Quantum SI Traceable Measurements and Calibrations: Radio Frequency Electric Fields and Power

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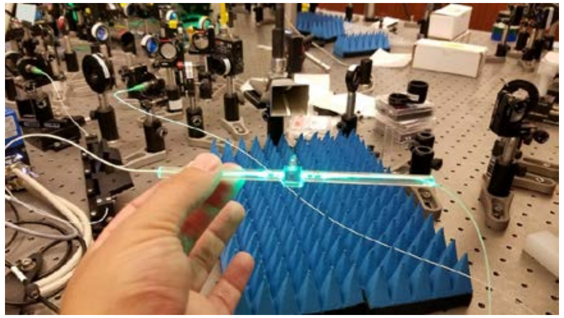
NIST

CTL

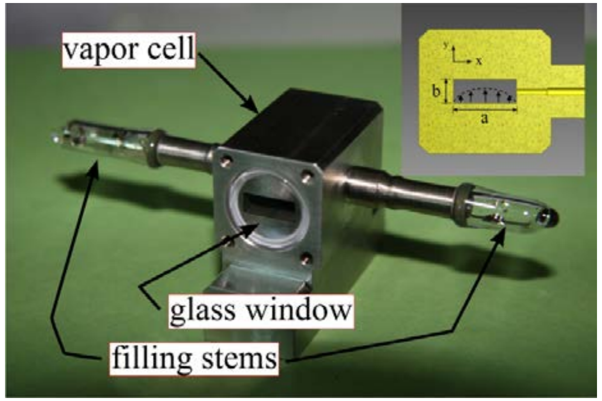
Boulder, CO

Outline

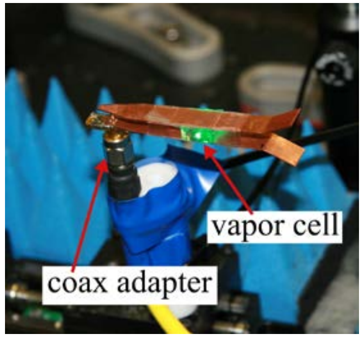
- Rydberg atom-based SI traceable measurements for electric fields

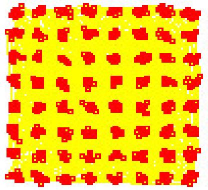


- Rydberg atom-based SI traceable measurements for power



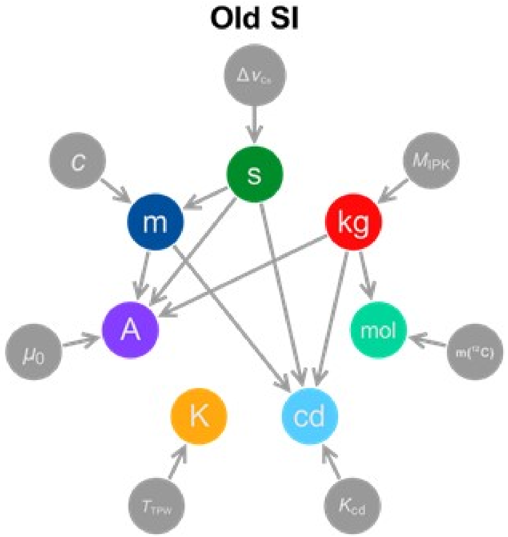
- Other applications

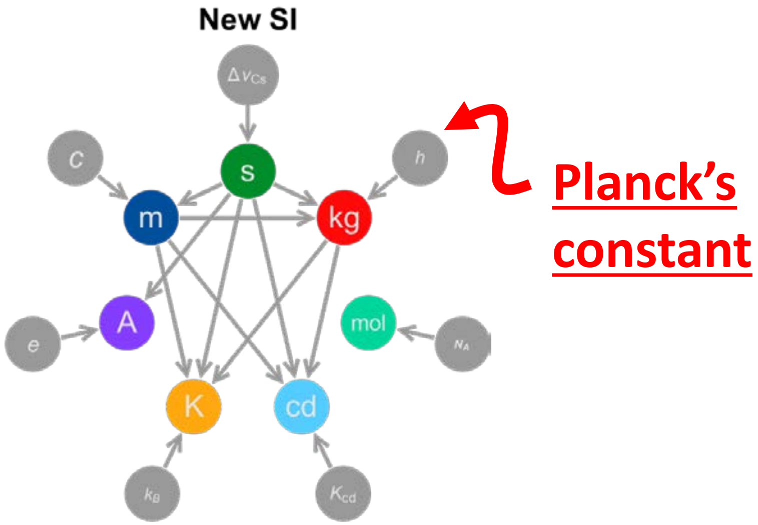




64 QAM

Re-definition of the SI in 2018





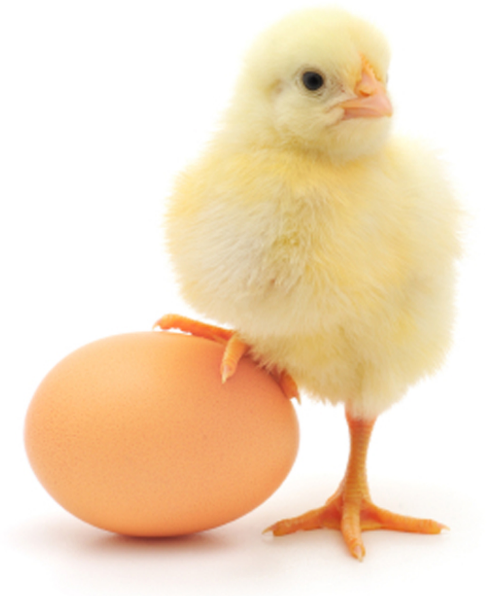
The world of measurement science changed with the SI redefinition that occurred in November 2018.

As a result of the shift towards fundamental physical constants, we can rethink about how SI traceable measurements and calibrations are done.

Hence, we are developing fundamentally new methods for SI traceable measurement techniques for *E-field* and *RF power* (defined as 100's MHz to just below THz).

Electric Field Measurements

What are We Trying to Solve: Calibrating an E-field Probe



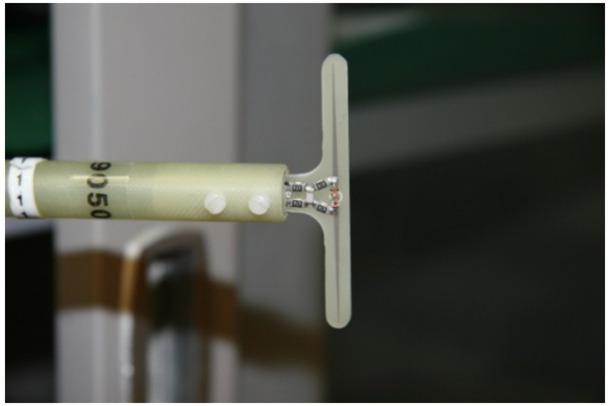
Somewhat of a “Chicken-or-Egg” dilemma

To calibrate a probe, one must place the probe (sensor) in a “known” field.

However, to know the field we need a calibrated probe.

What are We Trying to Solve: Current Techniques

E-field Probe



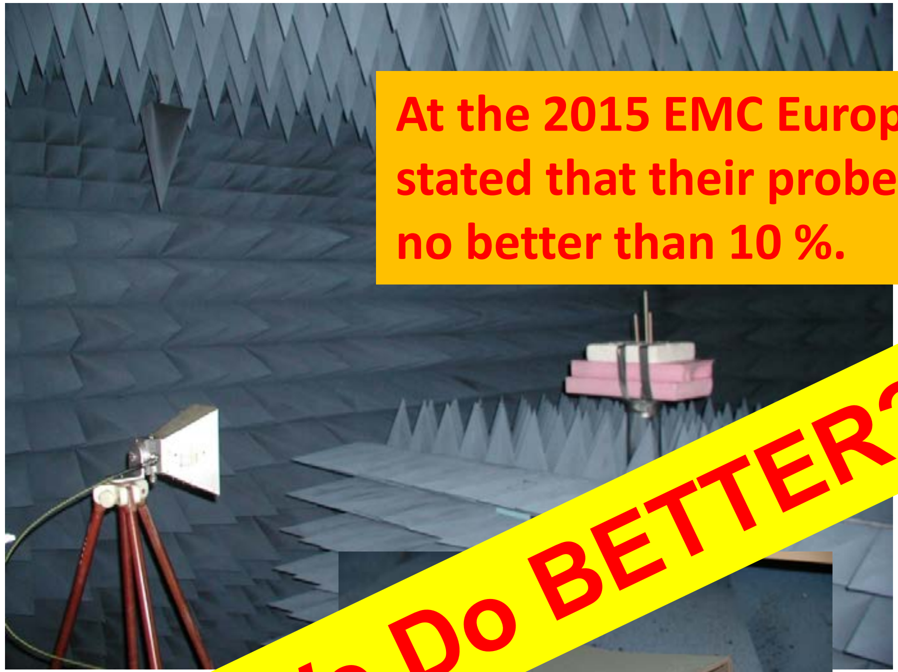
Limitations:

- Field-levels: about 100 mV/m
- Requires calibration
- Perturbs the field (due to metal)
- Relatively large in size

To calibrate the probe, we need a “known” field.

What are We Trying to Solve: Generating a Known Field

Horn antenna in an anechoic chamber



TEM cell

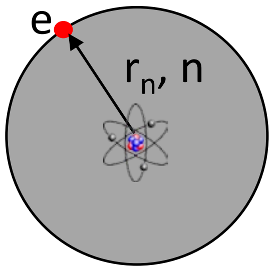
GTEM cell

At the 2015 EMC Europe conference probe manufacturers stated that their probes only allow them to measure fields no better than 10 %.

Can We Do BETTER?

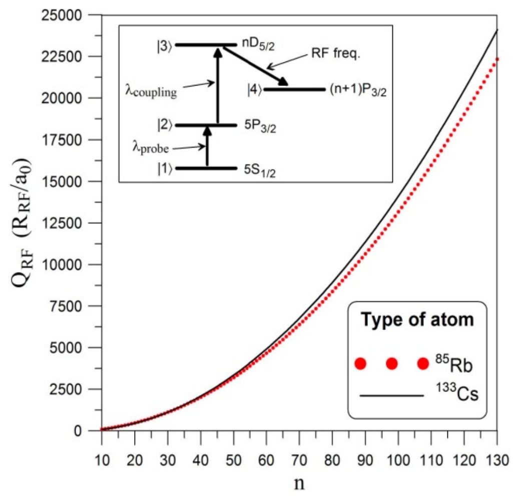
0.5 dB (or 5%) accuracy

Rydberg Atom Based Technique

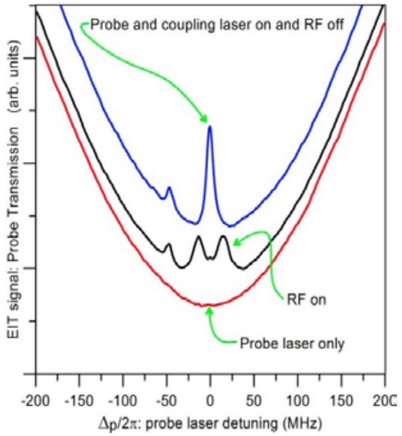


Rydberg atoms are atoms with one electron excited to a very high principal quantum number *n, i.e., r_n is very large*.

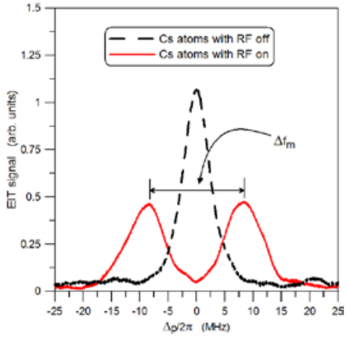
Rydberg states have very large dipole moments: Meaning they are very sensitive to RF E-fields (making for good RF E-field sensors).



We us electromagnetically induced transparency (EIT) for the E-field sensing, either on resonance (Autler-Townes (AT) splitting) or off resonance (AC Stark shifts).

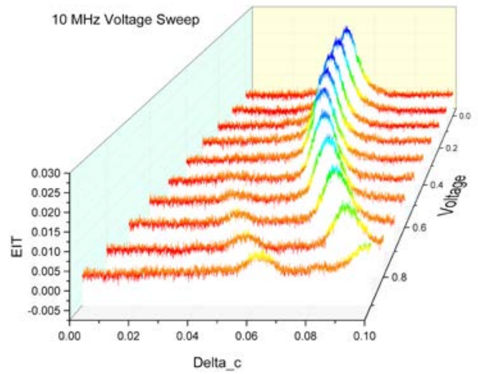


Autler-Townes (AT) splitting



$$|E| = \Delta f \, \frac{\hbar}{\wp}$$

AC Stark shifts



$$|E| = \sqrt{\frac{4\,\Delta f}{\alpha}}$$

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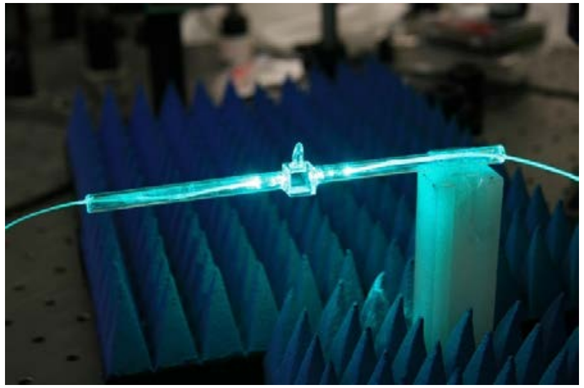
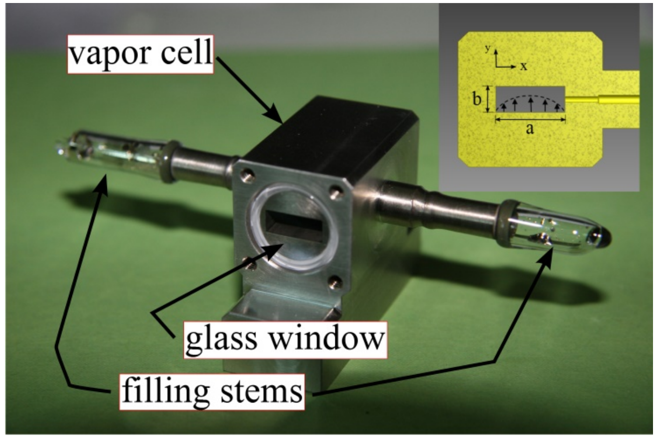
Rydberg Atom Based Technique: Purpose

- Develop an SI traceable microwave *Electric-field* measurement technique.
- Develop an SI traceable microwave *Power*.
- Implement in a compact SI traceable probe

•Useful as…

 –Stand alone probe usable for test and measurement
 –Calibration of existing probes
 –Calibration of existing test facilities
 –Calibration of existing power heads
 –Other Applications





IMPACT by NIST: Historical Perspective - eight years of effort

2010: NIST wrote paper discussing using Rydberg atoms for SI measurements of electric fields

2011: DARPA funded to two groups on atom-based electric field sensors:

one lead from the University of Oklahoma: Sedlacek et al., 2012
one lead from of NIST: Holloway et al., 2014

2014-Present: Great Pr orld.

Because of the success of this program, several groups around the world (including National Metrology Institutes, private companies, universities, and other government laboratories) have started programs in the area of Rydberg atom-based sensors.

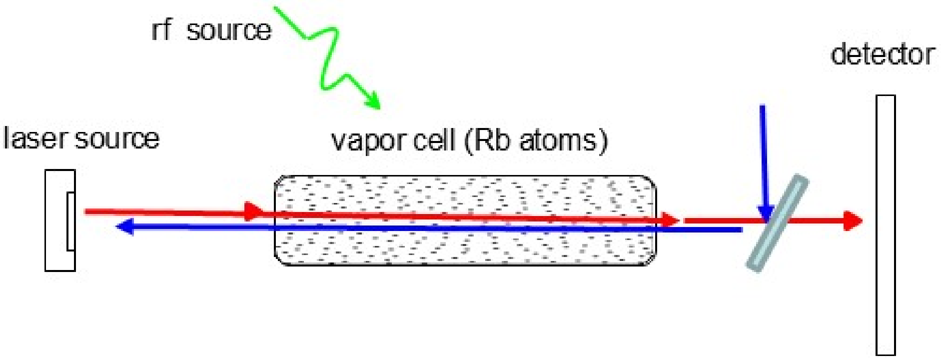
Including: USA, Germany, UK, Canada, China, Japan, South Korea, India, New Zealand, etc..

Gov. Labs: NIST, DOD, DOE, National Institute of Metrology (China), NPL (UK), etc..

Universities: U of Michigan, U of Oklahoma, U of Stuttgart, Durham Univ., U of Colorado, U of Maryland, Shanxi University, U College London, U of Ele. Science and Technology, U of Otago, U of Chinese Academy Sciences, Chongqing University, Institute of Laser Spectroscopy, Jiliang University, Jiliang University, Shandong University of Science and Technology, Pusan National University, Beijing Institute of Technology, etc.....

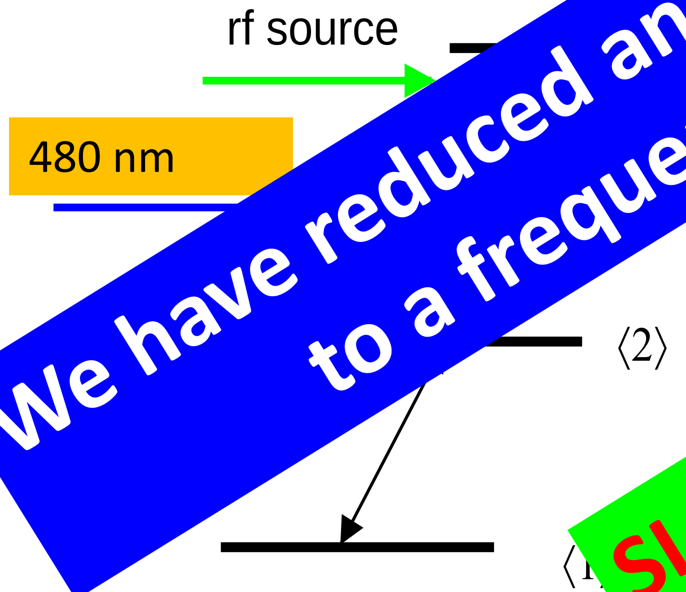
Several private companies: Rydberg Technologies, MITRE, SRI, other that I cannot mention, etc.......

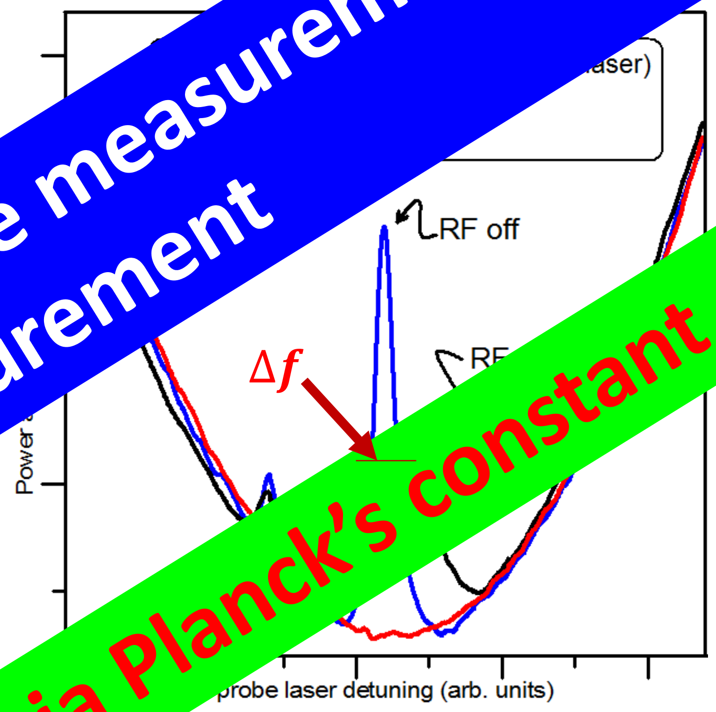
Electromagnetic Induced Transparency (EIT) for SI Traceable M… urements



Probe Laser Resp…

The blue laser gets us high…
next transition ca…





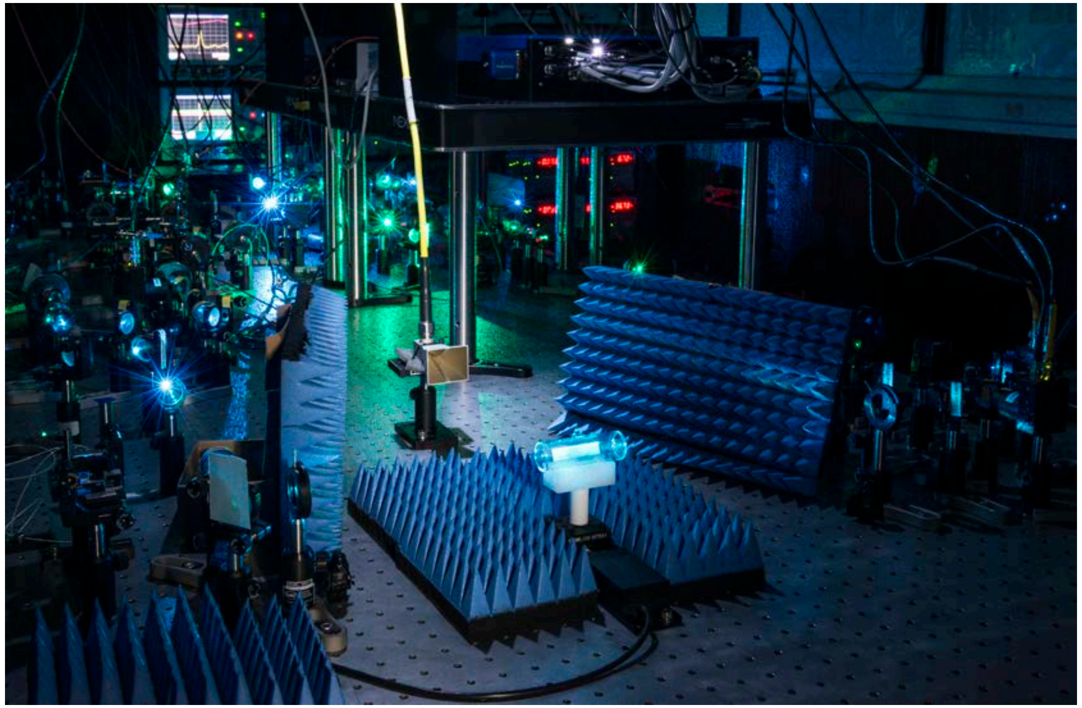
…plitting in the EIT signal
(Autler-Townes Splitting)

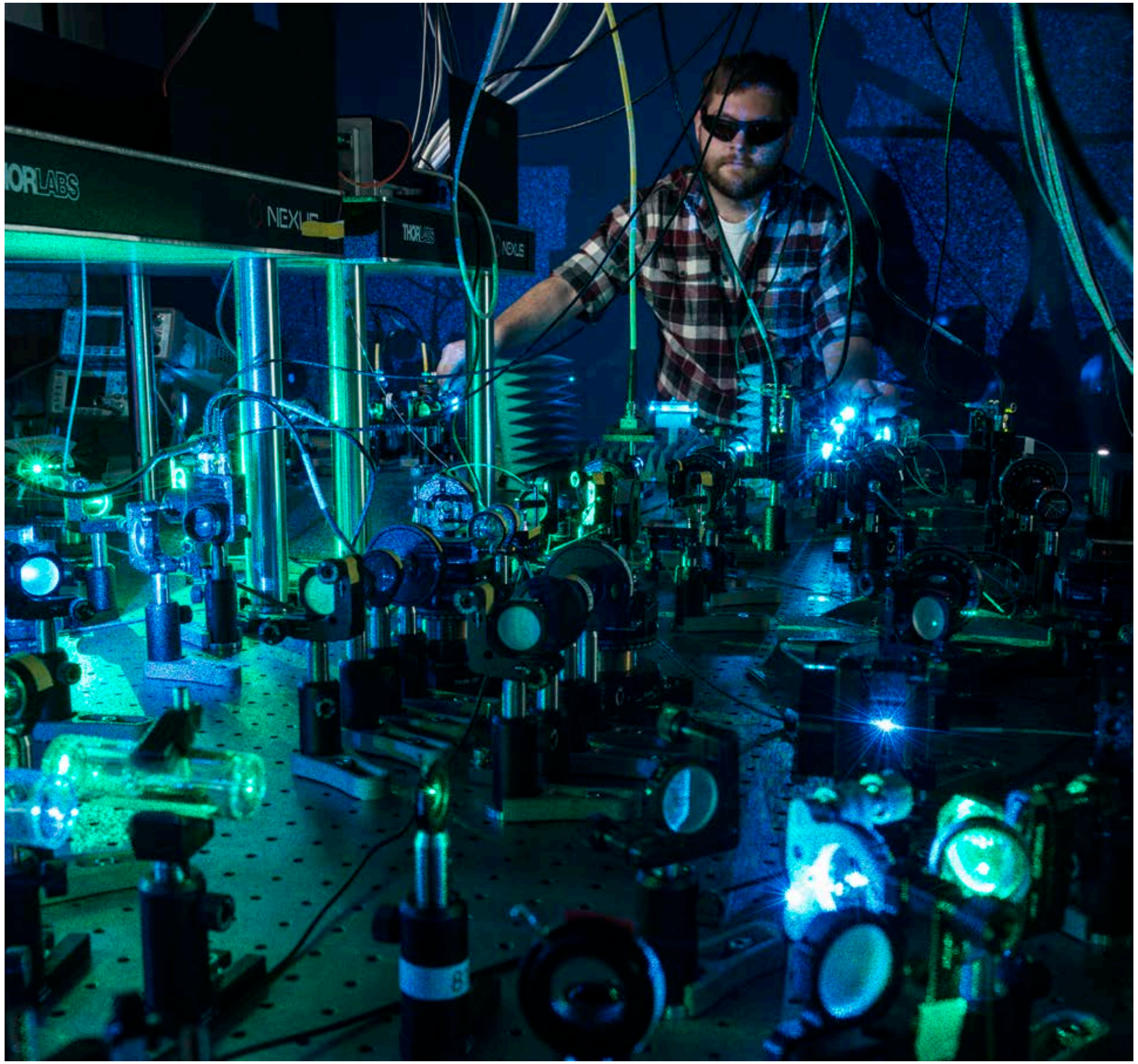
We have reduced an amplitude measurement to a frequency measurement

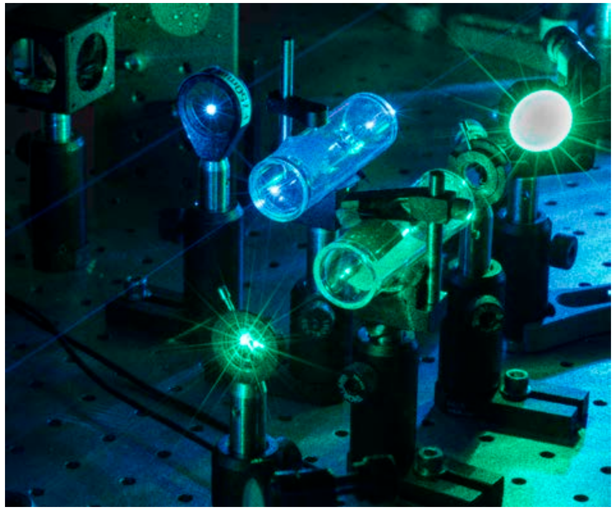
SI traceable via Planck's constant

$$\Delta f = |E| \frac{\mathcal{P}}{2\pi\hbar} \quad \rightarrow \quad |E| = 2\pi\,\Delta f \frac{\hbar}{\mathcal{P}}$$

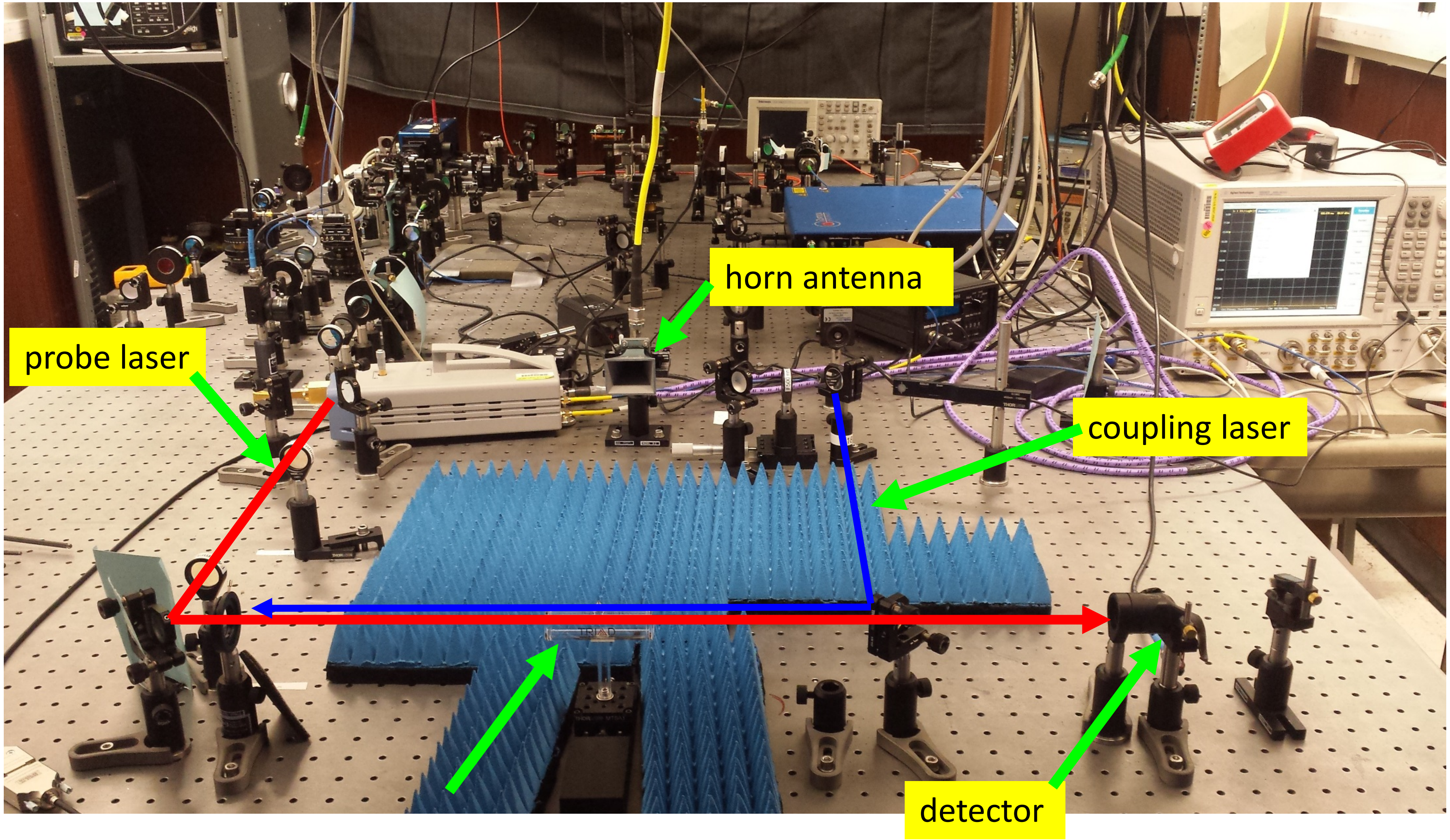
EIT: Room Temperature Measurement



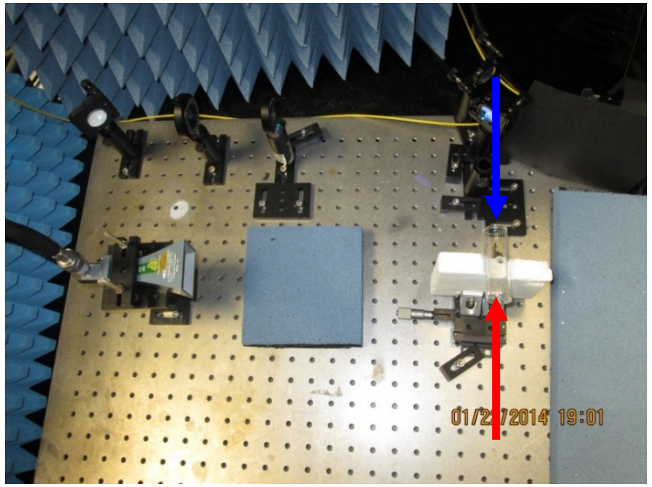


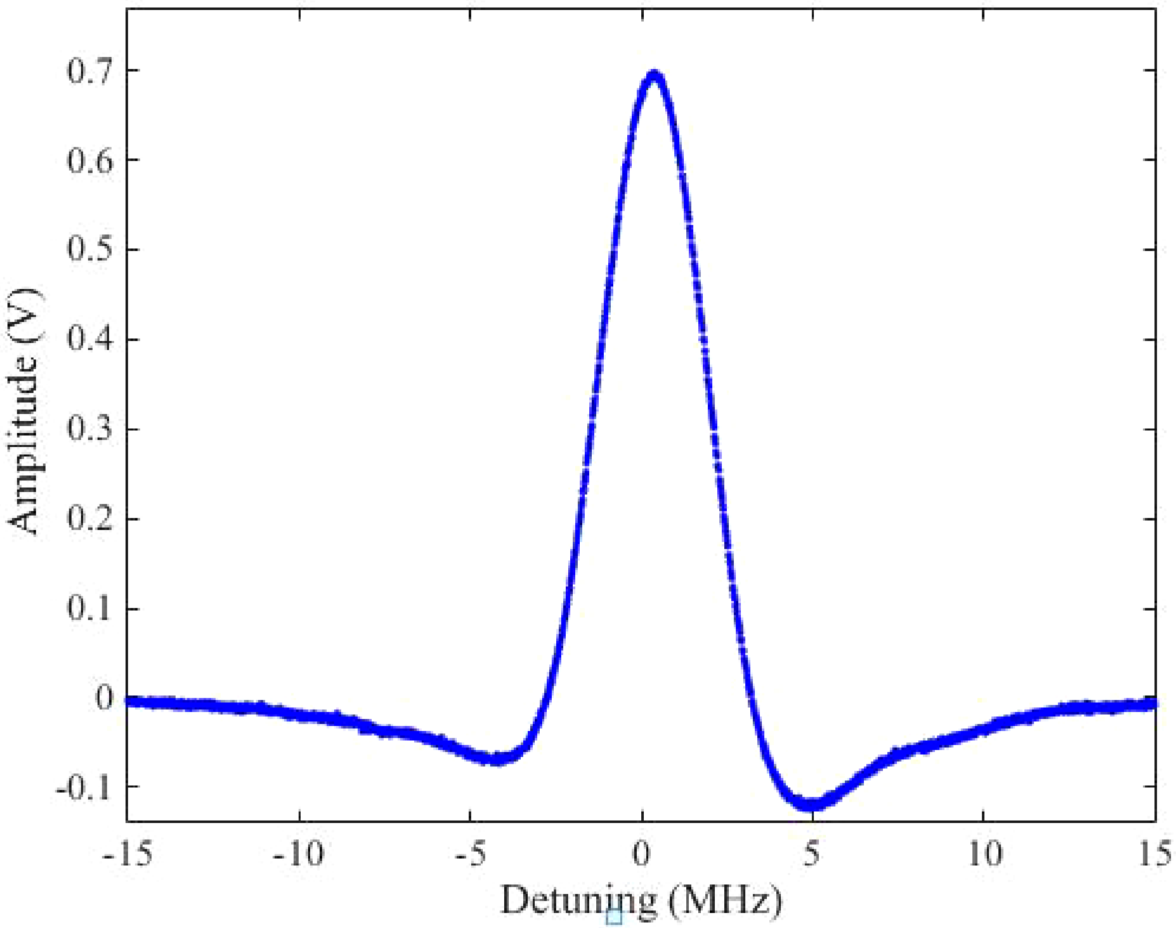


EIT: Room Temperature Measurement



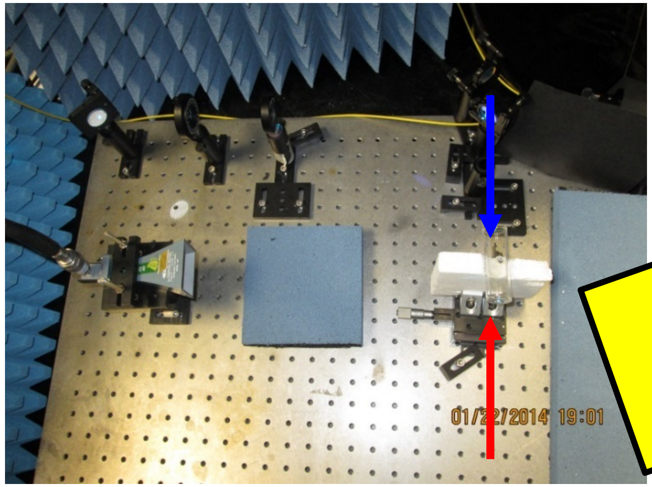
Typical Experiment Result for the EIT Signal

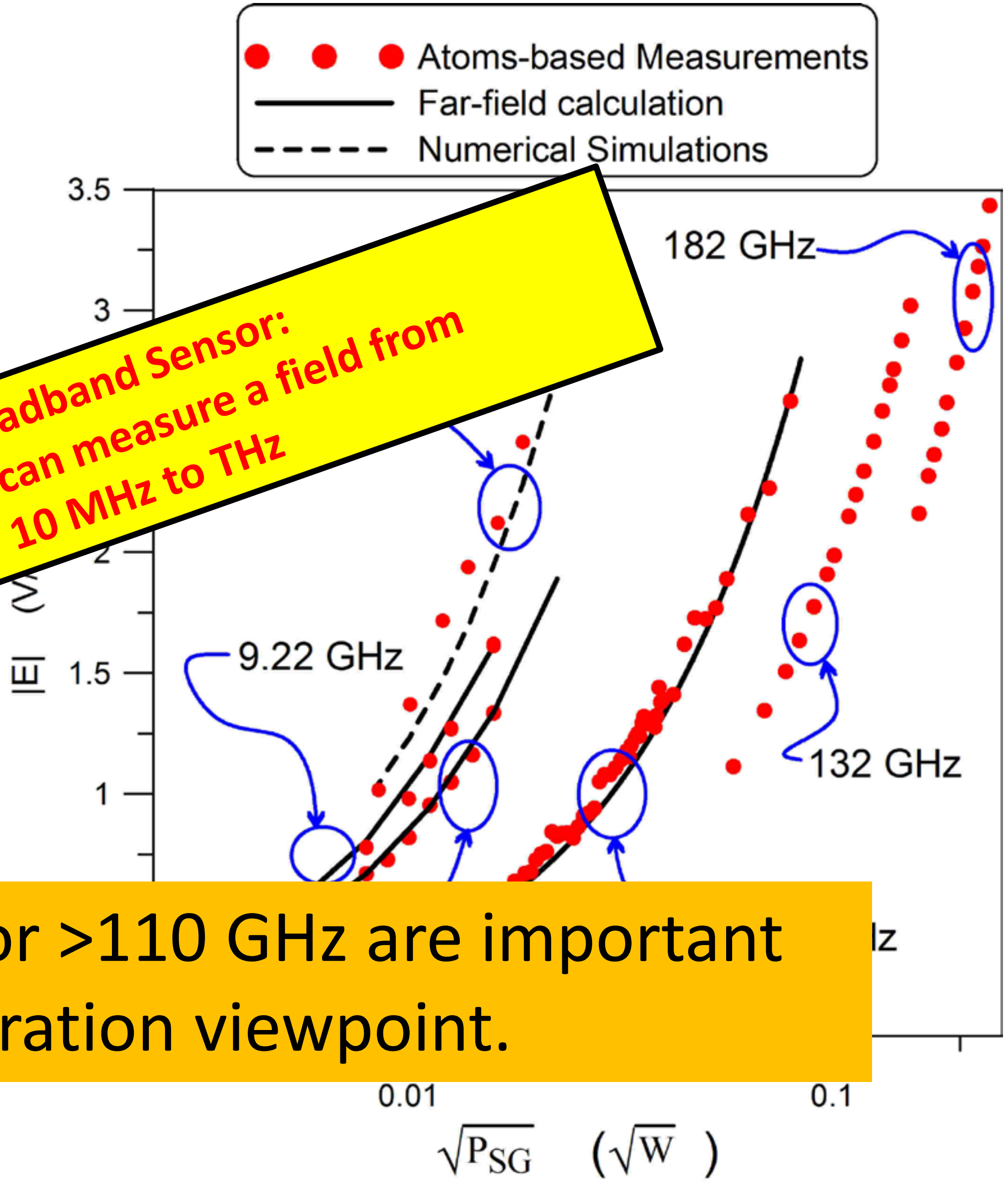




Typical Experiment Result for the EIT Signal

$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f$$

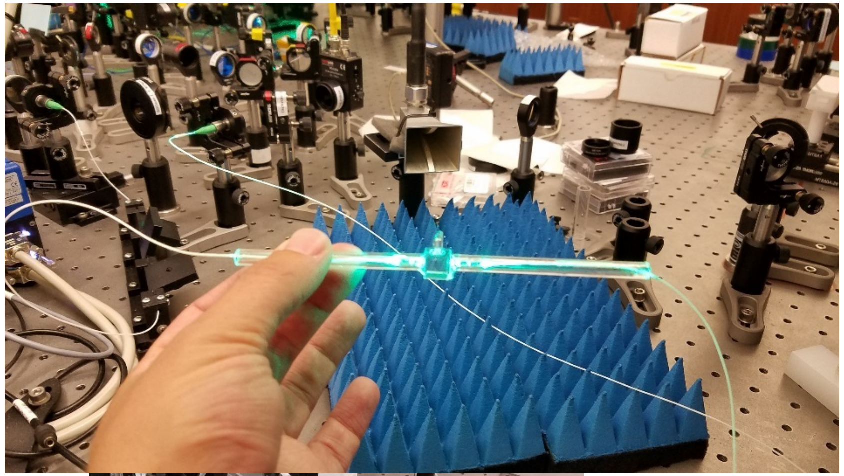


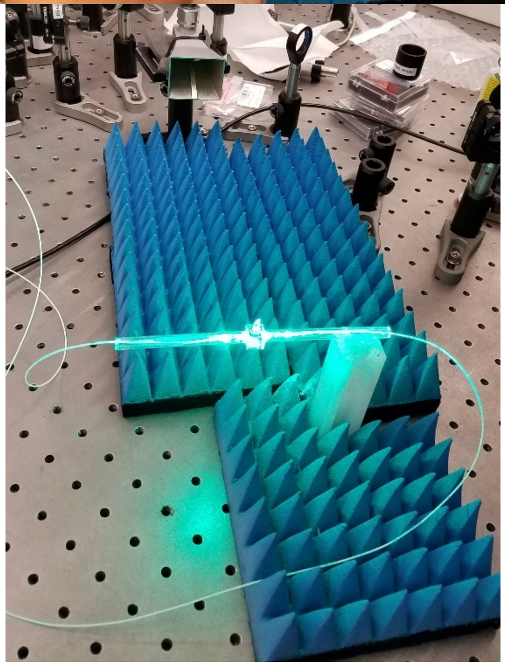


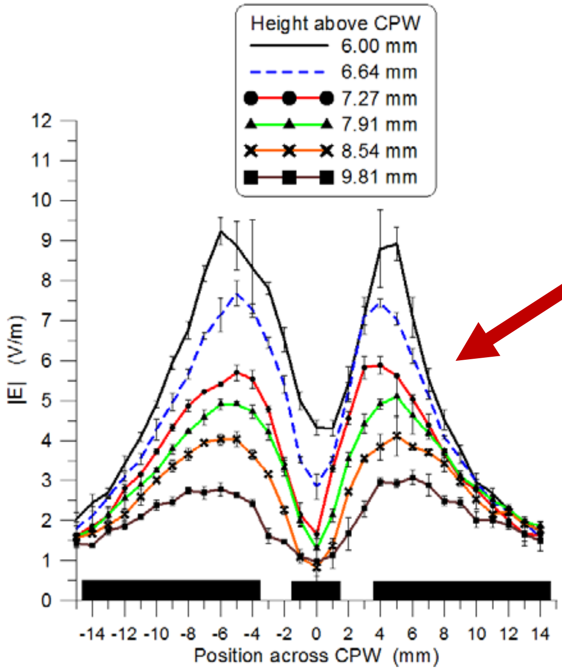
Broadband Sensor:
One setup can measure a field from 10 MHz to THz

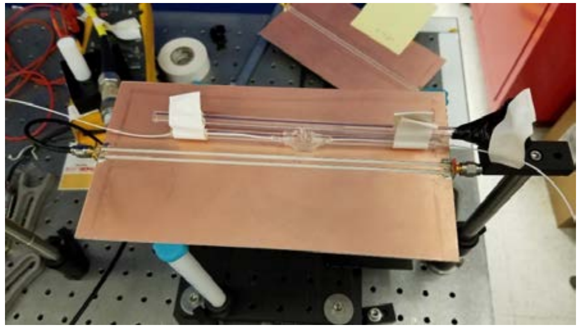
These results for >110 GHz are important from a calibration viewpoint.

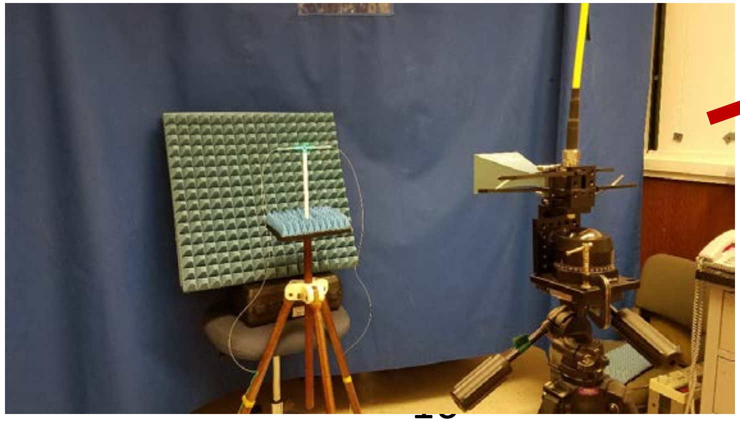
Fiber-Coupled Probe: Moving Probe OFF Optical Table

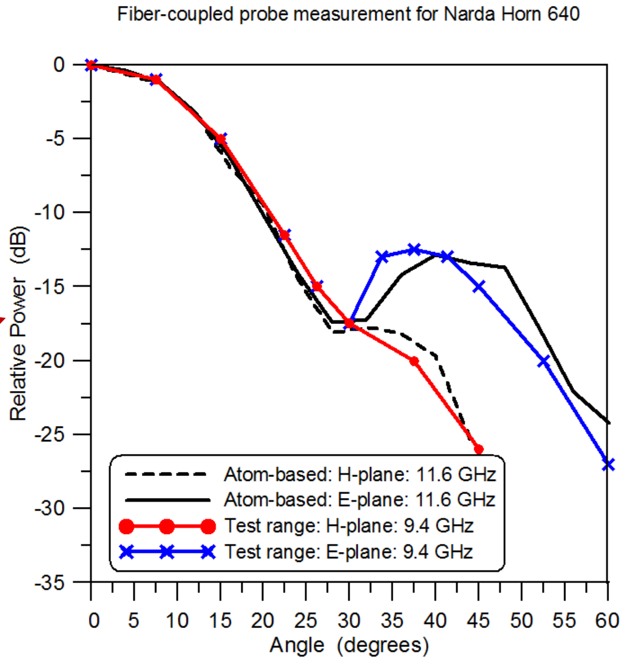












IMPACT by NIST: Historical Perspective - eight years of effort

Amplitude: Most of this work was toward amplitude of the E-field: [NIST and a few others].

Polarization: [Sedlacek et al., APL, 2013].

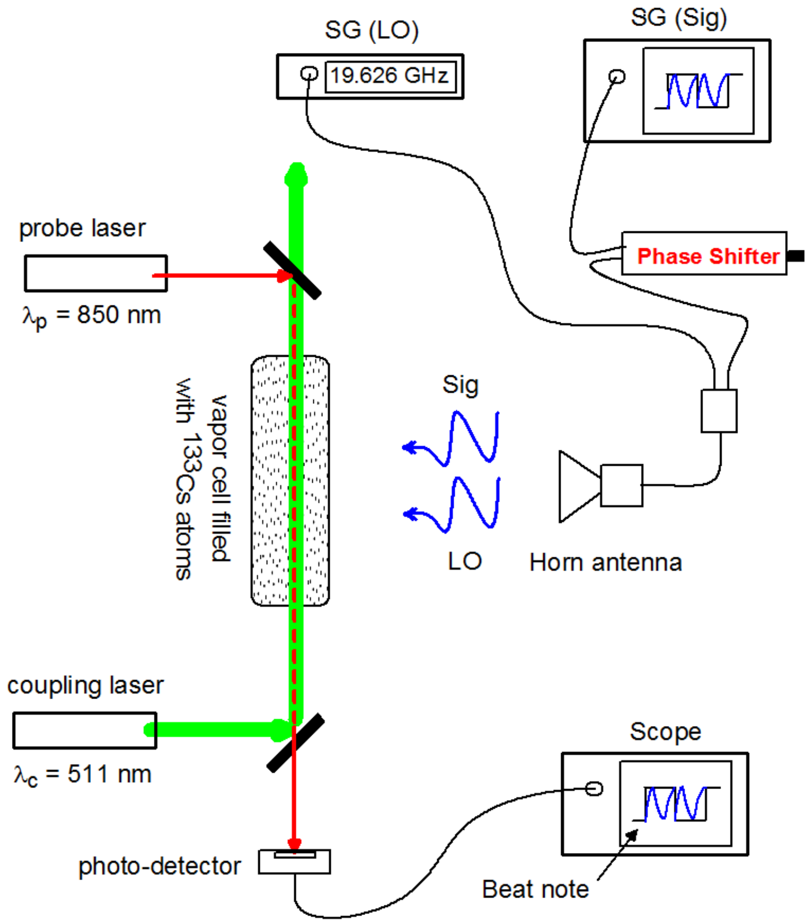
The missing link was "phase" !

Phase: NIST-[Simons et al., APL, 2019].

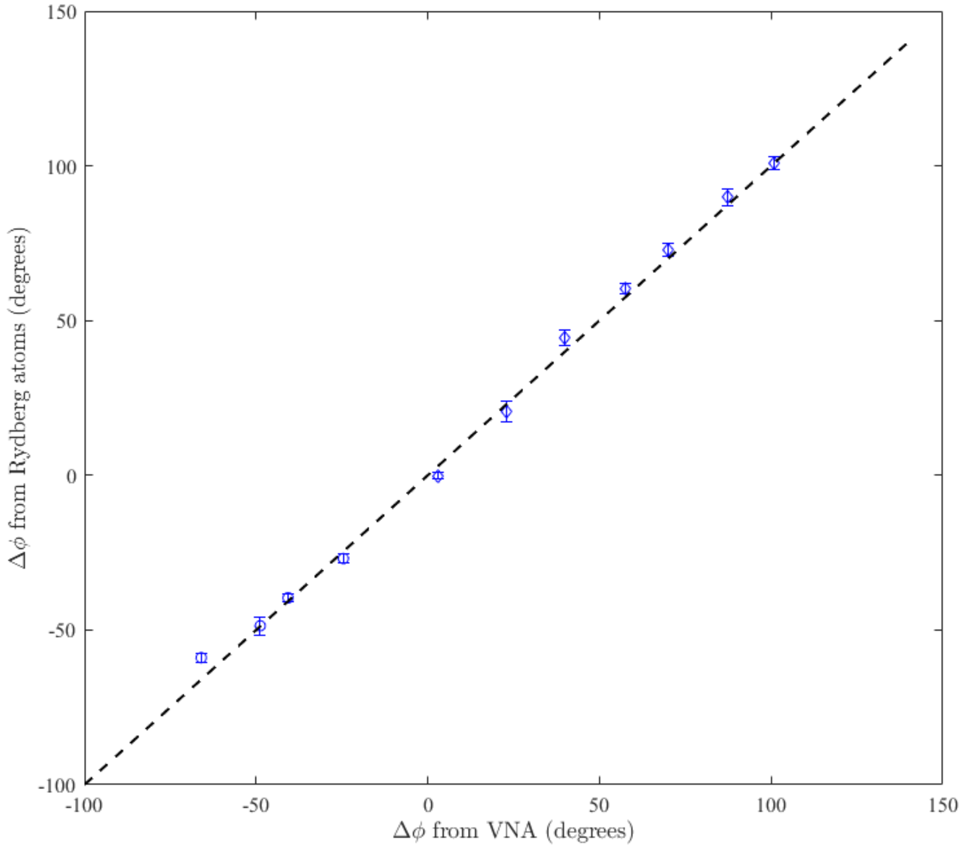
We can now *fully characterize* a radio frequency field, in that the amplitude, phase, and polarization of the field can be determined in one compact quantum-based sensor.

We can now start looking at a wide array of applications.

Rydberg Atom Mixer: Measuring Phase



CW carrier: Phase Shift



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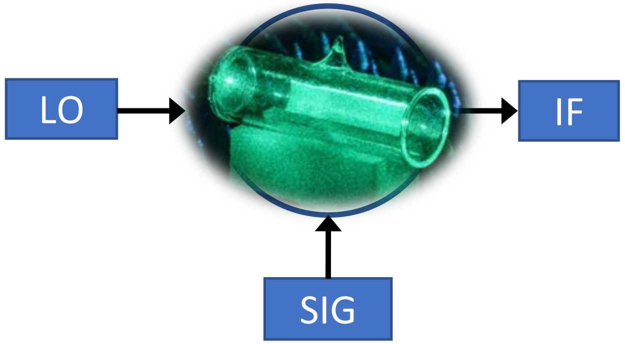
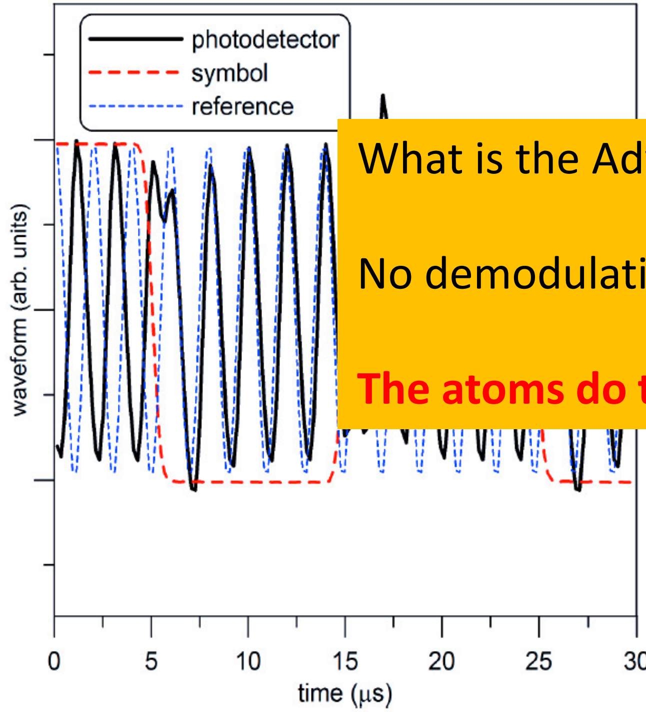
Rydberg Atom Mixer: Phase Modulation for Communications



BPSK (Binary Phase Shift Keying)



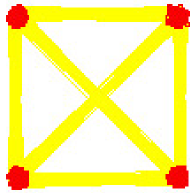
What is the Advantage?

No demodulation circuity is needed:

The atoms do the down-conversion automatically.

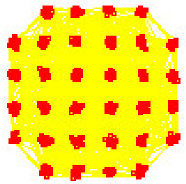
2047 symbols steam

BPSK
(2 phase states)
1 bits/symbol

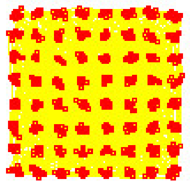


QPSK
(4 phase states)
2 bits/symbol

16 QAM
(16 phase states)
4 bits/symbol

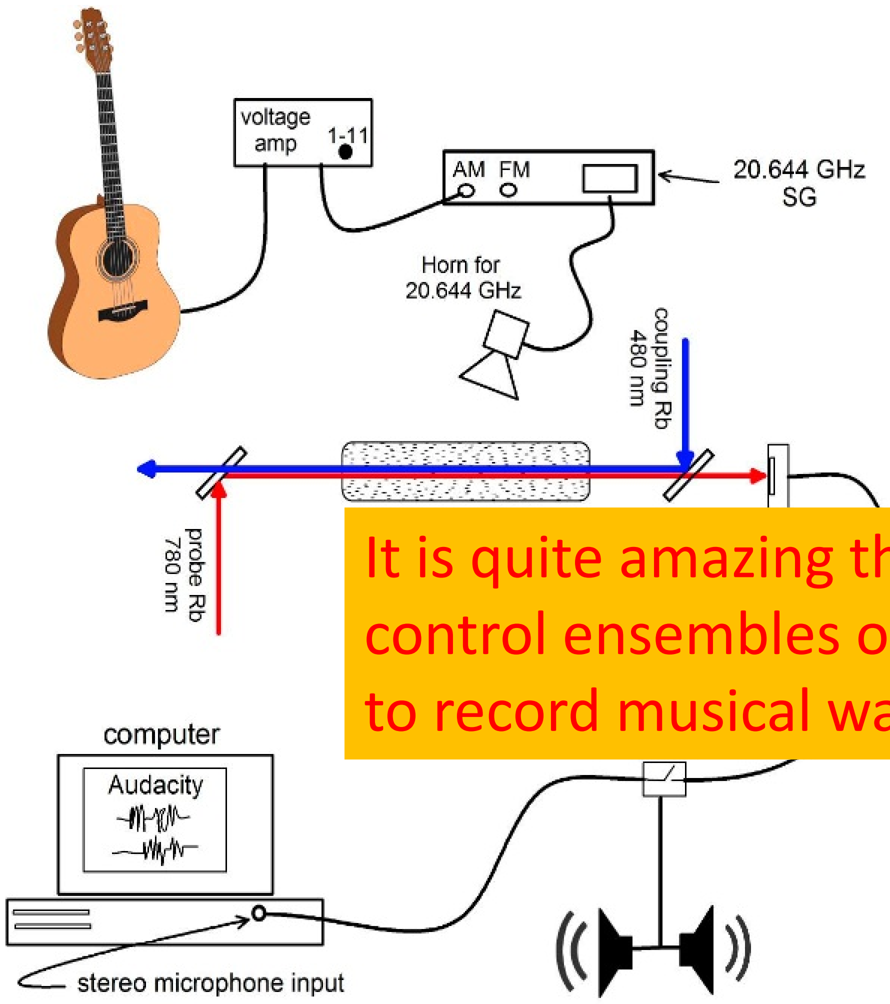


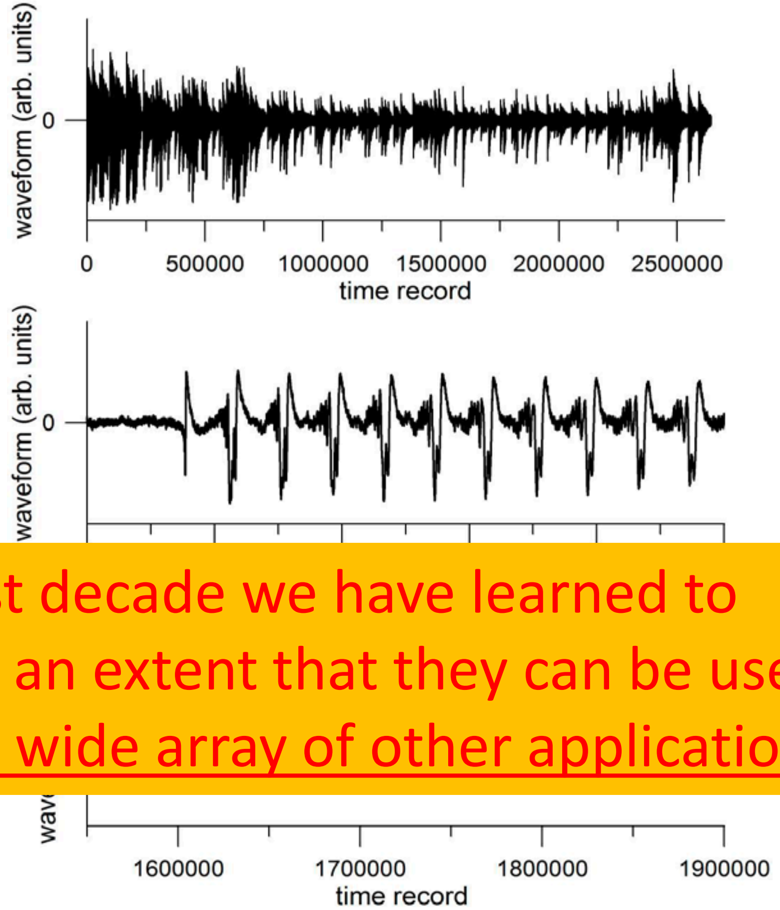
32 QAM
(32 phase states)
5 bits/symbol



64 QAM
(64 phase states)
6 bits/symbol

What Else Can We DO: Quantum-Physics-Meets-Music





It is quite amazing that over the past decade we have learned to control ensembles of atoms to such an extent that they can be used to record musical waveforms (<u>and a wide array of other applications</u>).

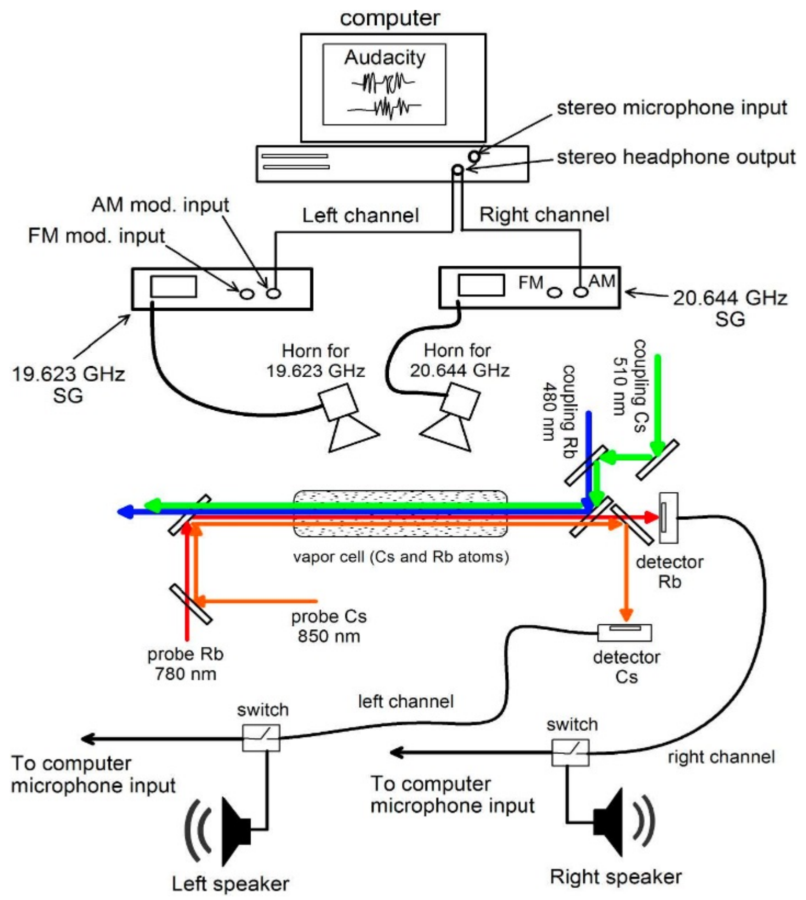
Holloway et. al., AIP Advanced, vol. 9, no. 6, 065110, 2019: Featured article at phys.org

AM/FM Stereo Reception

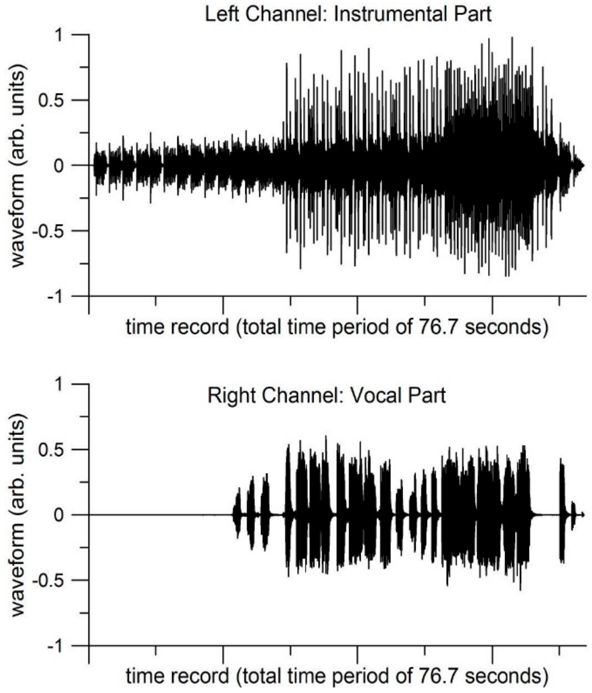
Dual Atomic Species Stereo Reception:

Instrumental on Rb atoms

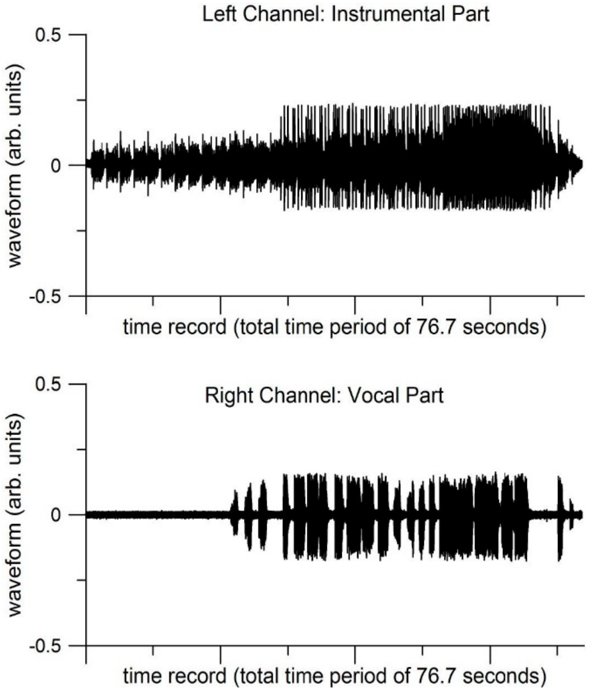
Vocals on Cs atoms



Original Waveform

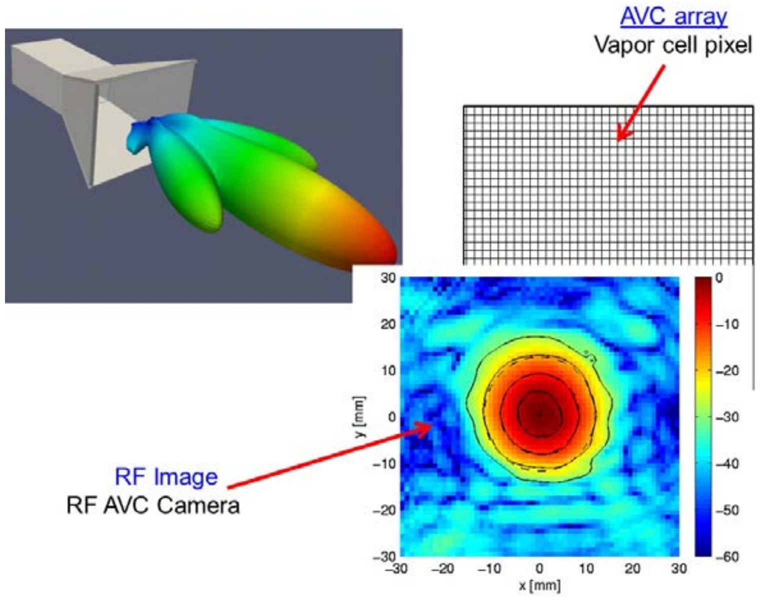


Received Waveform

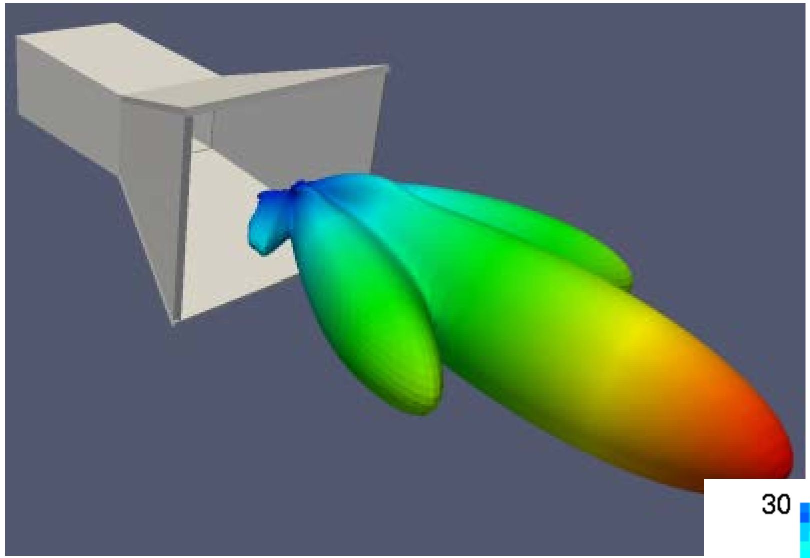


Other Applications

- Atom-based receivers/antennas
- Quantum RF imaging and visualization technology (RF camera)
- Quantum-enabled medical imaging and diagnostics
- Plasma sensors
- Atomic DC/AC voltage and current references
- Atomic thermal field sensing and measurement (blackbody radiation calibrations)
- Single microwave photon detection
- Quantum storage of radio frequency, microwave, and THz photons using slow light effects in Rydberg gases. (Quantum encrypted Rydberg atom quantum receivers from 1 GHz to 1 THz)
- Waveguide Power Measurements: Power Calibrations
- Sub-wavelength imaging
- Near-field imaging
- Measuring Noise sources

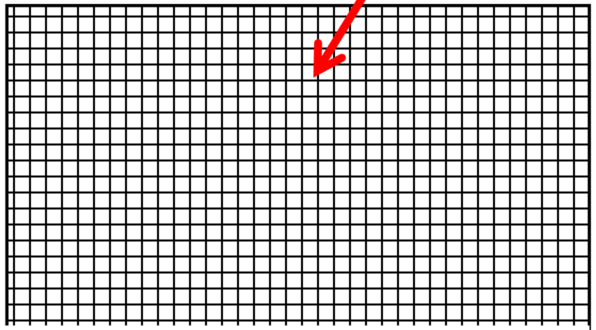


RF Atomic-Vapor-Cell (AVC) Camera



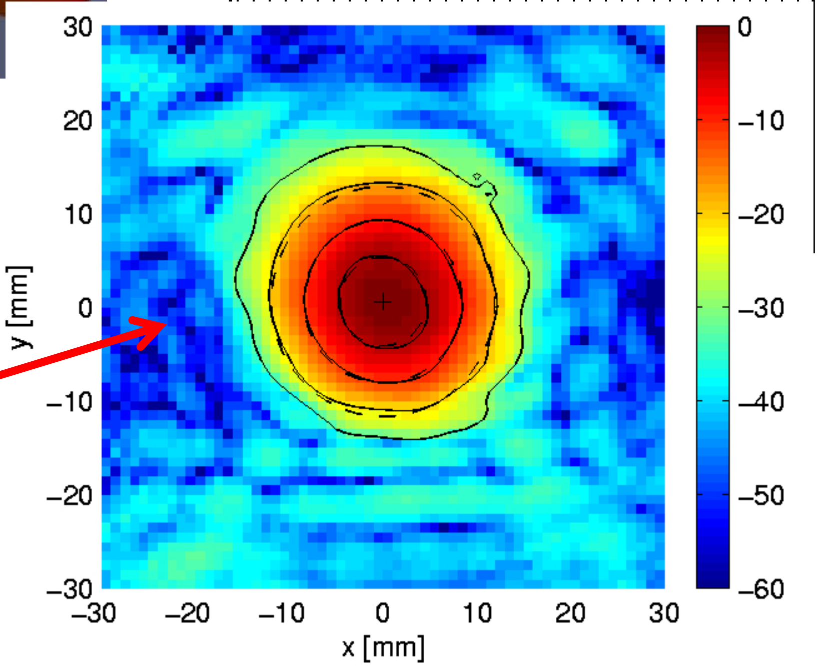
AVC array

Vapor cell pixel



RF Image

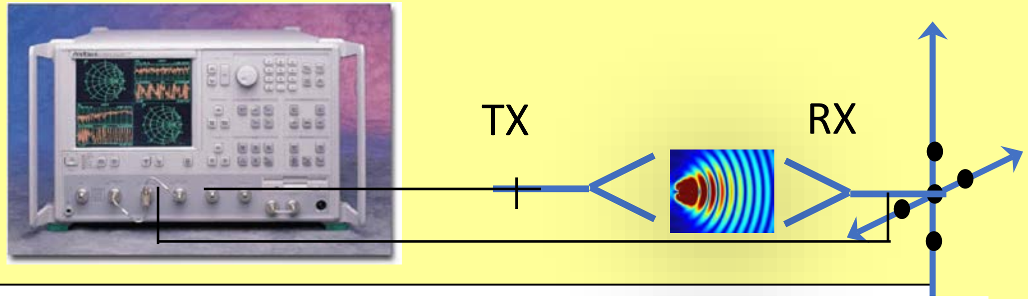
RF AVC Camera



Traceable Reference Fields for mmWave Wireless: Calibrated Facilities

Applications

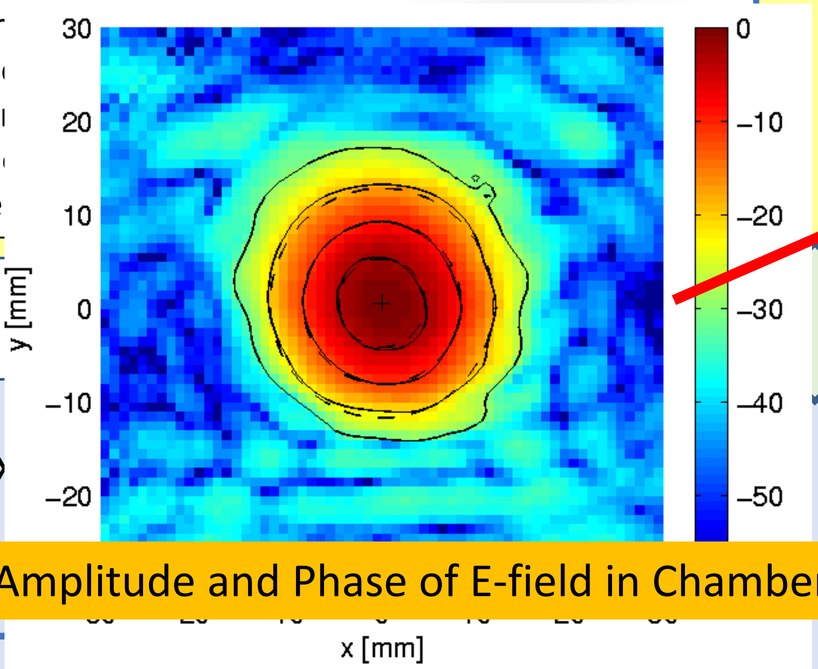
Environment Characterization Path



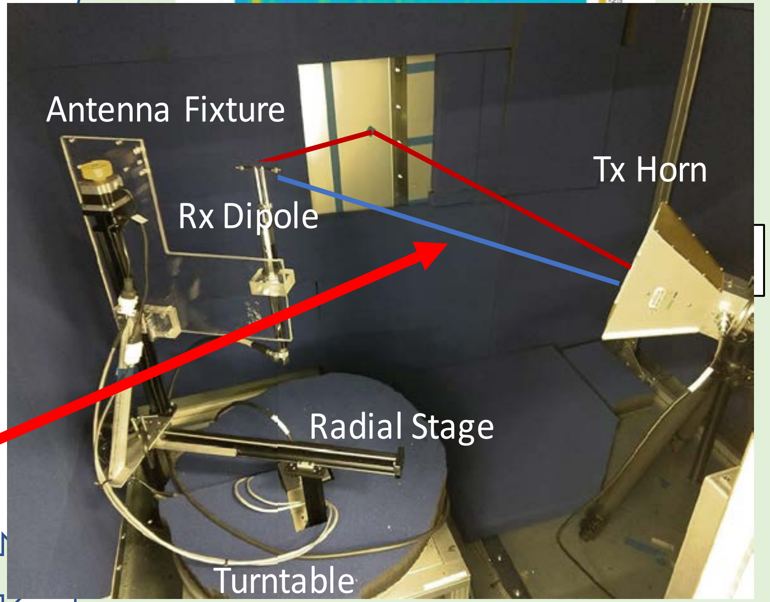
Traceable Modulated-Signal Source (FY15)

NIST Calibrated mmWave Modulated Signal Source 28 - 94 GHz

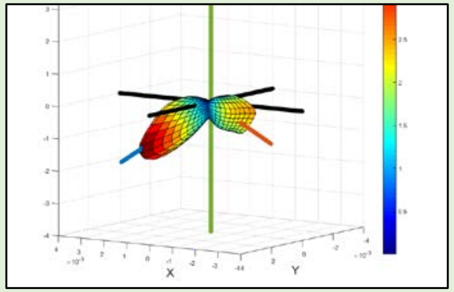
SAMURAI: Syr
Angle of Incid
- Calibratio
- Channel s
- Reflective



Amplitude and Phase of E-field in Chamber



Spatial-Channel EVM (FY19/20)



Emulated 3D Channel for 3GPP “New Radio” (FY19/20)

TX

Advantage: The SAMURAI system can be slow due to mechanical scan, while the Rydberg-atom approach is optically scanned.

uncertainty (FY18)

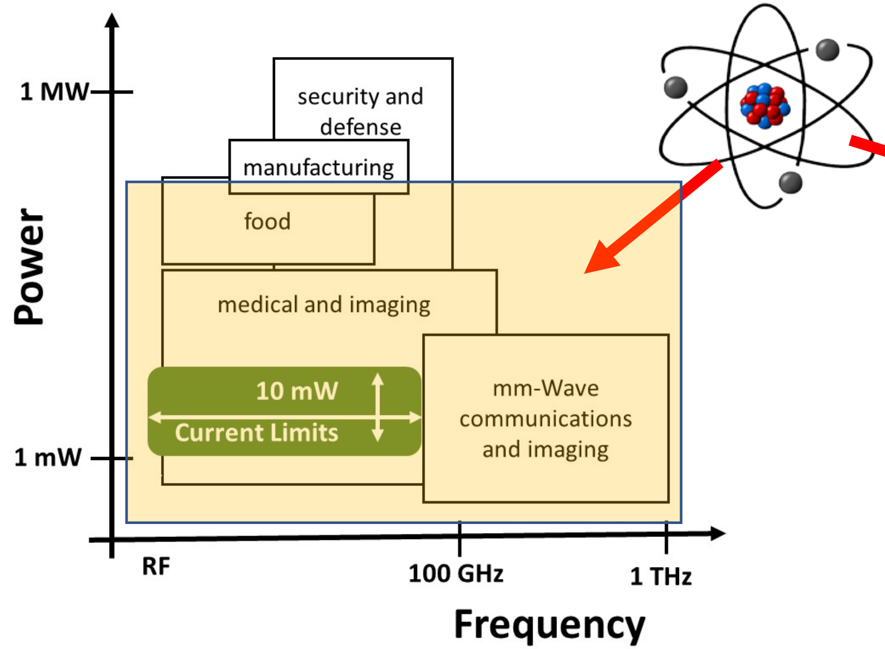
(FY18/19)

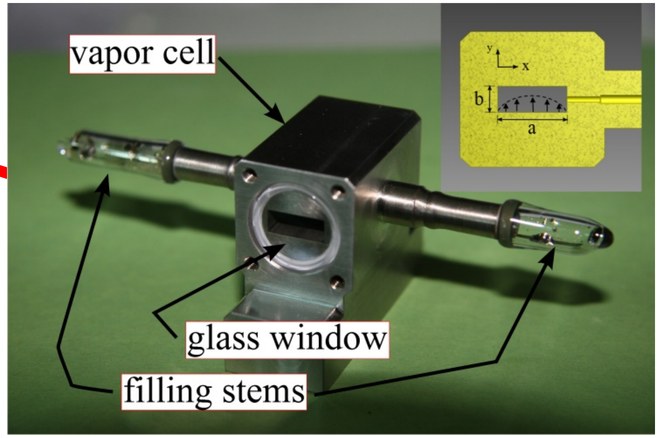
SI Traceable Power

We now have a SI traceable E-field measurement.

What else can we do?

NEW Atom-Based SI traceable Power Measurements.





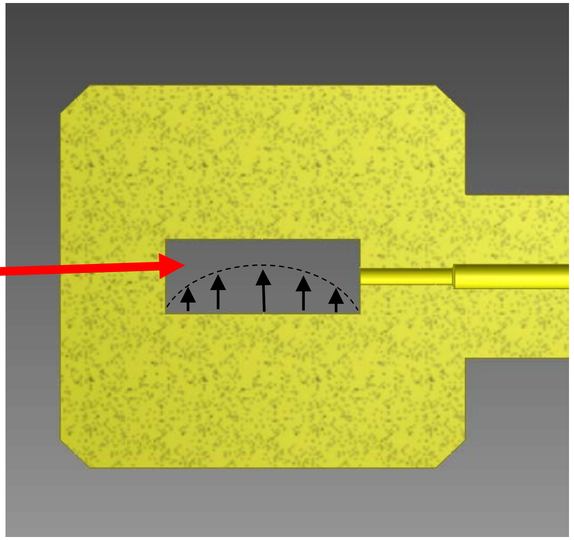
SI Traceable Power

TE$_{10}$ mode in rectangular waveguide

only allowed mode at measurement frequency

$$\vec{E} = E_0 \sin\frac{\pi x}{a}\left\{e^{-j\beta z} + \Gamma e^{j\beta z}\right\}\hat{y}$$

½ sinusoid in x, constant in y, partial standing wave in z



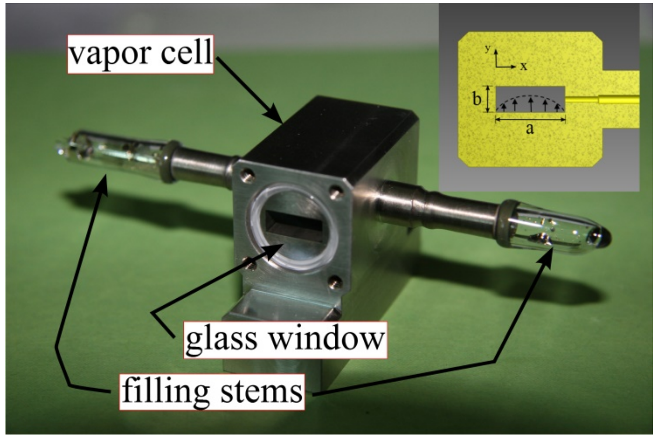
Transmitted Power

$$P_{trans} = E_0^2 \frac{ab}{4}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{1-\left(\frac{c}{2af}\right)^2}$$

Depends on E, physical constants (ε_0, μ_0, c), and geometry (a,b)

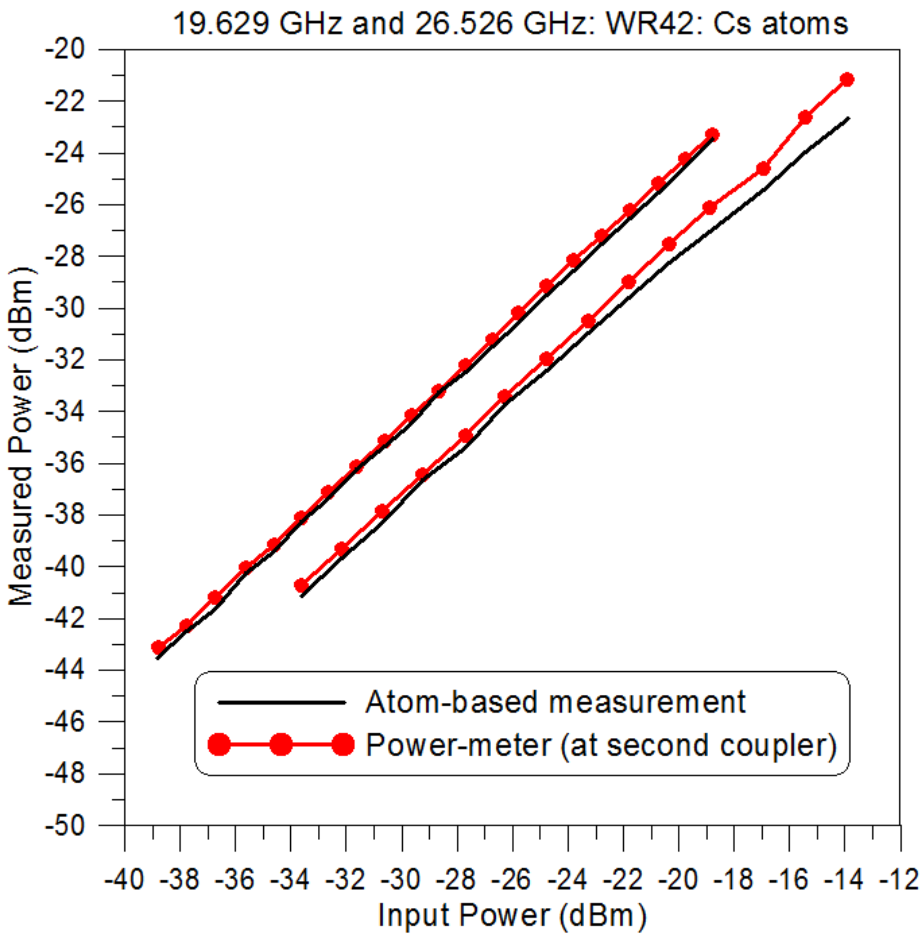
We measure E with the Rydberg atoms and power is traceable to Planck's constant.

SI Traceable Power



Transmitted Power

$$P_{trans} = E_0^2 \frac{ab}{4} \sqrt{\frac{\varepsilon_0}{\mu_0}} \sqrt{1 - \left(\frac{c}{2af}\right)^2}$$



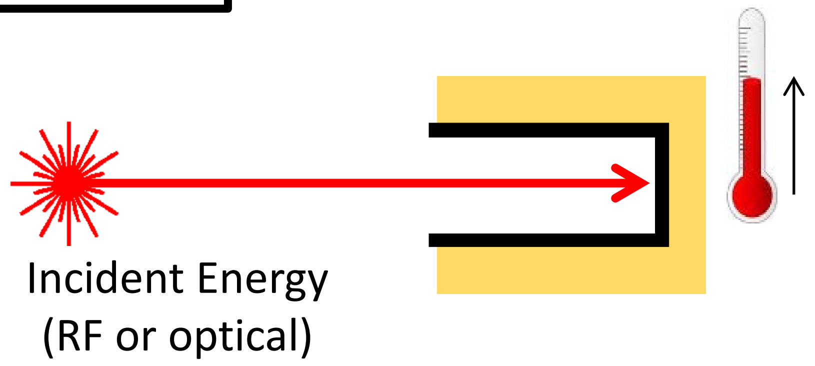
National Institute of Standards and Technology
U.S. Department of Commerce

CTL Communications Technology Laboratory

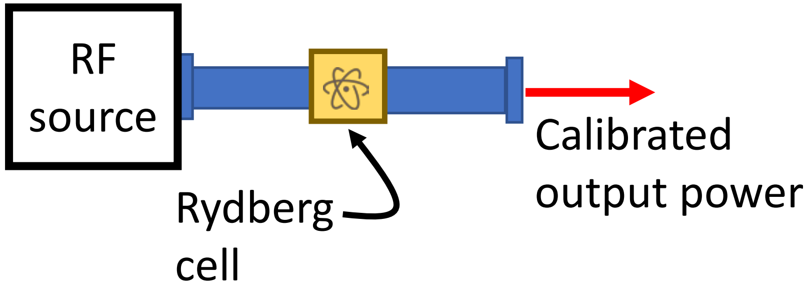
SI Traceable Power: *New Paradigm--Calibrated Source*

Current State of the Art

- Energy meter
- Absorption-based
- Energy $\propto \Delta T$
- Calibration through the power meter



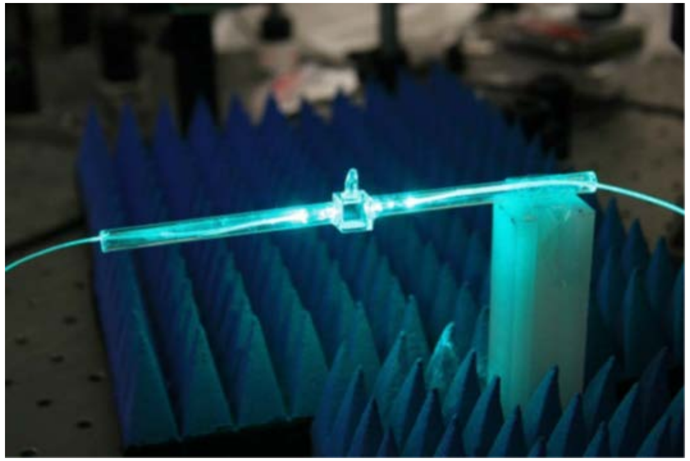
Real-time “*in situ*” traceability



Relies on VNA in calibration

Summary

Fundamentally new approach for E-field and Power measurements



<u>**E-Fields**</u>

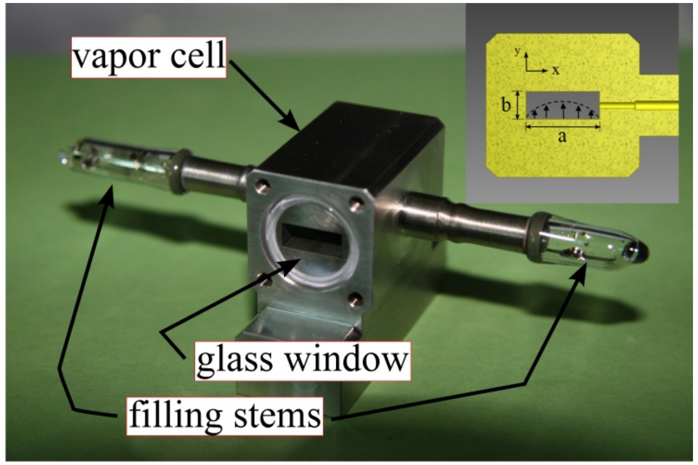
•<u>**Broadband probe/sensor**</u>**: 10 MHz-to-500 GHz (possibly to 1 THz)**

•Will allow direct SI units linked RF electric field (*E*-field) measurements

•<u>Would provide RF field measurements independent of current techniques</u>

•Very small and compact probe: fiber-coupled atom-based probe

•Measure *weak* and *large* E-field strengths over a large range of frequencies :
< 1 μV/m and > 10 kV/m:



<u>**POWER**</u>

•SI traceable Power measurements

•Calibrations above 110 GHz

•Real-time power calibrations

The bottom line is that we would be developing a measurement technique that could be applied to various form factors and applications.

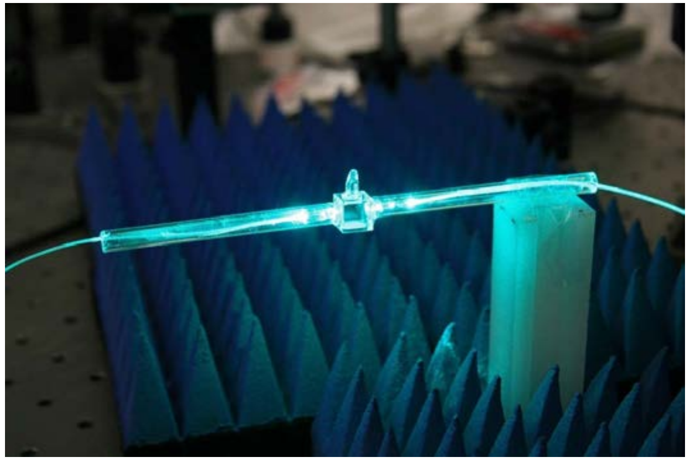
Journal Publications on Rydberg Atom Sensors

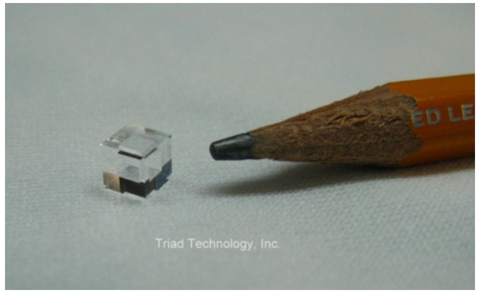
1. Holloway, et al. , “Sub-Wavelength Imaging and Field Mapping via electromagnetically induced transparency and Autler-Townes Splitting In Rydberg Atoms,” *Applied Physics Letters*, vol.1 104, 244102, 2014.
2. Holloway, et al., “Broadband Rydberg Atom-Based Electric-Field Probe/Sensor: From Self-Calibrated Measurements to Sub-Wavelength Imaging,” *IEEE Trans. on Antenna and Propagation*, vol. 62, no. 12, 6169-6182, 2014.
3. Gordon, et al., “Millimeter-Wave Detection via Autler-Townes Splitting In Rubidium Rydberg Atoms”, *Applied Physics Letters*, vol. 105, 024104, 2014.
4. Anderson, et al., “Two-photon transitions and strong-field effects in Rydberg atoms via EIT-AT,” Applied Physics Review, vol. 90, 043419, 2014.
5. Fun et al. “Effect of Vapor Cell Geometry on Rydberg Atom-based Radio-frequency Electric Field Measurements”, *Physical Review Applied*, vol. 4, 044015, 2015.
6. Anderson et al., “Optical measurements of strong microwave fields with Rydberg atoms in a vapor cell”, *Physical Review Applied*, 5, 034003, 2016.
7. Simons et al., “Using frequency detuning to improve the sensitivity of electric field measurements via electromagnetically induced transparency and Autler-Townes splitting in Rydberg atoms”, *Applied Physics Letters*, 108 174101, 2016.
8. Simons, et al. “Simultaneous use of Cs and Rb Rydberg atoms for dipole moment assessment and RF electric field measurements via electromagnetically induced transparency”, J. Appl. Phys., 102, 123103, 2016.
9. Holloway, et al., “Atom-Based RF Electric Field Metrology: From Self-Calibrated Measurements to Sub-Wavelength and Near-Field Imaging”, *IEEE Trans. on Electromagnetic Compat., Special Issue of Near-Field Imaging*, vol. 59, no. 2, pp. 717-728, April 2017.
10. Holloway, et al., “Electrical Field Metrology for a New SI: A Study of Systematic Measurement Uncertainties in Electromagnetically Induced Transparency in Atomic Vapor", *J. of Applied Physics*, May, 2017.
11. Anderson, et al., “Optical measurements of plasma fields using Rydberg atoms on electromagnetically induced transparency”, J. of Applied Phys, 2018.
12. Simons, et al., “Electromagnetically Induced Transparency (EIT) and Autler-Townes (AT) splitting in the Presence of Band-Limited White Gaussian Noise”', *J. of Applied Physics*, vol. 123, 203105, 2018.
13. Holloway, et al., “A New Quantum-Based Power Standard: Using Rydberg Atoms for a SI-Traceable Radio-Frequency Power Measurement Technique in Rectangular Waveguides”, *Applied Phys. Letters*, vol. 113, 094101, 2018.
14. Simons, et al., “Fiber-coupled vapor cell for a Rydberg atom-based electric field sensor”, *Applied Optics*, vol. 57, no. 22, pp. 6456-6460, 2018.
15. Simons, et al, “A Rydberg Atom-Based Mixer: Measuring the Phase of a Radio Frequency Wave,” *Applied Physics Letters*, vol. 114, 114101, 2019.
16. Gordon, et al., “Weak Electric-Field Detection with Sub-1 Hz Resolution at Radio Frequencies Using a Rydberg Atom-Based Mixer, *AIP Advanced*, vol. 9, 045030, 2019.
17. Holloway, et al. “Quantum Physics Meets Music: A ``Real-Time" Guitar Recording Using Rydberg-Atoms and Electromagnetically Induced Transparency," *AIP Advanced*, vol. 9, 065110, 2019.

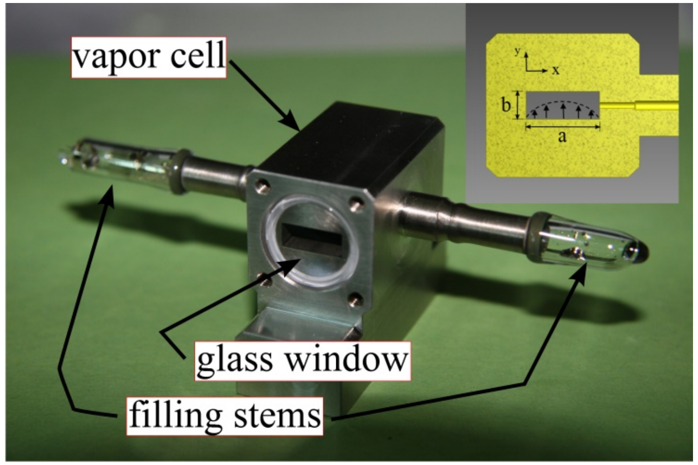
Conference Papers on Rydberg Atom Sensors

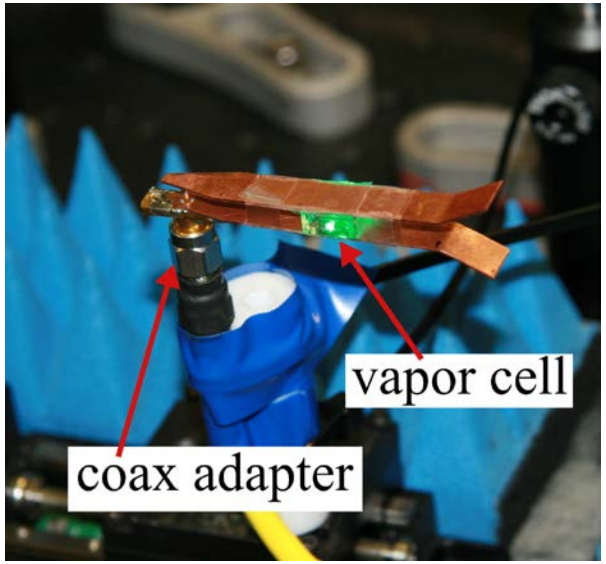
1. Gordon, et al, “Quantum-Based SI Traceable Electric-Field Probe,” Proc of *2010 IEEE International Symposium on Electromagnetic Compatibility*, July 25-30, 321-324, July 2010.
2. Holloway, et al., “Broadband Rydberg Atom Based Self-Calibrating RF E-Field Probe”, *2014 XXXIth URSI General Assembly and Scientific Symp*., Beijing, China, Aug, 2014.
3. Holloway, et al., “Atom-Based RF Electric Field Measurements: An Initial Investigation of the Measurement Uncertainties", *EMC 2015: Joint IEEE International Symposium on Electromagnetic Compatibility and EMC Europe*, Dresden, Germany, pp. 467-472, 2015.
4. Holloway, et al., “Atom-Based RF Field Probe: From Self-Calibrated Measurements to Sub-Wavelength Imaging”, *IEEE NANO 2015: 15th International Conference on Nanotechnology*, Rome, Italy, 2015.
5. Simons, et al., “Atom-based RF electric field metrology above 100 GHz”, *SPIE: Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications*, Feb, 2016.
6. Holloway, et al., “Using Cs and Rb Rydberg Atoms Simultaneously for SI-Traceable RF Electric-Field Metrology via Electromagnetically Induced Transparency”, *EMC Europe 2016*, Aug. 2016.
7. Holloway, et al., “Development of A New Atom-Based SI Traceable Electric-Field Metrology Technique", *AMTA*, 2017.
8. Holloway, et al., “Development and Applications of a Fiber-Coupled Atom-Based Electric Field Probe”, *EMC Europe 2018*, Amsterdam, NL, Aug. 2018.
9. Simons, et al., “An investigation of the uncertainties in the EIT/AT based approach for E-field metrology”, *EMC Europe 2018*, Amsterdam, NL, Aug. 2018.
10. Anderson, et al., “High-resolution antenna near-field imaging and sub-THz measurements with a small atomic vapor-cell sensing element”, *GSMM18*, Boulder, Co, 2018.

??Questions??




Triad Technology, Inc.


vapor cell
glass window
filling stems
y
x
b
a


vapor cell
coax adapter