration II

13:40 - 14:30

Session Chair: Thomas Gerrits

13:40 *INVITED*	Dirk Englund *MIT*	***Large Scale Photonic Integrated Circuits for Quantum Information Science and Machine Learning***
14:10	Sonia Buckley *NIST-Boulder*	***Low-temperature waveguide coupled Si LEDs and superconducting nanowire detectors***

Large-Scale Photonic Integrated Circuits for Quantum Information Science and Machine Learning

Dirk Englund[1], Nicholas C. Harris[1], Hyongrak Choi[1], Mikkel Heuck[1], Mihir Pant[1], Gregory R. Steinbrecher[1], Yichen Shen[1], Yoav Lahini[1], Mihika Prabhu[1], Changchen Chen[1], Franco N.C. Wong[1], Tom Baehr-Jones[2], Michael Hochberg[2], Marin Soljacic[1], and Seth Lloyd[1]

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Abstract. Photonic integrated circuits (PICs) can now perform unitary optical mode transformations with near-perfect fidelity. This talk will describe such programmable PICs and their use in quantum and classical information processing. The talk will also consider concepts for single-photon-level nonlinearities and high-fidelity single-photon generators that may be integrated into such PICs.

Photonic integrated circuits (PICs) have become increasingly important in classical communication applications, including as transmitters and receivers in long-haul, metro and datacenter interconnects. Many of the same attributes that make PICs attractive for these applications — compactness, high bandwidth, and the ability to control large numbers of optical modes with high phase stability — also make them appealing for quantum information processing and new forms of optical signal processing. This talk will review recent progress in adapting one of the leading PIC architectures — silicon photonics — as a programmable platform for arbitrary linear optical transformations between sets of optical modes. We analyze this programmable PIC for mode transformations in optical quantum information processing schemes and show that the PIC's reconfigurability allows near-perfect cancellation of fabrication imperfections[1]. This allows large-scale programmable quantum walk experiments with low loss[2]. Beyond quantum information processing, such programmable PICs also appear to have some promising classical applications, including in machine learning[3].

Photonic integrated circuits and nanophotonic devices could also enable new types of high-performance devices for single-photon generation and nonlinear interaction. In particular, we will discuss a concept for on-demand single-photon generation using heralded and temporally multiplexed spontaneous four-wave mixing on-chip[4]. Using a feedback mechanism of photon addition and subtraction, it is possible to prepare high-fidelity single-photon states on-chip by temporal and spectral multiplexing, as outlined in Fig. 1b. We will also describe a new concept for confining optical fields into far sub-wavelength mode volumes, which may enable single-photon-level nonlinearities through bulk-material Kerr nonlinearities[5]. Finally, we discuss possible usages and limitations of single-photon-level nonlinearities for many-photon quantum gates[6].

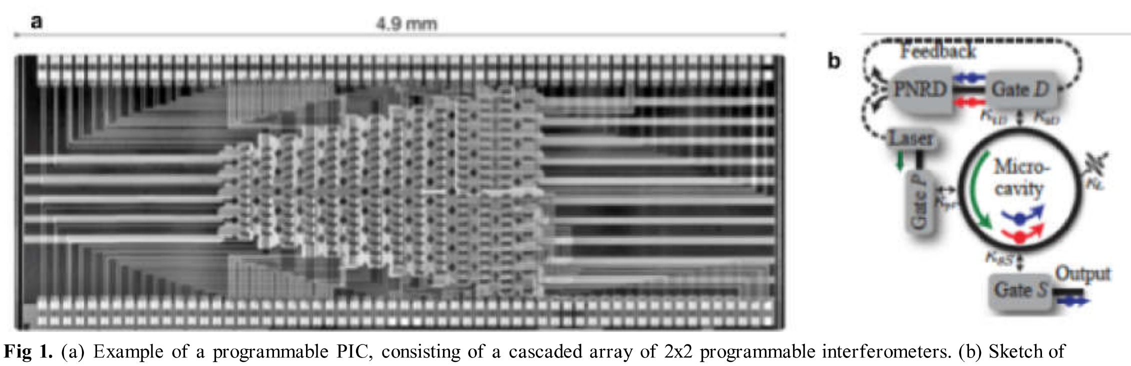

Fig 1. (a) Example of a programmable PIC, consisting of a cascaded array of 2x2 programmable interferometers. (b) Sketch of the single photon source indicating nonzero coupling rates. Subscripts i; p; s refer to idler, pump, and signal wavelength. Solid lines are optical waveguides, while dashed lines represent electrical control signals. PNRD: photon number resolving detector.

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Low-temperature waveguide coupled Si LEDs and superconducting nanowire detectors

S. Buckley[1], M. J. Stevens[1], J. Chiles[1], A. N. McCaughan[1], R. P. Mirin[1], S. W. Nam[1], J. M. Shainline[1]

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An on-chip, silicon-compatible light source has long been pursued for classical optical telecommunications without significant success. However, for applications where cryogenic operation is already required, for example, in quantum optics or neuromorphic or superconducting computing, point defects in Si may provide a suitable light source. Here we demonstrate a waveguide coupled light-emitting diode in Si, fabricated in an integrated platform with WSi superconducting nanowire detectors. We further demonstrate up to 11 detectors coupled to an LED in a single integrated photonic device.

W-centers are defect centers in Si composed of Si interstitials. They are generated by bombardment with Si ions [1]. With photoresist masking, W-center regions can be selectively defined (e.g. in the i-region of a p-i-n diode). They emit sub-bandgap light at 1.22 µm wavelength. We fabricate waveguide integrated W-center LEDs (optical microscope image inset Fig. 1 (a)) and nanowire detectors in a process using seven photolithography steps on a silicon-on-insulator substrate. An IV curve for a typical LED is shown in Fig. 1 (a). The turn on voltage is around 0.95 V. The light couples to a 1 mm silicon waveguide, which has a WSi SNSPD at the end for detection. Fig. 1 (b) shows the detector response for four different values of LED current, as the SNSPD current is increased. We observe counts for LED currents as low as 100 pA. We also verify that the light is waveguide coupled in Fig. 1 (c) by plotting counts/s on the SNSPD versus LED current for two devices on waveguide 1 and 2, 550 µm apart. We observe a 40 dB increase in counts for the waveguide-coupled LED/detector pairs. We observe a total system detection efficiency of 5×10^{-7}. While much of the inefficiency comes from the conversion from electrical energy to light in the LED, there is also likely loss due to inefficient coupling to the waveguide mode, and losses due to poor absorption from the waveguide mode to the nanowire.

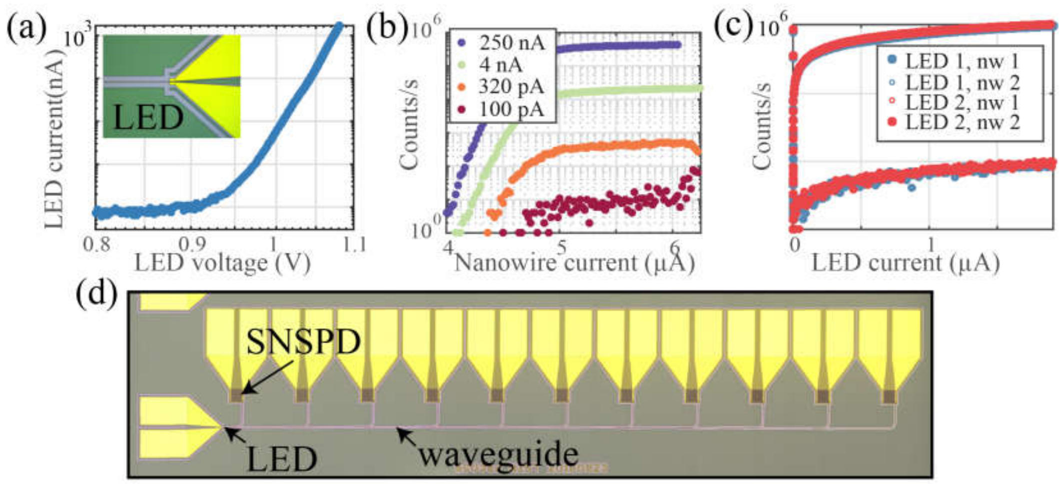

Fig 1. (a) IV curve for a W-center Si LED with optical microscope image inset..(b) Detector response for different LED currents. (c) LEDs on the same waveguide as the detector show 40 dB increased counts over LEDs on a separate on-chip waveguide. (d) Optical microscope image of a HiDRA device, demonstrating integration of 11 SNSPDs in a single integrated optic device.

Finally, we show that we can integrate these LEDs and SNSPDs in a scalable process. Fig. 1 (d) shows a device designed to measure light from the LED over several orders of magnitude of intensity. The device consists of a series of 10 beamsplitters with approximately 35/65 splitting ratio. We observed counts on all 11 SNSPDs.

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Metrology III

15:40 – 17:20

Session Chair: Ingmar Müller

15:40	Sergey Polyakov *NIST-Gaithersburg*	***Characterizing single-photon detectors within a second-order model and beyond***
16:00	Hugo Ferretti *University of Toronto*	***Beating Rayleigh's Curse Using SPLICE***
16:20	Jean-Philippe MacLean *University of Waterloo*	***Experimental observation of ultrafast biphoton correlations with energy-time entanglement***
16:40	Animesh Datta *University of Warwick*	***New aspects of quantum-optical sensing: multiple parameters & covertness***
17:00	Ivan Burenkov *NIST/JQI*	***Quantum Coherent Spectrometer: frequency discrimination below the standard quantum limit***

Characterizing single-photon detectors within a second-order model and beyond

Michael A. Wayne[1,2], **Joshua C. Bienfang**[2], **and Sergey V. Polyakov**[2]
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Abstract: We present a unified, device-independent autocorrelation-based model of a photon-counting detector. We show that all commonly characterized features of detectors, such as detection efficiency, dark count rate, afterpulse probability, dead time, and reset behavior are first and second-order effects. We developed and experimentally implemented a detector characterization method that includes such a verification. In addition to characterizing these detectors, we find a heretofore unreported afterpulse effect beyond the second-order model. Our technique is applicable to any type of click/no-click detectors.

Our method is based on using an attenuated calibrated cw laser beam as an input to the detector and a nearly deadtime-free time-tagging system that monitors the detector output. The critical requirement is that the time-tagging system's inactive time, the time when it is not capable of detecting next output from the detector (if any), is shorter than the detector's recovery time. The relative simplicity of the physical implementation of this technique is supplemented with advanced statistical analysis. Particularly, we calculate auto-correlations of second and third orders.

To first order, detection efficiency (DE) is a proportionality coefficient between the rate of incoming photons and the detection rate and the dark count rate is the rate of detections when no light is present at the input. These two parameters can be found from just the total number of single counts. Such a measurement gives the apparent rate of detected photons per exposure time. However, this approach leads to significant systematic errors. The recovery time, or the time immediately after a detection during which the detector is incapable of producing an electronic output, and afterpulsing, excess dark counts at the end of recovery time are the examples of effects that are identified from the physical operating principles of a detector. It turns out that mathematically all these effects are related through a second-order correlation of the photoelectronic detection times. Thus, we can generalize a device-independent second-order detector model. Using this model, we characterize a pair of single-photon avalanche diodes (SPAD)s.

A second-order model has been quite successful in describing single-photon detectors. However, its implicit assumption that the detector's behavior may only depend on the time passed since a previous detection has not been directly verified. This verification is particularly important, because a second-order model has difficulties with extrapolation to high count rates. To verify a second-order model, we employ a third-order autocorrelation. We show, for the first time, that second-order detector models that are commonly used to characterize a detector have limited accuracy and lead to systematic errors, which is particularly important for precision measurements and substantial at high count rates. Using our method, Fig. 1, we find that second-order model cannot accurately describe times immediately following the inactive time, indicating that more than one prior detection affects the detector's behavior.

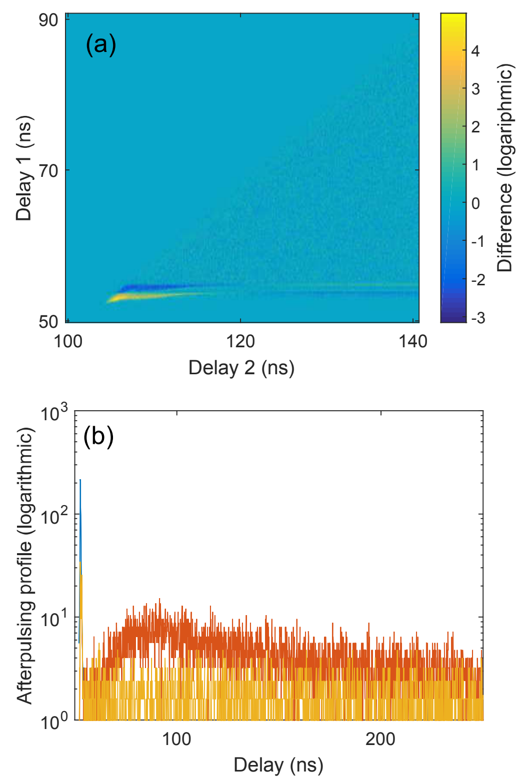

Fig. 1: Second-order model validation via third-order correlation histogram analysis. (a) Difference between expected and actual histograms expressed as a logarithm of the ratio of the measured and expected histograms. (b) Abnormal second afterpulsing and its transition to the steady-state in a SPAD. Distribution of detection times for the third pulse for a delay between the first two pulses fixed at 52, 54 and 56 ns.

Beating Rayleigh's Curse Using SPLICE

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It has been shown that the Fisher information about the separation between two light sources contained in the intensity at an image plane falls to zero as the separation drops, an effect called "Rayleigh's curse."[1]. The information about this separation present in the full electromagnetic field, however, is finite and independent of this separation. This suggested that there exists better measurement strategies for extracting this information. In this Letter, we introduce a simple scheme for measuring the separation of two closely separated equal-intensity incoherent light sources and experimentally demonstrate its advantages, achieving near-quantum-limited performance and immunity to Rayleigh's curse.

Imaging devices such as a microscopes or telescopes have a resolution limit, a minimum separation it can resolve between two objects or sources. This limit is typically called by "Rayleigh's criterion". In recent years, high-profile techniques have demonstrated that, by controlling the source of illumination in new ways, Rayleigh's limit can be surpassed. A proposal by Tsang, Nair and Lu [1] reexamines the problem of estimating the distance between two nearby incoherent light sources in situations where it is impossible to control the illumination. Inspired by quantum information and quantum metrology, they calculated that the Fisher information about the separation between two light-sources in both the *intensity* at the image plane and in the full electromagnetic field, *intensity* and *phase.* They found that, as the separation goes to zero, there was infinitely more information in the full field than in the intensity alone. Furthermore, they gave example of idealized measurement scheme capable of extracting that information.

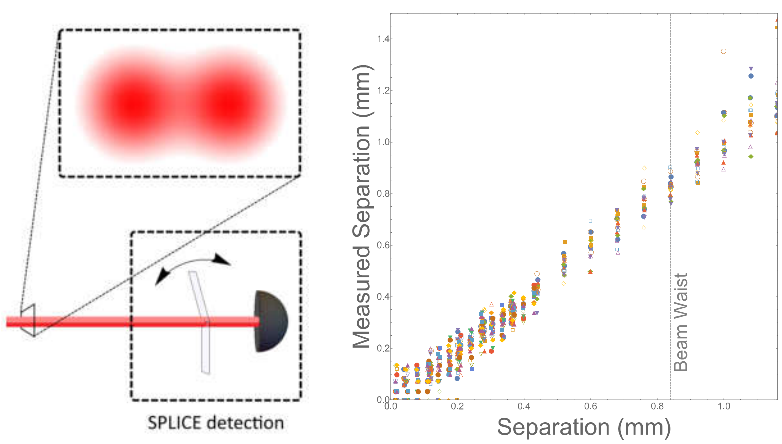

Fig 1. (Top left) Representation of the transverse intensity pattern of the two gaussian beams before the measurement. (Bottom left) Experimental apparatus used for SPLICE consisting of two glass plate followed by a fiber coupler. (Right) Beam separation measured with SPLICE vs known value of the separation.

With their results in mind, we designed and tested a new technique we call SPLICE (Super-Resolved Position Localisation by Inversion of Coherence along an Edge) which takes advantage of the phase information in the field. At low light levels (1200 photons), we were able to measure the distance between two 0.84 mm gaussian beams with a standard error of 0.05 mm even at small separations. This performance is provably better than the best performance achievable using intensity-based imaging, and is within a factor of 2 of the optimal quantum bound.

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Experimental observation of ultrafast biphoton correlations with energy-time entanglement

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The nonlinear process of spontaneous parametric down-conversion (SPDC) is an effective way of producing two photon states and moreover provides a reliable source of energy-time-entangled photons. Due to energy conservation, most SPDC sources produce photons with frequency anti-correlations [1]. This is accompanied by strong positive timing correlations in the arrival times of the two photons, arising from the coherence length of the pump. Precise control over these spectral and temporal correlations is of particular importance for quantum communications and metrology. The spectral or energy-time degree of freedom can be used to encode information in high-dimensional Hilbert space [2] and is naturally robust when transmitting through both long-distance fiber links [3] and photonic waveguides [4].

In order to fully characterize these correlations, both spectral and temporal measurements are required. Furthermore, the observation of many quantum effects, including nonlocal Franson dispersion cancellation as well as measuring Bell inequalities via Franson interferometry, require fast detectors. While ultrafast pulses are frequently analyzed in the spectral and temporal domain, extending these time domain characterization tools to single photons is challenging [5].

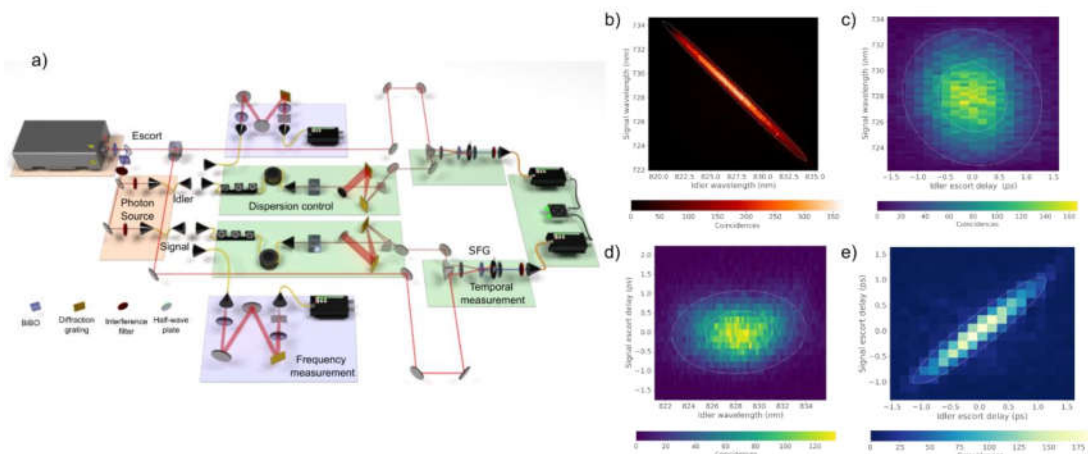

Fig 1. a) Experimental setup for spectral and temporal characterization of ultrafast biphotons. Frequency-entangled photons are created through spontaneous parametric down-conversion of an ultrafast pulse from a frequency-doubled Ti:sapphire laser. A combination of frequency and temporal measurements are made in coincidence in order to reconstruct (b) the joint spectral intensity, (e) the joint temporal distribution, as well as the (c,d) joint time-frequency correlations of the signal and idler photons. Spectral measurements are made with a monochromoter while temporal measurements are made using time-resolved frequency upconversion with noncollinear sum frequency generation between a strong escort pulse and the signal or idler. A fibre and grating compressor before the upconversion control the dispersion of each photon. Frequency anti-correlations observed in (b), are accompanied with positive correlations in the signal-idler arrival times (e). Time-frequency plots (c,d) show very little correlations indicating low dispersion in the signal and idler photons.

In this work, we experimentally reconstruct the spectral and temporal correlations of two ultrafast photons produced in spontaneous parametric downconversion with a pulsed pump. Time resolved single photon detection is achieved with sum frequency generation and we control the dispersion of the individual photons with a grating compressor. We directly observe energy time entanglement of the biphotons from the strong frequency anti-correlations between photons as well as the strong positive correlations in photon arrival times, measuring an energy time product $\Delta(\omega_1 + \omega_2)\Delta(t_1 - t_2) = 0.097 \pm 0.002$, well below the classical limit of 1. The experimental apparatus developed here provides a toolbox which we are using to explore ultrafast quantum effects with energy-time entangled photons.

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New aspects of quantum-optical sensing: multiple parameters & covertness

Animesh Datta[1], Dominic Branford[1], Magdalena Szczykulska[2], Christos Gagatsos[1], Boulat Bash[3], Saikat Guha[3]

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[2]*Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom*

[3]*Quantum Information Processing Group, Raytheon BBN Technologies, Cambridge, Massachusetts 02138, USA*

Abstract: I will present our recent results on two novel dimensions of quantum-optical sensing–the quantum limits of estimating multiple parameters simultaneously and the notion of quantum-secure optical sensing. I will discuss our theoretical results and the context of their quantum-optical experimental studies.

Body text: Interferometric estimation of a single relative phase has long been the canonical problem of theoretical and experimental quantum metrology. It has shaped our intuition of quantum metrology and underlay the development of sophisticated systems from atomic clocks to gravitational wave detectors. Yet, quantum metrology of a single parameter is *not* fully quantum. This is because the quantum limits for estimating individual parameters can always be attained, while estimating multiple parameters simultaneously might be prohibited by the non-commutativity of quantum measurements [1]. Metrology thus possesses a level of quantumness that only emerges when considering multiple parameter estimation.

Understanding this level of quantumess in metrology will be vital if we are to develop sophisticated applications of quantum metrology such as imaging and spectroscopy. Both of these are inherently multi-parameter problems. I will present some of our results on the simultaneous estimation of multiple phases as well as phase and phase diffusion. The former can be thought of as a crude model for phase-contrast microscopy while the latter as a model for noise spectroscopy. I will discuss the requirements for tangible quantum advantages in these cases. I will also discuss a fundamental gap that appears between Gaussian and non-Gaussian systems in multi-parameter estimation [2], for which photonic systems could be an ideal test bed.

I will next present a novel confluence of communication, sensing and security in the quantum domain – quantum-secure covert active sensing. Covertness in a notion of security more unassailable than computational encryption, information-theoretic secrecy and even quantum cryptography, all of which offer progressively stronger security against unauthorized deciphering but do not ensure stealth. Stealth renders the presence of the message undetectable, rendering issues about its undesired decoding irrelevant. The essential strategy is to hide the signal used for active detection in the thermal background such that an adversary is unable to detect its presence (as shown in Fig 1). This sets a limit on the signal power, but quantum-optical probes can then be used to extract more information about the unknown (phase) object. I will discuss the limits on the attainable precision and the nature of optical probes and detectors that may be necessary for achieving them [3].

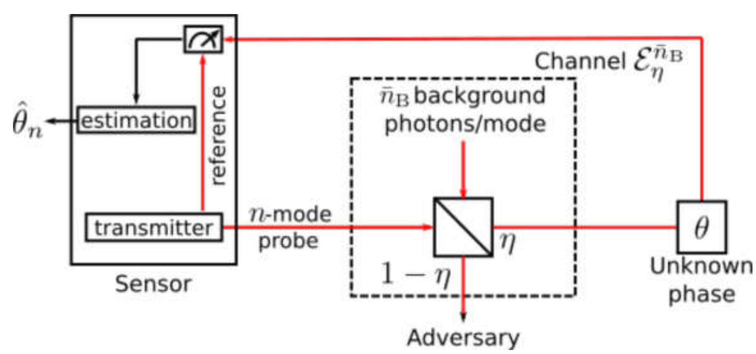

Fig 1 : Layout for a quantum-secure covert sensing setup

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Quantum Coherent Spectrometer: frequency discrimination below SQL

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Abstract: We introduce a new type of a quantum receiver based on an M-ary coherent frequency-shift keying encoding. We show that for sufficiently large alphabets ($M > 4$) the discrimination error of this receiver breaks Helstrom bounds of all previously reported quantum receivers.

The efficient, low-power communication is one of the most sought after developments in modern photonics. A typical communication link is engineered to deliver just enough optical power to the receiver so that the detection is made with a given accuracy (i.e. below a specific bit error rate). Therefore, the receivers and the associated communication protocols are being optimized for power. It was shown that receivers based on quantum mechanics can reach much lower error bounds (Helstrom bounds (HB)s) than classical receivers (whose performance is bounded by the standard quantum limits (SQL)s) with the same input conditions. The conventional quantum receiver approach for a multiple nonorthogonal state discrimination demonstrated so far consists of N consecutive adaptive measurement stages with equal duration sampling of an input signal. The local oscillator is set based on a hypothesis of the most likely state of the input such that it interferometrically nulls the output. If the hypothesis is correct, then, ideally, the probability to detect a photon at the output is zero. If the hypothesis is incorrect, a click on a single-photon detector can occur during a measurement stage. At the and of measurement stage, the local oscillator is adjusted to the new most probable state using the detection history.

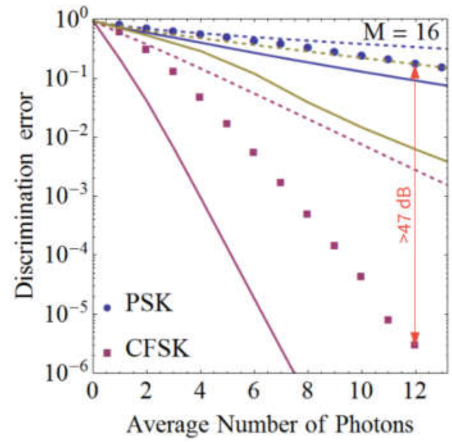

Fig. 1: Error probabilities for an ideal M-ary ($M = 16$) PSK (blue circles) and CFSK (purple squares) receivers as a function of the mean number of signal photons, compared to the HBs (solid lines), the SQLs (dashed lines) and color coded: blue - PSK, purple - CFSK, brown - QAM. The simulations assume 100% efficient detection.

There exist several encoding methods – or keying protocols. Each is characterized by its SQL and HB. The phase shift keying (PSK) has been thoroughly investigated, including an experimental demonstration [1]. Another type of receiver typically used for communication is based on quadrature-amplitude modulation (QAM). It turns out that a quantum receiver based on QAM can naturally surpass the PSK receiver in discrimination error probability, see Fig. 1. Here we introduce a coherent frequency shift keying (CFSK)-based quantum receiver and show that it beats all previously introduced quantum receivers in terms of discrimination error over a range of input field intensities and alphabet lengths. We found no attempts in the literature to calculate the Helstrom bound (HB) and the standard quantum limit (SQL) for CFSK, so we have derived the HB ans SQL from scratch.

Our CFSK quantum receiver is based on arrival times of detected photons. Performance of the CFSK receiver is calculated with Monte-Carlo simulations. We find that our CFSK strategy significantly surpasses PSK and QAM HBs for a sufficiently large alphabet length (M >4), thus it outperforms all currently known receivers, either quantum or classical. For M=16 and power of 12 photons per symbol CFSK provides 10^{-6} discrimination error probability which is more than 47 dB improvement in comparison to PSK, see Fig. 1.

Remarkably, the experimental complexity of our discrimination algorithm is similar to that of previously reported receivers and experimental implementation can be made with off the shelf components only. Our quantum enhanced receiver doubles the amplification-free length of the state-of the art optical communication links. To put this number in perspective, our technology enables an amplification-free optical fiber communication between Washington and New York at 1 Gb/s and bit error rate $\approx 10^{-9}$ with only 15 mW of input optical power.

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Conference Dinner

18:00 – 21:00

Thursday, August 3 2017

Quantum Measurements

8:30 – 10:00

Session Chair: Omar Magana Loaiza

8:30 *INVITED*	Andrew White *University of Queensland*	***Manifold single photons and their many uses***
9:00	Geoff Pryde *Griffith University*	***Unconditional shot noise limit violation in photonic quantum metrology***
9:20	Alex Jones *University of Oxford*	***Many-photon distinguishability and unambiguous characterization of multiport interferometers***
9:40	Michael Mazurek *University of Waterloo*	***Quantum-free state and measurement tomography***

Manifold single photons and their many uses

Andrew G. White[1–3]
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Quantum photonics requires production, processing, and detection of quantum light fields such as squeezed light, single photons or entangled photons. For quantum photonics to realise its potential, three technologies are necessary: efficient, fast, photon counters; linear and nonlinear photonic circuits; and single photon sources. Until recently, a significant roadblock to progress has been the lack of scalable photon sources: here we discuss the efforts of our research team and our collaborators to produce and apply *manifold* single photon sources.

Our single-photon source is the emission from an efficient and deterministic quantum dot-micropillar system. We introduce a scheme for active temporal-to-spatial demultiplexing of our photons. The scheme scales quasi-polynomially with photon number, providing a viable technological path for routing n photons in the one temporal stream from a single emitter to n different spatial modes. Active demultiplexing is achieved with a network of electro-optically reconfigurable waveguides monolithically integrated in a lithium niobate chip. The measured demultiplexer performance can enable a six-photon rate three orders of magnitude higher than the equivalent heralded SPDC source, providing a platform for intermediate quantum computation protocols [1].

Such a protocol is achieved with a BOSONSAMPLING device: a quantum machine expected to perform tasks intractable for a classical computer, yet requiring minimal nonclassical resources as compared to full-scale quantum computers. Photonic implementations to date employed sources based on inefficient processes that only simulate heralded single-photon statistics when strongly reducing emission probabilities. BOSONSAMPLING with only single-photon input has thus never been realized. Here, we report on a BOSONSAMPLING device operated with a bright solid-state source of single-photons with high photon-number purity, 99±1%. By demultiplexing into three single photons, our source is between 1 and 2 orders of magnitude more efficient than current heralded multiphoton sources based on spontaneous parametric down-conversion, allowing us to complete the boson-sampling experiment faster than previous equivalent implementations [2].

Quantum-dot systems also promise the capability of efficiently realising nonlinear photon-photon interactions, such as *photon sorting*—separating the single and two-photon components of an optical mode into two separate modes [3]—or *Fock-state filtering*, converting coherent states into a highly nonclassical states without any post-selection [4]. Such nonlinear interactions, if realised efficiently, it could be used to perform full Bell measurements, and to implement deterministic quantum logic gates between, photonic qubits.

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Unconditional shot noise limit violation in photonic quantum metrology

Sergei Slussarenko[1], Morgan M. Weston[1], Helen M. Chrzanowski[1,2] and Geoff J. Pryde[1]
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Quantum metrology exploits quantum correlations to perform measurements with precision higher than can be achieved with classical approaches. Photonic approaches promise transformative advances in the family of interferometric phase measurement techniques, a vital toolset used to precisely determine quantities including distance, velocity, acceleration and materials properties. Without quantum enhancement, the precision limit in optical phase sensing (i.e. the minimum uncertainty) is the shot noise limit (SNL): $\Delta\phi = 1/\sqrt{N}$, where N is the number of resources (e.g. photons) used. Entangled photons promise sensitivity surpassing the shot noise limit achievable with classical probes. The maximally phase-sensitive state is the NOON state [1], a path-entangled state of definite photon number N. Despite theoretical proposals stretching back decades, no measurement using such photonic (i.e. definite photon number) states has unconditionally surpassed the shot noise limit: by contrast, all such demonstrations employed postselection to discount photon loss in the source, interferometer or detectors. Here, we use an ultra-high efficiency source and high efficiency superconducting photon detectors [2] to respectively make and measure a two-photon NOON state, and use it to perform *unconditional* phase sensing beyond the shot noise limit – that is, without artificially correcting for loss or any other source of imperfection.

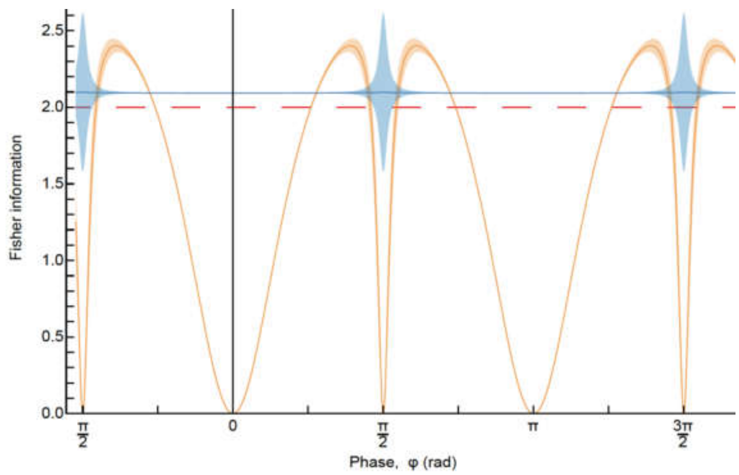

Fig 1. Fisher information. The orange curve is determined from uncorrected experimental interferometric data. The dashed red line is the naïve shot noise limit (SNL) for this scheme, and the blue curve is the SNL corrected for actual photon source and detector characteristics. Shading represents uncertainties. The experimentally-determined Fisher information surpasses the SNL over certain phase ranges.

We performed a 2-photon NOON state polarisation interferometry measurement on a birefringent test phase with photons generated from a high-heralding-efficiency, high purity source of telecom-wavelength photon pairs [3]. Unlike previous experiments, our measurement apparatus does not require post-selection to achieve phase uncertainty below that achievable in an ideal, lossless classical interferometer. For our experimental apparatus, we expected a fringe visibility of 0.98 and symmetrical interferometer arm efficiencies around 0.8 (which includes the detector efficiency), which is sufficient for beating the SNL with $N = 2$ NOON states.

Our results (Fig. 1) show a clear violation (for a range of phases) of the adjusted SNL bound, $F_{\mathrm{SNL}} = 2.09635$, that takes into account the information in unrecorded trials arising from loss and higher order terms – making our demonstration unconditional. We also performed a direct phase sensing measurement (not shown) and observed phase uncertainties many standard deviations below the SNL. Our results enable quantum-enhanced phase measurements at low photon flux and open the door to the next generation of optical quantum metrology advances.

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Many-photon distinguishability and unambiguous characterization of multiport interferometers

Alex Jones[1,2], Adrian Menssen[1], Benjamin Metcalf[1], Malte Tichy[3], Stefanie Barz[1], Steve Kolthammer[1], Ian Walmsley[1]

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The role of distinguishability in the quantum interference of two particles was highlighted in the famous experiment by Hong, Ou and Mandel 30 years ago [1]. Two photons incident on the ports of a balanced splitter tend to bunch at the outputs, and the more similar the photons, the stronger the bunching. For more than two particles, new aspects of distinguishability arise [2,3]. We study this through the interference of three independent photons in a three-port interferometer [4]. We demonstrate that pairwise similarity of the photons is insufficient to describe their behavior, and we investigate a collective three-particle aspect of distinguishability, the 'triad phase'.

We generate three heralded, pure single photons using four-wave mixing in a silica chip [5]. These photons are injected into a balanced three-port fiber beam splitter, whose output ports are monitored with photon counting detectors. Initially we use the coincident detection of a photon at each output port to study distinguishability. First all the photons' polarizations are made identical (Figure 1a) and this coincidence probability is monitored as relative time delays between the photons are changed (Figure 1c). These data correspond to the transition from identical to completely distinguishable particles. In a second variation, the experiment is repeated with the photons' polarizations prepared with minimal overlap (1b, 1d). Surprisingly we now observe probabilities lying outside the range of those in the first experiment. We show this is a direct consequence of the triad phase in distinguishability, which is unchanged by the temporal delays but differs by π due to the polarization preparation. These experiments suggest an interpretation of aspects of many-particle distinguishability not expressed in two-particle experiments.

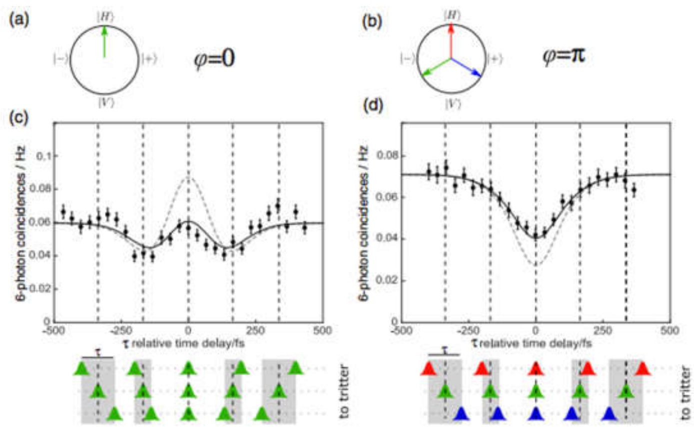

Fig 1. Interference of three heralded photons in a three-port splitter. The experiment is repeated twice with different polarization states (a,b). The rate at which one photon is simultaneously detected in each output port is recorded as a relative delay between the photons is changed (c,d). A simulation of the experiment (solid line) and ideal calculation (dashed) are shown. From [2].

The triad phase can reveal differences between interferometers that cannot be observed with identical particles. As an example, we study partially bunched outcomes in the experiment described above. We show that an asymmetry in these outcomes derives from the three-particle distinguishability. In the case of an ideal three-port splitter, this asymmetry differs for the two canonical forms, and can thus be used to differentiate between them experimentally. We discuss the generalization of this issue to arbitrary multiports, and its application to the unambiguous characterization of interferometers using single photons.

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Quantum-free state and measurement tomography

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[2]*Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario, Canada J2L 2Y5*

Quantum state and measurement tomography are extensively used analysis methods that are used to infer the quantum state and measurement operators that best explain a set of experimental data. Once found, the state and measurement operators describing the experiment are often used to draw conclusions about the current experiment, or make predictions about future ones. Some experiments [1] are designed to allow (or even explicitly search) for deviations between quantum theory and how nature truly behaves, and experiments of these types require data analysis methods that do not assume quantum theory. We introduce a tomography method for states and measurements that does not assume quantum mechanics, and we demonstrate it in an experiment on the polarization degree-of-freedom of single photons.

Our technique characterizes states and measurements within the framework of generalized probability theories (GPTs) [2,3]. The GPT representation of an experiment is operationally motivated, and states and measurements are identified by simple lists of measurement-outcome probabilities. The GPT framework is quite general and incorporates very few assumptions, and as a result the GPT state and measurement operators returned by our technique are inferred entirely from what can be learned from the data.

The GPT tomography procedure consists of two main steps: first, we infer the number of degrees of freedom, k, required to explain a set of data, and second we find GPT descriptions of the states prepared and measurements performed in the experiment. To achieve the first step, we fit a number of GPT models with varying values of k to the data, and we determine the most-likely value for k by evaluating all models with the Akaike information criterion [4]. Second, we extract the GPT state and measurement effects from the model, which are real-valued vectors. State vectors are length (k-1), and measurement effect vectors are length k.

We performed 100 polarization measurements on 100 single-photon polarization states, and applied our GPT tomography method to the data. We find that with very high probability $k = 4$. To visualize the GPT states and measurement effects in our experiment, we plot the 3-d state and 4-d effect vectors (Fig. 1) – these closely resemble the well-known qubit state and measurement-effect spaces from quantum theory. The solid shapes represent the minimum convex set of states and measurements accessible by our experiment. We infer the maximum state and effect spaces (wireframe shapes) from the minimal spaces and the fact that predicted measurement-outcome probabilities must be in [0,1]. The true state and effect spaces accessible by our experiment must be somewhere between the minimal and maximal spaces, and the small gap between the two spaces represents the maximum amount the true theory might deviate from quantum mechanics.

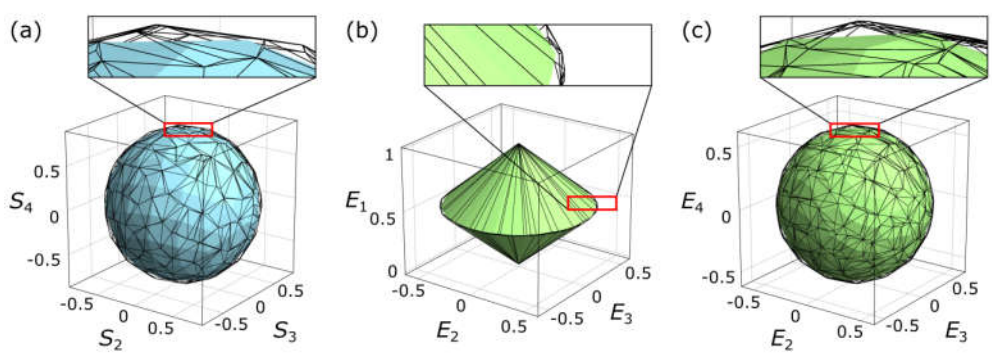

Fig 1. State and measurement-effect spaces for single photon polarization reconstructed by our GPT tomography technique. (a) The three-dimensional state space. (b) (c) Two three-dimensional projections of the four-dimensional measurement effect space. Solid shapes are the convex hulls of the states and measurement effects performed in our experiment, representing the minimum sets of states and measurements accessible by our experiment. Wireframe shapes represent the maximum possible state and effect spaces accessible by our experiment. The zoomed-in insets are to aid in visualizing the size of the gap between the minimal and maximal spaces.

References

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Thursday, August 3 2017

Imaging

10:30 – 12:00

Session Chair: Sae Woo Nam

10:30 *INVITED*	Eric Fossum *Dartmouth College*	***Photon-Number-Resolving Quanta Image Sensor***
11:00	Joshua Rapp *Boston University*	***Unmixing Signal and Noise for Photon-Efficient Active Imaging***
11:20	Davide Portaluppi *Politecnico di Milano*	***Monolithic CMOS SPAD array with gating, timing electronics and photon-coincidence detection for 3D-ranging***
11:40	Richard Younger *MIT-Lincoln Labs*	***Crosstalk Elimination in Infrared Geiger-mode Avalanche Photodiode Arrays***

Photon-Number-Resolving Quanta Image Sensor

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Abstract. The Quanta Image Sensor (QIS) is a silicon photon-counting image sensor intended as a platform tool for many applications, including scientific and consumer image capture [1]. In this invited paper, the QIS concept is reviewed and its imaging characteristics discussed. Recent progress by the team [2] is presented including both pixel design and low power readout electronics design. Test devices were designed and characterized at Dartmouth, and fabricated by TSMC in a 45nm/65nm stacked, backside-illuminated (BSI) CMOS image sensor process, with some small process changes. The QIS pixel (or "jot") with 1.1um pitch operates at room temperature without the use of avalanche multiplication. It relies on small detector capacitance (<0.5fF) and correlated double sampling to achieve output voltages above thermal background noise. Quantum efficiency is high due using BSI with high fill factor. Average dark current is low (<0.2e-/s) and read noise typically under 0.22e- rms, allowing photon-number resolution with low photon-counting error. Dead time is less than 0.1%. The 1Mpixel digital readout QIS operates at 1040fps and dissipates less than 20mW including I/O pads due to low voltage operation.

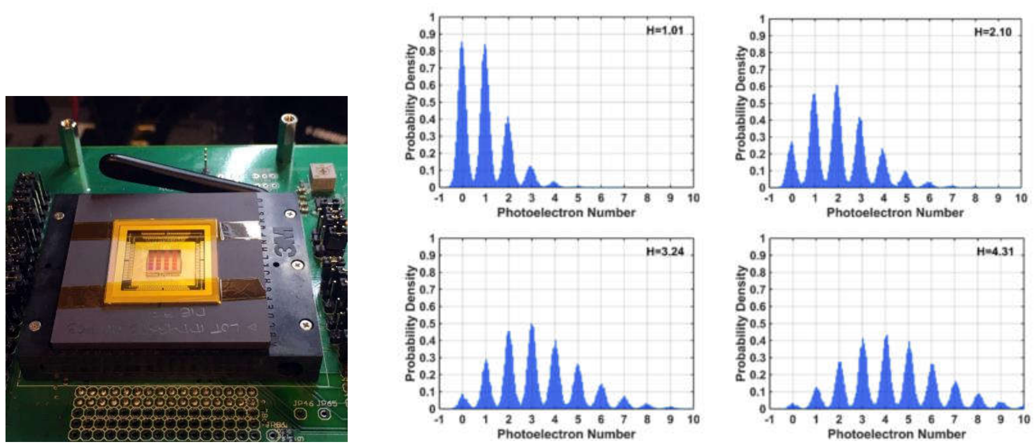

Fig 1. (Left) Test chip with 20 1Mpixel arrays implemented in a 45nm/65nm stacked BSI CIS process. (Right) four photon-counting histograms at different exposure levels, *H*, measured from one pixel with 20k reads of analog output. Read noise: 0.175e- rms, room temperature, no avalanche, 20 CMS cycles (to reduce board noise).

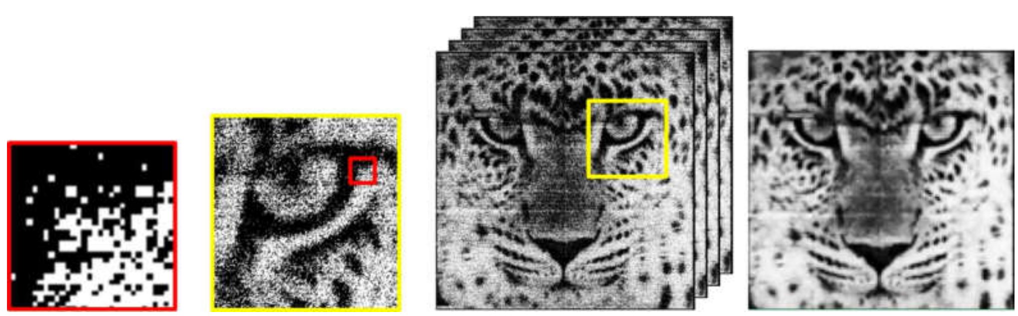

Fig 2. 1Mpixel single-photon image grabbed from 1b digital output sensor operating at 1040fps at room temperature, and then processed with time-adjacent frames to form gray scale image. Further denoising performed by S. Chan at Purdue.

References

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[2] Dartmouth: E.R. Fossum, S. Masoodian, J. Ma, and D. Starkey; TSMC: T.J. Wang and Y. Yamashita.

Design supported by Rambus, fabrication by TSMC, and measurement by DARPA DETECT program.

Unmixing Signal and Noise for Photon-Efficient Active Imaging

Joshua Rapp and Vivek K Goyal
Boston University, Boston, MA, USA

Real-time applications of LIDAR, such as autonomous vehicle navigation, demand both fast and accurate acquisition and processing. Photon-efficient active imaging therefore aims to form accurate depth and reflectivity images from as few back-reflected photons as possible. State of the art algorithms for photon-efficient imaging produce remarkably accurate results from as few as 1 photon detection per pixel on average, but their quality degrades when subjected to the high relative levels of ambient light that are realistic for daylight and long-distance operation [1], [2]. We propose an algorithm that fully exploits the probabilistic model of photon detection for single-photon detectors, as well as incorporating priors on the spatial correlation of depth and reflectivity in many natural scenes.

We verify our algorithm with respect to the LIDAR experimental data collected for the First-Photon Imaging project [3]. A 0.6-mW laser with 270 ps pulses was raster-scanned via a 2-axis galvanometer over a scene. Incident photons detected with a SPAD were time tagged with 8 ps resolution. The original data was collected with ambient light from an incandescent bulb set to a level such that the signal-to-background ratio (SBR) was approximately equal to 1. In order to explore the noise performance of our algorithm, synthetic background detections were generated as samples from a uniform distribution over the pulse-repetition period.

Our algorithm iterates between two major components. First, based on the conditional variance of signal detection times conditioned on the true depth being much lower than the variance of background detections, we define "clusters" of detections and assert that they are more likely to be due to signal than noise. We then implement a *windowing* procedure that uses the detection times at each pixel to search for clusters. Second, if no clusters of detections are found, we use detections from other pixels to boost the signal level at any particular pixel. We assume that patches with similar reflectivity and similar transverse position in natural scenes are likely at similar depths, so we form *superpixels* to determine from which neighboring pixels to borrow detections. We then return to the windowing procedure, updating the effective noise level and then increasing the superpixel size if still no clusters are found.

The figure below shows a selection of our results. Even when background levels are 25 times the average signal levels, we show that our algorithm approaches the results produced with noiseless data.

(a) (b) (c) (d)

Fig. 1: Results from our algorithm on the mannequin dataset from [3] with 4.05 signal photon detections per pixel on average and SBR = 0.04: (a) raw photon count, (b) recovered reflectivity image, (c) raw data ML depth, and (d) recovered depth image.

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Monolithic CMOS SPAD array with gating, timing electronics and photon-coincidence detection for 3D-ranging

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Time-resolved detection of faint light signals in the visible and near infrared is required by many industrial and scientific applications, ranging from LIDAR (Light Detection and Ranging), surveillance, object tracking and Time Correlated Single Photon Counting (TCSPC). We already proved [1] that silicon Single-Photon Avalanche Diodes (SPADs) can be manufactured in a CMOS process with excellent performance, together with analog or digital circuitry thus realizing rugged, low-cost monolithic imagers.

In this work we present the pixel architecture shown in Fig 1, which employs 4 SPAD detectors, each with a time-gated Variable Load Quenching Circuit (VLQC) and an event counter, but sharing a single flash TDC, arbitration and mode selection logic. The pixel targets LIDAR applications, yet it is flexible enough to be exploited also in scientific and biomedical applications. The pixel simultaneously performs both photon counting and photon timing, as well as time-gating of the detector, plus a photon-coincidence operation mode (shown in Fig 2) which can be suitably exploited for suppressing unwanted background counts [2][3].

This pixel operates with multiple gate windows per each acquisition frame and features global shutter and double buffering to minimize acquisition dead time.

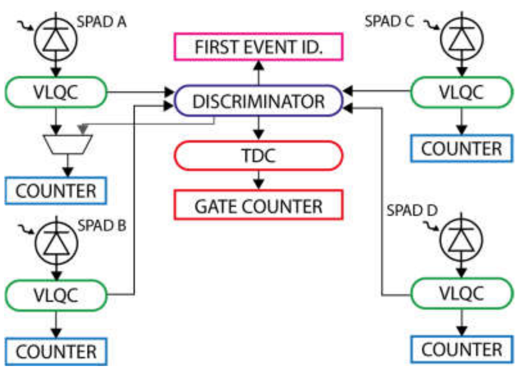

Fig 1. Block diagram of the proposed pixel.

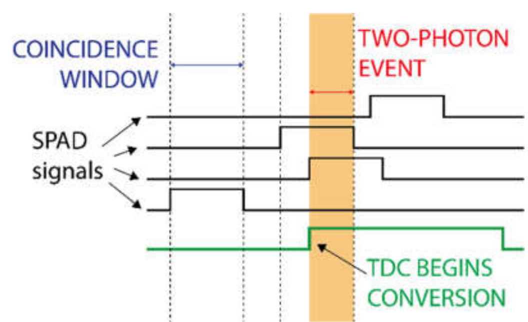

Fig 2. Timings of the coincidence detection.

In order to integrate a pixel into a large array, trade-offs must be made between performance, area occupation, power consumption and in-pixel features. Typically, SPAD arrays featuring in-pixel TDCs have very low (few percent) fill factor, due to the large silicon area required by the TDC itself. Instead, our approach was to share a single TDC among four SPAD detectors, thus providing higher fill factor and high conversion rate. The sharing is performed without losing spatial resolution thanks to a discriminator circuit and independent memory banks associated to each detector.

We developed a test chip in a 0.18 μm CMOS technology, consisting of a 32 x 32 SPAD array with 100 μm pitch and 9.6 % fill factor, with a 50 ps TDC resolution over 12 bits (i.e. full scale range of 204.8 ns) to prove the performance of this architecture, to be tested in an automotive 3D-ranging LIDAR setup.

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Crosstalk Elimination in Infrared Geiger-mode Avalanche Photodiode Arrays

R.D. Younger, R.J. Bailey, J.P. Donnelly, J. Frechette, W.D. Goodhue, K.A. McIntosh, L.A. Wright, E.K. Duerr

MIT Lincoln Laboratory, 244 Wood St., Lexington MA 02420

Intra focal plane array (FPA) crosstalk due to avalanche-emitted photons is a primary performance limiter of large 2-dimensional Geiger-mode avalanche photodiode (GmAPD) arrays. Analysis methods and experimental results from reduced-crosstalk InP-based detector arrays developed at MIT Lincoln Laboratory will be presented.

Operating principles of GmAPDs are detailed in [1]. Applications for these GmAPD FPAs include direct-detect flash LiDAR, photon counting coherent LiDAR [2], and communications [3]. Cross-sectional diagrams of three generations of InP-based GmAPD arrays are shown in figure 1. A single photon can trigger an avalanche event within the APD, resulting in milliamps of current over a few ns. Hot carriers within an avalanching APD can generate photons, which may couple to adjacent detector elements resulting in intra-FPA crosstalk. Crosstalk worsens both as pixel pitch is decreased [4] and as overbias is increased, limiting both scalability and performance. Starting with a primary avalanche event, crosstalk within the focal plane array may be seen as a space- and time-inhomogeneous random process [5]. Shown in figure 2 are crosstalk spatial maps measured from each of the designs shown in figure 1, demonstrating a significant reduction in crosstalk. We will discuss multiple methods for mitigating crosstalk inside InP-based GmAPD arrays.

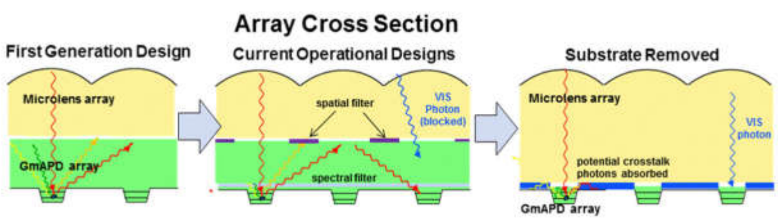

Figure 1: A cross section schematic of an InP GmAPD array, hybridized to a microlens array.

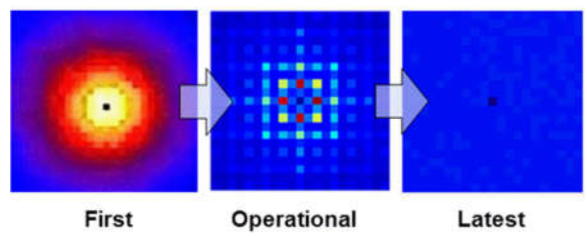

Figure 2: Spatial crosstalk response maps for the approaches shown in Figure 1. The dark square at the center is the originating pixel. Pixel offsets are colored with the probability of a correlated event at that relative position.

This material is based upon work supported by the Assistant Secretary of Defense for Research and Engineering under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Assistant Secretary of Defense for Research and Engineering.

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Thursday, August 3 2017

Sources III

13:30 – 15:00

Session Chair: Alessandro Farsi

13:30 *INVITED*	John Rarity *University of Bristol*	***Spins and photons***
14:00	Fumihiro Kaneda *University of Illinois*	***Memory-assisted time multiplexing for efficient multi-photon generation***
14:20	Morgan Mastrovich *University of Waterloo*	***Spectral manipulation of entangled photons with an upconversion time lens***
14:40	Till Weinhold *University of Queensland*	***Sub-Megahertz Linewidth Single Photon Source Suitable for Quantum Memories***

Spins and photons

J. G. Rarity,[1] P. Androvitsaneas,[1*] A.B. Young,[1] J.M. Lennon,[1] S. Knauer, J. Smith, C. Schneider,[2] S. Maier,[2] J.J. Hinchliff,[1] G.S. Atkinson,[1] E. Harbord,[1] M. Kamp,[2] S. Höfling,[2,3] and R. Oulton[1]

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[2]*Technische Physik, Physikalisches Institut and Wilhelm Conrad Röntgen-Center for Complex Material Systems, Universität Würzburg, Am Hubland, D-97474 Würzburg, Germany*

[3]*School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY16 9SS, UK*

Quantum dots and colour centres in diamond are atom-like two level systems that look promising as deterministic single photon sources [1]. They can also exhibit ground state spins that lead to spin dependent transitions and the potential to entangle ground state spin with emitted or reflected photons[2]. Spin-photon entanglers are effectively universal and deterministic quantum gates enabling quantum memories, quantum repeaters [3] and eventually large scale quantum computation. In III-V materials established growth and fabrication routes have been developed to incorporate quantum dots into microcavities and waveguides that enhance the light-matter interaction and it is a near unit efficiency (high β-factor) light-matter interaction that is essential for both efficient single photon sources and spin photon interactions. A singly charged quantum dot has a spin half ground state separating the optical transition into circularly polarized components sensing up and down spin. Previously we have shown that pillar microcavities possess a high β-factor even at low Q-factors and have seen time averaged spin dependent phase shift (Faraday rotation) [4] of resonant light limited by drift in the dot line centre. In our latest work we measure the rotation over timescales shorter than the spectral diffusion time (~100 μs) and identify times when the the dot is on resonance. Selecting those times we show that large spin dependent phase shifts can be generated [5]. In figure 1 low co-polarised scatter and high cross polarised scatter indicate strong resonant scattering and the dark blue region shows a heralded phase shift consistently above 0.63π. Once we take into account mode matching and background scatter this indicates that all photons resonantly scattered by the cavity-dot system carry a phase shift of π indicating that high fidelity spin photon entanglement could be achieved. Our present measurements were performed in a Faraday geometry magnetic field separating spin up and down transitions. In future measurements we intend to investigate low field and Voigt geometry measurements that may allow measurement of spin rotation via photon scattering, the first indication of a spin-photon interface.

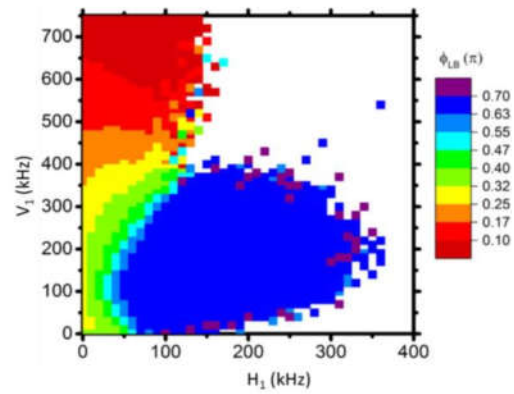

Fig 1. A contour plot showing the phase shift measured (in phase shift detectors) associated with count-rates measured in the heralding detectors V_1 (co-pol) and H_1 (cross-pol) using 100 μs time bins.

Quantum dot spins are hard to control with decoherence times measured in microseconds. In contrast the ground state spin in NV-centres in diamond has spin coherence out to milliseconds at room temperature and the polarisation of spin is simply dome by reading out the spin in fluorescence measurements. Fabrication of cavity structures coupled to NV-centres is still not perfected so single shot measurements of spin are still limited by light collection efficiency. However the long coherence times allow the spins to be used as electric field and/or nuclear magnetic field sensors. In our group we are perfecting strain sensing techniques using the ground state spin hyperfine split by the local nitrogen 14 nucleus. A review of our latest results in NV-centre spin-photon interfaces will be presented.

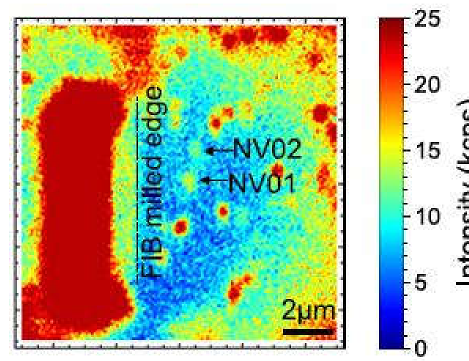

Fig 2. A confocal fluorescence image of NV centres close to a focussed ion beam milled edge used to show strain effects on ground state spin of NV-centres.

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Memory-assisted time multiplexing for efficient multi-photon generation

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We demonstrate time multiplexing of heralded single-photon sources, using low-loss quantum memories. Our scheme can realize largely enhanced multi-photon generation rates by compensating for the arrival time difference of photons from different HSPSs.

Single-photon sources play essential roles in quantum communication. Heralded single-photon sources (HSPSs) utilizing photon-pair generation processes (e.g., spontaneous parametric downconversion (SPDC) and spontaneous four-wave mixing (SFWM)) can produce highly indistinguishable photons with nearly perfect heralding efficiency. However, probabilistic generation of the photon-pair state is a key obstacle to scaling up quantum information applications beyond proof-of-principle experiments. In order to efficiently overcome the probabilistic nature of HSPSs, we demonstrate time multiplexing of HSPSs, using low-loss bulk optical quantum memories (QMs) [1] that can compensate for the arrival time difference between photons from each HSPS. Our scheme can realize efficient optical quantum computation as well as low photon-number-noise quantum communication, for example, measurement-device-independent quantum key distribution (MDI-QKD) [2].

A schematic diagram of the time-multiplexed M-photon generation is depicted in Fig. 1 (a). M HSPSs pumped by laser pulses with a period τ, generate photon pairs probabilistically and in general not simultaneously. Each trigger photon is sent to a single-photon detector (SPD); a photon detection heralds in which time slot the corresponding twin photon is present. Each QM triggered by a heralding signal from its corresponding HSPS, stores heralded photons for an arbitrary integer time of τ from whenever they are generated until other sources produces their pairs. After the last source heralds a "last-born" photon, M - 1 memories storing the earlier-born photons release them simultaneously, thereby producing M simultaneous photons. Thus, the M-fold coincidence rate can be greatly increased compared to the non-multiplexed case in which only photons produced simultaneously from the M HSPSs can make success events.

We applied this scheme to two high-indistinguishability (>90%) HSPSs [3]. Our QM implemented by low-loss bulk optics stores photons with 98.8% efficiency for τ = 10 ns delay. Figure 1 (b) shows coincidence count rates of time-multiplexed heralded single photons versus the maximum number of storage cycles N. Due to the high storage efficiency, the coincidence count rate increases approximately as N^2. We observed the highest enhancement factor (~30x) with N = 40. Note that this same approach, generalized to preparing, e.g., 10 simultaneous photons, would have an enhancement factor of over $30^9 = 2\times10^{13}$! Moreover, we measured Hong-Ou-Mandel interference of the time-multiplexed photons, a direct measure of indistinguishability of the independent sources. We demonstrated 87% and 96% visibilities without and with narrowband (1.1 nm) spectral filtering, respectively. Our demonstrated time-multiplexed HSPSs can be directly applied to memory-assisted MDI-QKD.

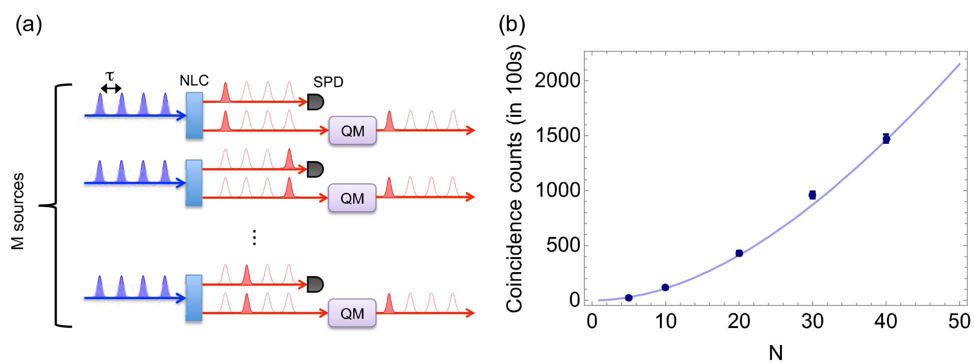

Fig 1. (a) Schematic diagram of M-photon generation via memory-assisted time multiplexing. (b) Coincidence count rate by multiplexing two HSPSs versus the maximum number of storage cycles N.

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Spectral manipulation of entangled photons with an upconversion time lens

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Sources of entangled photons with precisely controlled properties are necessary for effective and efficient photonic quantum communication, computation, and metrology. The nonlinear process of spontaneous parametric downconversion (SPDC) provides a reliable source of energy-time entangled photons, but most SPDC sources tend to produce photons with frequency anti-correlations. Photon pairs with positively correlated spectra may be useful for quantum-enhanced clock synchronization [1], but control over the correlations after state generation has not yet been demonstrated. Spectral control over a photon after it has been created is highly desirable for ultrafast manipulation and state engineering, especially at wavelengths where materials with suitable phasematching do not exist [2, 3].

A time lens operates on the temporal and frequency distributions of light in the same way that a conventional glass lens manipulates the spatial and momentum profiles of a beam [4]. Chromatic dispersion, or chirping, spreads the temporal profile of a beam such that each temporal slice of the beam has a distinct central frequency. One promising implementation of a time lens combines a single photon with a strong classical escort pulse using sum frequency generation (SFG), leaving an imprint of the spectral dispersion of the escort on the upconverted photon. Combined with an appropriate amount of dispersion on both the single photon and the escort beam, as shown in Fig. 1a, this time lens can stretch, compress, and invert the spectral and temporal waveforms of the photon. Using this temporal imaging technique to invert the spectral waveform of one photon in an entangled pair will reverse the spectral correlations between the entangled photons.

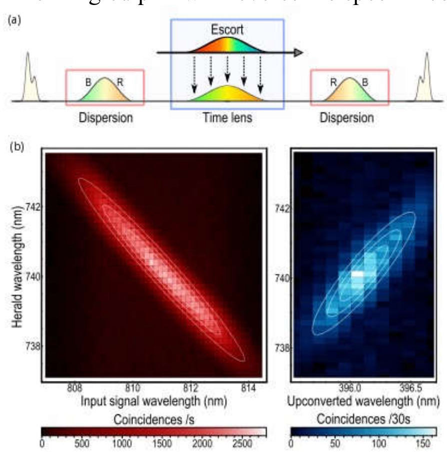

Fig 1. (a) The complete temporal imaging system, consisting of calibrated dispersion and upconversion in a nonlinear medium, will reverse the temporal structure of the pulse, akin to an imaging system with negative magnification. The time lens introduces a time-dependent frequency shift, which can allow the wavepacket to refocus itself after more chromatic dispersion is applied. (b) The experimentally measured joint spectral intensity distribution of entangled photons produced by SPDC before and after the application of the time lens.

In this work, detailed in [5], we demonstrate control of a twin-photon joint spectral intensity through the use of an upconversion time lens on the ultrafast timescale. We measure a statistical correlation of −0.97 in the joint spectral intensity of an energy-time-entangled pair produced with SPDC, indicating strong frequency anti-correlations consistent with energy conservation found in traditional bulk SPDC sources (Fig. 1b). We apply the temporal imaging technique shown in Fig. 1a to the signal photon of the downconverted pair, and observe a strong positive statistical correlation of +0.86 between the untouched idler photon and the upconverted signal photon (Fig. 1b). We also show that the central frequency of the upconverted joint spectrum can be manipulated by introducing a time delay in the escort pulse. The technique presented is free of intense broadband noise at the target wavelengths. Control of the correlation of joint spectra as demonstrated in this work may be directly useful for shaping the spectra of entangled pairs for long-distance communications [2] and quantum-enhanced metrology [1] and, more generally, to mold the time-frequency distributions of entangled photons for experiments both fundamental and practical.

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Sub-Megahertz Linewidth Single Photon Source Suitable for Quantum Memories

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Abstract: We report 100% duty cycle generation of sub-MHz linewidth single photon pairs at the Rubidium D_1 line. The photons are well-suited for storage in quantum memory schemes with sub-natural linewidths, such as gradient echo memories.

Hybrid quantum technologies seek to combine the advantages of two individual quantum architectures by transferring the information between the two systems. We seek to combinethe high mobility of photons and exploit the excellent readout and storage capabilities of atomic qubits as a quantum memory, to build up quantum repeater networks. Efficient interaction of photons and atoms requires matched spectral properties. The atomic transition usually has a much narrower bandwidth than single photons generated by spontaneous parametric down-conversion (SPDC). Hybridization therefore requires significant reduction of the single photon emission spectra. We achieve this is by using an optical cavity to enhance the probability of creating the photons in the spectral and spatial resonator mode.

Previous cavity-based SPDC sources achieved bandwidths comparable to atomic linewidths, but divide their operation time into stabilisation and photon production phases, resulting in typical duty cycles $< 50\%$. The so far narrowest photons from SPDC [1] have bandwidths still well above a MHz and only one source has demonstrated 100% duty cycle [2].

We report 100% duty cycle generation of sub-MHz single photon pairs at the Rubidium D_1 line using cavity-enhanced spontaneous parametric down-conversion [3] exhibiting a bandwidth of 666 ± 16 kHz for the single photons, an order of magnitude below the natural linewidth of the target transition and the narrowest single photons from SPDC to date. A new method of birefringence compensation using an intra cavity half-wave plate inside the cavity helps to achieve triple resonance The quantum nature of the source is confirmed by the idler-triggered second-order autocorrelation function at $\tau = 0$ to be $g^{(2)}_{s,s}(0) = 0.016 \pm 0.002$ for a heralding rate of 5 kHz and antibunching below 0.5 is observed up to heralding rates of 250 kHz [3]. The high purity of the source is matched by high indistinguishability of the photons demonstrated in a Hong-Ou-Mandel (HOM) interference experiment with a visibility $V = 96.5 \pm 0.5$ %. Additionally, the mode-locked two-photon state of the generated pairs leads to revivals of the HOM dip [4]. We observe these revivals up to 100 m path difference between signal and idler photon, independently proofing the long coherence length of our photons.

Our system is designed for integration with gradient echo memories [5, 6], one of the most promising candidates for quantum memories to date, or hollow-core glass fibers filled with rubidium gas to allow the construction of novel quantum logic gates [7].

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Thursday, August 3 2017

Detectors III

15:30 – 17:00

Session Chair: Josh Bienfang

15:30 ***INVITED***	Seth Bank *University of Texas*	***Emerging Semiconductor Single Photon Counters***
16:00	Bernicy Fong *Excelitas Technologies*	***Transit time, timing jitter and time walk in SLiK APD – measurement and implication for single photon counting applications***
16:20	Alberto Gola *FBK, Trento*	***Overview of Silicon Photomultipliers Developed at FBK***
16:40	Hesong Xu *FBK, Trento*	***Detecting entangled photons using CMOS SPAD arrays***

Emerging Semiconductor Single Photon Counters

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We review recent progress on GaSb-based InAlAsSb avalanche photodetectors (APD), including preliminary room temperature Geiger mode single photon counting.

AlInAsSb APDs (Fig. 1a) grown digitally [1] on GaSb have recently shown tunable cutoff wavelengths across the telecommunications band (Fig. 1b), and noise comparable to that of silicon (Fig. 1c), independent of alloy composition [2]. We review this progress and describe initial Geiger mode single photon counting success at room temperature (Fig. 1d).

Geiger performance of an $Al_{0.7}In_{0.3}As_{0.3}Sb_{0.7}$ APD was characterized with a capacitance-balanced gated quenching circuit in which an avalanche event was quenched by the trailing edge of the gate pulse. The width of driving gate was 5 ns, and repetition rate was 1 MHz. The excess bias was varied from 0.3% to 1% of breakdown voltage. As shown in Fig. 1d, both photon-induced breakdown probability and dark count probability increase with excess bias until photon-induced breakdown probability saturates at 55%, which is due to high dark count rate. The dark count probability per gate went to as high as 60%, which is consistent with the 0.17-nA primary dark current.

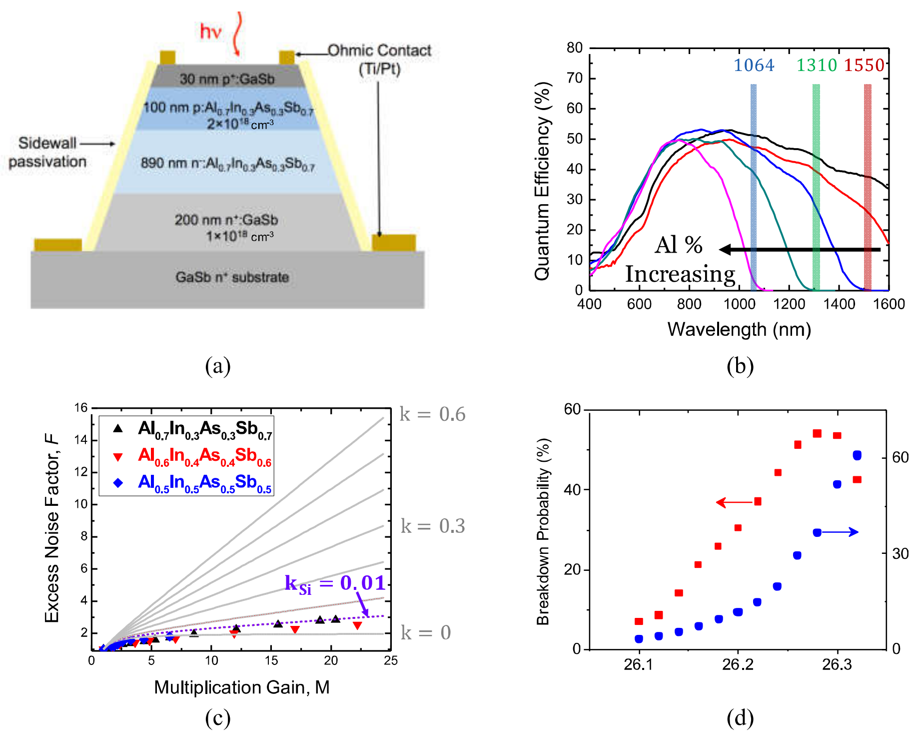

Fig 1. (a) AlInAsSb APD device cross-section, (b) quantum efficiency with Al%, (c) excess noise factor versus multiplication gain, and (d) Geiger-mode breakdown probability and dark count rate measured at room temperature.

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Transit time, timing jitter and time walk in SLiK APD – measurement and implication for single photon counting applications

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Abstract:

Transit time (response time), timing jitter (or timing resolution) and time walk are three separate parameters associated with a detector's response time. Studies have been done on mostly the time jitter of various single photon detectors. Being the designer and manufacturer of the ultra-low noise (ƙ-factor) silicon avalanche photodiode the SLiK APD, which is used in many single photon counting applications, we often get inquiries and questions to better understand how this detector behaves under different operating conditions. Hence, here we will be focusing on the study of these three time related parameters specifically for the SLiK APD, as a way to provide the most direct information for users of this detector to help with its use more efficiently and effectively. We will be providing the study data on how these parameters can be affected by temperature (both intrinsic to the detector chip and environmental input based on operating conditions), operating voltage, wavelength of photons, as well as light spot size. How they can be optimized, the trade-offs from optimization of the desired performance and if adjusting one time aspect will affect the other will be presented. Subsequently we will outline the implications of each of these parameters on some of the key single photon counting applications such as Lidar and Lidar imaging, time correlated single photon counting, and quantum experiments.

Overview of Silicon Photomultipliers Developed at FBK

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Abstract. Silicon Photomultipliers (SiPMs) are arrays of many single-photon avalanche diodes (SPADs), connected in parallel to a common anode and cathode. They are gradually replacing Photomultiplier Tubes (PMTs) in a number of applications, offering, among other features, higher sensitivity, ruggedness, lower operating voltage, lower cost and higher gain uniformity, making them an excellent candidate for single and few-photon counting applications. In this presentation, we report on the latest developments in SiPM technology carried out at FBK (Trento, Italy) together with some examples of the results achieved in the most common applications.

Among them, Near Ultra Violet, High Density (NUV-HD) SiPM technology features a peak photon-detection efficiency (PDE) of 65% at 410 nm (including the fill factor), Dark Count Rate (DCR) in the order of 50 kHz/mmm^2, correlated noise of 10% at 55% PDE, and microcell pitch ranging from 15um to 40um [1]. NUV-HD SiPMs provide state-of-the art 85 ps FWHM coincidence resolving time (CRT) in PET applications, reading out the light of a Ca co-doped LYSO crystal [2]. Other ongoing optimizations of the NUV-HD technology include the development of devices with extended deep-UV sensitivity (down to ~178nm).

Single Photon Timing Resolution (SPTR) of NUV-HD SiPMs was below 30 ps FWHM, when measured on single SPAD with covered edges, and increased to 75 and 180 ps FWHM for SiPMs with active areas of 1x1 mm^2 and 3x3 mm^2, respectively, because of the electronic noise [3].

Recent interest in the SiPM readout of liquid scintillators (mainly Ar and Xe), thus operated at cryogenic temperatures, triggered the development of a Low-Field variant of the NUV-HD technology (NUV-HD-LF), which is optimized for operation at such low temperatures and features a DCR of a few mHz/mm^2 at 77 K [4]. At this temperature, single and few-photon counting capability was demonstrated using a 10x10 cm^2 SiPM array coupled to a single analog readout channel.

At FBK, we also developed the RGB-HD SiPMs with peak sensitivity of 45% at 550 nm and of ~10% at 900 nm. Ongoing developments aim at increasing the sensitivity in the near-infrared. Based on the RGB-HD technology, we developed the Linearly-Graded SiPMs (LG-SiPMs), which provides XY position sensitivity over the active area down to the microcell level using only four analog readout channels [5].

Ultra-High-Density SiPMs (RGB-UHD) are an evolution of RGB-HD SiPMs, characterized by an even smaller cell size to reduce the SiPM non-linearity. Cell pitch ranges from a 12.5 um down to 5 um, corresponding to the remarkable cell density of 7400 and up to 46000 cells/mm^2. The 10 um cell reaches a PDE of 35% at 515 nm, while the microcell recharge time constant is below 5 ns for the 7.5 microcells.

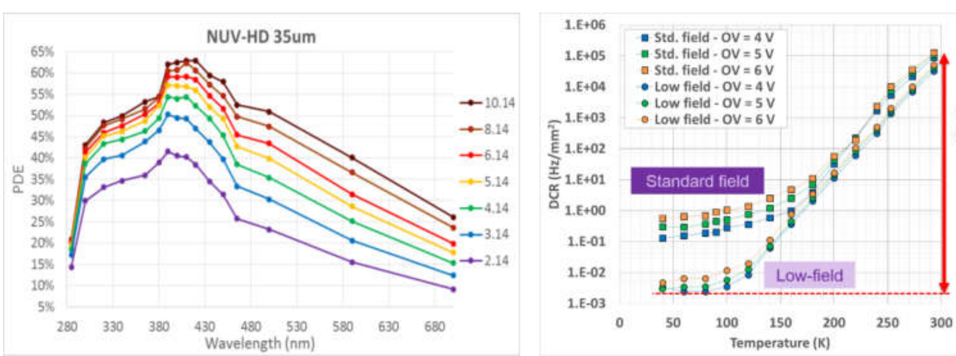

Figure 1. Left : PDE vs. Wavelength measured on NUV-HD SiPMs with 35um cells at different over-voltages (bias in excess of the breakdown voltage). Right: DCR vs. temperature for NUV-HD SiPMs at different over-voltages.

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Detecting entangled photons using CMOS SPAD arrays

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Abstract. SUPERTWIN is a European H2020 project developing the technological building blocks (emitter, detector and system) for an all solid-state microscope exploiting quantum photon states to overcome the λ/2 Rayleigh limit, targeting a resolution of 40nm. This work focuses on the SUPERTWIN detector, that aims at measuring high-order spatial correlation functions by multiple coincidences between entangled photons.

The goal of SUPERTWIN consists in the development of a new all solid-state super-resolution microscopy technique that exploits N-partite photonic states. SPAD-based imaging has been selected as the most promising technology to measure the spatial correlation patterns of quantum photon states after interaction with a target object. Preliminary experiments in the near- [1] and far-field [2] have been performed using a previously developed sensor [3], specifically designed for Positron Emission Tomography. The optical setup and some results are shown in Fig. 1 and Fig. 2. Nevertheless, the sensor characteristics are far from the specifications set by the SUPERTWIN project (pixel pitch in the 30-80µm range; array size 256×256; 20% fill factor, 10% photon Detection Efficiency at 780nm; observation rate 10MHz). A new test chip has been developed. Fig. 3 shows the chip micrograph. It includes three arrays of 32×32 pixels, implementing a per-pixel Time-to-Digital Converter (TDC), a per-pixel Time-to-Analog Converter (TAC), and an approach based on real-time coincidence detection. Preliminary results of the TDC-based architecture are given in Fig. 4 and Fig. 5, showing the DCR distribution and pixel single-photon precision, respectively. More characterization details and measurement results using entangled photons will be given at the time of the workshop. A second chip will be developed within the project targeting a 256×256-pixel array, based on the best performing pixel architecture.

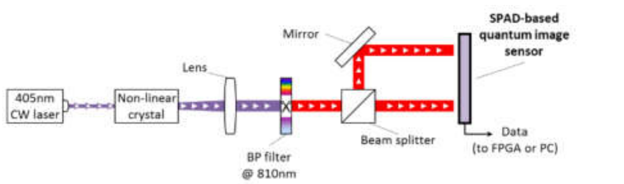

Fig. 1. Block diagram of the optical setup for spatial second-order correlation measurements of transverse momentum entangled two-photon states in the far-field using a CMOS SPAD array to record the photon statistics. The imaging plane lies in the focal plane of the lens.

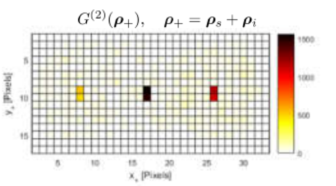

Fig. 2. Second-order correlation function showing three anti-correlation points, corresponding to the three possible outcomes of the beam splitting stage.

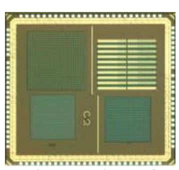

Fig. 3. Micrograph of the first SUPERTWIN chip, including three arrays implementing different pixel architectures and an array of SPAD test structures.

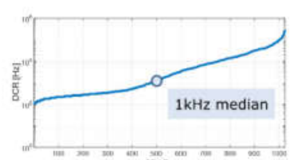

Fig. 4. Cumulative DCR distribution for a 32×32 array of 19.80×19.80µm² SPADs.

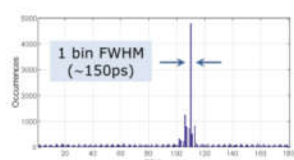

Fig. 5. Pixel single-photon precision. The measurement has been obtained using an attenuated 460nm 70ps laser.

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Poster Abstracts (online only)

Reception and Poster Session

Monday, July 31st 2017: 16:45 – 19:15

The poster session will be held in the east UMC ballroom during the workshop reception. We have arranged for the posters to be up for the duration of the whole workshop to encourage further discussions beyond the actual poster session.

There will be a sponsored 'Best Student Poster Award'. If you are a student and presenting the poster, please sign up for the best student poster award if you have not already done so. All eligible and signed-up posters are marked with a red sticker next to the poster number. If you are eligible you can still get a red sticker at the registration desk. However, please do so before the poster session starts.

#101

Metrological characterization of a single-photon source based on a deterministic quantum dot microlens

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Single-photon sources based on quantum dots are promising candidates to be used as efficient quantum-light sources in quantum computing and quantum cryptography [1]. Moreover, they also have the potential to be used as new non-classical standard source in radiometry [2, 3]; especially for its use in the calibration of single-photon detectors in the near infrared spectral region. From the radiometric point of view, a single quantum dot also has the advantage of on-demand emission of single-photons at a specific wavelength with narrow bandwidth, which allows for the determination of its optical radiant flux with a low standard uncertainty. However, to achieve this, an efficient photon extraction from a single quantum dot and a low-loss optical setup are required.

In this conference, we will present the setup as well as the metrological characterization of a single-photon source based on a single InGaAs quantum dot as emitter for radiometric applications. The single-photon emitter, fabricated by the TU Berlin, consists of a single InGaAs quantum dot precisely integrated into a monolithic microlens coated with a Ta_2O_5 anti-reflection layer for enhancing the photon-extraction efficiency (see Figure 1a) [4]. The complete source was characterized in terms of its photon flux, spectral characteristics, single-photon purity (Figure 1b-c), i.e. second order auto-correlation function, and background. The photon flux was measured under pulsed optical excitation at 80 MHz using a calibrated Si-single-photon avalanche detector (Si-SPAD) traceable to the primary standard for optical power (cryogenic radiometer), while the spectral characteristic was determined with a calibrated spectrometer. The maximum photon flux measured for this emitter was up to 1200 kphoton/s, the background of approx. 100 counts/s and the lowest $g^{(2)}(0)$-value obtained was 0.05 ± 0.02. The complete metrological characterization and the setup will be reported on at the conference.

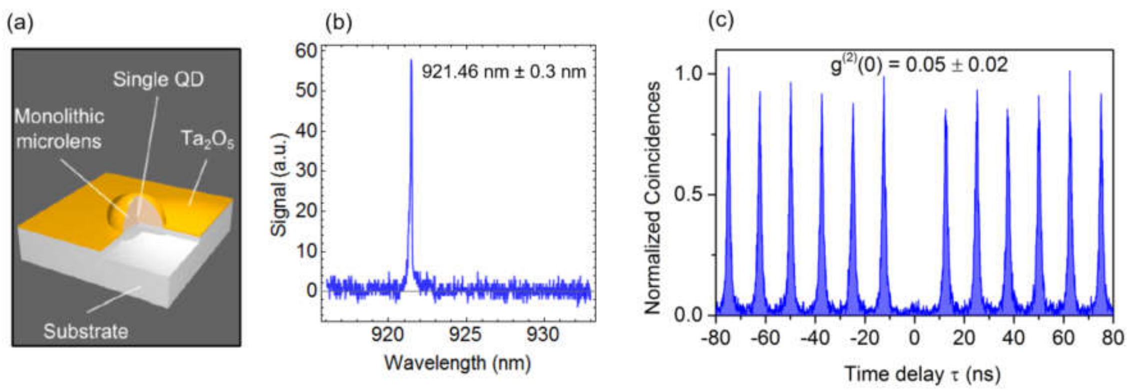

Fig 1. (a) Schematic of the deterministic quantum dot microlens [1]. (b) Micro-photoluminescence (µPL) spectra of the single-photon emission. (c) Autocorrelation measurement $g^{(2)}(0)$ under pulsed excitation at a wavelength of 850 nm and frequency of 80 MHz.

Acknowledgment:

This work has been supported by EMPIR-14IND05 "MIQC2" (the EMPIR initiative is co-funded by the EUH2020 and the EMPIR Participating States).

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#103

Pure downconversion photons through sub-coherence length domain engineering

Francesco Graffitti[1], Dmytro Kundys[1], Derryck Reid[1], Agata Brańczyk[2] & Alessandro Fedrizzi[1]

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Abstract. We present sub-coherence length nonlinear crystal domain engineering algorithms for the creation of pure downconversion photons. Our techniques outperform previous work in particular for short crystals and we demonstrate their superior performance experimentally.

Photonic quantum technology relies on efficient sources of *pure* single photons. Heralded single photons from parametric downconversion (PDC) can approximate on-demand single photons to a desired degree, but in a typical heralded PDC source the signal photon emerges in a spectrally mixed state due to strong (anti)correlation in the joint spectrum of PDC photon pairs. One method for reducing spectral correlations is spectral filtering, but this compromises the heralding efficiency and brightness of the source and introduces mixture in other degrees of freedom: further source engineering is therefore required to enhance the signal photon purity. To this end, several studies have introduced domain-engineering techniques for controlling the spectral response of a poled nonlinear crystal by shaping its phase matching function (PMF).

Here we report on crystal nonlinearity engineering techniques with sub-coherence-length domains [1]. We first introduce a combination of two existing methods: a deterministic approach with coherence-length domains [2] and probabilistic domain-width annealing [3]. We then show how the deterministic domain-flip approach can be implemented with sub-coherence length domains, allowing higher flexibility in tailoring the PMF with respect to other engineering methods. Our new techniques are fast, can readily be implemented commercially, and create high purity photons outperforming previous algorithms in particular for short nonlinear crystals matched to femtosecond pump lasers (see fig.1). We experimentally characterise our method through a high-precision measurement of multi-photon interference between two heralded photons generated by two independent sources. We also show that by considering sub-coherence-length domains it is possible to generalise the algorithm in [2] to the case of complex target field amplitude, allowing us to approximate more exotic cases such as complex-chirped nonlinearity profiles or antisymmetric PDC joint spectra.

We expect that the versatility of our new domain engineering techniques can offer a range of interesting applications both in single photon generation through four-wave mixing in integrated photonics as well as in 'classical' nonlinear optics for which domain engineering was originally designed.

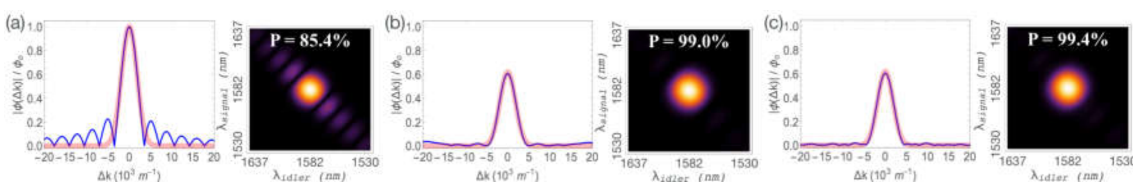

Fig 1. Phase matching function and corresponding joint spectral amplitudes and purities for a short (2 mm) KTP crystal. (a) Standard ppKTP crystal having a sinc-shaped PMF. (b,c) Crystal engineered with our new methods: annealing (b) and sub-coherence length domains (c). Our new algorithms improve the heralded photon's purity by about 2% with respect to the algorithm proposed in [2].

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#104

Device-independent quantum key distribution with single-photon sources

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Security of our daily communications is strikingly enhancing with the commercialisation of quantum encryption systems immune to adversaries with unlimited classical computational power. While in principle these quantum crypto-systems provide unconditional security [1], in practice they are vulnerable to hacking attacks exploiting inescapable mismatches between protocol assumptions of trustworthiness and their actual physical implementation [2].

Device-independent quantum key distribution (DIQKD) provides a formalism that supersedes traditional quantum key distribution, as its security does not rely on any detailed modelling of the internal working of the devices, eliminating in this manner all security breaches from implementation imperfections [3]. The implementation of DIQKD protocols is however challenging, as it requires the observation of a Bell inequality violation between two distant users free from the so-called "detection loophole", which would jeopardize the security of the scheme.

In our work we introduce a new-generation architecture based on single photons (see Fig.1) which qualitatively changes resource requirements to solve the main limitations of previous DIQKD proposals, providing much greater robustness against noise and losses, and significantly higher key-generation rates. Our work opens a new and promising avenue for implementations of DIQKD protocols, especially taking into account the recent progress on single-photon-source fabrication [4-5].

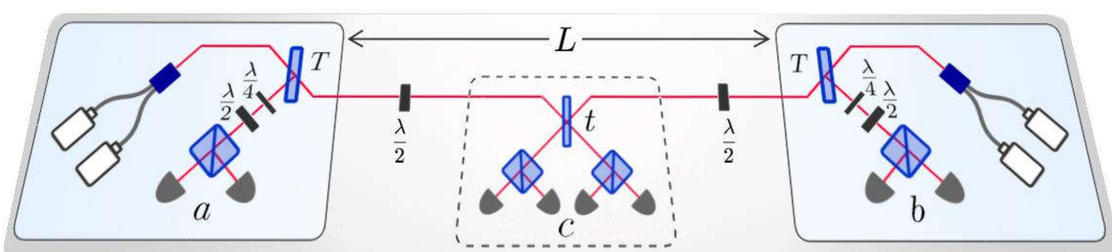

Fig 1. DIQKD with single-photon sources scheme. Alice and Bob are in secure locations (black squares) separated by a distance L. They couple two single photons encoded in orthogonal polarizations into a beam-splitter (BS) of transmittance T. Half-wave plates combine the transmitted polarization components, which are analyzed with a partial Bell-state measurement (dashed square) composed of a partial BS of transmittance t, polarizing-BS (splitted squares) and non-photon number resolving photodetectors (half-circles). The reflected modes are measured by the users with polarization analysers: a sequence of a quarter-wave plate, a HWP, a polarizing BS and two binary detectors producing the outcomes *a* and *b* respectively.

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#105

Light-matter interfacing with quantum dots: a polarization tomography approach

C. Anton[1], C. A. Kessler[1], P. Hilaire[1,3], J. Demory[1], C. Gomez[1], A. Lemaître[1], I. Sagnes[1], O. Krebs[1], N. D. Lanzilloti-Kimura[1], N. Somaschi[1], P. Senellart[2] and L. Lanco[3]

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The development of future quantum networks requires an efficient interface between stationary and flying qubits. Single semiconductor quantum dots (QD) deterministically coupled to a micropillar cavities constitute a promising approach: they are bright single photon emitters [1], and can be coherently manipulated with few incoming photons [2]. Moreover, single QD spin qubits can induce giant rotation of photon polarization [3].

Here, we investigate the polarization rotation of coherent light interacting with a QD-cavity system, by analyzing the photon polarization density matrix in the Poincaré sphere. The superposition of emitted single photons—namely, H-polarized—with reflected photons—V-polarized, see scheme in Fig.1(a)—leads to a rotation of the output polarization by as large as 20°, both in latitude and longitude [4]. The evolution of the output state is illustrated in the Poincaré sphere as function of the excitation laser wavelength scanned across the QD transition, see Fig.1(b). We furthermore demonstrate that the coherent part of the QD emission contributes to polarization rotation, whereas its incoherent part contributes to degrading the polarization purity. Our observations yield crucial information on the ability of light-matter interface to coherently convert quantum information from a stationary qubit to a flying one.

Our results open the way to numerous experiments whereby the evolution of a single electron spin—described in the Bloch sphere—can be monitored by, or entangled with, the evolution of a photon polarization qubit described in the Poincaré sphere.

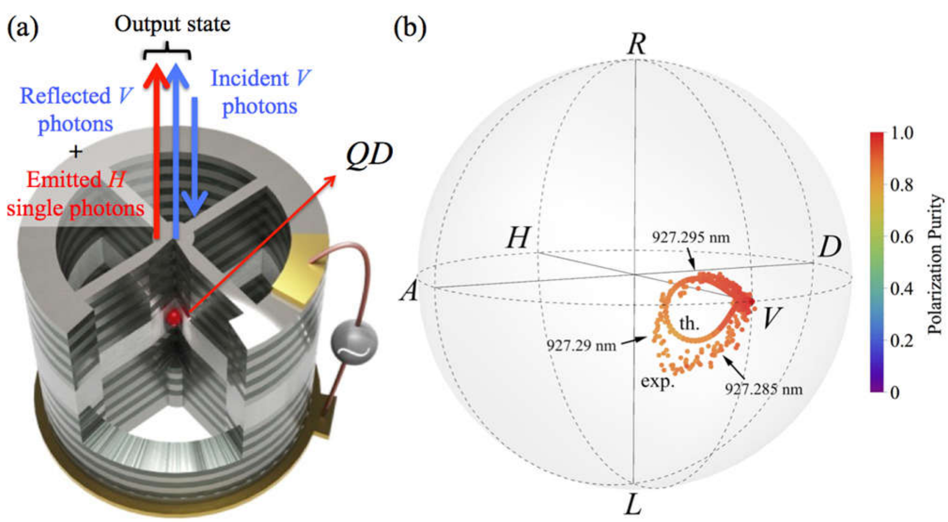

Fig 1. (a) Scheme of the electrically-controlled QD-cavity device and the input-output fields. (b) Representation of the polarization state in the Poincaré sphere for varying excitation laser wavelength. The colorscale represents the purity of the polarization density matrix which is kept above 84% at all wavelengths.

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#107

Towards integrated superconducting detectors on lithium niobate waveguides

Jan Philipp Höpker[1], Moritz Bartnick[1], Evan Meyer-Scott[1], Frederik Thiele[1], Stephan Krapick[1], Nicola Montaut[1], Harald Herrmann[1], Sebastian Lengeling[1], Raimund Ricken[1], Viktor Quiring[1], Adriana Lita[2], Varun Verma[2], Thomas Gerrits[2], Sae Woo Nam[2], Christine Silberhorn[1] and Tim J. Bartley[1]

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Superconducting detectors have become well-established tools for quantum optics, due to their high efficiency and low noise [1,2]. Superconducting nanowire single photon detectors (SNSPDs) additionally offer exceptional timing characteristics, whilst transition edge sensors (TES) boast intrinsic photon number resolution. As an important integration platform for quantum optics, lithium niobate offers many advantages, with its high second-order nonlinear optical coefficient enabling high-speed electro-optic modulation and polarisation conversion, as well as frequency conversion and integrated sources of quantum light[3]. Combining these technologies completes the requirements for a single platform capable of generating, manipulating and measuring quantum light in many degrees of freedom, in a compact and potentially scalable manner.

We will report on progress combining tungsten TES and amorphous tungsten silicide SNSPDs on titanium in-diffused lithium niobate waveguides. Crucial for quantum optics applications, our waveguides offer extremely low losses of <0.02dBcm^{-1}, and support both polarisation modes. The ultimate goal is to couple the evanescent field from the waveguides into the superconducting absorber. We will report on simulations and measurements of the effect of the detector deposition, which we can characterise at room temperature prior to cooling down the devices. Independently, we report on how the detectors respond to flood illumination, normally incident on the devices, and, in the case of the SNSPD structure, saturation of the internal detection efficiency. In contrast to previous work using lithium niobate as a substrate for the detectors [4], our result is enabled by the amorphous nature of the tungsten silicide which is tolerant to the surface roughness of the lithium niobate waveguides. This allows us to demonstrate functional detectors deposited directly on top of the in-diffused waveguide structures. Finally, we report on efficient end-face pigtailing at 77K from fibre to waveguide with 1dB loss per interface.

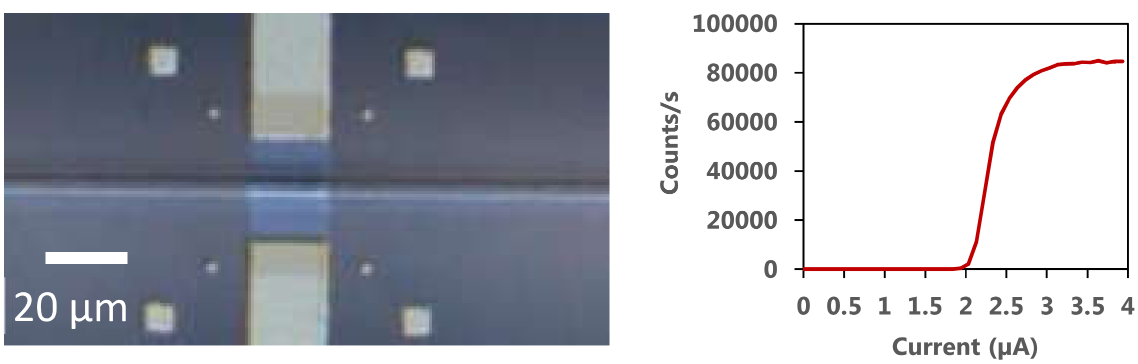

Fig 1. (left) Image of tungsten silicide SNSPD deposited directly on top of the in-diffused waveguide in lithium niobate. (right) Count rate as a function of bias current for one device under flood illumination. The plateau above 3µA is indicative of saturated internal detection efficiency.

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#108

Free space optical communication employing multi-plexing single photon detection

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Abstract. We demonstrate a free-space optical communication system employing multi-plexing single photon detection to increase the transmission efficiency. The detector in use involves a spatially multi-plexed device of 4 single-photon counting modules. The background noise is suppressed by optimizing the discrimination level. This method greatly restrain the error bit rate even in daylight, which promotes the high accuracy optical communication for 24 hours a day.

Body text. In our experiment, an 8-ary pulse position modulation was used to increase the data rate under the background noise of 6 MHz. the incident photons per pulse was 10 for each module. The code generation ratio was over 99.5% for bit 1 and bit 0.

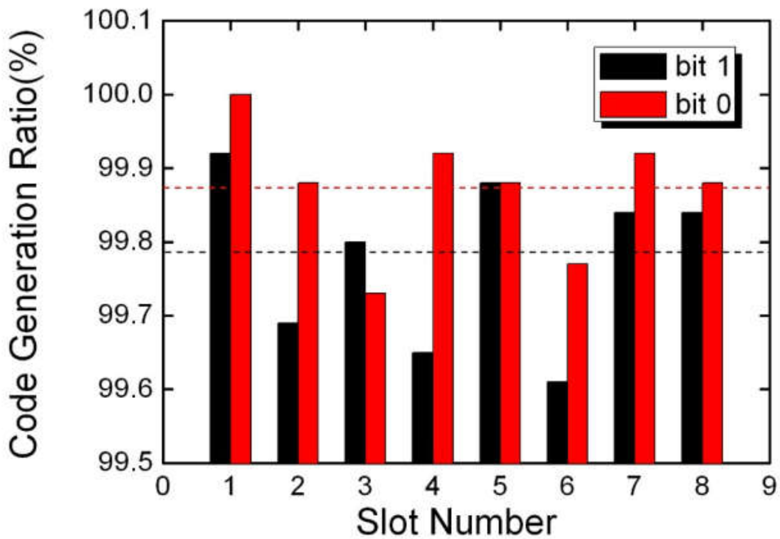

Fig 1. The coed genaration ratio in eight slots. The dotted lines represent the average CGRs.

#109

Photon-number-resolving detectors: an enabling technology for quantum state engineering

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The measurement of quantum states of light is necessary for both fundamental Quantum Optics and Quantum Information. Different kinds of detection strategies exist, giving access to different aspects of light: optical homodyne detection is used to investigate the wave-like properties of the states while direct detection is used to explore the particle-like features. Moreover, different intensity regimes can be explored by using either single-photon detectors or photon-number resolving (PNR) detectors or macroscopic detectors.

In particular, PNR detectors give access to the number of photons in pulsed states, thus allowing the reconstruction of the photon-number statistics, of auto- and cross-correlations, both in the classical and in the quantum domain. Many kinds of PNR detectors are available nowadays, but the optimal choice is still missing. In fact, some detectors have a low value of quantum efficiency (hybrid photodetectors, HPDs), others (Si-photomultipliers, SiPM) are affected by unwanted effects (dark counts and cross-talk), others have a limited dynamic range (fiber-loop detectors, and visible-light photon counters), and few of them are quite cumbersome as they operate at cryogenic temperature in a bulky apparatus (transition-edge sensors and superconductive nanowires).

In our work, we used HPDs and SiPMs to demonstrate, in spite of their limitations, the reconstruction of photon-number statistics of classical and nonclassical states, to measure classical and quantum correlations, to generate non-Gaussian and sub-Poissonian conditional states. Moreover, we exploited the photon-number-resolution capability of HPDs to optimize a phase-estimation protocol.

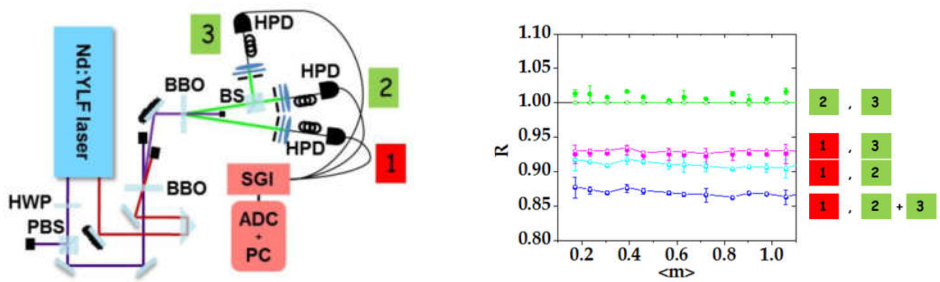

Fig 1. Left: Experimental setup for the generation of conditional sub-Poissonian states. Right: Evaluation of the noise reduction factor R. If R<1 the states are nonclassically correlated [8].

Finally, we implemented a new hybrid detection scheme, in which the homodyne detection technique is performed by employing PNR detectors instead of pin photodiodes and the difference between the two outputs of the interferometer is calculated in post processing. At variance with other existing homodyne-like detection schemes, which can only operate in a very low intensity regime, the detection apparatus can work in a wider dynamic range (up to tens of photons).

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#111

Sub-20ps IRF Width from Hybrid Detectors, Superconducting NbN Detectors, and MCP-PMTs

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Hybrid detectors, superconducting NbN detectors and multichannel-plate (MCP) PMTs achieve a timing resolution (IRF width) of less than 20 ps FWHM when operated with the bh SPC-150NX TCSPC modules. We tested a bh HPM-100-06 and a HPM-100-07 detector (based on Hamamatsu R10467-06 and -07 tubes), a Hamamatsu R3809U-50 MCP PMT and the SCONTEL superconducting NbN detector. In all cases, an IRF width around 20 ps FWHM and below was obtained. This is considerably shorter than previously reported for these detectors. We attribute the improvement to the superior bandwidth of the SPC-150N discriminators and the extremely low timing jitter of the timing electronics of the SPC-150NX modules. These modules have ultra-high bandwidth (5 GHz) discriminators and internal timing electronics with less than 6.5 ps and 3.5 ps FWHM timing jitter. In this presentation, we will address several key components to this performance achievement.

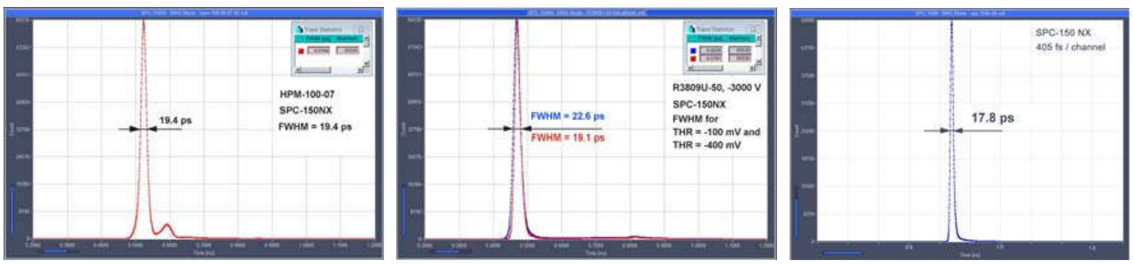

Fig 1. Left: IRF of HPM-100-06 (bi-alkali cathode). Center: IRF of HPM-100-07 (multi-alkali cathode). Right: IRF of SCONTEL superconducting NbN detector. The full with at half maximum is 18.9 ps, 19.4 ps, and 17.8 ps respectively. (SPC-150NX, 100 ps/div, 405 fs/channel)

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#112

Wide-Field Photon Counting Imaging with bh SPC-150N System and Photek FGN 392-1000 Detector

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We present a wide-field photon counting imaging system consisting of a position-sensitive MCP-PMT of the delay-line type, three SPC-150N TCSPC modules, a bh BDS-SM picosecond diode laser, an inverted microscope, and optics that projects a fluorescence image on the active area of the detector. The operation of the system is fully integrated in the bh SPCM software, data analysis is performed by bh SPCImage. The system is able to record wide-field image data with 1024 time channels and up to 1024 x 1024 pixels. The effective spatial resolution of the detector / photon counting combination is about 250 x 250 pixels FWHM, corresponding to about 160 µm on the active area of the detector.

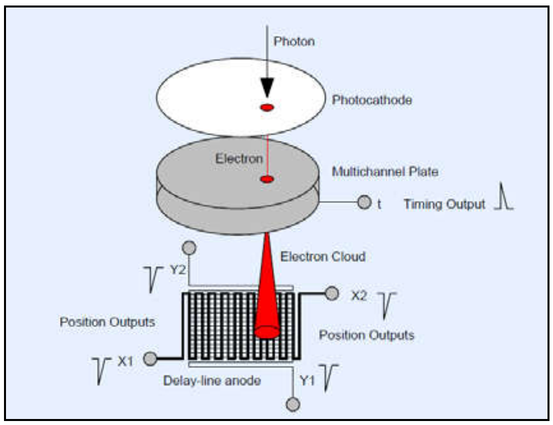

Fig 1. Principle of position-sensitive detector: The detector has a delay-line structure as an anode. The X position of a photon is proportional to the delay between X1 and X2. The Y position of a photon is proportional to the delay between Y1 and Y2. The time of the photon is derived from a signal from the low-side of the channel plate, t.

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#113

Software solution for complete statistical mode structure analysis of mesoscopic states of light

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Abstract: We present a software package aimed at simulating photon-number probability distributions of a range of naturally occurring classical and non-classical states of light. This software can generate arbitrary probability distributions based on the known mode structure of a light field. It also can solve the reverse problem, i.e. reconstructing the mode structure of a light field based on a given probability distribution.

The mode structure fully describes a light field and contains the information about the source of light without a direct access to the source. Here we offer the tool to extract this information from the measured photon number resolved (PNR) distribution. Particularly we are interested in bright (mesoscopic) light states, characterized by the average number of photons greater than one. In this case, a conventional approach based on second order Glauber correlation functions cannot be directly applied. In contrast, our algorithm scales favorably with source brightness [1].

The probability to generate k photons in a mode $p_\mu(k)$ is governed by that mode's statistics and its mean photon number μ. PNR measurements are increasingly popular. They directly measure a probability distribution of a multi-mode light source. To find underlying modes, one writes:

$$P(M) = \sum_{\sum k_j = M} \prod_j p_{\mu_j}(k_j). \tag{1}$$

We consider three types of modes: thermal modes governed by Bose-Einstein statistics: $p_\mu^{\mathrm{Therm}}(k) = \mu^k/(1+\mu)^{k+1}$, Poissonian modes: $p_\mu^{\mathrm{Pois}}(k) = \exp(-\mu)\mu^k/k!$, and single-photon modes governed by binomial statistics: $p_\mu^{\mathrm{SP}}(0) = (1-\mu)$; $p_\mu^{\mathrm{SP}}(1) = \mu$; and $p_\mu^{\mathrm{SP}}(k>1) = 0$.

Conjugated multimode sources (such as those created via parametric downconversion or four-wave mixing) are the only mesoscopic nonclassical sources known to date. This software provides a nearly-perfect reconstruction of multimode fields. A conjugated source generates two multimode outputs typically denoted as 'signal' (s) and 'idler' (i). The joint photon number statistics is simultaneously acquired in a PNR measurement. This measurement gives a joint probability distribution (JPD) $P(n_\mathrm{s}, n_\mathrm{i})$, i.e. the probability to simultaneously get $n_\mathrm{s}(n_\mathrm{i})$ photons in the signal(idler) arms:

$$P(n_\mathrm{s}, n_\mathrm{i}) = \sum_{\substack{N_\mathrm{s}+M_\mathrm{s}=n_\mathrm{s} \\ N_\mathrm{i}+M_\mathrm{i}=n_\mathrm{i}}} P_\mathrm{c}(N_\mathrm{s}, N_\mathrm{i}) P_{\mathrm{u_s}}(M_\mathrm{s}) P_{\mathrm{u_i}}(M_\mathrm{i});$$

$$P_\mathrm{c}(N_\mathrm{s}, N_\mathrm{i}) = \sum_{\substack{k= \\ \mathrm{Max} \\ (N_\mathrm{s},N_\mathrm{i})}}^{\infty} \sum_{\substack{\Sigma k_j = k \\ \Sigma n_j^\mathrm{s} = N_\mathrm{s} \\ \Sigma n_j^\mathrm{i} = N_\mathrm{i}}} \prod_j p_{\mu_j}(k_j) L_{n_j^\mathrm{s},k_j}(\eta_j^\mathrm{s}) L_{n_j^\mathrm{i},k_j}(\eta_j^\mathrm{i}); \qquad P_{\mathrm{u_{s,i}}}(M) = \sum_{\sum k_j = M} \prod_j p_{\mu_j}(k_j). \tag{2}$$

Loss factors L can be written in form of binomial coefficients $L_{n,k}(\eta) = \eta^n(1-\eta)^{k-n}k!/((k-n)!n!)$, where η is efficiency, k is the number of generated photons and n is the number of detected photons.

The experimentally acquired JPD may be processed either independently for a signal(idler) arm, in which case a reduced distribution is obtained by summing over $n_\mathrm{i}(n_\mathrm{s})$ and applying eq. (1) or jointly, by applying eqs. (2). Our code calculates joint and reduced probability distributions for any superposition of multiple modes and solves the reverse problem: the reconstruction of an underlying statistical mode structure from a PNR distribution with a minimal set of assumptions. If a joint analysis of a conjugated source is used, nonclassicality assessment of mesoscopic states of light becomes possible [1].

The code is going to be published in Journal of Research of NIST. The web-based demonstration of the software is in beta testing.

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#114

Characterization of detector efficiencies with a high intensity source of entangled photon pairs in the presence of Raman noise

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Abstract: A fiber-based entangled photon distribution system is fully characterized by measuring the singles and coincidence counting rates and fitting to the expected counting statistics. It is shown that all relevant system parameters can be determined with measurements at as few as two different pump power settings.

In order to characterize an entangled photon source and detection system, knowledge of the photon generation rates, channel transmission, and detector efficiencies is required. Single photon detectors have been accurately characterized with crystal-based entanglement sources [1]; however, the presence of Raman noise photons in fiber-based systems [2] has resulted in less detailed analysis of these systems.

In this paper, we show that a fiber-optics entanglement distribution system can be fully characterized by measuring the singles and coincidence counting rates when attenuating the pump by varying amounts. The detector efficiencies, pair generation rate, and Raman rates were determined by fitting the singles and coincidence data with a theoretical model of the counting rates including multi-photon effects. The data and fitted models are plotted in Fig. 1.

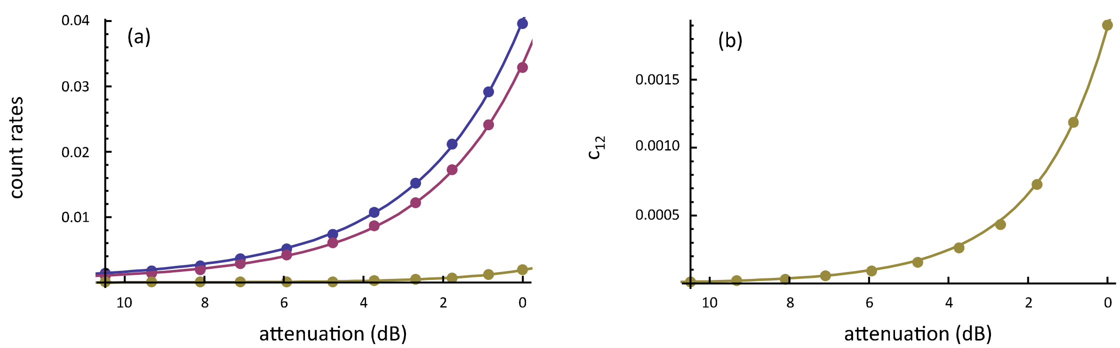

Fig. 1: (a) Plot of singles count rate in both channels (blue, purple) and coincidence rate (yellow). (b) Magnified plot of coincidence rate.

Further, it will be shown that as few as two measurements in the high power regime are sufficient to fully characterize the system. Such a condition allows fast and accurate characterization of the system in the lower power, high-fidelity regime by measuring the system in the less noisy high power regime.

In conclusion, we have presented a method to determine all relevant parameters of a fiber-optics entangled photon distribution system by measuring the singles and coincidence rates when attenuating the pump. This method allows complete characterization of the system by taking measurements at only two different pump powers.

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#115

Metrology for Quantum-Cryptography: the Coordinated European Effort

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Quantum Key Distribution (QKD) is essentially the generation of perfectly secure random keys shared between two parties that communicate by an open quantum channel. This enables the parties to establish a secret key from short pre-shared secret and public exchanges, something which has never been shown to be possible by classical, i.e. non-quantum, means [1]. QKD is today no longer confined to laboratories. Practical QKD networks have been realised in the metropolitan area in all five continents [2]. Nowadays, commercial products or industrial prototypes for point-to-point QKD are available from SMEs and large companies. Despite this strong industrial interest in QKD, the standardisation process of QKD systems is still in its initial phase, as is the development of a measurement framework for the characterisation of the physical (optical) components inside QKD system.

Specifically, European National Metrological Institutions under the EURAMET research programmes EMRP and EMPIR (by means of the funded project EMRP IND06 "MIQC" [http://projects.npl.co.uk/MIQC/] and EMPIR 14IND05 "MIQC2" [http://empir.npl.co.uk/miqc2/]) are pushing the development of a metrology framework to foster a market take-up of quantum communication technologies, in order to achieve the maximum impact for the European industry in this area.

It should be noted that, irrespective of the underlying technologies, there are quantum devices that appear in most QKD systems, namely sources and detectors. The characteristics of these quantum optical components are crucial for security analysis at the quantum optical level. In this sense, the above mentioned EMRP IND06 "MIQC" project (ended in September 2014) had been the first answer of the metrological community to these needs. In the framework of the EMRP IND06 "MIQC" project, measurement techniques for the characterisation of QKD quantum optical components in the telecom regime (around 1.55 μm) were developed. The activities in the project were mainly focused on pseudo-single-photon sources and single-photon detectors, but also attention was paid to the characterisation of quantum random number generators (QRNG).

Following the lines of the good results achieved by MIQC, and in order to sustain advances of the metrology for quantum technologies, a follow-up project, namely EMPIR 14IND05 "MIQC2", was then conceived, funded and is actually ongoing. It focuses on aspects of primary importance as outlined in the following. Firstly, two pilot-comparisons in photon counting regime will be carried out in the context of this project: one on single-photon sources and the other on single-photon detectors.

The second covered topic takes into consideration the fact that fibre and free-space Quantum Key Distribution (QKD) systems use real devices, which do not have the ideal characteristics envisaged by the initial QKD concept. This means that practical systems can be vulnerable to one or more of the many quantum hacking attacks proposed and/or demonstrated. Counter-measures against these attacks have already been identified, but their effectiveness should be ensured by rigorous characterisation of the optical components. The 14IND05 "MIQC2" has already started the work to assess and fix these issues [3-5].

In parallel and synergy with all these aspects, it is worth noting that some of the National Metrological Institutions and industrial partners of the EMPIR 14IND05 "MIQC2" project actively participate in the standardisation effort in the context of the ETSI Industry Specification Group for QKD (ISG-QKD) [6]. In summary, the aim of this poster is to provide an overview of this European Effort for the development of the Metrology needed for the standardisation of the QKD.

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#117

Overcomplete quantum tomography of a spatially encoded 2-photon NOON state

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Multi photon entangled states are at the hearth of quantum metrology, where the property of quantum entanglement can be exploited to go beyond the measurement accuracy allowed by classical approaches. This field has strongly benefited from the advances in the production and manipulation of single and entangled photons, and a very interesting resource is represented by NOON states. These states can be used to achieve super resolved measurements and a precision beyond the Standard Quantum Limit [1]. The mostly investigated ones are polarization-entangled NOON state, typically generated with parametric sources and characterized in the polarization basis [2,3]. In an alternative approach the Hong-Ou-Mandel (HOM) effect, which is commonly used to quantify the indistinguishability of single photons, allows to deterministically obtain a spatially-entangled 2-photon NOON state. In this work, we create such a state and develop a novel method to perform an overcomplete tomography of the two photon state path basis density matrix.

We use single photon sources fabricated by deterministically coupling a quantum dot to an electrically-controlled semiconductor micropillar cavity [4]. Using resonant excitation, these sources provide a highly indistinguishable stream of single photons used for the generation of the NOON state. The output state of the HOM beam splitter (BS1) can be described by a 3 level system, whose basis is constituted by the 3 possible distribution of the 2 photons on the two output spatial modes: $|20\rangle$, $|11\rangle$, $|02\rangle$ (see Fig. 1(a)). To fully reconstruct the 3×3 density matrix of such a state, we developed a measurement scheme consisting of three experimental configurations based on beam-splitters, a phase shifter and photon counters in order to perform a Quantum State Tomography directly on the spatial-mode basis. This protocol excludes the need for a polarization mapping of the NOON state allowing us to use the interferometric setup both to observe the phase super-resolution coming from the biphoton interference (Fig. 1(b)) and at the same time collect the full tomographic data. We realize an overcomplete set of 83 measurements, owing to which we can obtain the density matrix of the NOON state with a Maximum Likelihood Estimation. Even with a limited or noisy statistics we can optimally reconstruct the density matrix for our state, revealing spatial coherences terms that would be hidden using standard tomography protocols. (Fig.1c).

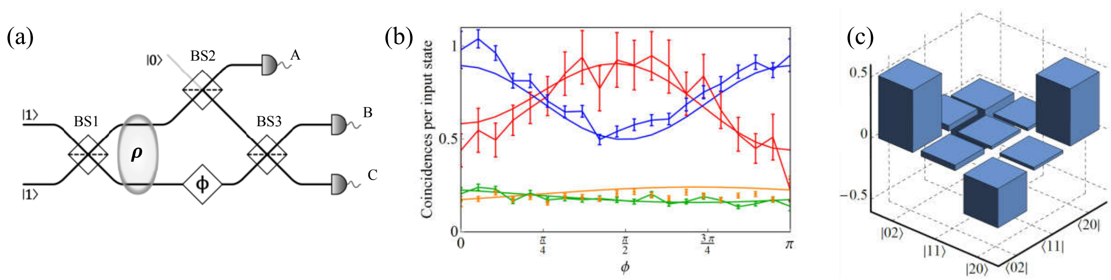

Fig 1. (a) Schematics of one of the configurations used in the experimental setup: two input single photons interfere in BS1, and the resulting state ρ is transformed with a phase shifter (Φ) and two beam splitters (BS2 and BS3). Correlation measurements are performed among the three detectors as a function of the interferometer phase. An additional BS (not shown in the scheme) is placed in mode C to achieve a total of 83 different measurements. (b) Correlations between detectors at modes B and C showing the 2Φ interference of the biphoton state. (c) Real part of the reconstructed density matrix of the NOON state.

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#118

Detection Efficiency Measurement of Single Photon Detectors from 250 nm to 1000 nm

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We present the experimental setup for measurement of detection efficiency of single photon detectors by direct comparison with a calibrated photodiode at the power level of 100 fW. The monochromatic-based tunable light source can provide an incoherent free-space beam that can be focused on a diameter of less than 80 μm in a wavelength range from 250 nm to 1000 nm.

For single photon detectors such as the avalanche photodiode operated in the Geiger mode, the detection efficiency depends strongly on wavelength. Therefore, measurement of detection efficiency should be performed as a function of wavelength in the range, in which the detector is active. In 2016, we demonstrated the measurement technique of detection efficiency as a function of wavelength by directly comparing the single photon detector under test with a photodiode, whose spectral responsivity is calibrated traceable to the SI [1]. In that work, the wavelength range of the measurement was from 480 nm to 840 nm, which was limited by the source used.

In this work, we present the improved experimental setup, which can realize the measurement method of Ref. [1] from 250 nm to 1000 nm. Moreover, a single photon detector for the free-space input can be also measured by using the monochromator-based light source with a point-like source. Fig. 1 shows the schematic setup, which consists of a laser-driven light source (LDLS), a double-grating monochromator, and the reference photodiode with the switched integrating amplifier (SIA), which can measure the photocurrent in the 100 fA level. The cylindrical telescope is used to correct the astigmatism error caused by the monochromator, and the pinhole is used as a spatial filter. At the position of the detector under test (DUT), the beam diameter is measured to be smaller than 80 μm, which is suitable to measure the detector with a very small active area [2]. The spectral responsivity of the reference detector (REF) is calibrated against the radiant power at the position of the DUT by using another standard Si detector calibrated in the wavelength range from 250 nm to 1000 nm.

We will present the performance of the experimental setup including the preliminary results for the uncertainty evaluation for the detection efficiency measurement, and discuss the possibility for expanding the wavelength range up to 1600 nm.

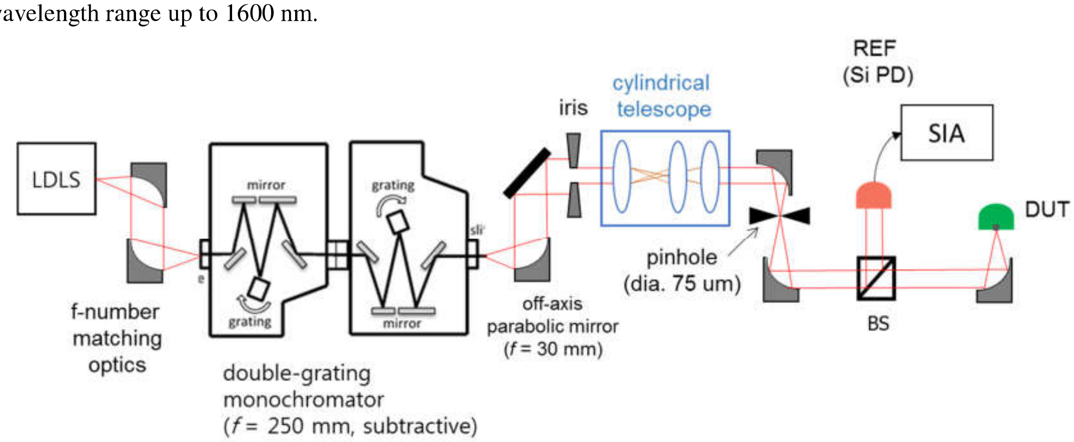

Fig 1. Schematic diagram of the experimental setup for measurement of detection efficiency by direct comparison with a photodiode (LDLS: laser-driven light source, SIA: switched integrating amplifier, DUT: detector under test)

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#119

Decomposition of the 1/*f* Noise in QDOGFET Single-Photon Detectors

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QDOGFET (quantum dot optically gated field-effect transistor) single-photon detectors combine photon-number-resolving detection with quantum memory - two important capabilities for building quantum networks. In these detectors, quantum dots (QDs) are embedded in a specially designed high-electron-mobility transistor, as shown in Fig. 1(a), and used as optically addressable floating gates. A Si δ-doped region produces a pair of two-dimensional electron-gas (2DEG) regions, one closer to the QDs (primary) and one further away (secondary). A photon incident on the gate contact is detected when it is absorbed in the structure and electrically charges a QD with a photo-generated hole carrier. The stored charge subsequently alters the current flowing through the primary 2DEG by screening the gate field, where the change in current is proportional to the transconductance ($g_m = \Delta I/\Delta V_{gate}$) of the 2DEG. The photoconductive gain associated with this process provides QDOGFETs with single-photon sensitivity when cooled below 40 K [1]; however, at elevated temperatures increased electrical noise degrades the photosensitivity, as quantified by the signal-to-noise ratio (SNR). In addition, the SNR has been shown to vary dramatically depending on the exact bias conditions, a dependence that is not yet fully understood.

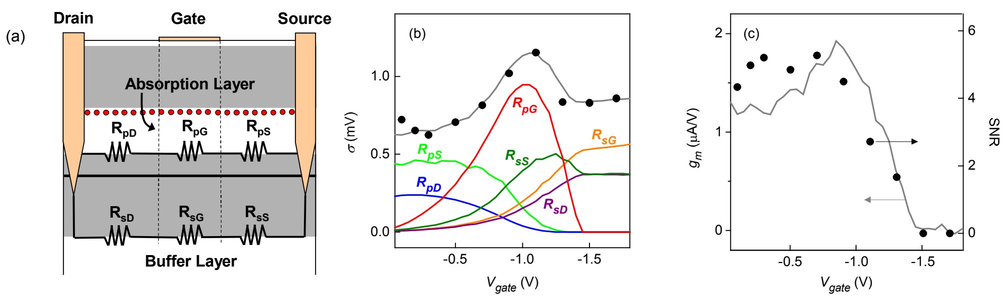

Fig 1. (a) A QDOGFET is composed of alternating layers of GaAs (white) and AlGaAs (gray) with a layer of QDs (red dots) along the top of the GaAs absorption region. A Si δ-doped layer (thick black line) produces a primary 2DEG along the bottom of the absorption layer and a secondary 2DEG along the top of the GaAs buffer layer. R_{pG}, R_{pD} and R_{pS} (R_{sG}, R_{sD} and R_{sS}) denote the resistances of the gated and ungated portions of the primary (secondary) 2DEG. (b) Standard deviation, σ, of the noise in the detector's output as a function of V_{gate}. The total modelled noise (gray) is decomposed into contributions due to the six resistive portions of the 2DEGs and compared to measured data (dots). (c) Transconductance, g_m, and signal-to-noise ratio, SNR, as a function of V_{gate}. All data shown in (b) and (c) were acquired for T = 7 K.

Here, we use a linear-systems model to show how independent noise sources contribute to the overall noise in the QDOGFET detection system and to investigate how those sources of noise vary with bias conditions and temperature. In previous work [1], we showed that the power spectral density (PSD) of the noise in QDOGFETs exhibits a 1/*f* character and described in detail how it impacts the SNR of the detectors. Here we provide a more detailed look into the fundamental sources of the noise by treating each resistive element of the 2DEG system [see Fig. 1(a)] as an uncorrelated source of 1/*f* noise with an independent Hooge parameter ([2] and references therein). The primary (secondary) 2DEG is characterized by a gate-controlled resistance, R_{pG} (R_{sG}), in series with the resistances of the ungated conductive regions nearest the source and drain contacts, R_{pS} (R_{sS}) and R_{pD} (R_{sD}), respectively. Taking the Hooge parameters of the six regions to be independently adjustable, the standard deviation, σ, of the noise in the detector's output is calculated and compared to experimental data.

Samples of our investigation are shown in Fig. 1(b) and (c), were σ, g_m, and SNR are plotted as functions of V_{gate} for a 7 K operating temperature. For $|V_{gate}| < 1.4$ V, the transconductance is dominated by that of the primary 2DEG and a SNR of greater than 5:1 is achieved. Notice that optimum SNR does not occur where g_m peaks, but instead is observed for lower gate voltages where the noise contributed by R_{pG} is reduced. As $|V_{gate}|$ is increased, the noise generated by the gated portion of the primary 2DEG increases (due to increased R_{pG}) and the SNR decreases. For $|V_{gate}| > 1.4$ V, there is little photoresponse, and the noise originating in the secondary 2DEG dominates that of the detection system. In our presentation, we will describe how the structural composition, temperature, bias conditions, and elements of the external detection circuitry (not shown) influence the various sources of noise and show how this information can be used to optimize the performance of the detector.

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#120

Ghost imaging based on superconducting nanowire single-photon detector at the wavelength of 1.5 µm

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Abstract: Ghost imaging is a novel technique that produces the image of an object by correlating the intensity of two light beams, neither of which independently carries information about the shape of the object. Combining the photon counting method and ghost imaging, we established a ghost imaging system using an superconducting nanowire single photon detector at the wavelength of 1.5 µm.

Ghost imaging (GI) methods can be used through the spatial intensity-correlation measurements to acquire the image of an object indirectly [1]. GI can be obtained using pseudothermal light produced by a laser beam with a rotating diffuser, and detectors using in object path usually are photomultiplier tubes (PMTs). However, with the increasing demand for remote sensing imaging, when the emission energy is limited, and return signal from the target is weak to several photons, it is difficult for PMTs to obtain accurate responds in these photon-starved situations. In the mean time, single-photon detectors can offer high quantum efficiency and tremendous noise suppression capabilities. Thus GI sysyem using a single photon detector can work in the environments with a small photon-flux. Recent progress in erbium-doped lasers suggests burgeoning various applications at the wavelength of 1550 nm, which lies in the eye-safe region of the spectrum and offers much lower solar background noise, as well as lower atmospheric attenuation. In the last decade, SNSPDs have been demonstrated with a near unity detection efficiency, low dark counts and wide response spectrum from visilbe to infrared. Thus, employing an SNSPD in GI system would not only afford the capacity to work under weak light source but also extend the GI technology to near-infrared wavelength.

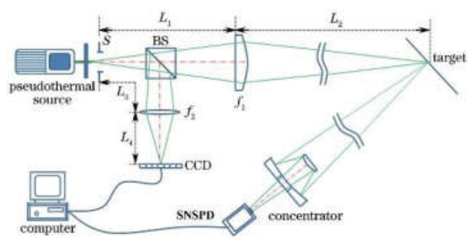

Fig 1. Experimental setup of 1550-nm GI system with pseudo-thermal light using an SNSPD.

The experiment setup is schematically illustrated in Fig. 1. A series of independent random speckle patterns, obtained by modulating a pulsed laser with a rotating diffuser, were divided by a beam splitter into two paths and then projected onto the target and a charge-coupled device (CCD), respectively. Synchronized by a synchronization controller, the fixed CCD was used to record the distribution of speckle patterns and the signals reflected from the target were recorded by a mutimode-fiber-coupled SNSPD. According to the distribution of speckle patterns and the corresponding reflection signals from the target, the target's image can be restored by the image reconstruction method. We selected some simple targets for the imaging, and the results are shown in Fig 2. The results can be improved by optimizing the uniformity of the speckle patterns or utilizing advanced algorithms.

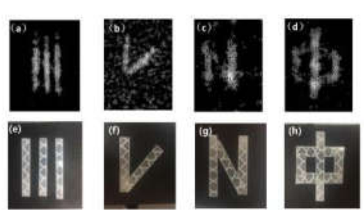

Fig 2. Experimental demonstration results of the GI system.
(a)-(d), the images of the target; (e)-(f), the photographs of the targets.

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#121

Integrated SNSPD with on-chip SFQ readout and time stamping

(poster presentation)

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Advancement in single photon detectors are enabling significant progress in many areas of science and technology, particularly quantum information processing. In this poster, we will present the recent progress at HYPRES, Inc. in building integrated SNSPD with SFQ technology readout and precise time stamping. We will discuss the state-of-the-art integrated fabrication process development of SNSPD and optical components with Josephson junction circuits at HYPRES. It will be shown that by integration of all different components into one chip, large arrays with great performance can be built economically. Few sample applications that would benefit from this system will be presented.

#122

Observation of the optimal form of quantum state-independent contextuality

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Quantum contextuality, with results violate the bounds of non-contextual inequalities set by the non-contextual hidden-variable modes, is a critical resource for quantum computation and communication. Finding and testing optimal non-contextual inequalities are important because they offer in general a larger deviation from classical bounds and are thus more friendly in experimental tests. Moreover, an essential requirement for any test of contextuality, namely, no-signaling between successive measurements should be accomplished, which is difficult to achieve in practical. In this work, we provide an optimal state-independent contextuality inequality, which is then experimentally tested using single photons generated from a defect in a bulk silicon carbide, while satisfying the requirement of no-signaling within the experimental error. Our results shed a new light on the study of quantum contextuality under no-signaling conditions.

Single Molecule Dynamics with Variable Dephasing for Molecular Single-Photon Sources

#123

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Alex S. Clark and E. A. Hinds
Imperial College London, London, UK

Single organic molecules are attractive candidates for solid-state quantum emitters. They show strong, stable and narrow emission at cryogenic temperatures acting as a good approximation to a two-level system. An isolated dibenzoterrylene (DBT) molecule doped into an anthracene matrix is influenced by the surrounding environment of the crystal. The crystal causes an inhomogeneous broadening allowing us to isolate a single molecule in a sparsely doped crystal using a confocal microscope. However, it also dephases the two-level system and changes the transverse decay rate Γ_2 as a function of temperature. We have probed the excited state population of a single molecule over time by measuring the second order correlation function of the emitted light ($g^{(2)}(t)$)[**1**]. The solid-state nature of the single organic molecule means we were able to control the transverse decay rate (Γ_2) by changing the sample temperature and to investigate $g^{(2)}(t)$ across various dephasing rates and saturation intensities, as shown in Fig. 1a. In reference [**1**] we show that this behaviour is accurately described by general solutions of the optical Bloch equations (theory curves in Fig. 1a) and discuss the applicability of various approximations that are commonly made in the literature within different regimes of dephasing and saturation.

The use of these molecules as single-photon sources will require increasing their coupling to single optical modes. To achieve this coupling our current experiments place single DBT molecules inside optical fibre microcavities. An optical fibre, mounted in a v-groove block and mirror-coated, is aligned with a small round mirror (radius of curvature, R$= 150\,\mu$m) etched in silicon and also mirror coated, to form a Fabry-Pérot cavity. This construction is shown in fig. 1b. These cavities are designed so that the output is well coupled to a single mode fibre which is highly desirable for single photon production. With our current design we expect the cavity decay rate (power) to be 2κ where $\kappa/(2\pi) = 1.5\,$GHz and that of the molecule (population) to be 2γ with $\gamma/(2\pi) = 22\,$MHz. We estimate that the interaction energy $\hbar g$ between the molecule and the cavity field will be given by $g/(2\pi) = 98\,$MHz. This enables us to have a coupling of the molecule to the fibre of $> 20\%$. Figure 1c shows the reflection spectrum we should observe from the molecule-cavity system, which shows an increase in the reflected power when the laser is resonant with the molecule and the cavity at the same time allowing us to measure the coupling directly. Increasing the reflectance of our mirrors will improve the coupling of the molecule to the cavity and let us greatly increase the collection efficiency. This will allow single DBT molecules to act as highly efficient sources of indistinguishable photons for a wide range of quantum technology applications.

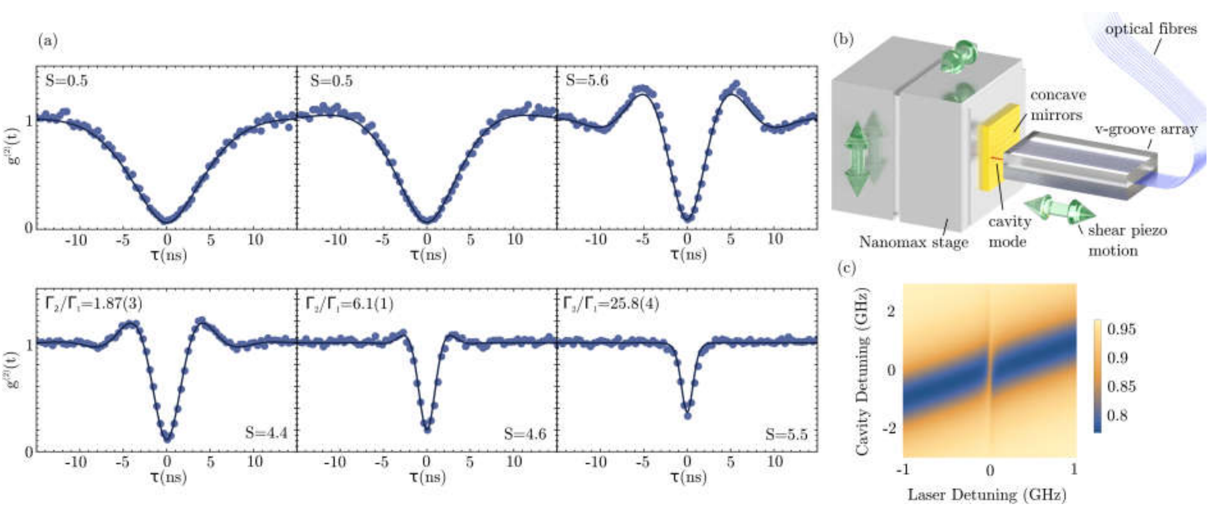

Fig. 1 (a) The second order correlation function ($g^{(2)}(t)$) for a single molecule at various values of dephasing (Γ_2/Γ_1) and saturation (S). Black lines are theory curves. The central panel in the top row is fitted to determine the lifetime of the molecule, in the other panels the curves have no free parameters[**1**]. (b) shows the design of the fibre optic microcavities made by aligning mirror-coated optical fibres in a v-groove array with another array of concave mirrors. (c) The predicted reflection from a molecule coupled to a microcavity as a function of detuning of laser and cavity from the molecule. An increase in the reflection is seen when the molecule is resonant with both the laser and cavity (vertical line in centre of plot).

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#124

Disturbance-free measurement and experimental test of CHSH inequality

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Abstract. One of the strange features of quantum mechanics is the inevitable measurement-induced disturbance, i.e., any acquisition of information from a quantum system causes disturbance. Here, however, we propose a method of asymptotic disturbance-free measurement using the so-called "weak-value scheme". The key concept is that the weakly measured quantum system is measured again to confirm that it is not disturbed. The weak-measurement outcomes of the Bell state post-selected in this manner exhibit classical behavior in the sense that they satisfy the Clauser-Horne-Shimony-Holt (CHSH) inequality. We experimentally confirm our idea by performing joint weak measurement of polarization-entangled photon-pairs and subsequent fiber-based Bell-state measurement.

Our proposed disturbance-free measurement (DFM) is schematically described in Fig 1. After an observable *M* is very weakly measured, we obtain the expectation value *m* and the initial state $|\psi_i\rangle$ is slightly changed to ρ due to the measurement-induced disturbance. Using the post-selection to the initial state $|\psi_i\rangle$, we collect non-disturbed subset of ρ and their outcomes m^*. Since, in the weak measurement limit, the probability of the post-selection is near unity, we call this measurement as asymptotic disturbance-free measurement.

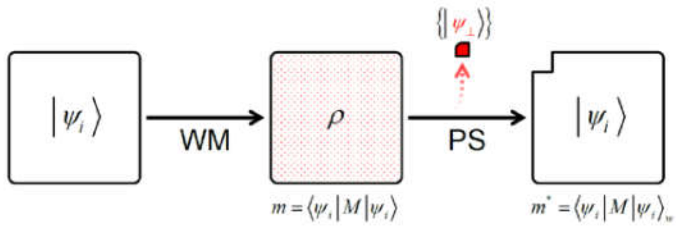

Fig 1. Schematic diagram of disturbance-free measurement. WM: weak measurement; PS: post-selection.

Using DFM, we experimentally test the CHSH inequality [1] based on polarization-qubits of photons and linear optics. First, we generate polarization-entangled photon-pairs via a type-II spontaneous parametric down-conversion (SPDC) process of a periodically-poled $KTiOPO_4$ (PPKTP) crystal [2]. The each photon of a pair is mode-filtered by single-mode fiber (SMF) and traverses polarization weak-measurement apparatus [3]. The weakly polarization-measured photons are re-coupled into SMFs and post-selected on one of Bell states via fiber-based Bell state analyzer. We perform experiments as decreasing measurement strength and observe the tendency of CHSH inequality's violation, because it is hard to experiment in the weak measurement limit.

The experimental results in the weak limit follow the theoretical prediction, i.e., the inequality is satisfied even the initial state is a maximally entangled state. However, if we negate the post-selection (include all results of post-selections), the inequality is violated as it was originally. This implies that a quantum state behaves classically if we measure it without disturbance (or extract disturbance). Thus it shows that measurement-induced disturbance is the essence of quantum mechanics (or non-classicality). This classical behavior of quantum states via DFM is different with previous works of quantum-to-classical transition via decoherence [4], and faulty measurements [5,6]. In the presentation we will show experimental setups and results in detail.

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#125

Nanophotonic advances for room-temperature single-photon sources

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For practical device implementation, e.g., for long-distance secure quantum communication with quantum repeaters, *room-temperature* single-photon sources (SPSs) are necessary [1]. This review outlines state-of-the-art in development of *room-temperature* SPSs with photons exhibiting antibunching, including the authors' results on SPSs with definite circular and linear polarizations. It is focused on nanophotonic aspects of the problem describing advances in stable room-temperature single-emitters as well as the methods of their fluorescence enhancement [2]. Photon indistinguishability at room temperature is a very challenging task, but a high degree of indistinguishability was predicted in [3] on the examples of two typical *room-temperature* single emitters within photonic crystal and fiber-based microcavities. (The special regime was found in which the broad spectrum of the single emitter was funneled into a narrow cavity resonance).

In the first part of this review the best emitters with long operational life for room-temperature SPSs will be discussed: single giant colloidal semiconductor nanocrystal quantum dots (NQDs) and dot-in-rods, color-center diamonds (both bulk and nanodiamonds) and trivalent rare-earth ions (TR^{3+}). Some new stable single-emitters (silicon carbide, zinc oxide, SiO_2 doped with carbon nanotubes, two-dimensional hexagonal boron nitride (hBN), and borosilicate glass and quartz) will be considered as well. Table 1 provides comparison between main stable single emitters for room-temperature SPSs.

Methods of single-emitter fluorescence enhancement (microcavities (including photonic bandgap, Bragg reflector, chiral liquid crystal, and fiber-based), plasmonic nanoantennas, metamaterials, and the alignment of anisotropic single emitters with liquid crystals) will be outlines in the second part of my review. In spontaneous emission enhancement for SPS applications achieving two goals are equally important: (1) ultrafast spontaneous emission for high-speed SPSs with emission rate exceeding 10-100 GHz and (2) enhancement of the total count rate per second from SPSs (greater than Mcounts/s). For instance, using metamaterials can be a solution to reach the first goal, but to extract photons with high efficiency from metamaterials they should be combined with other nanostructures or should be nanopatterned.

Table 1: Comparison of main room-temperature emitters with long operational time for SPS applications.

Single emitters	Advantages	Disadvantages
Color-center diamonds	• NV-nanodiamonds are on the market; • stability against bleaching; • Si-V, Cr and NE8 centers have narrow lines at room temperature (less than few nanometers)	• NV-centers have a wide spectral band; • difficult to find a single color center with $g^{(2)}(0) \sim 0$; • Si-V center has lower stability and brightness; • no color center exists at optical communication wavelength
Giant (large shell) nanocrystal quantum dots and dot-in-rods	• relatively easy to prepare; • relatively stable; • fluorescence at both visible and optical communication wavelengths; • possibility of alignment of dot-in-rods to create definite polarization of photons	• less stable than color-center diamonds and rare-earth ions; • wide spectral lines
Rare-earth ions in nanocrystals	• emitters with highest stability (no bleaching); • variety of ions with fluorescence wavelengths both in visible and at optical communication wavelengths; • short fluorescence lifetimes for allowed transitions	• forbidden transitions (including 1.55 μm) have low oscillator strengths and long (millisecond) fluorescence lifetimes; • allowed transitions have wide spectral bands and require two-photon excitation of specific wavelengths

Theory predicts [1], that for application in long-distance quantum communication systems with quantum repeaters, SPS efficiency should be higher than 70% with a negligible double-photon emission (less than 10^{-4}). SPSs also need to be compatible with the memory wavelength and bandwidth (hundreds of MHz).

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#126

A QRNG system based on the oversampling principle

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Abstract. A new QRNG system is presented in this paper. The new system consists of a compact QRNG, made by a Silicon Nano Crystals Light Emitted Diode (Si-NCsLED) coupled with a SPAD-based detector, controlled by an FPGA, connected, through USB cable, to a PC for data visualization, and saving. The QRNG is based on the measurement of the arrival time of photons in a presence of low photon flux (oversampling regime). The maximum bit rate is limited to up 0.4Mbps in favour of a more system compactness.

QRNGs are characterized to have relevant performance in term of output quality and bit rate [1-2]. However, QRNG systems are typically expensive and bulky, preventing the spread of this technology in many applications such as in the Internet of Things (IoT) or, in general, in portable devices. In this paper a compact QRNG is reported. It is made by a SPAD-based detector coupled with a Si-NCsLED [3] in a 3D packaging implementation to reduce the QRNG size. The device has been then embedded into a prototype and interfaced to the PC through an FPGA (see Fig.1). The QRNG architecture is based on a cluster of 16 SPADs connected to four TDCs to detect the arrival time of photons into a specific time window Tw and the address of the triggered SPAD. When working as QRNG, the system is forced to operate in oversampling regime. In this case the sampling frequency (1/Tw) is greater than the photon rate (λ) and the resulting code distribution of the TDC is approximately linear and uniform (see Fig.2a.). The Total Variation Distance (TVD) of output codes is a measure of the system bias. Fig.3 shows a measurement of the TVD of the QRNG with respect to different light conditions. Data raw of the system is given by the time stamp of photons sorted by SPAD addresses. The randomness of the device has been tested through NIST tests as shown in Table 1, where a post-processing was needed in order to reduce the resulting bias of raw data.

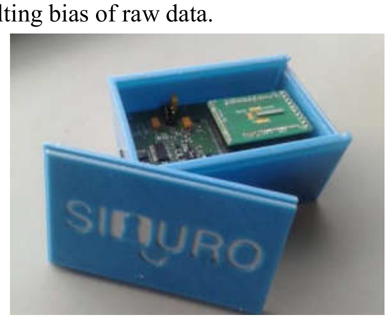

Fig 1. Prototype of the proposed QRNG

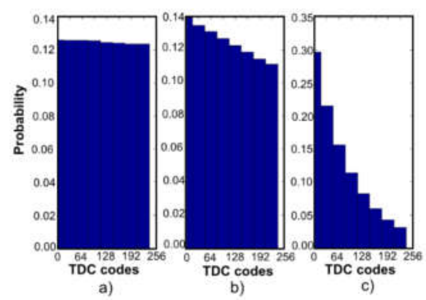

Fig.2: Simulated output of the TDC in case of: a. oversampling; b. moderate oversampling and c. undersampling regime.

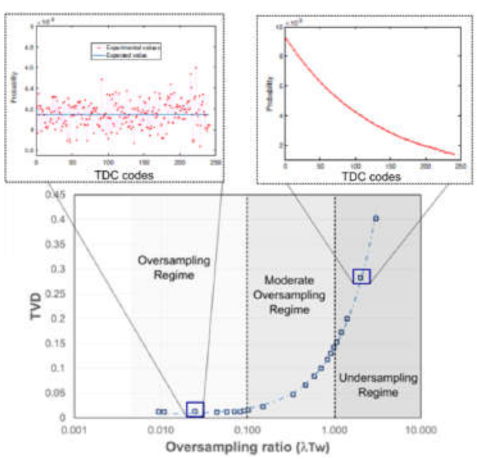

Fig 3. Measurement of TVD vs photon rate.

	Raw data			Toeplitz-extracted data		
Statistical test	P-value$_T$	Proportion	Result	P-value$_T$	Proportion	Result
Frequency	0.000000	0.000	Failed	0.051942	1.000	Passed
Block frequency	0.000000	1.000	Failed	0.401199	0.990	Passed
Cumulative Sums	0.000000	0.000	Failed	0.249284	1.000	Passed
Runs	0.000000	0.000	Failed	0.816537	0.990	Passed
Longest run	0.000000	0.000	Failed	0.015598	0.990	Passed
Rank	0.637119	1.000	Passed	0.037566	0.990	Passed
FFT	0.145326	0.990	Passed	0.455937	0.960	Passed
Non-overlapping template	0.000000	0.000	Failed	0.678686	1.000	Passed
Overlapping template	0.000000	0.000	Failed	0.334538	1.000	Passed
Universal	0.000000	0.000	Failed	0.964295	0.990	Passed
Approximate entropy	0.000000	0.000	Failed	0.040108	0.990	Passed
Random excursions	n/a	n/a		0.756476	1.000	Passed
Random excursions variant	n/a	n/a		0.619772	0.952	Passed
Serial	0.000000	0.150	Failed	0.010988	0.960	Passed
Linear complexity	0.494392	1.000	Passed	0.181557	0.980	Passed

Table 1: Result of NIST tests of raw data and with post-processing

Acknowledgement: The research was funded by the Autonomous Province of Trento, call "Grandi Progetti 2012", project "On silicon chip quantum computing and secure communications –SiQuro".

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#127

An Absolute few-Photon Detector based on a Predictable Quantum Efficient Photodiode and a Switched Integrator Current Amplifier

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A few-photon detector based on a custom-made induced junction photodiode with predictable quantum efficiency is under development. It is equipped with a switched integrator current amplifier to render possible the low noise amplification of photocurrents down to the pW level.

The few-photon detector (see Figure 1(a)) is based on the Predictable Quantum Efficient Detector (PQED) [1,2] and, hence, the detector can be used with radiant power levels from approximately 300 µW down to the detection limit. To minimize the lower detection limit, the detector is actively cooled and a low-noise switched integrator current amplifier is installed next to the photodiode and on the same temperature controlled base plate. The housing can be purged with dry nitrogen in order to prevent condensation on top of the photodiode. The photodiode is mounted under an angle of 45° relative to the incoming beam. This configuration, that is close to Brewster's angle, reduces the reflection losses to less than 10 % for p-polarized radiation at 850 nm. The inside of the detector is all black, which reduces the relative false light level below 1 %. However, while the internal quantum efficiency can be calculated using sophisticated software models and is higher than 0.9999 in the range from 400 nm to 800 nm [3], the calculation of the reflectance is more difficult because the actual thicknesses of the SiO_2 layers have to be known precisely. A single photodiode usually has a strong spectral dependence of the reflectance on the incident wavelength. This has to be taken into account for this system, for instance, by measuring the photodiode reflectance at all used wavelengths.

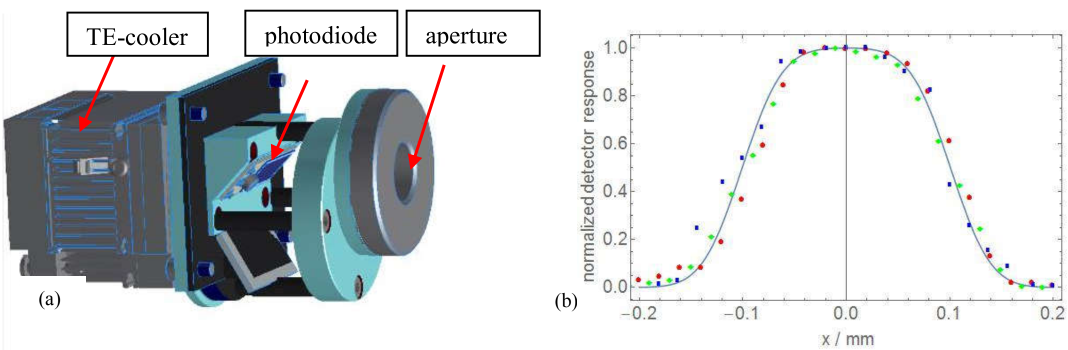

Fig 1. (a) CAD-drawing of the few-photon detector. The outer housing and the current amplifier are not shown. (b) Horizontal scan with the few-photon detector (red marker) equipped with a 210 µm pinhole, two single photon counting modules (green and blue markers) across the focal spot and the calculated response of a detector with an active diameter of 210 µm (FWHM) and a spot size 30 µm (standard deviation).

Furthermore, this detector can be equipped with different apertures from 25 mm down to several µm. This feature can be used to minimize the influence of the different detector sizes of detectors used in classical radiometry and single photon detectors (see Figure 1(b)). When the lowest possible uncertainties are required, the detector can be calibrated against another standard, such as an PQED or a calibrated trap detector.

This detector system is ideal to be implemented as a stable reference detector [4] with a huge dynamic range into applications such as commercial Quantum-Key-Distribution systems and to be used by research and calibration laboratories that work with radiant power levels from hundreds of µW down to the pW level.

This work was performed in the context of the project EMPIR 14IND05 MIQC2. The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States.

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#128

Position dependence of W-TES photon counting capabilities

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Superconducting tungsten (W) in an optical stack has demonstrated near unity absorption at 1550 nm. High detection efficiency and a low operational temperature (0.16 K) provide energy resolution sufficient for discerning subtle variances in the single-photon counting response of the device. The spatial dependence of the device response has been measured, revealing dependencies in detected photon number, energy resolution, and thermalization that result from small misalignment from the device center.

Additional measurements at 785 nm demonstrating the position-dependent behavior of this Transition Edge Sensor (TES) at a suboptimal wavelength are also reported. Single photon measurements at 785 nm and higher photon energy have demonstrated a characteristic "half photon" anomaly, shown in Figure 1, which may be caused by one of several proposed interactions. Preliminary results of the position dependence of this phenomenon supports the hypothesis of thermal absorptions off detector in the substrate.

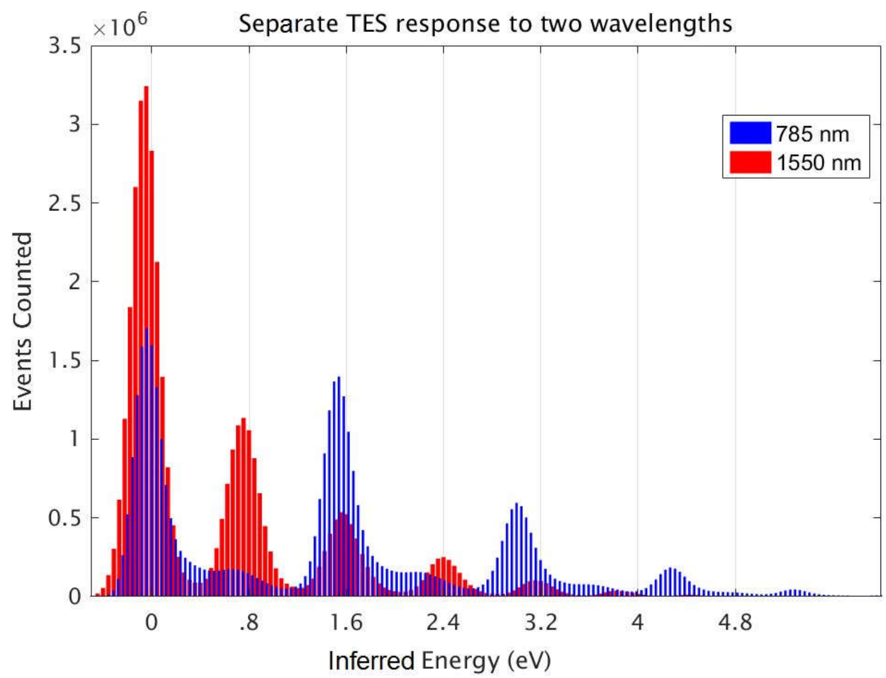

Figure 1: Comparison of 1550 nm and 785 nm energy histogram generated from the response of the TES. Every 0.8 eV (1 photon at 1550 nm has E = 0.8 eV) has been marked. Note the secondary feature between the primary peaks for 785 nm, these are the "half photon" detections, which do not occur at 1550 nm.

A second type of TES, the Electrical Substitution TES (or ESTES) is calibrated by the inclusion of a thermal reference in the form of a non-superconducting heater. This reference source of power can be equated to an equivalent photon flux, providing calibration of the measure of power which is absent from the TES without the addition of the resistive heating element. Scans of ESTES at 1550 nm with a 5 μm beam spot will provide calibrated, high resolution data on the spatial dependences of the photon counting capabilities of W-TES.

#129

Fabrication of the Superconducting-Nanowire Single-Photon Detector with Low Polarization Sensitivity

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Single-photon detectors based on superconducting nanowires (SSPDs) have attracted much attention in the last years thanks to a remarkable progress that has been made in increasing their detection efficiency. System detection efficiency up to 93% with dark count rates below 1 count/s has been demonstrated using an SSPD based on WSi [1]. Recently, the same value of detection efficiency of 93% with a timing jitter as low as 14.8 ps was obtained using NbTiN as superconducting material [2]. Such high values of efficiency are obtained by inserting the superconducting nanowire in an optical cavity. However, in such a configuration, the efficiency becomes strongly dependent on the polarization of the incident light due to the optical anisotropy introduced by the nanowire geometry. This polarization sensitivity limits the application potential of SSPDs. We have recently proposed a new, cost-effective approach to reduce the polarization sensitivity [3].

In this work, we demonstrate an experimental confirmation of the theoretically predicted effect. SSPD detectors were fabricated on NbTiN films. The wire is 100 nm wide with a fill factor of 0.5, and covers a round spot with a diameter of around 16 μm (Fig. 1). The difference between the detection efficiency for TE- and TM-polarized light has been measured (TE refers to the electric field being parallel to the nanowire length, whereas TM refers to the perpendicular direction), obtaining a TM/TE responsivity ratio of 0.3 – 0.5 at 1310 nm. These values are in a good agreement with theoretical simulations performed with the commercial *RSoft Fullwave* software (Fig. 2). In a previous work [3], we showed that the polarization sensitivity of SSPDs can be significantly reduced by inserting a high-refractive-index dielectric layer in the optical cavity, which reduces the refractive index anisotropy. In order to validate these results, a 390 nm thick SiN_x layer was deposited on the devices after characterization. The polarization sensitivity was significantly reduced (TM/TE responsivity ratio = 0.7). In the future, even better results can be obtained. Our theoretical calculations predict a TM/TE ratio of 1 keeping relatively high absorption efficiency of 90.8% at 1550 nm using dielectric layers with higher refractive indexes (n > 2) such as TiO_2 (n ≈ 2.3-2.5) [3].

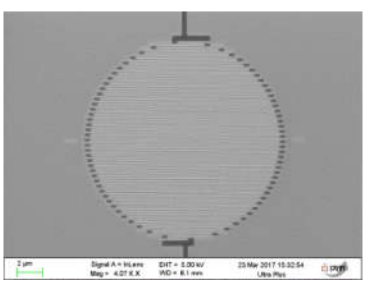

Fig. 1. Scanning electron microscopy image of the SSPD meander.

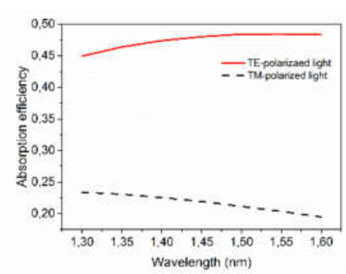

Fig. 2.Theoretical simulation of the TE and TM absorption efficiency as a function of wavelength.

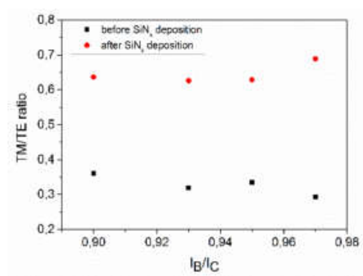

Fig. 3. TM/TE responsivity ratio vs the bias-to-critical current ratio (I_B/I_C) for SSPDs before and after SiN_x deposition.

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Acknowledgment
Work funded by the European Commission via the Marie Sklodowska Curie IF grant 'SuSiPOD' (H2020-MSCA-IF-2015, #657497), the French National Research Agency via the 'WASI' (ANR-14-CE26-0007) program, and the Grenoble Nanoscience Foundation.

#130

Photon number and timing resolution of a near-infrared continuous-wave source with a transition edge sensor

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The slow recovery time, on the order of microseconds, of Transition Edge Sensors (TES) limits their number resolving and timing accuracy for high photon-flux detection. This is usually resolved by pulsing the light source or discarding overlapping signals, thereby limiting their applicability. In this work, we analyze the output signal when detecting a continuous wave source, and present a procedure to determine amplitude and timing of overlapping pulses. As a direct application, we measure the arrival-time difference distribution of a coherent source in a single spatial mode using a single detector.

Detection of a single photon by the TES produces a pulse with a fast rising edge of tens of nanoseconds and a decay time in the order of microseconds [1]. Standard techniques for time-tagging a detection event, based on threshold crossing or constant fraction discrimination, do not work when two pulses have a large overlap (see Figure 1), limiting the applicability of the TES for high photon-flux detection. In [2], Fowler et al. proposed a technique initiated by signal differentiation that works well for the high signal-to-noise ratio typical of the detection of high energy photons (γ and X-rays). For NIR photons the signal-to-noise ratio is lower, and the timing accuracy is affected by the bandwidth limitations necessary to reject false positives.

We refined the results obtained by signal differentiation by fitting the signal with a model obtained from a linear superposition of single-photon traces. In the experimental demonstration, we modulate a 810nm laser diode to obtain 4 ns light pulses, each containing an average of 1 photon, and record the TES signal. We select the traces corresponding to single photon detection and use them to create the detector response model.

We then switch the laser diode to continuous wave, record 10 μs long traces, and select traces containing two photons. We apply a low-pass filter to the signal and estimate the time-tags by differentiation. When the individual photon detection events are sufficiently separated, we obtain two time-tags which are used to initialise a least-squares fit on the unfiltered trace. For overlapping pulses we obtain a single initial time-tag. In this case, we perform a Monte-Carlo Markov Chain fit (see Figure 1), using the expected single photon pulse amplitude distribution as a prior. With this method, the maximum detectable flux is ~5.9 MHz. We obtain an arrival-time difference distribution that agrees well with our prediction (see Figure 2).

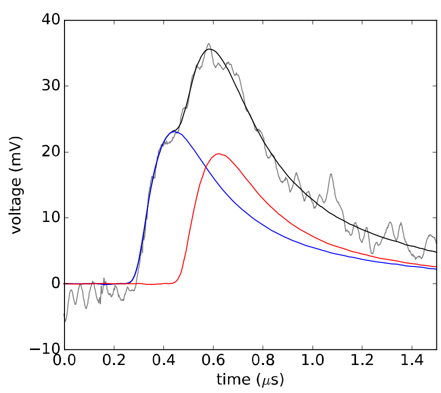

Fig 1. Monte-Carlo Markov Chain fit (black) of a 2-photon signal (grey) composed of individual single photon events (red, blue) separated by ~170ns, comparable to twice the rise time of a single photon pulse.

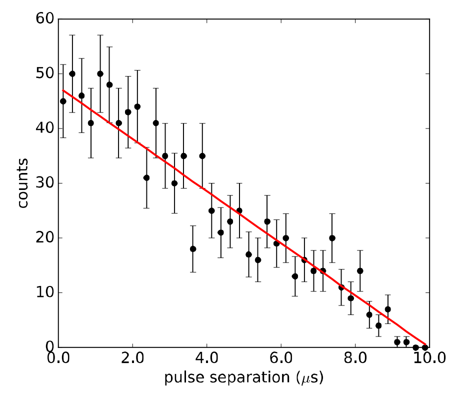

Fig 2. Arrival-time separation histogram of a continuously running laser diode. Bin size ~ 250 ns. Error bars indicate Poissonian standard deviation. Red line: Theoretical prediction. Due to the finite duration of our oscilloscope traces, the coincidence probability of two photons decreases with increasing separation.

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#131

Toward the integration of photonic device with nanocrystal and superconducting nanowires:

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Abstract

Nowadays superconducting nanowire single photon detectors (SNSPDs) are the most advanced devices to detect single photon in the visible and the infrared range[1]. In addition to their high detection efficiency, they prove very low dark count rate, high time resolution[1] and they show their compatibility with Si technologies[2]. Colloidal quantum dot (QD) or semiconductor nanocrystal is a reliable quantum emitter which is an attractive alternative to atoms, ions, molecules or nitrogen-vacancy center in diamond. The control of their synthesis methods and the wide choice of the semiconductor allow to tune their optical properties of emission and to integrate them in photonics circuits[3]. Optimized single photon sources and detectors are crucial for quantum optics technologies and their integration on photonic circuits will allow more complex devices for optical communication and quantum optical experiments.

In this poster, I will present integrated nanophotonic devices that emit and detect single photons with the ultimate goal of performing antibunching experiments directly on chip at cryogenic temperature (~ 4 Kelvin). U-shaped nobium titanim nitrate (NbTiN) nanowires, 25µm long and about 100 nm wide are fabricated on a silicon/silicon oxide chip. Silicon nitride waveguides are added on top of them with a single layer of quantum dots embedded inside (figure 1). The layer is patterned by Langmuir Blodgett which allows accurate control of the quantum dots location. The photoluminescence of the quantum dots is confined in the waveguide mode and will be coupled evanescently to the SNSPD. We have performed optical FDTD simulation and we observe that due to the long interaction distance waveguide/SNSPD, all the QD emission is absorbed by the nanowire and it generates an electrical signal which, after amplification, can be recorded by any pulse counter or time tagging electronic instrument.

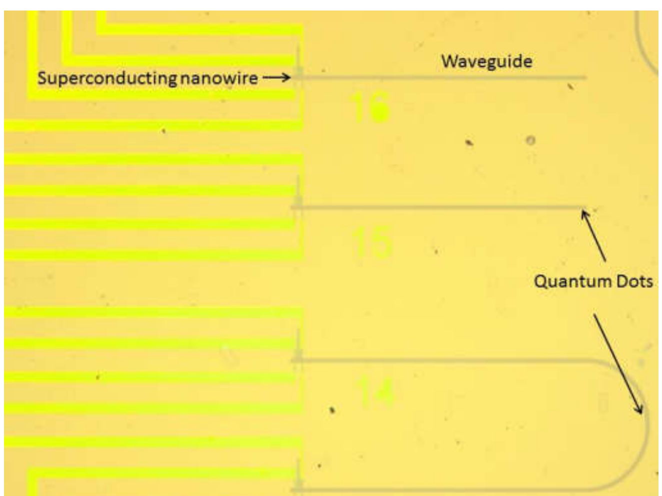

Figure 1: Optical microscope image of integrated nanocrystals devices.

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#134

Hot-spot relaxation time current dependence in NbN waveguide-integrated superconducting nanowire single-photon detectors

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Superconducting nanowire single-photon detectors (SNSPDs) have emerged as essential building blocks for quantum optical experiments. Efficient and small footprint niobium nitride SNSPDs can be realized by placing the detectors atop nanophotonic waveguides. Both high speed and high efficiency are needed, but usually require different designs. Photon-number resolving capability is also desirable, even though SNSPDs cannot be directly used for this purpose. However, by reducing the bias current of the nanowire, more than one photon has to be absorbed in a localized section of the wire within a very short time delay (hot-spot relaxation time) to break the superconductivity and trigger a detection event. To exploit this effect for multiphoton sensing applications, full characterization of the dependence of the bias current on the hot-spot relaxation dynamics in niobium nitride is therefore essential. We adopt a near-infrared pump-probe technique in a cryogenic environment to measure the bias current dependence of the hot-spot relaxation time. We find a minimum relaxation time of (22 ± 1) ps when applying a bias current of 50% of the switching current at a bath temperature of 1.7K. Similar to WSi detectors, our experiments reveal a strong increase of the picosecond relaxation time with increasing bias current.

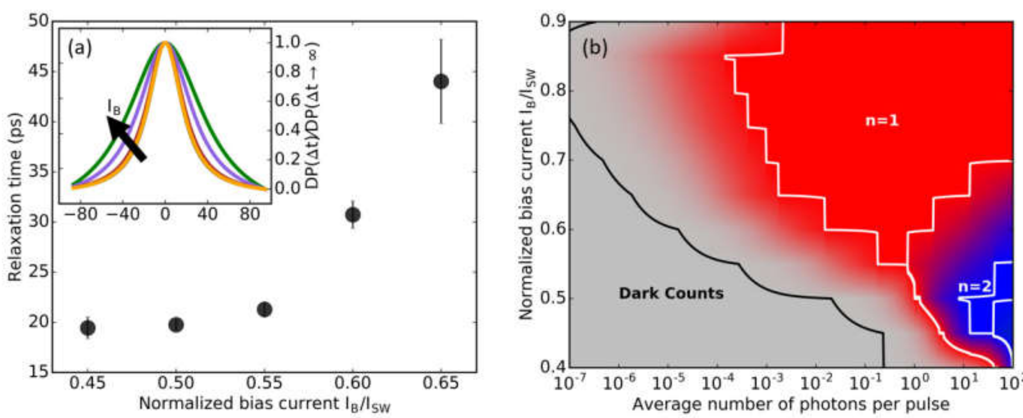

Fig. 1(a) Bias current dependence of the hot-spot relaxation time. (b) Practical detector tomography, showing the detection working regimes at different bias currents and illumination obtained applying our model. The solid contour lines indicate pure $n = 0$ (Dark counts), $n = 1$ single- and $n = 2$ two-photon detection regimes.

By adopting the same technique, we introduce a reconstruction method for determining different detector sensitivity regimes. Our work provides a complete description of the detector working operation in both photon number threshold sensitivity and time-delay sensitivity. The results allow for implementing on-chip measurement architectures for the characterization of weak classical light emitters and fast single photon sources with only one detector, driven at different biasing currents, with a drastic reduction of the time uncertainty limitations of typical correlation measurement systems.

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#135

Single Photon Source based on Silicon Vacancy in Nano-Diamond at KRISS

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We report on the progress of the development of single photon source at KRISS, which is based on the isolated silicon vacancy in nano-diamond. The anti-bunched stream of single photons with a narrow spectral bandwidth will be the essential tool in the field of quantum radiometry.

Quantum radiometry is the metrology for the amount of light by counting the number of photons. With the advance of the single photon-based applications such as quantum cryptography, quantum imaging, and quantum computation, the need for quantum radiometry is increasing. An on-demand or predictable single photon source would play an important role to establish the measurement standards for quantum radiometry [1].

At KRISS, we are developing a single photon source based on the fluorescence from one isolated silicon vacancy (SiV) center in a nano-sized diamond. The schematic setup of the source is shown in Fig. 1. The nano-diamonds containing a low concentration of SiV centers is fabricated by the wet-milling process from a polycrystalline CVD diamond and is spin-coated on the Ir substrate. An isolated single SiV center on the coated surface of the substrate is searched by scanning the confocal microscope with a pulsed pico-second pump laser at 671 nm in a repetition rate of 143 MHz. The single photon emission is verified by measuring the second-order correlation by using the Hanbury-Brown-Twiss (HBT) interferometer consisting of two single photon avalanche detectors (SPADs) and the coincidence counting module. The spectral property of the emitted single photon is measured by using a spectrometer with a photon-counting array detector.

In the presentation, we will show the up-to-date performance of the single photon source and discuss the ideas for further improvements as well as the proposals for applications.

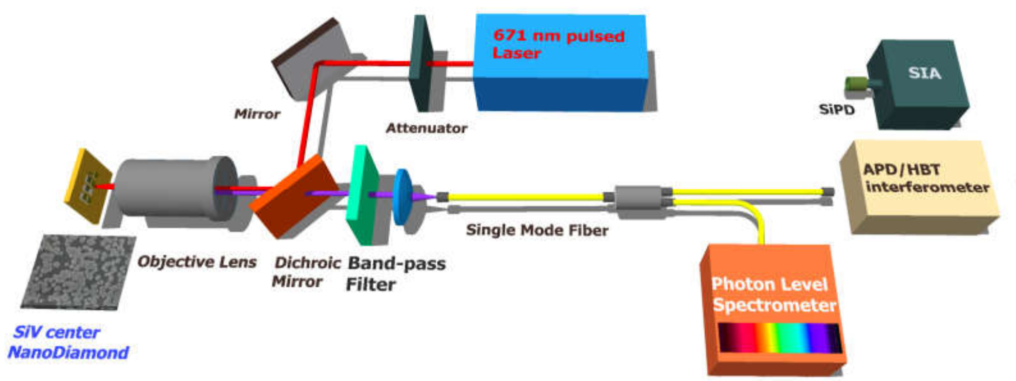

Fig 1. Schematic setup of the single photon source based on the SiV center in nano-diamond at KRISS

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#136

Towards CMOS compatible, fully depleted single-photon detection using avalanche multiplication

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Abstract. IMEC is developing a CMOS compatible platform for fully depleted image sensors [1-4]. Full depletion allows enhancement of the charge collection speed, signal detectivity and sensitivity in photodetectors. This abstract addresses the integration of linear and breakdown mode single-photon sensitive devices within our fully depleted CIS platform.

The device concept of transferring a photogenerated charge packet (1) through an avalanche multiplication region (2) towards a pinned storage region (3) is depicted in Fig.1 [2-3]. The device can be readout by transfer (4) towards a floating diffusion. We presented that this device may be used in linear mode in combination with a low-noise threshold detection circuit (Fig. 2 - left) [3]. In this work we address that this device concept can also be operated in breakdown region (Fig. 2 - right). Crucial for both operation modes is the trade-off between breakdown bias [2-3] and punch-through leakage current over the built-in potential barrier that embeds the readout circuitry [2-4].

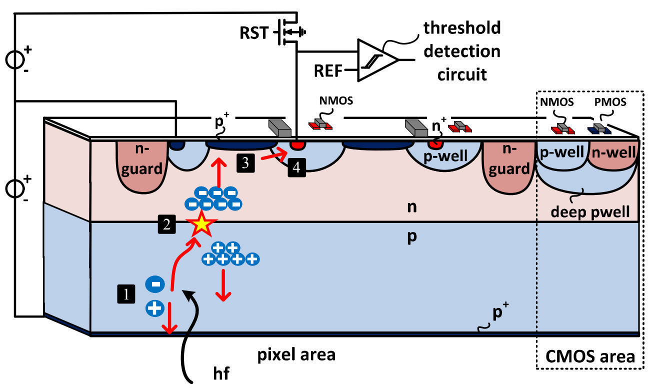

Fig 1. Cross-sectional view of fully-depleted device concept using photosensitive region (1), avalanche multiplication region (2), storage and transfer regions (3, 4) [3-4].

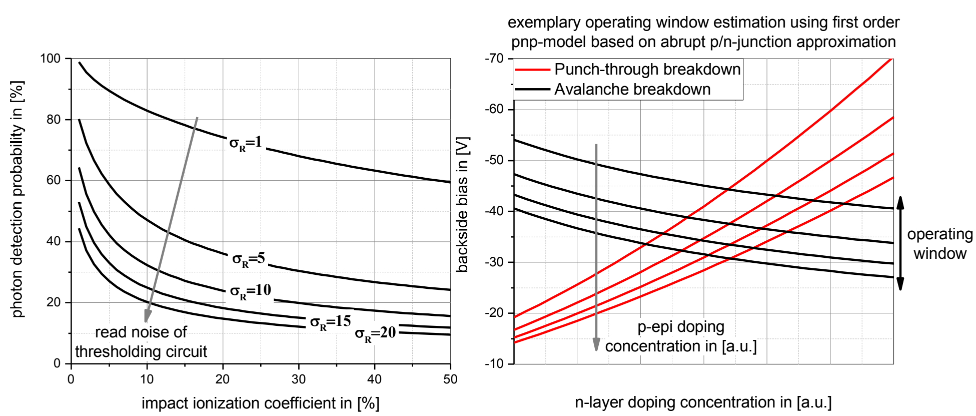

Fig 2. Left: single photon detection through linear avalanche multiplication in combination with a thresholding circuitry [3] Right: single photon detection through breakdown operation in compatibility with full depletion.

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#137

Second order phase holograms without coherence between the sources

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Interferometric methods are essential in making precise measurements and typically require high coherence between the measured and the reference beam. When phase delay changes randomly, faster than the capability of our measurement, the first order interference fringes average out, erasing all the spatial phase information. Similarly, if two independent light sources are used, interferometric measurements become technically demanding. What is more, if intensities of light beams are low, there might be only a few photons which can be detected within coherence time.

Nevertheless, higher order correlations of detected photons' positions are resistant to the fluctuating phase between the interfering beams. As presented in the "Hologram of a Single Photon" [1] (HSP), such higher order correlations may carry full information about the phase structure of a light beam. In our experiment, we show how to obtain a similar effect for classical light sources (coherent states) with erased coherence between them. Obtained holograms created from correlated positions of detected photons resemble those obtained by using the HSP method. Notably, presented approach can work efficiently even when first order correlations (intensity fringes) cannot be observed.

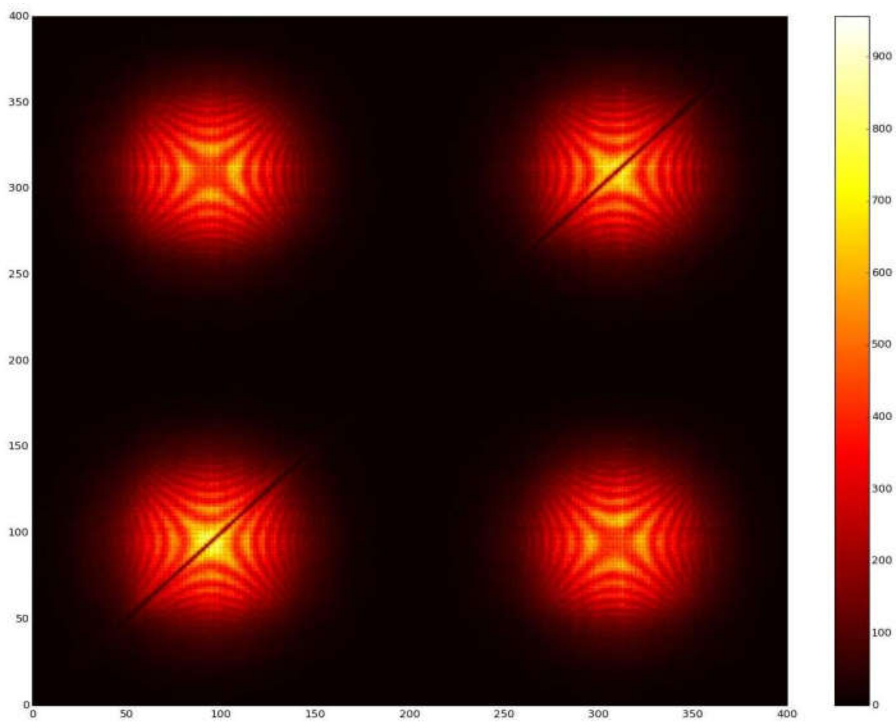

Fig 1. Measured hologram for quadratic spatial phase that emerges from a joint probability of the coincidence events. The color encodes the number of coincidences registered at the camera.

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Single Photon Quantum State Oscillator

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We describe a single photon quantum oscillator and show generalizations to the two and three photon cases. This structure operates by *continuously regenerating* a quantum basis state that oscillates among a subset of different basis states while also evolving a superimposed state at other points in the circuit. This basic architecture is then generalized to the case of a two- and three-qubit architecture wherein the evolved basis states oscillate, similar to the single photon case, but wherein the quantum state at other internal portions of the circuit is entangled. The motivation for the conception of these structures is to provide a means for evolving the quantum states in a deterministic and repeating fashion such that the time interval required for them to maintain coherence is minimized thus decreasing the likelihood that decoherence or unintentional observations occur. Additional motivation is to provide an architectural building block to support an quantum photonic implementation of a basis state oscillator for metrology, a true random number generator, and others.

The structure of single, double, and triple qubit oscillators is shown in Fig. 1 where either two or four linear stages are in cascade and the evolved state produced by the rightmost stage is used to excite the first stage in a continuous fashion via a "feedback" loop. We refer to the serial cascade of the stages depicted in the dashed boxes as the "feedforward" path and the lines that couple the produced quantum state of the rightmost stage to the input of the leftmost stage as the "feedback" path. The single, double, and triple photon circuits are referred to as the Quantum Ring Oscillator (QRO), Bell State Oscillator (BSO), and Greenberger-Horne-Zeilenger State Oscillator (GSO) due to the subcircuits in the feedforward paths.

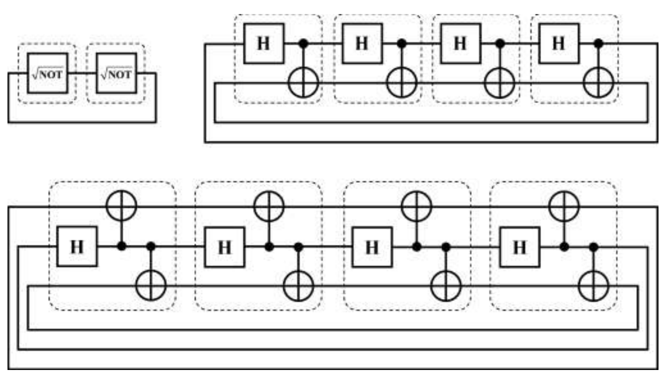

Fig 1. Quantum circuit diagrams for a) single-photon QRO, b) dual-photon BSO, and c) triple-photon GSO oscillator

In order to maintain proper operation and to avoid problems due to the accumulation of loss in the components, it is necessary to periodically inject new information carriers. Furthermore, it is necessary to include a means to observe the state of the oscillator. We exploit the fact that the quantum state at the output of the rightmost stage is a basis state which allows for the structures of Fig. 1 to be augmented with operators that provide for information carrier injection and extraction. The injection and extraction structure is shown in Fig. 2 for the case of a single qubit oscillator.

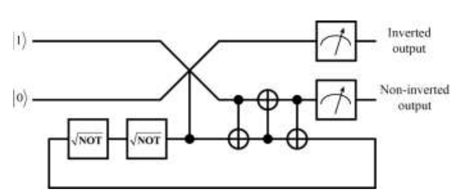

Fig 2. Single Qubit Oscillator Structure with Injection/Extraction

In addition to the obvious application of the use of these oscillators as a synchronization circuit, additional operators (and their inverses) may be added in the feedforward portion of the structure to cause intentional and arbitrary quantum states to be continuously regenerated. By coupling the Fredkin operator control point to the evolved quantum state at the output of the leftmost square-root of NOT operator in Fig. 2 (not shown), the oscillator can function as a true random qubit generator (TRNG) that continuously provides a random stream of qubit basis states due to the continuous regeneration characteristic.

#140

Ultra-fast time-correlated single photon counting system for rapid fluorescence lifetime imaging

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Time-resolved fluorescence microscopy is an essential tool in life science today. It comprises methods such as Fluorescence Lifetime Imaging (FLIM), lifetime based Foerster Resonance Energy Transfer (FRET), and Fluorescence (Lifetime) Correlation Spectroscopy (F(L)CS). When the structures of interest in the observed specimen consist of single molecules as e.g., in sparsely labeled living cells, Time-Correlated Single Photon Counting (TCSPC) with sensitive detectors such as Single Photon Avalanche Diodes (SPAD) or Hybrid Photon Detectors (HPD) is the method of choice. Even though time-resolved cameras begin to emerge, they are often limited in spectral sensitivity, fill factor, noise, and image size. In situations where these limitations matter, it is often necessary and quite viable to resort to highly optimized point detectors in combination with rapid image scanning. In this case it is important to perform TCSPC with the highest possible throughput in order to compensate for the relatively slow process of scanning, while still obtaining images of good quality. One key factor to high throughput is eliminating dead-time. However, ultimate time resolution and low differential nonlinearity (DNL) in timing can typically only be obtained with dedicated time-to-digital converters that incur a dead-time on the order of some tens of nanoseconds after each photon detection. On the other hand it is possible to build simpler timing electronics (typically based on FPGA) that allow effectively zero dead-time but with a compromise on timing resolution and DNL.

We have designed a TCSPC system based on FPGA that achieves 40 Mcps throughput with multi-stop, negligible dead-time, and a resolution of 250 ps, without compromising on DNL. Together with a sensitive and fast HPD, the system allows carrying out ultra-fast FLIM and all related fluorescence microscopy techniques. Our new rapidFLIM imaging method exploits not only the recent hardware developments in TCSPC but also novel data analysis methods addressing the relatively low time resolution and residual detector pulse-pile-up effects. Depending on the image size, rapidFLIM allows for measurements with up to tens of frames per second, enabling the imaging of dynamic processes like protein interactions or chemical reactions, following highly mobile species such as vesicle transport in cells, or even investigating FRET dynamics. We show the key hardware design features as well as some application results with labeled beads and fluorescent proteins in mammalian and plant cells.

#141

Integrated single photon source based on SU8 waveguide with colloidal quantum dots

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Abstract. We fabricated SU8 waveguide and microcavity embedded colloidal quantum dots with low concentration, and the photoluminesce spectrum and the single photon emission were measured from the end of the SU8 waveguide.

Integrated photonic chip is essential for developing high-perform devices and systems for high-speed, high-capacity data transmission, telecommunication and quantum information. Several integration schemes in optoelectronic area have been developed, such as the schemes based on indium phosphide material, SOI material and polymer material, etc. Meanwhile, integrated circuits using polymer composites have advantages in easy operation, flexibility and low cost. SU8 waveguide with colloidal quantum dots for classical integrated chip have already been investigated [1], however, report about SU8 matrix with colloidal quantum dots for quantum integrated chip has not been found. SU8 and colloidal quantum dots are possible to fabricate both classical and quantum integrated photonic circuit.

Integrated single photon sources will have important applications in quantum information, including quantum communication, quantum computing and quantum metrology. Single photon source in microcavity coupled waveguide system is an important step for integrated photonic quantum circuit [2]. Single quantum dots embedded in waveguide and microcavity can be maded as single photon sources on chip, which is one of promising direction in integrated photonic quantum technology. Our goal is to make active integrated photonic quantum chip combining polymer matrix with colloidal quantum dots, where only solution process and photolithography are required. Single photon sources based on colloidal quantum dots can operated at room temperature, which is a useful factor for pratical application. Single colloidal quantum dots usually are not compatible with the other dielectric materials and are difficult to fabricate as active waveguide.

In this study, we fabricated SU8 waveguide embedded with colloidal quantum dots by photolithography, and the concentration colloidal quantum dots is less than 1×10^{-9} M, which is possible to produce single photon source. The fabrication process likes this: we prepared a layer of SiO_2 with thickness of 4 μm produced on silicon substrate by wet oxidation. A layer of SU8 resist was spun coating on the SiO_2, and colloidal quantum dots was introduced on the surface of SU8. And then, another layer of SU8 was spun coating on the colloidal quantum dots. Lastly, the SU8 waveguide with collidal quantum dots fabricated simply by photolithography, and the width of the SU8 waveguide was approximately 2 μm. In the measurement, an objective lens was used to focus the excitation laser in vertical direction onto the SU8 waveguide with colloidal quantum dots, and the photoluminescence spectrum and single photon emission from a quantum dot in the waveguide were measured through a single mode fiber coupling from the end of the SU8 waveguide. It was found that the emission intensity from colloidal quantum dots decreases several times after it was embedded in SU8 compared with that on the surface of SiO_2. Even though, the emission from colloidal quantum dots with very low concentration transmitted through the SU8 waveguide is detectable. We also designed and fabricated SU8 microring with side coupling waveguide, and colloidal quantum dots are embeded in SU8 microring. The transmission spectra from the waveguide-coupled microring based on SU8 were measured, judged from which, light in waveguide can be coupled to microring modes. The photoluminescence emission from the quantum dots in microring in vertical direction is measured. Moreover, the single photon counts from the microring coupled to the waveguide was investigatged.

In conclusion, we fabricated waveguide and microring based on SU8 resist embedded with colloidal quantum dots by using photo-lithography and solution process. The single photon emission coupled out from the SU8 waveguide was detected. The active waveguide from polymer and quantum dots compotes may provide a way for low-cost, flexible integrated quantum photonic circuit.

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#143

An integrated emitter-detector quantum random number generator based on a silicon photomultiplier and a single-photon avalanche diode

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Thanks to the quantum mechanical properties of light, “truly" random numbers can be produced by photonic quantum random number generators (PQRNG). Cryptographic tasks (encryption and decryption) can be executed using secret keys based on random numbers. Mathematical algorithms are extensively used to generate random numbers but could suffer from “guessability”. QRNGs benefit from the intrinsically unpredictable properties of physical processes involved. As an example, the randomness in path taken by photons on a beam splitter or the comparison of photon arrival times [1] have been exploited to generate random numbers.

In this paper, we present an implementation of a compact solid-state QRNG with integrated photon-emitter (source of entropy) and detector in the same silicon chip, producing a compact RNG. Not only they are integrated one close to the other, but also they have been fabricated (in FBK, Trento, Italy), with the same manufacturing steps and similar layouts. This makes the structure very interesting for possible low-cost production. Fig. 1 shows the layout of one implementation of this structure: the emitter is a small silicon photomultiplier (SiPM), composed by many “cells”: each cell is a single-photon avalanche diode (SPAD), as well as the detector. Two different detectors are present, making it more flexible (e.g. using two detectors and the temporal difference between their clicks), but in the method presented here we used only one of them. The characteristics of emitter cells and detectors are similar: they are based on the FBK NUV technology reported in [2]. This technology has been chosen since it demonstrates a reduced delayed correlated noise probability (i.e. including afterpulsing). Emitter is reverse biased: photons are emitted during avalanche multiplication. The detector has been shielded from ambient light thanks to a top metal layer: only photons form emitter are detected, making this integrated approach more robust.

To extract the random bits we employed the recently developed robust method described in [3]: it is based on the measurement of photon arrival times, using discrete time bins, in a time frame repeated in time. A dead time is present between the frames, to get rid of the effects of afterpulsing and the detector non-idealities. The autocorrelation function of the detector counts has been measured and used to fix the dead time at the beginning of each frame to ~4.5μs. The output bit rate reaches a maximum of ~100 kbps. The joint probability mass function for generated random symbols has been measured, showing a deviation of $5x10^{-6}$ from expected theoretical value. We then apply statistical tests in NIST tests suite to the generated raw data, obtaining results shown in table below.

Based on this concept we are developing a CMOS version with an array of emitter-detector structures.

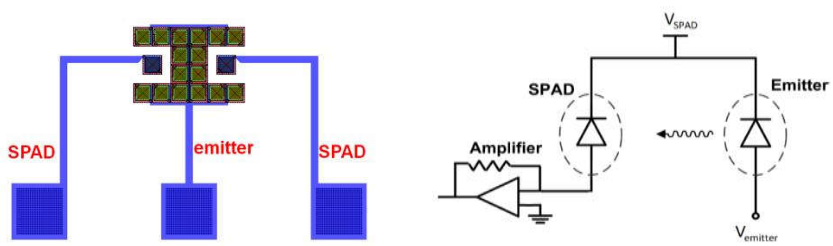

Fig 1. Layout of the integrated emitter-detector QRNG and schematic of the connections.

Table 1: NIST tests results for 1 G random bits. The significance level is α=0.01.

Statistical test	$P\text{-value}_T$	Proportion	Result
Frequency	0.424453	0.9880	Passed
Block frequency	0.336111	0.9930	Passed
Cumulative sum	0.516113	0.9920	Passed
Runs	0.933472	0.9930	Passed
Longest run	0.686955	0.9910	Passed
Rank	0.075719	0.9940	Passed
FFT	0.715679	0.9880	Passed
Non overlapping templ.	0.363593	0.9920	Passed

Statistical test	$P\text{-value}_T$	Proportion	Result
Overlapping templ.	0.009071	0.9890	Passed
Universal	0.522100	0.9870	Passed
Approximate entropy	0.965083	0.9920	Passed
Random excursions	0.083143	0.9853	Passed
Random excursions var.	0.152493	0.9918	Passed
Serial	0.164425	0.9950	Passed
Linear complexity	0.610070	0.9920	Passed

Acknowledgment: the research was funded by the Autonomous Province of Trento, call “Grandi Progetti 2012”, project “SiQuro”

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Optical Fiber Power Meter Calibration for use in Determining the Efficiency of Single Photon NIR Nanowire Detectors

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We describe the calibration of an InGaAs optical fiber power meter (OFPM) to -90 dBm, at wavelengths of 1310 and 1550 nm, for use in determining the efficiency of near infrared nanowire detectors. Specifically, we measure the non-linearity and relative gain of each power range to determine the relative instrument response to optical power. The absolute power response of the meter is calibrated at 20 µW, with an observed expanded uncertainty, at a confidence factor of 95 % (k = 2), of 0.38 %. We will discuss detector non-linearity issues, range discontinuity or gain, and present a comprehensive uncertainty budget for the power responsivity calibration.

The non-linearity of an OFPM is defined as the ratio of the relative difference between the measured or displayed responsivity of the meter at an arbitrary power and the responsivity at the power the meter was absolutely calibrated at, to the responsivity at the calibrated power [1,2]. The triplet superposition method is used to determine the non-linearity. This method is implemented, in its simplest form, with a fiber splitter, optical switches and a fiber coupler. Each output A, B and A + B is measured in turn. The ratio of the sum of A and B to A + B is a direct measure of the non-linearity of the device. As the method is relative, it has the distinct advantage of not requiring a calibrated artefact.

Optical fiber power meters are designed to operate over a large dynamic range, often greater than 60 dBm. This necessitates gain ranging, whereby each range of a power meter has a set amplification, often implemented by switching feedback resistors with a gain factor of 10. Range discontinuity is defined as the step change in power reading when the meter ranges from one gain to the next. Some meters incorporate the facility to internally store calibration factors, which are designed to correct for this offset. However, as the gain circuits of a power meter age, the original stored calibration factors to correct for range discontinuity, become less reliable. The uncertainty associated with the correction factor becomes larger, necessitating the requirement for periodic recalibration. We will describe the uncertainty components and detail how we determine the expanded uncertainty.

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Quantum Communications Network Based on Polarization Entanglement at Telecom Wavelength

#146

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Here we implement a novel network architecture which enables scalable quantum communication networks at telecommunication wavelengths. Our simple scheme uses wavelength multiplexed polarization entangled photon pairs. In our experiment we have demonstrated the network with 4 clients and used 12 wavelength channels to share 6 bi-partite entangled states between each pair of clients in a mesh-like network topology using only one fiber per client.

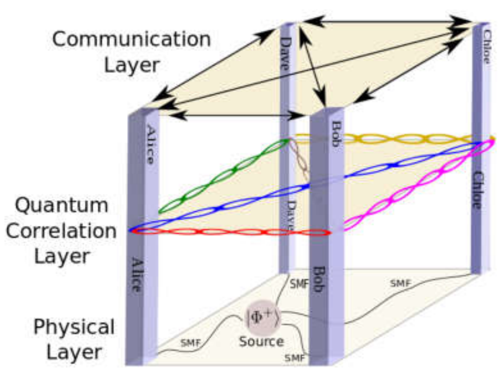

FIG. 1. Scheme of our network architecture. Different layers represent different levels of abstraction. *Physical connections layer:* contains all tangible components. Each of the 4 clients receives a combination of 3 channels via a solitary single mode fiber. Thus, the source distributes 6 bi-partite entangled photon states to the four clients Alice, Bob, Chloe and Dave. *Entanglement distribution layer:* shows the 6 entangled states (each corresponding to a different secure key) that link the 4 clients. *Communications Layer:* Entanglement-based two-party QKD protocols like E91 can be used to generate secure keys between all pairs of clients.

Quantum Key Distribution (QKD) is intrinsically a point-to-point protocol. However, in order to come closer to the declared goal of a "Quantum Internet", extending QKD to several clients is essential and is a very active research area [4]. To our knowledge, so far two approaches have been implemented for Quantum Communications networks: Access networks [2, 3], which make it difficult to implement arbitrary network topologies or change existing topologies, and networks based on trusted nodes which essentially are a mesh of two-client links and therefore duplicating a lot of resources and involving a potential security vulnerability on each node.

We experimentally demonstrate a fully connected network with 4 clients all of which simultaneously share entanglement with every other client. Thus, allowing them to generate 6 separate secret keys without the need for trusted nodes or active switching. Using only one source of polarization entangled photon pairs and wavelength multiplexing, every client shares entanglement via several wavelength channels using only one single mode fiber each. Clients need minimal resources – only one polarization detection module and time tagger each.

All multiplexing and de-multiplexing is centralized with the source. This allows adding/removing clients and changing network topology with minimum effort and no client side changes. The architecture is not limited to a fully-connected graph but can be adapted easily to all possible sub-graphs.

The source makes use of type 0 spontaneous parametric down-conversion centered at 1550 nm. The spectrum is split symmetrically into 6 pairs of wavelength correlated channels similar to Ref [1]. Each client receives 3 channels which are polarization-entangled with the channels sent to each of the other clients. Every client measures all three channels in a single polarization analyzer in either the HV or DA basis and records the results using a time tagger. Photon pairs were identified by their arrival times.

RESULTS AND DISCUSSION

We successfully implemented a 4 client network with uncorrected polarization correlation visibilities > 85% in both bases and for all pairs of clients. These visibilities, and our pump power of $\approx 10\,\mathrm{mW}$ are enough to obtain secure key rates between 2 and 17 bits/s.

The scalability and ease of upgrading of this network architecture as well as its telecom compatible implementation make it one of the best candidates for Quantum Communication networks.

Distributed computation tasks or problems like the millionaire's problem can be easily implemented on this network.

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#147

Photon Statistics of Electroluminescence from Suspended Carbon Nanotube Field Effect Transistors

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Abstract. We report the photon statistics of electroluminescence from suspended carbon nanotube (CNT) field effect transistors (FETs) under extremely low applied electrical powers (~nW). Thermal emission is avoided by operating the devices under positive applied gate voltages, with the FET in its "off" state. In the off state, a high bias voltage (4V) results in only 1nA current, and corresponding electrical power of 4nW. Second-order correlation, $g^{(2)}$, and number-resolved photon detection are reported for emitted photons in the range of 1,300 to 1,550 nm. Number-resolving photon detection is accomplished using a superconducting Transition Edge Sensor (TES) developed and built by the National Institute of Standards and Technology, Boulder [1]. The photon statistics are used to assess the potential suitability of these devices as electrically actuated single photon emitters.

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Optically probing the detection mechanism in a molybdenum silicide superconducting nanowire single-photon detector

#148

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Superconducting nanowire single-photon detectors (SNSPDs) are a key technology for optical quantum information processing. Their low dark count rate, fast response time, small jitter, and high efficiency favours their use in various demanding quantum optics applications. One striking difference with polycrystalline materials (such as NbN) is that amorphous SNSPDs have a detection efficiency that saturates at bias currents well below the critical current. Despite extensive studies, the question remains if these differences are due to a fundamentally different detection mechanism. Understanding the nature of the detection mechanism may ultimately lead to novel SNSPD structures with better performances or SNSPD-inspired devices targeting a broader range of applications.

In this work, we experimentally investigate the detection mechanism by illuminating a 170 nm wide MoSi SNSPD packaged in a self-aligned mount (see Fig. 1a) with wavelengths ranging from 750 to 2050 nm (0.6 to 1.6 eV); see Fig. 1b. More details can be found in Ref.[1]. We obtain several results: i) a nonlinear energy-current relation, see Fig. 1c, ii) an energy-dependant width of the transition between no detections and a fully saturated efficiency, iii) an energy-dependant fit with an error function model. These observation are consistent with both the position dependance of the local detection efficiency across the nanowire, and with Fano fluctuations, which helps pinpointing the mechanisms driving the superconducting-to-resistive transition after photon absorption. We detail these results below.

The long plateau and the broad response also allows us to study the full shape of the PCR curves, revealing a new intrinsic parameter. One theory attributes the shape of the transition region to Fano fluctuations, which are the result of the statistical nature of the quasiparticle creation process[3]. Some recent theoretical models of the physics of the detection mechanism include Fano fluctuations[3] and/or position-dependance effects[4], and are nearing in on making quantitative predictions that can be compared with our results.

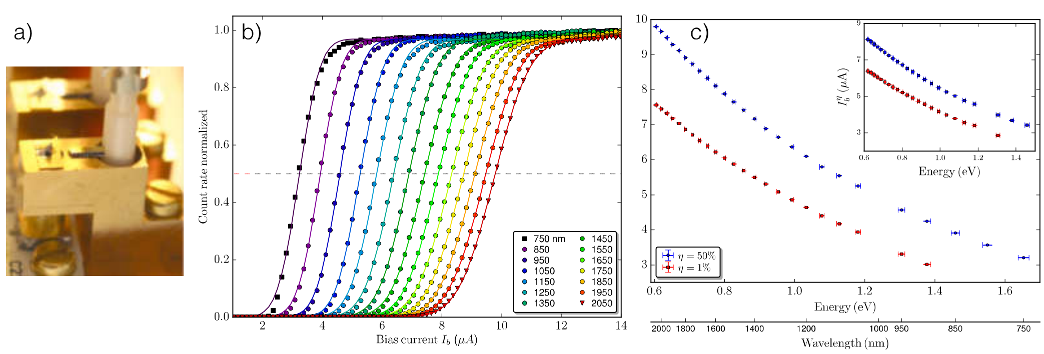

FIG. 1: a) MoSi SNSPD in a self-aligned package. b) Normalised photon count rate (PCR) as a function of the bias current I_b at 0.75 K. Each solid line traces an error function fit for the respective data curve. c) Energy-current relation for two different normalised detection probabilities, at 0.8 K and 1.5 K (inset).

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#149

Superconducting single-photon detectors integrated with multitudinous photonic devices

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Integrated photonic devices and systems offer exceptional potential for control and characterization of light. Single-photon detectors integrated with high-index-contrast waveguides can be used to measure properties of optical signals such as power, coherence, frequency, and statistics. We will present devices which accomplish these tasks with WSi detectors integrated with both silicon and silicon nitride waveguides.

For advanced optical systems, complete knowledge of the characteristics of the photonic signals is required. This includes accurate assessment of metrics including: optical power from the single-photon level up to milliwatt levels used in telecommunications; coherence of laser sources; frequency of various types of emitters and optical sources; and photon statistics to distinguish between thermal, single-photon, and coherent sources. On-chip devices can be utilized to perform all these measurements in a compact, versatile manner. We will present single-photon detectors integrated with nanophotonic devices [1] to characterize many of the properties of light sources.

Superconducting-nanowire single-photon detectors (SNSPDs) have been exceedingly impactful for optical measurements at the few-photon level [2]. Yet they also can serve to measure higher-power signals when combined with the appropriate photonic devices. We will show how cascaded SNSPDs coupled to an optical waveguide can measure optical power with a large dynamic range. To accomplish this, a fraction, f, of the light is tapped from the waveguide before the remainder is routed to an SNSPD. This unit cell repeats so that the i-th detector receives $f^{i-1}(1-f)$ of the initial power. By choosing the tapping fraction f and the number of detectors appropriately, one can cover many orders of magnitude in dynamic range. This is useful, for example, if one wishes to characterize a light source both below and above laser threshold.

To demonstrate laser action, one must show not only that the power generated as a function of the power supplied has the characteristic threshold behavior, but also that the light generated is coherent. One way to conclusively demonstrate this is to pass the light through a Mach-Zehnder interferometer (MZI). We will demonstrate the integration of SNSPDs with an MZI.

In addition to characterizing laser sources, MZIs can be useful for manipulating non-classical light. Demonstration of non-classical light can be achieved by analysis of photon statistics at the two output ports of a 50/50 beam splitter—the infamous Hanbury-Brown-Twiss experiment. We will demonstrate the implementation of such an experiment in an integrated-photonic environment using a beam splitter manifest in waveguides and coupled to SNSPDs to differentiate between single-photon sources, light-emitting diodes, and lasers.

For all types of classical and quantum light sources, it is necessary to characterize the spectral content of the photons. This can be accomplished with on-chip spectrometers based on ring-resonator based filters or arrayed-waveguide gratings. We will demonstrate these devices and discuss the strengths and limitations of each.

In addition to using these photonic devices to characterize integrated light sources across a broad range of operating conditions, we also wish to be able to use them to characterize off-chip sources. To perform such measurements, the insertion loss from an optical fiber to a nanophotonic waveguide must be minimal. This is best accomplished with an adiabatic transition for wide bandwidth and low loss. We present a device based on a terminating tapered optical fiber to an on-chip polymer waveguide coupled to a high-index waveguide.

One of the great challenges of integrated quantum photonics is to generate entangled photon pairs on-chip and utilize them for quantum information processing. A promising avenue to accomplish this is to pump a ring resonator with a coherent state to produce entangled pairs through cavity-enhanced spontaneous four-wave mixing [3]. A key challenge in scaling up this technology is that the pump generally contributes 10^{16} photons per second to the chip, while only 10^5 photon pairs are produced per second. Thus, 120 dB pump rejection is required, and the presence of scattered light renders this impossible. To overcome this limitation, we will present a design for enclosed waveguide-integrated detectors which allow in only a single optical mode and suppress all stray light.

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#151

Tunable quantum light from a crystalline whispering gallery mode resonator

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We present a highly efficient source of tunable quantum light based on parametric down-conversion in a triply resonant whispering gallery mode resonator made from lithium niobate. We can produce squeezed states of light above threshold and narrow-band single photon pairs over a widely tunable wavelength range below threshold, which is under 1μW.

Optical whispering gallery mode resonators offer an extraordinary platform for various nonlinear optical applications due to their unique combination of high Q-factor, broad spectral range, and tunable in- and out-coupling rates [1]. In the past, we have shown that a triply resonant whispering gallery mode resonator made from lithium niobate ($LiNbO_3$) can provide single-mode photon pairs [2] via spontaneous parametric down conversion with a tunable bandwidth of several MHz [3]. These features allowed to interface atomic transitions of cesium and rubidium with single photons, heralded by single photons in the telecom band [4]. This is an important step towards a quantum repeater. Furthermore, this type of whispering gallery mode resonator was used as a source of non-classical light featuring quantum correlations between signal and idler, i.e. two-mode squeezing, as well as intensity squeezing in each parametric beam individually [5].

Here, we present our current research, which mainly focuses on two topics. First, we are realizing a Sagnac-type setup to investigate two-photon interference with heralded photons that originate from two counter propagating whispering gallery modes. An x-cut lithium niobate prism is used for coupling the two pump beams at 532nm via polarization selective coupling [6] in order to minimize the loss of the parametric light through this port. The parametric beams are coupled out with a second prism made of diamond and aligned to interfere on a beam splitter above threshold. Below the threshold, this allows us to carry out a Hong-Ou-Mandel experiment with two spectrally identical, heralded single photons originating from the same resonator. In the next step, we are going to use this configuration to generate polarization entangled photons following the approach described in [7], which are highly desired for entanglement distribution.

Second, we investigate the generation of squeezed vacuum states, which requires a degenerate optical parametric oscillator operated below threshold. Above threshold, we realized parametric amplification of a second in-coupled seed beam at 1064nm. We observed a considerable gain of 10 already at pump powers around 20μW showing the outstanding efficiency of our triply resonant system. In order to quantify squeezing, a homodyne detection scheme is installed after a second out-coupling prism, which benefits from the nearly Gaussian spatial mode profiles of the fundamental whispering gallery modes [8]. All this is accomplished in the low μW regime. Second harmonic generation is studied further in this low power regime in order to realize another source of non-classical light [9].

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#152

Interference between Different Colors in Single- and Bi-Photon States

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Abstract: We experimentally demonstrate quantum coherence of the frequency translation process implemented via Bragg scattering four-wave mixing. We observe first-order interference effects on a single photon placed on a bi-chromatic superposition and second-order interference effects on a frequency non-degenerate bi-photon state.

Optical frequency translation (FT), originally developed to fully shift the color of a light field [1], provides tunable coherent coupling between different frequency fields, with the efficiency of the translation defining the strength of the coupling. As such, FT acts on frequency modes similarly to the action of a beam-splitter on spatial modes [2].

We investigate the processing of quantum states of light in the frequency domain using FT via the parametric optical nonlinear process of Bragg Scattering four-wave mixing (BS-FWM) [3]. The advantage over other implementations, e.g. sum-frequency or electro-optical modulation is that BS-FWM-BS can selectively drive the interaction between two frequencies with arbitrary detuning, from 10's GHz to hundreds of THz. In our fiber-based setup, we demonstrate full control between two frequency modes respectively at 1280 nm and 1284 nm, which can be conveniently separated using standard wavelength division multiplexing technology.

As a proof of principle of the powerful processing capabilities of FT via BS-FWM, a single photon is placed in a bi-color superposition for the case in which the FT is set to 50% efficiency. After a tunable delay line, the phton undergoes a second 50%-efficiency interaction. The two colors are spectrally separated and collected on two different detectors. In Fig. 1 (left) it is shown that the count-rate on each detector oscillates in a fringe-like pattern that depends on temporal separation between the two stages. This is an optical analogue of a Ramsey interferometer [4] and demonstrates how a qubit could be implemented and manipulated in the frequency domain.

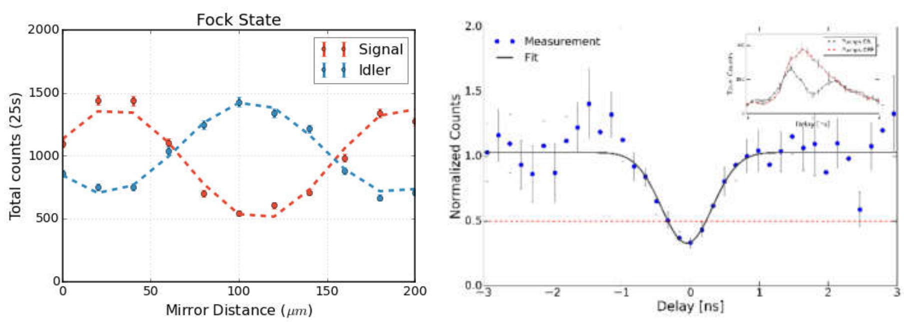

Fig 1. Left side: 'Ramsey' interference on a bi-chromatics single photon state. Right side: Hong-Ou-Mandel interference dip between a bi-chromatic bi-photon.

In a second series of experiments, we demonstrate the frequency-domain Hong-Ou-Mandel (HOM) interference. A pair of quasi-degenerate energy-correlated photons, centered around 1282 nm, are generated via spontaneous downconversion. This bi-photon state is mixed together via 50%-efficiency BS-FWM interaction and subsequently dispersed to map frequency correlations into temporal correlations, and the two frequencies are separated and collected on two different detectors. Measurement of the two-photons coincidences is shown in Fig. 1 (right). For those pairs in which the energy separation matches the FT shift (at zero delay), the coincidence counts drop with a visibility greater than the classical limit of 0.5. This observation represents the frequency domain version of HOM interference, in which photons bunch together at either frequency due to their bosonic nature.

In conclusion, we demonstrated how FT provides a tool to manipulate the relatively unexplored high-dimensional frequency space, enabling both single-photon chromatic qubits and qubit-qubit interaction via linear optics bosonic interference.

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#153

Picosecond-Resolution Time-Lens for Single Photons

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Abstract: We demonstrate a nonlinear time-lens at the telecom range of 1280 nm, using Bragg-Scattering four wave mixing (BS-FWM), a low-noise nonlinear interaction that preserves quantum coherency. We demonstrate a temporal magnification factor of 105x on single-photon coherent pulses, and a resolution of 2.7 ps

Space-time duality is the mathematical equivalence between the equations describing spatial diffraction of a monochromatic beam and temporal dispersion of a short pulse in dispersive medium. Similar to how a regular thin-lens that imparts a phase varying in the transverse spatial dimension magnify an image, a time-lens, obtained by imparting a phase shift varying across a pulse, can be utilized to temporally resolve ultra-fast signals [1]. While time-lenses have been successfully implemented on classical signals, such techniques cannot always be directly applied to quantum states. So far, time-lens implemented via $\chi^{(2)}$ nonlinearity, has been utilized to sorting and detect picosecond-scale time-entanglement [2], and, very recently, fast temporal correlations on a bi-photon pair have been resolved using electro-optical modulators [3].
In this work, we demonstrate a temporal magnification factor of 105x on weak coherent pulses, resolving a temporal separation of 2.7 ps on 100ps-resolution single-photon detectors, using a nonlinear time-lens.
We utilize four-wave mixing Bragg-Scattering (FWM-BS), a low-noise nonlinear $\chi^{(3)}$ interaction that preserves quantum coherence [4]. Our setup, shown in figure 1 (left) utilizes two pumps, respectively a 1552 nm CW laser and a femtosecond passive modelocked fiber laser, to magnify a broadband signal at 1278 nm, while translating to 1284 nm idler wavelength. Signal and idler are separated using fiber wavelength demultiplexer, and filtered of the pump noise and detected on superconductive single photon detector [5]. The efficiency of the conversion is measured using a tunable CW-probe, and is larger than 70% over a 6nm- range centered at 1278 nm.

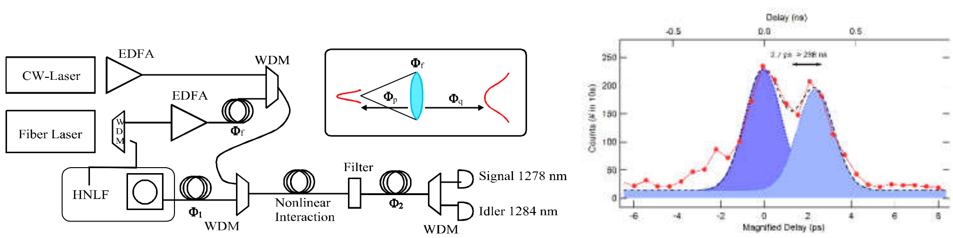

Fig 1. Left side: Experimental setup. Right side. Two weak pulses (<0.1 photon per pulse), separated by 2.7 ps, are magnified by a 105x factor and temporally resolved. Red dots: experimental measurement. Blue filled curve: fit result.

The signal is a 2-picosecond weak coherent state generated from part of the supercontinuum amplification of the pump modelocked laser. The pulse is duplicated using an unbalanced interferometer and synchronized to the time-lens. The temporal separation is measured accurately using an intensity autocorrelator. All fields, pump, signal and idler, are dispersed using appropriated fiber length to produce a magnification factor of 105%.
In figure 1 (right) we show the temporally resolved pulses, that appear to be separated by 286 ps. Because of the large dispersion, both unconverted signal and the broadband residual technical noise is temporally spread and do not affect the measurement.
In conclusion we demonstrated a time-lens setup that can operates on quantum states that can supports sub-ps resolution. The system can be used to probe ultra-short temporal correlations proper of time-entangled photon pair, as well as to measure extremely weak events on timescales unachievable with current detection technology.

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#154

Using an effective-medium approach for designing superconducting nanowire single-photon detectors

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Superconducting nanowire detectors are an important resource in quantum information science because of their high detection efficiency, low dark count rates, and high saturated detection rates. To detect optical and infrared photons, the nanowire is necessarily sub-optical-wavelength in dimension and must be meandered back and forth to increase the active area of the detector, leading to a grating structure across the illuminated area. Frequently, the nanowire is embedded in an optical cavity to increase the photon absorption. Optimizing the design of these devices often requires numerical simulations of the optical cavity, which can be quite time consuming because of the need to model accurately the electromagnetic properties of the sub-wavelength nanowire grating. Here, we show that the planar layer containing the grating is accurately modeled as a homogenous thin film characterized by an effective-medium complex index of refraction. For incident transverse-electric (TE) polarized radiation we find the simple analytic expressions of Rytov [1] and Lemercier-Lalanne [2] to be reliable. For transverse-magnetic (TM) polarized radiation, the effective index is determined using rigorous coupled-wave analysis using freely available software [3]. This value may then be used to predict the optical properties of candidate cavities using homogeneous-film propagation methods. We compare our effective-medium results to the predictions of the rigorous coupled-wave analysis for the absorption in a recently-studied superconducting nanowire detector [4] over a wide wavelength range as shown in Fig. 1 and find excellent agreement between the predictions for both TE and TM waves [3]. Such an approach greatly facilitates optimizing the design of detector optical structures.

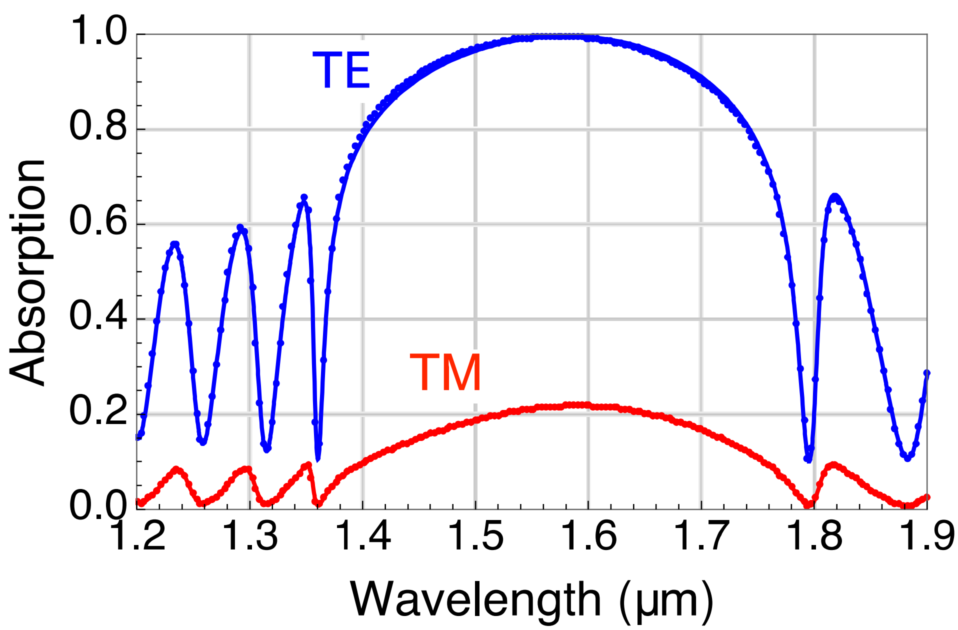

Fig 1. Effective medium refractive index model (continuous) and full numerical solutions (dots) for the structure studied in Ref. [4].

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#155

Studies of single-photon emission from hexagonal boron nitride

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Studies of localised, excitonic states in monolayer semiconductors recently revealed that defect-bound excitons can act as single-photon emitters.[1,2] Hexagonal boron nitride (hBN) is one of many van der Waals (vdW) crystals recently emerging as host to single photon emitting defects. Unlike other vdW crystals such as transition metal dichalcogenides (TMDCs), hBN shows promise as a source of single photons in both bulk and monolayer at room temperature[2]. hBN is host to many optically-active defects due to its large bandgap (~6 eV)[3]; however, the exact nature of the defects and physical processes which give rise to their luminescent properties are largely unknown, and their study is the focus of this work.

Mechanically exfoliated flakes of hBN down to monolayer thickness were fabricated and studied using atomic force microscopy (AFM) and photoluminescence (PL) spectroscopy. AFM height profile analysis was used to identify monolayer samples and the thickness confirmed with Raman spectroscopy. Thermal annealing in argon at 850ºC for 30 minutes was used to create stable emitting defects.

Using laser excitation at 532 nm, sub-bandgap defect states in hBN samples have been probed and identified from their photoluminescence spectra. Our findings suggest that a number of different defect zero-phonon lines (ZPL) present across a wide spectral range (~1.6-2.3 eV). A custom-designed confocal microscope has been constructed for optically exciting the samples and collecting the emission, which can then be sent to a Hanbury Brown-Twiss (HBT) interferometer to measure the second-order correlation function, $g^{(2)}(t)$. AFM, PL and HBT measurements will be presented, together with analysis towards understanding the observed emission.

Further studies are planned with ultrafast laser pump-probe measurements to identify the physical processes governing the kinetics of excitons, from generation to radiative recombination. It is hoped that the result of this comprehensive study will improve our understanding of the physics underlying the single-photon emission in hBN.

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#156

Absolute calibration of single-photon detectors using a multi-element transmission-trap attenuator and switched-integrator amplifier

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Abstract. A method for implementing the absolute traceable calibration of the detection efficiency of free-space-coupled single-photon detectors with incident sub-fW photon fluxes has been implemented at NPL and CMI. The core element is a multi-element silicon tunnel trap (MET) [1] that provides a fixed attenuation of 5 to 6 orders of magnitude with very low beam distortion.

A collimated and polarized laser beam is incident on the input aperture of the MET, which is mounted to allow horizontal, vertical and angular adjustments. When properly aligned, the MET preserves geometrical properties of the beam such as collimation and beam profile, while providing an attenuation that can range from 5 to 6 orders of magnitudes depending on the laser wavelength [1]. The attenuated transmitted beam can then be focused with a lens onto the sensitive area of the single-photon detector to be calibrated (DUT). The DUT and a calibrated reference detector, the Low Photon Flux standard detector (LOFD) [2] [3], are mounted on a motorized linear stage. The DUT and LOFD are also positioned on precise 2D motorized stages which allow automated measurement of the spatial uniformity of both detectors, thus locating the spatial plateaus of their quantum efficiency.

The MET is used as an uncalibrated attenuator with a linear response. The photocurrent induced by the input beam to the MET is measured using a calibrated switched integrator amplifier [4] equipped with a 100 pF integration capacitor that can vary the I/V conversion factor from 1e7 to 1e10. For an input laser power around 1μW the transmitted beam power can be measured with the LOFD with an uncertainty below 0.1%.

In order to reach the low photon flux required by the DUT (typically of the order of a few tens of fW) the input laser beam power is then reduced to the level of a few nW. The power at the DUT is then derived by measuring the reduction in input power measured by the MET. When set to the highest sensitivity the SIA can measure the MET photocurrent with a noise level of approximately 100 fA/Hz^{½}. This low noise level allows the photon flux impinging on the DUT to be calculated down to a fraction of a fW with an uncertainty below 1%. For photon fluxes above 50 fW the DUT and the LOFD can be alternately illuminated by the transmitted beam, providing an extra cross-check on the power incident on the detector, and the stability of the MET alignment. Results confirmed the excellent noise performance of the LOFD: power levels as low as 20 fW at 850 nm have been measured with a noise to signal ratio below 3% using a measurement time of 80 s.

This method has been implemented in facilities constructed at NPL and CMI. A three-element trap detector can be mounted on the translation stage to provide SI traceability; this can then be used to calibrate the LOFD at the approximately nW level of the output beam of MET. The set-up and performance of the facilities at NPL and CMI will be described, illustrated by data obtained in calibrating a single-photon detector.

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#157

Towards the Integration of Single Photon Source and Cesium Based Quantum Memory

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Towards the implementation of a quantum repeater for quantum communications applications, we have developed a quantum memory system and compatible single photon pair sources. The quantum memory is based on Electromagnetically Induced Transparency (EIT) using a Cesium atomic ensemble as the memory medium. Combinations of several filtering schemes greatly reduce the noise in the memory system so as to be suitable for single photon level storage and retrieval. To satisfy the linewidth and wavelength requirement for integration with the quantum memory system, we have developed two types of narrow linewidth single photon pair sources working at the D1 transition line of the Cesium atom. The first source, a cavity enhanced SPDC source is locked to the peak of a Doppler-free Cesium transition and generates greatly non-degenerate (895 nm and 1310 nm) photon pairs with a linewidth of 50MHz separated by a cavity free spectral range of 5GHz. A second source is based on a high-Q micro-resonator producing slightly non-degenerate (near 895 nm) narrow linewidth FWM pairs with a pump locked to the side of a Doppler-Free Cesium transition. Ongoing work is the integration of the sources and the quantum memory.

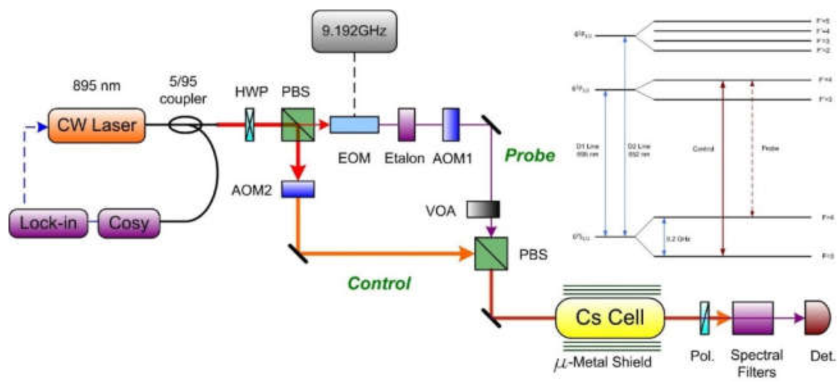

Figure. 1. Quantum Memory setup.

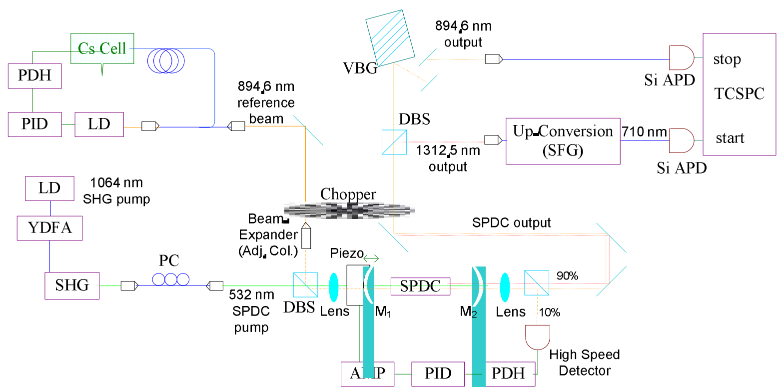

Figure. 2. Narrow linewidth non-generate SPDC photon source

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#158

High-Rate Quantum Key Distribution using Time-bin Qudits

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Development of scalable quantum computer is a rapidly expanding area of research in quantum information science. With many commercial companies working towards building quantum computing platforms, a medium scale quantum computer capable of carrying out tasks superior to classical computers may be only a few years away [1]. Advances in quantum computing technology poses a long-term threat to current crypto systems, such as the Rivest, Shamir and Adleman scheme (known as the RSA) [2]. One approach for quantum-safe secure communication is quantum key distribution (QKD), a technique that allows provably secure transmission of a cryptographic key between two users. A major limitation of most current QKD systems is that the rate at which the key is transmitted (within metropolitan distances) is orders-of-magnitude smaller than digital communication rates. One possible solution to increase the secure key generation rate involves encoding information in a high-dimensional (dimension d) state space of a photon. High-dimensional encoding offers a promising platform to overcome some of the practical limitations of QKD systems, such as the long recovery time of single-photon detectors, or large noise in the quantum channel. In an effort towards making QKD more viable for practical commercial use, we present a discrete-variable time-bin qudit ($d>2$)-based QKD system that can transmit a secure key between two parties at a rate of megabits-per-second (Mbps) over metropolitan distances (up to ~80 km). To secure the time-bin quantum states, we generate and detect mutually unbiased basis states in the frequency domain, which allows us to place a tight bound on the amount of information leaked to an eavesdropper. Our system is built using commercially available off-the-shelf equipment, including a multiplexed detection scheme consisting of high-efficiency (>70%), low-jitter (<40 ps) superconducting nanowire single-photon detectors for measurements in the temporal basis. In addition, we also provide a finite-key security analysis taking into account various experimental non-idealities. With these advances, we achieve record-setting secret key rates of 26.2, 11.9, 7.71, 3.40 and 1.07 Mbps with channel losses of 4, 8, 10, 14 and 16.6 dB, respectively, corresponding to transmission distances of 20, 40, 50, 70 and 83 km in standard telecommunication optical fiber.

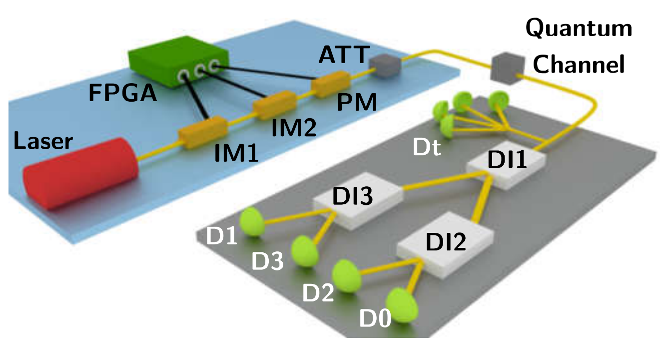

Fig 1 Schematic Illustration of Experimental Setup: Alice modulates the phase and intensity of a continuous wave laser to create the $d = 4$ time-phase states. Bob uses a 90/10 beamsplitter to direct 90% (10%) of the incoming photons for time (phase) basis measurement. Both the time and phase basis measurement devices are coupled to four superconducting nanowire single-photon detectors.

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#159

Quantum state tomography by photon-number-resolving measurements

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Photon-number-resolving detection (PNRD) allows the direct measurement of the Wigner quasi-probability distribution of an optical mode at the origin of the phase space, and quantum state tomography can then be achieved by displacing the state so as to scan that phase space [1]. The PNR detection method thus circumvents the need for numerical tomographic reconstruction of the state with the balanced homodyne detection method. Using superconducting transition-edge sensors, which resolve up to five photons at 1064 nm, we previously demonstrated quantum tomography of a pure coherent state, and phase-diffused mixture of coherent states [2]. We report here on our progress toward the more challenging quantum tomography of non-Gaussian pure states by PNRD, for which the importance of the detection efficiency is crucial.

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#160

Quantum non-Gaussian light: a compass for experimental Fock states

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Generation of Fock states of light is a considerable experimental challenge, chiefly due to noise and inevitable optical loss. There are some established measures of quality that generally rely on recognizing quantum aspects of ideal Fock states. Prominent among these are nonclassicality (Fano factor, $g^{(2)}(0)$), Wigner function negativity, and quantum non-Gaussianity (QNG) [1-3]. In this contribution, we review the significance of QNG for both single-photon and multiphoton Fock states, we present experimental verifications and recent development in recognizing multiphoton light.

QNG is a quantum property of Fock states that can be directly witnessed using multiplexed binary detectors [4]. It is a necessary condition on the way towards perfect Fock states. Compared to nonclassicality, it is not as easily achieved. Single-photon and multiphoton states have already been produced and proven to be nonclassical, which typically does not change with virtually any amount of optical loss introduced to these states. On the other hand, negativity of the Wigner function is extremely sensitive to both noise and loss, and has been only demonstrated for Fock states up to $|3\rangle$. On an experimentally simulated ensemble of up to 9 single-photon emitters, we demonstrate that practical noisy multiphoton states exhibit QNG that can be detected in the laboratory [4].

The practical benefit of QNG lies in experimental development of Fock states. On this path, it is eventually necessary to pass all the necessary conditions that concern ideal Fock states. Satisfying these conditions on a true/false basis is an objective way of navigating through all the experimental imperfections. Among these conditions, there is a large gap between two quantum features - nonclassicality and negativity of the Wigner function. We offer a middle ground in the form of QNG, which is reasonably robust to optical loss: up to 30 dB in case of single photons [2].

This maximum tolerable loss, called QNG depth, can also serve to recognize the number of single-photon emitters. In our experiment, the measured light represents a simulated collective emission of a group of noisy single-photon emitters that are identical and independent. The QNG depth exhibits a clear dependence on the number of such emitters, which suggests a new direction for distinguishing individual single-photon emitters based on their collective emission.

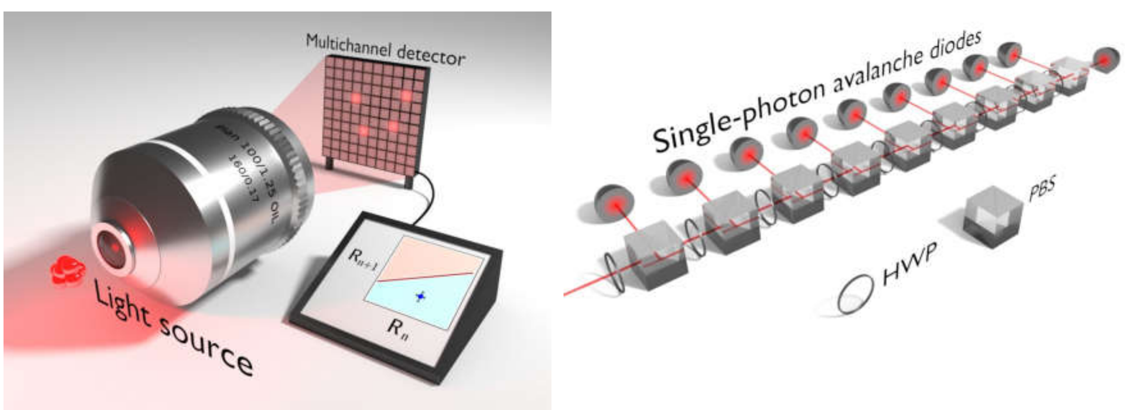

Fig 1. Left: Multiphoton light is collected and brought to a balanced multichannel detector, where coincidences R_n, R_{n+1} are compared to the QNG threshold. Right: the multichannel detector consists of a network of polarizing beam splitters (PBS) and half-wave plates (HWP) that evenly split the incoming signal to $n+1$ single-photon avalanche diodes.

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#161

Testing the limits of human vision with quantum states of light

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We present our progress using a single-photon source designed for human vision experiments to study various aspects of the visual system, including temporal summation, single-photon detection, and the interaction between neural activity and visual detection. The rod photoreceptors in the retina are known to be sensitive to single photons [1], but it has long been debated whether these single-photon signals propagate through the rest of the visual system and lead to perception. Previous research on single-photon vision was limited by the statistics of classical light, but true single-photon sources now enable direct tests of single-photon vision [2]. We use a forced-choice experimental design in which observers are presented with a single photon (or other visual stimulus) on the right or left side of the retina at random, and must indicate where they think the stimulus appeared. If observers can see the stimulus, their accuracy should differ from the chance value of 50%.

Single-photon source. We use a well-known method of producing heralded single photons by spontaneous parametric downconversion. Ultraviolet laser photons enter a nonlinear (BBO) crystal, where some of them split into pairs of lower-energy daughter photons; detecting one daughter photon heralds the presence of its partner [3]. The wavelength of the signal photons is chosen to be 505 nm, at the peak of the rods' spectral sensitivity. Each herald detection activates a Pockels cell and allows one signal photon to pass through a polarizer, blocking any unheralded photons. A half-wave plate is used to switch heralded signal photons between two fibers so they can be sent to the left or right side of an observer's retina. The pump laser is shuttered after a predetermined number of herald photon detections (1 for single-photon trials, or N to generate multiple photons).

Single-photon vision test: preliminary results and outlook. As an experimental proof of principle, we have shown that observers can achieve an accuracy of 54.2 ± 0.8% in forced-choice trials with a mean of 37 photons at the cornea. Due to the low efficiency of the eye (5-10%) and the heralding efficiency of our source (~38%), the expected accuracy in single-photon trials is much closer to the chance value; additionally, observers may not always "notice" a rod signal when it is present. Monitoring the observer's brain activity with EEG may present a way to enhance detection probabiliy. Previous work has found that in a short window before a visual stimulus is presented, the amplitude and phase of the alpha wave can predict whether observers will subsequently detect the stimulus [4,5]. Preliminary results suggest that this alpha-wave effect may also be observed in our experiment, and we are developing a real-time EEG-contingent stimulus presentation method to deliver photons at the subject's most attentive moment.

Temporal summation in visual detection. A key feature of visual processing is the summation of signals that arrive at different times. We measured the integration time of the eye (the period over which incoming signals are summed) for 11 volunteers, using our source to produce stimuli with varying durations and numbers of photons. The average integration time was found to be approximately 650 ms, much longer than previous measurements (~100 ms) at higher light levels. We also found significant variation between individuals (with integration times ranging from 400 ms to >960 ms).

Can people see single photons? A recent study by Tinsley et al. [6] used a similar single-photon source and forced-choice experimental design to test whether people can see single photons, and claimed to show that they could. However, our analysis of the data from this study suggest that the strongest evidence for single-photon vision—the measured accuracy in a small subset of trials rated "high confidence" by the observers—is not consistent with other data from the experiment, and is more likely to be an experimental artifact. This study also had a critical lack of statistical power for the expected effect size, demonstrating the importance of collecting a very large number of single-photon trials. Inappropriate statistical analysis (one-tailed tests without *a priori* knowledge of the effect direction) also distorted the significance of the measured accuracy among all trials. We argue that a conclusive test of true single-photon vision is still needed.

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#163

Improvement of Diffuse Correlation Spectroscopy sensitivity to brain through Time-Correlated Single-Photon Counting technique

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Diffuse Correlation Spectroscopy (DCS) is a near-infrared spectroscopy (NIRS) technique able to measure an index of microvascular blood flow (BF_i) [1]. A long-coherence light source is fed into the tissue while a single-photon detector collects the light from a single speckle spot and tags the photon arrival. By computing the autocorrelation function of the detected light, DCS measures the temporal speckle fluctuations due to the moving scatterers in tissue (blood cells). A limitation of DCS is the requirement of an accurate knowledge of the tissue optical properties to precisely compute BF_i. Therefore, a DCS device is usually paired with time-domain (TD-) or frequency-domain (FD-) NIRS systems to measure absolute BF_i [2]. A second limitation is the low light detected from a single speckle, especially when measuring cerebral BF_i (CBF_i), due to the large source-detector separation needed to reach the brain.

Our novel approach, Time-Domain Diffuse Correlation Spectroscopy (TD-DCS) aims at merging DCS with TD-NIRS in a single instrument [3]. The idea is to measure simultaneously the optical properties of the tissue as well as temporal speckle fluctuations, but also to take advantage of the time-domain information to discriminate between short and long photon paths to perform DCS processing only on photons that travelled deep in the tissue, increasing the sensitivity to the brain. This discrimination allows to shorten the source-detector separation, increasing the signal-to-noise ratio.

We present a TD-DCS system suitable to become a convenient, continuous, and reliable bedside measure of cerebral blood flow. As shown in Fig.1, the system employs a picosecond pulsed laser source that is able to provide 100-200 ps full-width half-maximum pulses with enough coherence length to performe DCS measurements. In addition, to acquire multiple simultaneous light paths, we utilized 4 Red-Enhanced single photon avalanche diode (SPAD) detectors which combine high-temporal resolution (50 ps FWHM) with high photon detection efficiency (25%) in the near infrared range. We also designed a custom FPGA-based board to host time-correlated single photon counting cards (TDC-cards) used for measuring the time of flight (ToF) of individual photons with 10 ps resolution. The FPGA then pairs the ToF information with the absolute photon arrival times, measured by an internal counter locked to the laser clock. The ToF histogram is called temporal spread point function (TPSF). A validation with a two-layer phantom is showed in Fig. 2, comparing the autocorrelation function of two groups of photons: the first one uses the light that travelled close to the surface, while the second one uses the light that travelled about 5 cm further (i.e., 300 ps after the peak of the TPSF curve). As expected, the resulting BFi in the superficial layer ($0.9 \cdot 10^{-9}$ cm^2/s) is lower than the one in the deeper layer ($3.8 \cdot 10^{-9}$ cm^2/s).

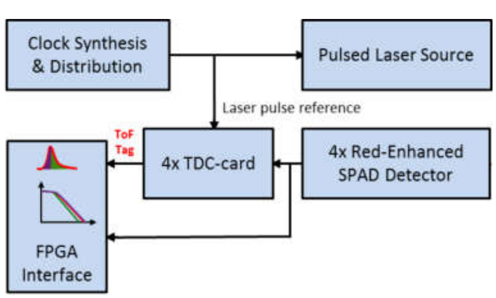

Fig. 1: Block diagram of the TD-DCS system.

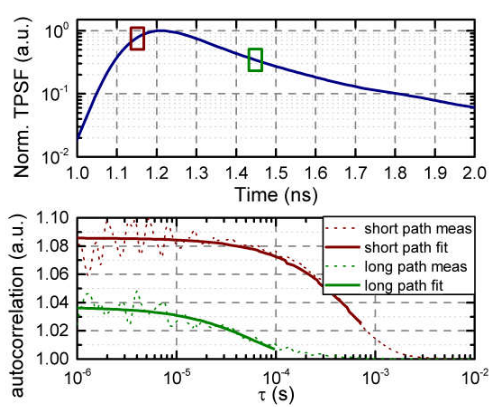

Fig. 2: Validation of TD-DCS approach by computing DCS processing on two groups of photons, selected by the TPSF data.

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#164

Molybdenum Silicide Thin Film Optimization for High Efficiency Superconducting Nanowire Single-Photon Detectors

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The high efficiencies in Superconducting Nanowire Single-Photon Detectors (SNSPD) achievable with amorphous superconductor materials such as WSi [1] and MoSi [2] are due to both the intrinsic photon detection mechanism, as well as the amorphous structure of the material. The smaller superconducting gap energy and lower carrier density in lower superconducting transition temperature (T_c) materials, such as WSi, compared to higher T_c materials, such as NbN, are believed to induce a larger size of the photon-induced perturbation of the superconducting state leading to saturated internal detection efficiency [1]. The amorphous structure implies a homogeneously disordered material which proves to be more robust to structural defects allowing for fabrication of larger area devices. Moreover, the amorphous structure is more forgiving on the substrate choice as well as allowing for easier optimization of optical absorption through integration in multilayer optical structures.
In this study we are investigating the optimization of MoSi thin films for the highest T_c corresponding to an amorphous structure, as a function of sputtering deposition conditions through a design of experiment approach. One of the challenges that needs to be overcome for T_c optimization of amorphous MoSi thin films, is the thickness-induced crystallization during sputter deposition of nanoscale MoSi films [3]. We present measurements of T_c as a function of deposition conditions and film thickness, as well as X-Ray Diffraction (XRD) analysis for thin films phase identifications and X-Ray Reflectivity (XRR) for thickness measurement.

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#165

Temperature Dependence of the Kinetic Inductance in a WSi Superconducting Nanowire Single-Photon Detector

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Developing detectors for efficiently measuring single photons is of great interest to applications in quantum information science. One appealing platform is superconducting nanowire single-photon detectors (SNSPDs). Here, single-photon absorption causes a region of the nanowire to transition to the normal state, which is sensed by passing a small current through the device [1] and reading out this current with a low-noise circuit. For many applications, including high-rate quantum key distribution, crucial detector characteristics are low timing jitter and high detector saturation rate. Both of these depend on the kinetic inductance (L_k) that arises from the ballistic motion of Cooper pairs through the nanowire. For higher values of L_k, the timing jitter increases while the saturation rate decreases. Recent work has highlighted the fact that L_k diverges when the nanowire is warmed to the superconducting critical temperature (T_c) [2]. Therefore, it is expected that the timing jitter and the detector saturation rate will be negatively impacted by operating SNSPDs at temperatures near T_c due to increased L_k. Here, we measure the temperature dependence of L_k in a WSi SNSPD [3], as shown in Fig. 1, by fitting the falling edge of measured single-photon pulses for various temperatures. As seen in the figure, our results are consistent with theoretical predictions for the temperature dependence of L_k. Over the range of temperatures that we investigate, we observe a doubling of L_k at 2.8 K vs. at 800 mK, which corresponds to halving the detector saturation rate. Thus, this work has important implications for operating SNSPDs at higher temperature as well as for developing novel superconducting devices.

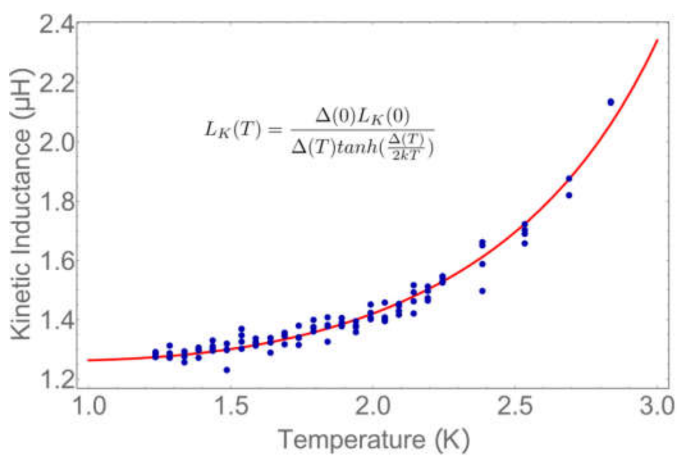

Fig 1. Temperature dependence of the kinetic inductance measured via our experiment (blue points) and predicted by theory (read curve). The theoretical expression for the kinetic inductance is given in the inset.

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#166

Digital Delay Optical Quantum Memory

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Abstract: Current quantum memory systems can achieve somewhat high efficiency but with narrow bandwidth [1], or lower efficiency and shorter storage over somewhat broader bandwidths [2]. Here we develop a system with multiplexed free-space storage cavities, able to store single photons with high efficiency over variable delays [N x 12.5 ns, $1 \leq N \leq 999$], and bandwidths exceeding 10 nm. We have demonstrated transmission > 10% for delay times up to 12.5 μs.

Using high quality mirrors a and meter-scale delay line, it is relatively straightforward to achieve low-loss fixed quantum storage; by combining this with an optical "switch" (e.g., a Pockels cell and a polarizing beamsplitter), we can create a variable time delay. However, this switch comes at the cost of much higher loss in our setup, as the Pockels cell contributes a ~3% loss. In order to minimize the use of the lossy switch, we combine three different optical delay lines, corresponding to optical delays of 12.5 ns, 125 ns, and 1.25 μs (shown in **Fig. 1a**); for example, in order to store for 537 12.5 ns intervals, we use the short/middle/long delays for 7/3/5 cycles, limiting our pass through the lossy switch to 15 times (instead of the 537 necessary if just a single 12.5-ns delay were used. The loss is exponentially reduced, as shown in **Fig. 1b.** In addition, to make our scheme polarization independent, we incorporate a polarization to time-bin transducer so that we can convert and store polarization qubits.

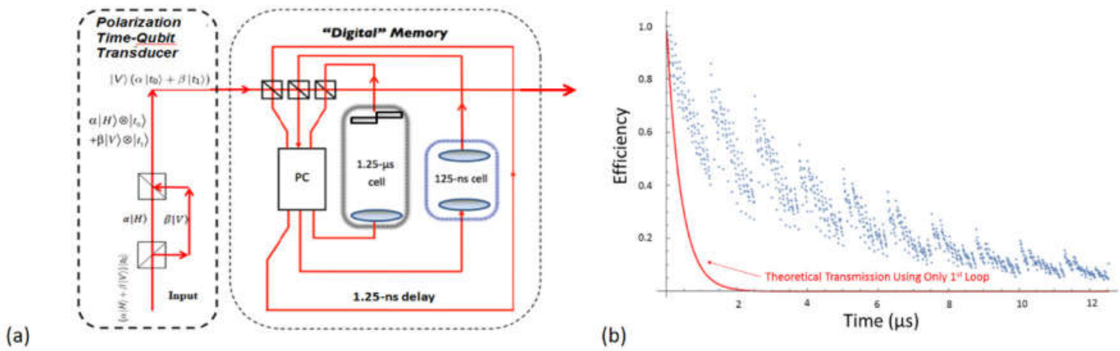

Fig 1. (a) Schematic of digital quantum memory, combined with polarization-time-qubit transducer. **(b)** Storage efficiency versus time, including the theoretical transmission curve if one were to only use cycling of the shortest delay line.

In addition to high transmission, our quantum memory also benefits from a much larger bandwidth than many quantum memory storage systems. In our largest delay line (1.24 μs), we have measured 85% transmission at a bandwidth $\geq$ 10 nm, and our Pockels cell itself should theoretically be able to achieve 97% transmission with $\Delta\lambda = 76$ nm. Thus we potentially have a time-bandwidth product exceeding 2.4 x 10^7, orders of magnitude higher than most other approaches. We have measured a fidelity of 0.9783 $\pm$0.0015 for the transducer alone, and are currently working on incorporating the transducer into the quantum memory setup. We also look to test our setup with spatial mode and time-bin qubits, demonstrating successful storage of single photons from downconversion, as well as hyperentangled photons.

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#167

Characterization of a waveguide SPDC source for nondegenerate polarization entanglement

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Current research into the use and improvement of integrated optics for optical quantum information processing provides insight into the exciting future of small and stable quantum devices. For our purposes, channel waveguides on a periodically poled KTP (PPKTP) crystal [1] allow us to create a relatively robust and compact highly nondegenerate Spontaneous Parametric Down-Conversion (SPDC) source. The SPDC process within the waveguide produces polarization-entangled signal and idler photons at 1550 nm and 810 nm, respectively. The polarization-entanglement is created within the waveguide where either H→HV or H→VH type-II polarization correlation can take place (Fig. 1). The signal and idler photons are then separated by wavelength using a dichroic mirror. Our intended application of the source is to implement a superdense teleportation (SDT) protocol between the International Space Station and collection telescopes on Earth [2, 3].

Quantum communication protocols over long distances require high photon count rates and excellent heralding efficiency. These metrics become even more critical when sending information from Earth's orbit. To verify that the design of our waveguide source is suitable for such application, we are working on precise characterization of each of the 22 waveguides on the crystal, which includes measurement of the insertion loss, SPDC count rates, wavelengths and bandwidths of the signal and idler photons, joint spectral intensity, fidelity of the polarization-entangled state, and heralding efficiency. The complete characterization of the waveguides on the crystal will then provide feedback on how to improve the physical design to create an optimized SPDC source for the SDT protocol.

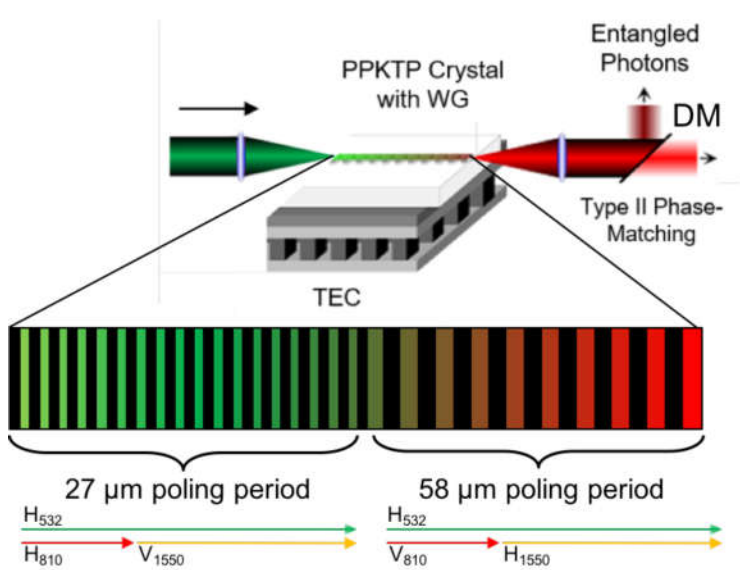

Fig 1. Schematic of waveguide SPDC source. 532-nm light is focused into the waveguide (WG) where it then down-converts into signal and idler photons. A dichroic mirror (DM) then separates the 1550-nm signal photons from the 810-nm idler photons. The different poling periods allow two type-II phase-matching processes to occur, producing nondegenerate polarization entanglement.

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#169

Frequency Multiplexed Single-Photon Sources

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Heralded single photon sources based on parametric down conversion (PDC) are a standard tool for experiments in quantum optics and quantum information. However, the probabilistic nature of PDC sets the fundamental limit on the emission of single photon pairs at 25%. In practice this is further restricted to a few percent in order to supress the emission of higher order photon number states. Multiplexing strategies, where the emission of several independent heralded sources can be routed into a single mode, in principle can be used to achieve an arbitrarily large probability of delivering a single photon. Progress has recently been made multiplexing sources in distinct spatial and time bin modes [1]. Here we consider a complimentary approach, frequency multiplexing, which takes advantage of the inherent spectral structure of PDC by using several frequency modes in a single non-linear interaction as independent sources [2, 3, 4]. Unlike spatial and temporal multiplexing, the mode number can be increased without a corresponding overhead in physical components or operating time.

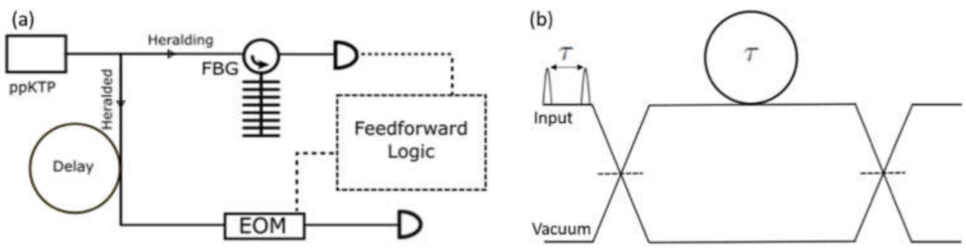

Fig 1. (a) Schematic of the frequency multiplexing setup (see text for details). (b) Unbalanced Mach-Zehnder interferometer for interfering photons in consecutive time bins. The relative delay (τ = 100 ns) between the two arms is equal to the repetition period of the source.

We demonstrate a frequency multiplexing scheme (Fig 1 (a)) with continuous frequency control and a number of components independent of the number of modes. Highly correlated photon pairs are generated by pulsed type-0 PDC in a periodically poled KTP waveguide. The heralding photon is spectrally resolved using a time of flight spectrometer constructed using a highly dispersive fibre Bragg grating (FBG) [5]. Feedforward logic is used to shift the heralded photon into a central frequency mode based on the spectrally resolved measurement of the herald. Frequency shifting is achieved by applying a linear temporal phase to the heralded photon using an electro optic modulator (EOM) driven by a time varying voltage synchronised to the photon arrival time [6]. We show that multiplexing several frequency modes increases the probability of single photon production without increasing higher order state emission.

The standard method for assessing the purity and indistinguishability of photons from independent sources is via two-photon interference on a beam splitter. We discuss interfering photons in subsequent temporal modes to characterise the purity of our source. We use an in-fibre, unbalanced Mach-Zehnder interferometer where the relative delay on one arm is equal to the repetition period of the source (Fig. 1 (b)). In this way, photons originating from distinct frequency modes probabilistically interfere, thereby allowing the photon quality from the multiplexed source to be assessed.

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#170

Photon counting detector with sub-picosecond passive stabilization of detection delay

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The theoretical principle and experimental results of passive temperature stabilization of detection delay of single photon avalanche detector will be presented. The resulting detection delay is constant with sub-picosecond precision in selected temperature interval. The passive solution is intended for a space segment of single photon detection for picosecond optical time transfer.

Together with detection efficiency and timing jitter, the interesting parameter of single pixel SPAD is its internal delay. The absolute value of delay between incoming optical impulse (photon absorption) and electrical signal output from detector is an additive constant in the most of photon counting experiments and it is not taken into account. But if it is unstable, then it can seriously decrease a timing properties of detector. Reasons of the instability can be in temperature changes (both detection chip or control circuit) or e.g. in relative position of photon absorption in active area, if the detector is position sensitive. We are focused on temperature changes and from them on a special situation when active temperature stabilization of detection chip cannot be used.

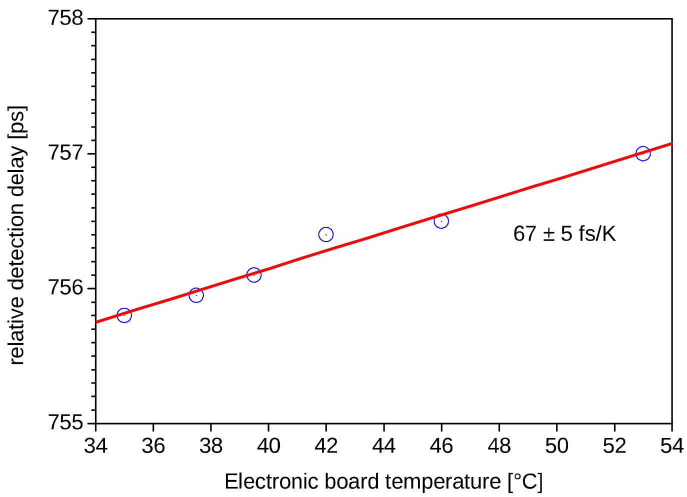

Fig 1. The photon counting detector detection delay as a function of control electronics board (active quenching and gating circuit) temperature. In contrast with presented results, in this case the detection chip itself temperature was actively stabilized at −60 ± 0.1 °C. [1].

Usually, the temperature stabilization is realized by an active, typically thermoelectrical, stabilization of detection chip, and the control circuit have a passive compensation of temperature drifts. We will demonstrate, that with proper over-compensation of control circuit the entire detector delay can be stabilized for selectable temperature interval of few Kelvins. The motivation for completely passive solution is a utilization of SPAD for laser time transfer in space missions. In considered application we are looking for minimal power consumption and robustness of detector package.

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#171

Cryogenic Amplifiers for a Superconducting Nanowire Single Photon Detector System

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Superconducting nanowire single photon detectors (SNSPD) provide one of the leading solutions for high performance detection systems in quantum information and communication applications. Here we describe the design and performance of cryogenic amplifiers that provide three critical advantages for SNSPD readout circuits: (1) the intrinsic amplifier noise can be reduced dramatically, improving the signal-to-noise ratio (SNR) and hence the timing jitter [1]; (2) placing the first-stage preamplifier close to the device provides flexibility to design the load impedance of the amplifier, which influences the maximum achievable count rate [2]; and (3) lower power consumption compared to commercial options enables multi-channel scalability. The main goal of our effort is to identify a readout circuit that minimizes timing jitter while maintaining high count rate capabilities, low cost and low power consumption. These characteristics have a significant impact on the speed and fidelity of quantum communication protocols such as time-bin encoded QKD [3].

Our most successful circuit uses a GaAs MMIC amplifier chip from Broadcom Limited (MGA-68563). Amplifier prototypes are assembled on patterned Rogers 4003C high-frequency printed circuit board with passive components selected for cryogenic compatibility. We compare our readout circuit to the high-performance cryogenic amplifier CITLF 3 built by Cosmic Microwave Technology, formerly part of the Microwave Research Group at California Institute of Technology, and commercial low-noise, room-temperature amplifiers (Miteq AU1310). These readout options are characterized in a detection system with an amorphous material SNSPD from Quantum Opus. This detector has kinetic inductance of 880 nH and critical current of 13 μA. Shown in Figure 1 are the measured jitter and maximum count rate results for each electrical readout. The CITLF 3 dissipates 22 mW of power. It has better timing resolution because of its superior bandwidth and SNR, but reduced maximum count rate because it is AC-coupled. Our GaAs scheme has a unique circuit design that enables high count rate capabilities with only a modest trade-off in detection jitter. This circuit achieves $<$ 40 ps timing resolution and count rates exceeding 20 MHz while operating at 3 mW power dissipation.

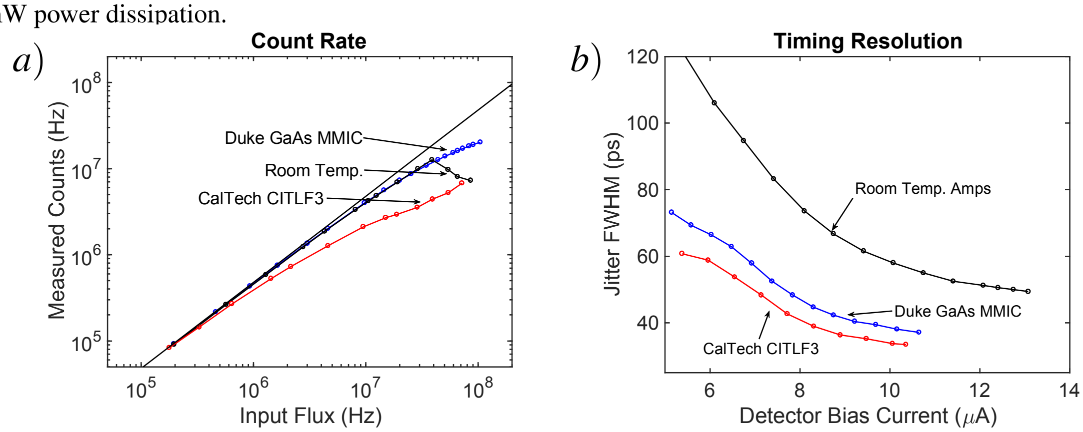

Fig. 1: **(a)** Measured count rate at 1550 nm as a function of input optical flux. Detection efficiency is given by the vertical position of the points. The black line shown is a fixed efficiency of 48%. **(b)** Detection jitter as a function of detector bias current for three different readout schemes - low-noise room temperature amplifiers, our GaAs MMIC circuit, and the CalTech CITLF 3.

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#172

Bragg cavities enhanced narrowband four-wave-mixing sources in UV-written silica

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Abstract: An integrable, narrowband source of heralded single photons is presented, based on four-wave mixing in silica waveguides enhanced and mode-shaped by a UV-written Bragg grating. Small-spot UV writing allows the spectral properties of the pump and daughter modes to be separately shaped, ensuring high separability of the two-photon state.

High-quality heralded single-photon sources are one possible avenue toward the generation large-scale photonic states for quantum information. Previously, we have shown [1] that we can fabricate arrays of 30 identical sources based on spontaneous four-wave mixing (FWM) in direct UV-written waveguides in silica. However, in order to escape contamination by broad-spectrum Raman noise the daughter photons must be split by several hundred nanometers, which makes handling the three beams difficult and often lossy, as well as complicating fabrication significantly.

Here we present a scheme whereby the three wavelengths are designed with only 200 GHz spacing between the signal, degenerate pump, and idler. All four photons involved in FWM are co-polarized, eliminating the need for the fabrication of a highly birefringent waveguide. The spacing is chosen such that standard dense wavelength division multiplexers can be used to separate the three beams. All three wavelengths are held in weak UV-written Bragg cavity, with the linewidth of the pump field approximately three times that of the daughter fields to ensure that the signal and idler photons' spectra are separable. This cavity is designed by inverse scattering techniques [2], where the reflection spectrum (Fig. 1) to defines the profile of a Bragg grating (Fig. 2). Our small-spot UV-writing technique [3] can fabricate an almost arbitrary apodisation profile, allowing us to fabricate this design in both optical fibre and planar silica-in-silicon waveguides, allowing for flexibility in the experimental design around the photon source.

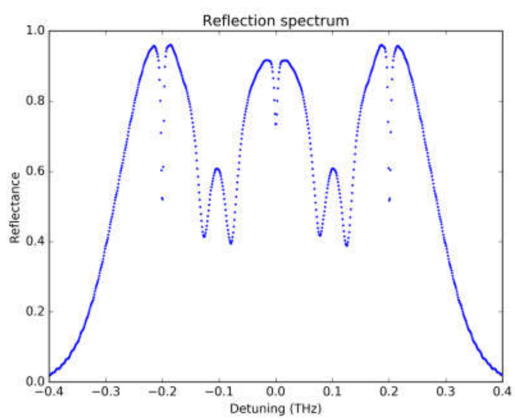

Fig. 1: Absolute value of the reflection spectrum. The dips at 0 and ±0.2 GHz are the cavities of interest.

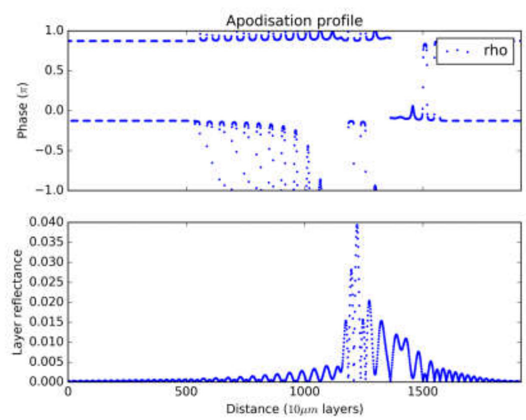

Fig. 2: Apodisation profile corresponding to Fig. 1. The high-frequency oscillation is due to beating.

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#173

Heisenberg-limited quantum interferometry with photon-subtracted twin beams

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In a classical interferometer, the vacuum fluctuations at the idle input port limit the phase difference sensitivity between the two interferometer arms to the shot-noise limit of the input beamsplitter [1]. When both input modes of the interferometer are properly "quantum engineered,"one can, in principle, reach the ultimate limit, called the Heisenberg limit [2]. We study a new type of quantum interferometer, based on an indistinguishably photon-subtracted twin-beam input. Such an interferometer can yield Heisenberg-limited performance while at the same time giving a direct fringe reading unlike the simple twin-beam input [3]. We propose a feasible experimental realization employing an optical parametric oscillator below threshold.

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#174

SNSPD integrators for neuromorphic applications

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Superconducting nanowire single-photon detectors (SNSPDs) have potential applications as elements in a neuromorphic hardware system based on integrated superconductors and optoelectronics [1]. In such a system, the SNSPDs would act as the synaptic elements, triggering when a photon is received from a neighboring neuron. In a biological neuron, these synaptic events are integrated in the neuron body and thresholded to determine when the neuron fires; however, this integrate-and-fire functionality is non-trivial to reproduce using solely SNSPDs. Although a single SNSPD can behave similarly to a single synapse, a hardware neuron must integrate hundreds or thousands of SNSPDs. In this work, we present a SNSPD integrator design which uses the 3-terminal yTron [2] to perform this integrate-and-fire functionality.

In this integrator, multiple SNSPDs are resistively coupled into the sense terminal of a readout yTron. The yTron is able to read out the SNSPDs because the critical current of a yTron's bias terminal depends on the input current to its sense terminal. When a SNSPD triggers, it diverts current into the yTron, reducing the critical current of the bias terminal. If enough SNSPDs fire in a given time period, it will reduce the yTron critical current enough to cause the yTron to generate an output pulse, thus producing the desired integrate-and-fire functionality. This design allows the neuron to have a tunable threshold level and integration time, and additionally produces zero static power dissipation. Beyond neuromorphic hardware applications, this SNSPD integrator may additionally be useful as a means of row and column readout in SNSPD arrays.

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Spatial Mapping of Optical Transition Edge Sensors Response

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Superconducting single photon detectors based on transition edge sensors (TES) are energy resolving detectors with extremely low noise and no dark counts [1]. Because they are energy resolving, TESs are uniquely positioned for non-dispersive imaging spectroscopy down to single photon level. Understanding and improving the energy resolution of a TES is a key parameter for wide range of applications including imaging spectroscopy and quantum optics. By using a strongly focused laser beam controlled in a cold scanning setup in combination with solid immersion lenses, sub-micron spot sizes can be achieved [2], to probe the spatial energy resolution in a micron-length TES detector. In addition, the cold scanning setup can enable study of proximity effects due to different TES wiring materials or noise mitigating structures.

At NIST we have successfully implemented an Attocube cold scanning setup inside a dilution refrigerator (DR). Figure 1(a) shows a photograph of the setup. The Attocubes are mounted on the 100 mK stage of the DR. An input fiber with grin lens assembly serves to direct the light onto the sample, mounted on the 10 mK stage of the DR. The TES can be located by scanning the Attocubes and illuminating the sample with 1550 nm light. The contrast between 1550 nm light interaction with different materials enables us to find the exact location of the TES. Figure 1(b) shows a scan of a 25x25 µm TES. The scanning setup will be described and preliminary data of mapping TES response in a cold scanning setup, will be presented.

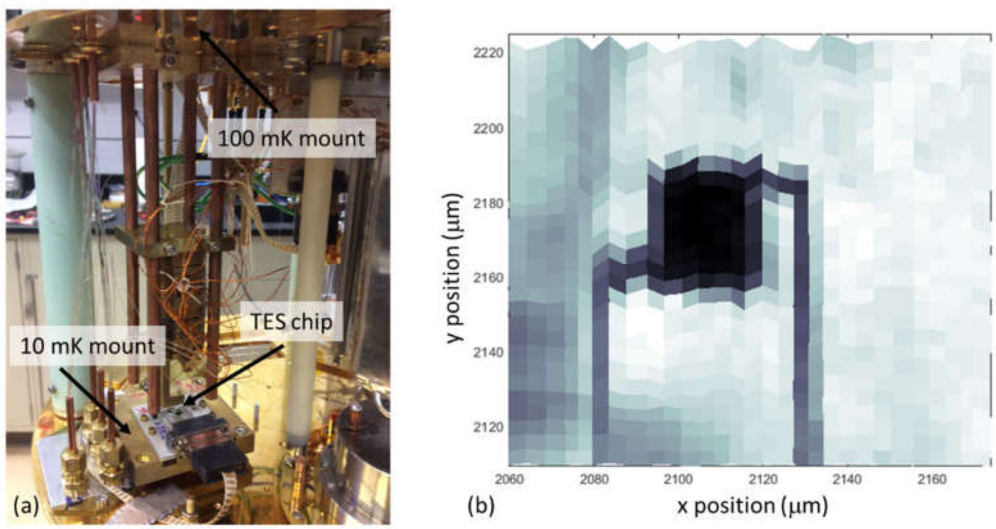

Fig 1. (a) A photograph of the Attocube scanning setup inside the NIST dilution refrigerator. (b) Scan of a 25x25 µm TES using an Attocube system.

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#176

Progress toward high-efficiency single-photon-level interactions in crystalline microcavities

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Abstract: High-Q whispering-gallery modes (WGMs) in crystalline microcavities can have very strong three-wave mixing. With a small enough cavity, even a single photon can have a strong effect. We show theoretically that a phase-matched nonlinear process can be driven by a single photon in a lithium-niobate cavity with a realizable diameter of 70 microns. This strong interaction can be used to create a deterministic source of anti-bunched light, as well as to implement a deterministic (non-maximally) entangling gate, among a great many other possibilities. We also present our experimental progress on the fabrication of small microcavities with radius < 100 microns.

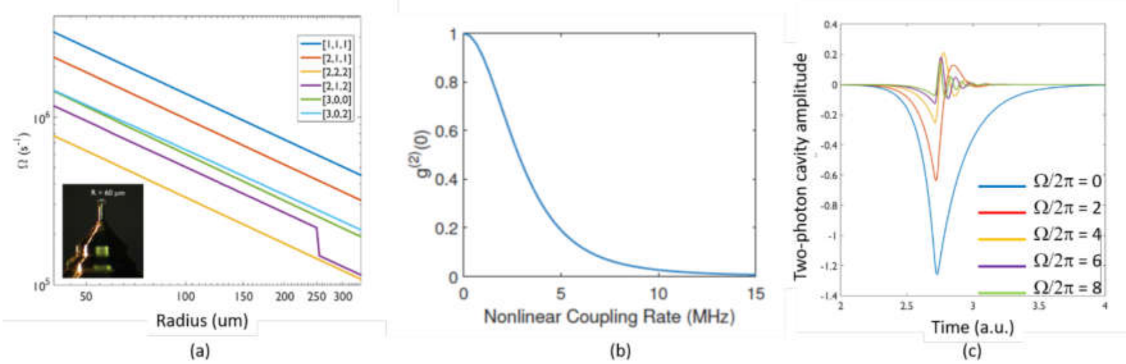

Figure 1: (a) Nonlinear coupling rate, Ω, is shown as a function of resonator radius. (b) The equal time autocorrelation function, $g^{(2)}(0)$, for the transmitted quantum state through a SHG phase-matched microcavity. (c) Following Ref. [4], multimode analysis is used to show that two-photon amplitude in a SHG phase-matched microcavity decreases significantly, yielding antibunched outputs.

Single-photon-driven nonlinear processes have been demonstrated with conversion efficiencies of only 10^{-6} in state-of-the-art optical waveguides[1]. High- finesse optical microcavities can enhance the material nonlinearity to the extent where only a few photons are required for deterministic wave mixing, stemming from a large cavity Q-factor and a small mode- volume. In Fig. 1(a), it is shown that MHz-level nonlinear coupling rates can be reached in periodically-poled lithium-niobate crystalline microcavities exploiting type-0 phase-matching for various radial orders of the WGMs in the interaction, e.g., the [1,1,1] curve is the mixing of the fundamental radial order modes for the pump, signal, and idler waves respectively. In combination with a Q-factor of $>10^8$, demonstrated in lithium-niobate microcavities[2], sub-millimeter-scale devices can support single-photon-driven nonlinear processes approaching 10^{-1} efficiencies, providing a 10^5-fold improvement over the existing state-of-the-art.

Considering specifically the case of strongly coupled second-harmonic generation (SHG) in such a microcavity, we show using a single-mode analysis[3], (Fig. 1(b)), that the transmitted state is antibunched. This is a manifestation of the quantum Zeno blockade, wherein, due to the strong nonlinear coupling, resonance splitting of the cavity mode at the fundamental frequency, ω, occurs for the two-photon state, causing its probability amplitude in the cavity to be significantly suppressed. In Fig. 1(c), using a multimode analysis[4] for the case of a waveguide-coupled microcavity, we show that for an exponentially rising pulse at ω, the two-photon state amplitude is suppressed by an order of magnitude for $\Omega/2\pi = 8$ MHz, achievable in a cavity of 30-micron radius (Fig. 1(a)).

As a first step toward realizing these phenomena experimentally, we have fabricated sub-100-micron radius lithium-niobate microcavities via diamond polishing[2] (Fig. 1(a), inset) with measured Q-factors reaching 10^6. With further improvements in fabrication, 10^8 absorption-limited Q-factors can be reached. Such strong coupling in microcavities can be used for antibunched emission of photon pairs[2] and to design deterministic single-photon-level quantum logic gates[3,4], providing a powerful alternative approach to optical quantum information processing.

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#177

A frequency multiplexed heralded single-photon source

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Abstract: We demonstrate a novel method for multiplexing single photons in the frequency domain. We use frequency translation via Bragg scattering four-wave mixing (BS-FWM) for active feed-forward switching of photons into a single frequency mode. We achieve a 180% enhancement in the heralded single photon rate, enhanced coincidences-to-accidentals ratio (CAR) and an improved $g^{(2)}(0)$ of 0.03, confirming that the enhancement does not come at the cost of additional multi-photon generation.

Deterministic single photon sources are fundamental to large scale implementations of quantum-enhanced technologies. Building sources that simultaneously satisfy stringent indistinguishability, brightness and fidelity requirements is a long standing challenge in quantum optics. Parametric sources based on nonlinear materials have been used for proof-of-principle demonstrations in quantum optics. However, the maximum heralding probability from these sources is fundamentally limited to 25% due to multi-photon generation. Active feed-forward switching of photons from multiple sources can potentially overcome these fundamental limits[1]. Recently, there have been a number of promising demonstrations of multiplexed sources using spatial and temporal modes[2,3]. However, the performance of these schemes is limited due to scaling losses in the switch when multiplexing a large number of modes.

Here, we demonstrate frequency multiplexing using three modes, where losses are fixed irrespective of the number of multiplexed modes. Our frequency multiplexing scheme is based on frequency translation using Bragg scattering four-wave mixing (BS-FWM), which has recently been demonstrated with close to unity efficiency using nonlinear fiber[4,5]. We use a broadband spontaneous parametric downconversion (SPDC) source to create three narrowband frequency channels and use tunable frequency conversion to route photons to a common frequency mode. Figure 1 shows our experimental results. Our measurements confirm that we achieve enhanced single-photon heralding probability for the multiplexed source at fixed multi-photon generation rates.

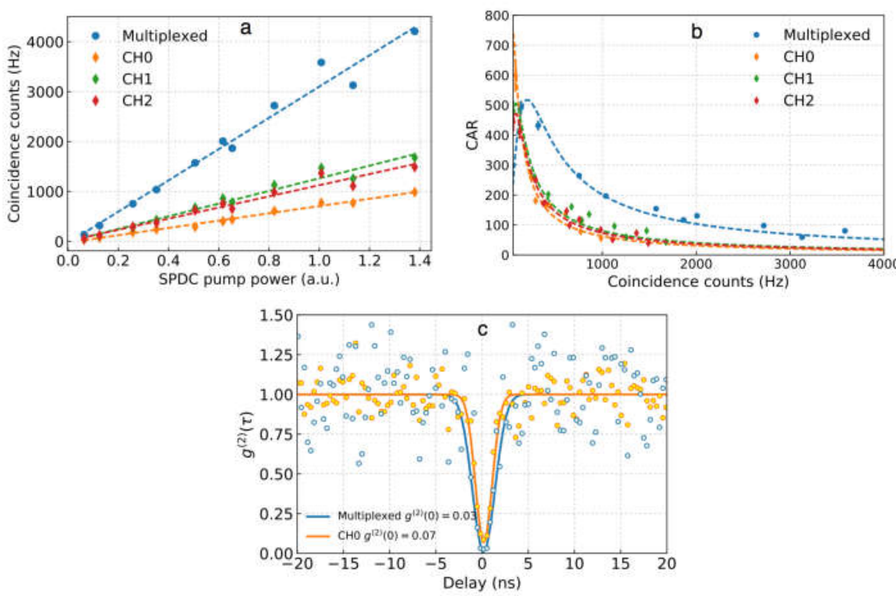

Fig 1. Experimental results, multiplexing of three frequency modes CH0, CH1 & CH2: a) The single photon heralding probability for the multiplexed source is higher for the multiplexed source as compared to the average of the individual channels by about 4.7 dB, accounting for switching losses of 2.2 dB, results in a net enhancement of 2.5 dB (180%). b) Coincidences-to-accidentals ratio (CAR) for the multiplexed source and individual channels. For the same coincidence rate, the multiplexed source has an enhanced CAR by a factor of 2.5 c) We measure a $g^{(2)}(0)$ of about 0.03(1) for the multiplexed as compared to 0.07(1) for the single channel CH0.

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#178

Towards a Waveguide-based Single Photon Detector for Integrated Quantum Photonics Platforms

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The scalability of quantum networks is a key challenge in developing practical quantum technologies. Recent developments in quantum photonics platforms show remarkable promise, but nonetheless still require the coupling of light from the device to external photodetectors [1,2]. For a truly integrated photonics platform, these quantum devices need to be combined with on-chip single photon detectors. Here, we present our efforts towards a waveguide-based Geiger-mode Si single photon avalanche diode (SPAD), optimized for visible wavelengths.

Input light is end-coupled from a Si_3N_4 waveguide, which has low losses at visible wavelengths, into the Si waveguide in the same layer, which forms the SPAD [3]. We design our devices with p-n+ (heavily doped n) junctions such that the depletion regions extend largely into the p-doped side; the absorption of a photon in the depletion region would then trigger an avalanche of electrons, resulting in a macroscopic photocurrent signal. We study two doping profiles. The first design is a straight doping profile with a single continuous depletion region along the direction of light propagation. The position of the p-n+ junction results in a large overlap of the depletion region and the optical waveguide mode, which results in a high detection efficiency. This approach requires a stringent control during fabrication as a misalignment of the junction will result in a large mismatch between the optical mode and the depletion region. The second design is an interdigitated doping profile perpendicular to the direction of the light propagation which is less sensitive to such fabrication errors, but has a lower efficiency due to discontinuities in the depletion region along the waveguide.

Both the devices have an absorptivity of >98% at 638 nm. We simulate device performance by calculating their electric field (E-field) distribution profiles, which determine the avalanche triggering probability of the photo-generated carriers. The calculated breakdown voltage is about 12V. The calculated efficiencies for straight asymmetric doping profile and interdigitated doping profile at 638 nm are 78.5% and 42.2%, respectively, for a reverse bias voltage of 22V.

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#179

Photon Counting Microchannel Plate Imaging Sensors

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Abstract: Photon counting imaging sensors using microchannel plates (MCPs) as an amplification stage in front of a cross strip (XS) anode readout coupled to high performance electronics have proven to be highly effective detectors for many applications, including Astronomy, high energy physics, atomic physics, biology and high time resolution remote sensing. For applications in the visible/NIR regimes, high performance photocathodes, such as Super-GenII or GaAs, have been incorporated into sealed tubes with a pair of MCPs and a XS anode. The efficiency of these tubes has been relatively stable for more than 4 years, the GaAs peak QE has degraded ~5% from the initial 30% and the peak Super-GenII QE has remained unchanged at ~17%. Single photon counting rates of >5 MHz with time stamps to better than 25 ps have be achieved using the XS anode readouts with the PXS-II high speed event processing electronics and a custom time to digital converter. Open face MCP devices with alkali halide photocathodes have been used for wavelengths shortward of 100 nm. A new class of MCPs are also under investigation, they are produced by the application of resistive and high secondary emissive materials onto borosilicate microcapillary arrays by atomic layer deposition (ALD). These MCPs have many properties which have the potential to improve single photon detectors[1]. In addition, application specific integrated circuits (ASICs) called the CSAv3 and the HalfGRAPH are under development that would decrease the mass and power of the readout electronics while improving its event throughput performance by speeding up the amplification and event processing times[2].

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#180

Counting Near Infrared Photons with Microwave Kinetic Inductance Detectors

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Abstract:We demonstrate photon counting at 1550~nm wavelength using microwave kinetic inductance detectors (MKIDs) made from TiN/Ti/TiN trilayer films with superconducting transition temperature T_c ~ 1.4K. The detectors have a lumped-element design with a large interdigitated capacitor covered by aluminum and inductive photon absorbers whose volume ranges from 0.4~um^3 to 20um^3. The energy resolution improves as the absorber volume is reduced. We achieved an energy resolution of 0.22eV and resolved up to 7 photons per optical pulse, both greatly improved from previously reported results at 1550~nm wavelength using MKIDs. Further improvements are possible by optimizing the optical coupling to maximize photon absorption into the inductive absorber.

#181

Gating techniques for InGaAs/InP and silicon SPADs

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Time gating is becoming an important technique for SPADs, both for improving their performance (e.g. the maximum count rate) and for detecting faint signals hidden by strong unwanted pulses.

A growing number of applications in the 1 µm - 1.7 µm range require single-photon detectors with high count rates (greater than a few Mcount/s), high detection efficiency (> 30%), low noise (few kcount/s), narrow temporal response (FWHM < 100 ps). InGaAs/InP SPADs show good performance and are suitable for practical and reliable systems, but their main drawback is the strong afterpulsing, which limits the maximum count rate [1]. Afterpulsing can be mitigated either by increasing the hold-off time (even > 10 µs), though strongly limiting the count rate, or by reducing the avalanche charge. The latter approach is effective, but requires smart circuital solutions for working with short gates (<< 1 ns) that quench the avalanche during its build-up [2]. Here we describe two short-gate techniques for high-speed photon counting with InGaAs/InP SPADs: i) a sinusoidal gating system at 1.3 GHz, with very low afterpulsing (~ 1.5 %), high count rate (650 Mcount/s), high photon detection efficiency (> 30 % at 1550 nm), low dark count rate ($2.2 \cdot 10^{-5}$ per gate) and low timing jitter (< 70 ps FWHM); ii) a SiGe integrated circuit (ASIC) for sub-nanosecond gating with < 300 ps rising/falling edges and low (< 20 ps) time jitter.

Concerning silicon SPADs, time gating is employed mainly for time filtering the optical waveforms.

Picosecond time-gating of wide-area single-photon detectors enables higher depth penetration and higher contrast in time-domain diffuse optical spectroscopy as compared to CW systems [3]. To this aim, we first developed high-performance single-pixel silicon SPAD systems, which were then miniaturized for integration in portable and wearable imaging devices that can be employed in many applications, e.g. medical diagnostics techniques (from oncology to neurology) and quality assessment of food.

Images of objects hidden from the camera's direct line of sight can be reconstructed exploiting time-of-flight of multiply scattered photons. A fast-gated SPAD (either Si or InGaAs/InP), along with a pulsed laser, is employed for reconstructing complex scenes: the time gate blocks the first bounce light, thus increasing the effective dynamic range since successive bounces (required for reconstruction) are many orders of magnitude fainter [4].

Miniaturization with integrated circuits (ASIC) will further reduce size and cost of time-gating technology. To this aim, we are developing arrays of fast-gated integrated circuits (based on the SPAD-dummy approach) that will be wire-bonded to both InGaAs/InP and silicon SPAD arrays.

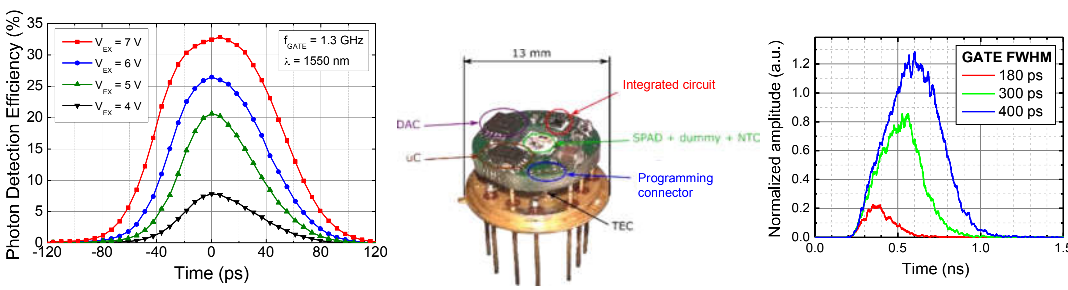

Fig 1. Left: Photon detection efficiency of InGaAs/InP SPAD at λ = 1550 nm within a sub-ns gate. The FWHM is 60-100 ps. Center: System-in-package including an InGaAs/InP SPAD and its fast-gating ASIC. Left: Short gate applied to an InGaAs/InP SPAD by the fast-gating ASIC: a width < 300 ps is feasible.

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#182

Temporal jitter in free-running InGaAs/InP Single-Photon Avalanche Detectors

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Single-photon detectors (SPDs) at telecom wavelengths play an important role in many applications such as quantum key distribution (QKD), photon counting optical communication, singlet-oxygen dosimetry for photodynamic therapy, optical time domain reflectometry and general quantum optics experiments. InGaAs/InP single-photon avalanche diodes (SPADs) are the most frequently used detectors for the near-infrared range (NIR, 1000 nm – 1700 nm), thanks to their compact size, ease-of-use (cryogenic temperature not required) and competitive performance. When the expected time of photons arrival is unknown, the detectors need to be operated in free-running regime. The simplest implementation for this is to use a passive circuit, such as a series resistance which is able to quench the avalanche current following a detection event. So far, the most effective self-quenching NIR SPAD is known as the negative-feedback avalanche diode (NFAD) [1], which has an integrated monolithic thin-film resistor.

The temporal resolution, also known as timing jitter is a critical characteristic for a vast majority of SPD applications. Although this has been extensively studied in gated-mode SPADs [2], which has shown that these detectors can be a competitive alternative to superconductor-based devices, it has not been demonstrated if free-running NFADs can achieve a jitter of <100 ps. Moreover, the nature of jitter at low temperatures has not been thoroughly studied in NFADs, which is crucial if operation with a low DCR is an additional requirement.

In a recent paper [3], we demonstrated that free-running InGaAs/InP NFADs can operate with a temporal jitter as low as 52 ps, which puts them on par with the best gated-mode devices. We also conducted a detailed characterization of the timing response for different NFADs with a particular focus on the temperature dependence.

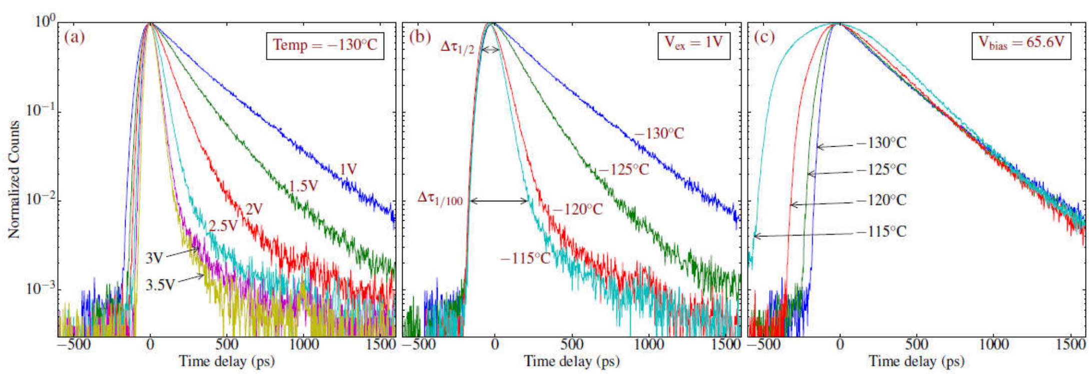

Fig 1. Jitter histograms for NFADs in different conditions. (a) Varying excess bias voltage at a constant temperature of -130C. (b) A constant excess bias voltage of 1 V for different temperatures. (c) A constant bias voltage of 65.5 V for different temperatures.

Moreover, we analyzed the effect of carrier transport between the absorption and multiplication regions in these devices, which has enabled the understanding of the jitter contribution due to charge-carrier pile-up, a phenomena which has been rarely studied. Finally, we showed that the minimum operating bias voltage for a given timing jitter is limited at the lowest operation temperatures. Subsequently this gives rise to the connection between the lowest achievable DCR and the temporal jitter, when operating at low temperatures.

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#183

Progress on Single Photon Detector Efficiency Calibrations at NIST

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Abstract. We report on our progress towards implementing a measurement service aimed at the calibration of single-photon detectors. We present how our calibration is tied to the calibration of our transfer standard optical fiber power meters. We also developed and built a superconducting nanowire single photon detector system for use as an in-house reference for single photon detection efficiency measurements. This system can also be utilized in comparisons among NIST and other NMIs.

Calibration of single-photon detector efficiency

Our measurement of single-photon detector efficiencies is based on a simple beamsplitter method, where an attenuator is used to attenuate from light levels that allow high-accuracy absolute-power measurements to levels compatible with photon-counting detectors. First, the transmittance of the beamsplitter is measured at optical powers that allow both its input and output powers to be accurately measured with optical power meters, then its input power is reduced such that the output is in the range of the device under test (DUT). Using this measured transmittance and the measured input power, the low level optical power on the DUT can be determined, thus allowing the calibration of a transfer standard optical power meter, *e.g.* Si trap detector, to be transferred to the DUT. We have implemented a fiber-coupled and free-space measurement system. In both cases we were able to achieve a measured detection efficiency with an extended relative uncertainty of less than 1 %.

Superconducting nanowire single photon detector system

For use as in-house reference and comparisons between NIST and other NMIs, we have built a superconducting nanowire single-photon detector (SNSPD) system. The system is based on a 1K cryostat design, capable of operating our WSi SNSPDs [1]. Currently, the system hosts two SNSPDs, optimized for 1550 nm. The compact and robust detector packaging [2] allows shipping of the SNSPDs inside the cryostat without noticeable degradation of the SNSPD performance over many temperature cycles. In the future, we will equip the cryostat with SNSPDs optimized for ≈850 nm, 1064 nm and ≈1310 nm. The system is fully automated and turn-key and as such, the operator does not need extensive cryogenic experience or knowledge.

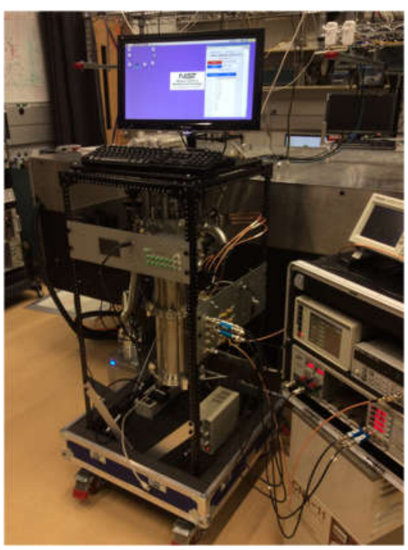

Fig 1. 1K SNSPD system used as in-house reference.

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#184

Single-photon avalanche detectors – their characterisation and use in measuring single-photon pulses

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Abstract. A sound understanding of correlated signals generated by single-photon detectors is important when such devices are employed in schemes to distribute quantum keys and generate random numbers. We have derived analytic expressions to describe observed time-sequences of dark counts and after-pulses; this permits a measurement of the after-pulse probability distribution. When such detectors are used to measure the mean photon number of optical pulses, dark counts and after-pulses must also be accounted for. We also derived analytic expressions to extract the mean photon number from measurement data obtained using a calibrated SPAD. We have applied these to experimental procedures described in a recent ETSI Group Specification for characterizing gated single-photon avalanche detectors and measuring mean photon number; results obtained by the different procedures will be presented.

Single-photon avalanche photodiodes (SPADs) are the most widely-used single-photon detectors today. They possess non-ideal detection efficiency (< 1), no photon-number resolution, occurrence of dark counts and after-pulses, and dead-time. In the telecom regime, they have traditionally been gated to reduce the occurrence of dark-counts and their induced dead-time. Within a gate, a 'click' can be caused by a true detection, a dark count, or an after-pulse; one, two, or all of these may occur in a single gate. Furthermore, the after-pulse probability is generally a function of elapsed time since the previous 'click'.

These properties have led to the development of a number of methods, of different degrees of experimental complexity, to characterize SPADs. Particular methods are able to quantify some or all of the properties. Similarly, when using a SPAD to measure the mean photon number of emitted pulses, one also has to account for the SPAD properties and their consequences.

We derive algebraic expressions (and present the assumptions underlying them) that can be used to: (i) analyse a sequence of detector 'clicks' comprising dark counts and after-pulses, enabling the temporal behaviour of after-pulses to be extracted from time-sequence data; (ii) extract the mean photon number from measurement data obtained using a calibrated SPAD. The cases where every SPAD gate is illuminated and where only the Nth SPAD gate is illuminated are analysed.

These expressions are used to: (i) analyse data obtained using three of the methods described in a recent ETSI Group Specification document [1] for characterising gated SPADs. The methods were applied to the characterization of a gated detector, and extended, where applicable, to a free-running detector; (ii) analyse data obtained using the 2 methods described in [1] for measuring the mean photon number of pulsed sources.

A comparison of the results obtained by the different methods, together with their respective uncertainties, is presented. This demonstrates the level of detail and accuracy that can be extracted from the respective methods.

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