Future of Vector Network Analysis

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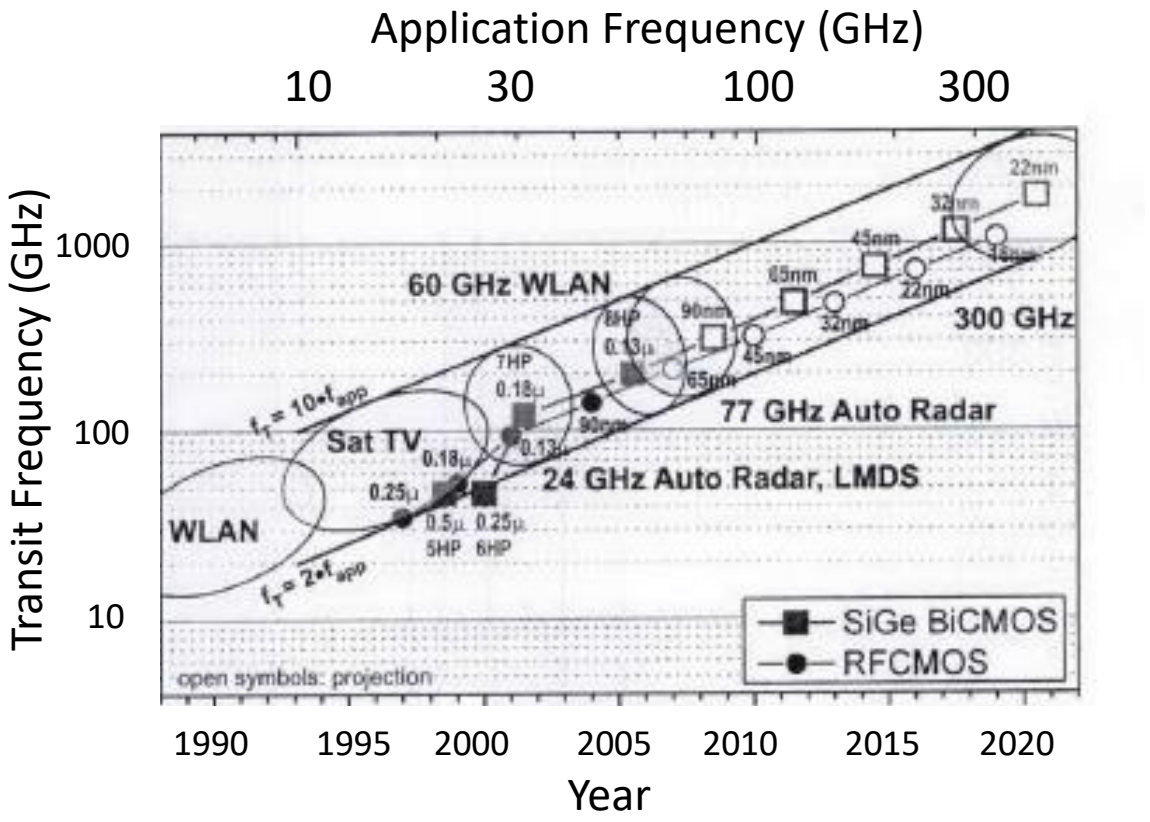
U.S. Department of Commerce

CTL Communications Technology Laboratory

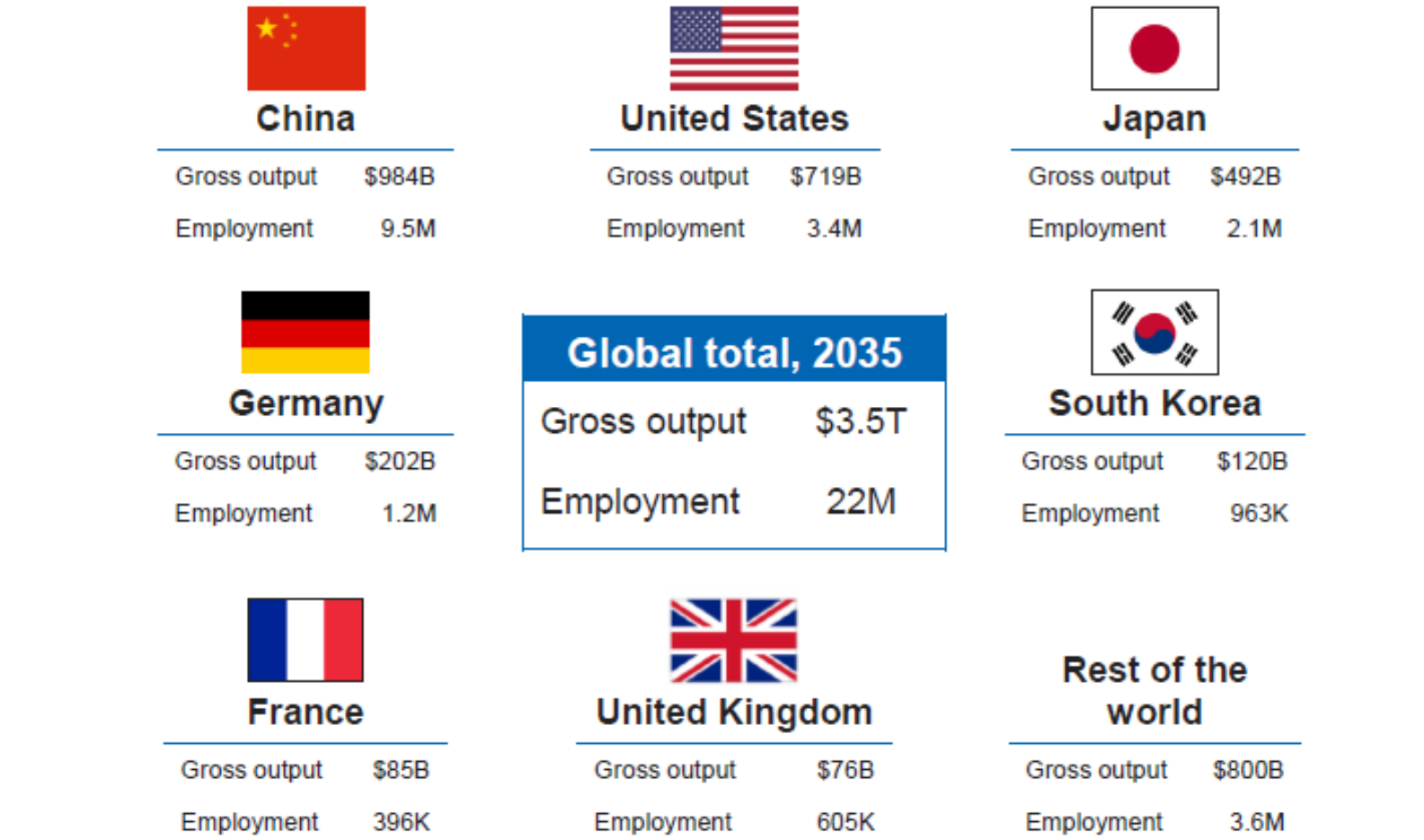
Integrated Circuits Drive Wireless Communications



We Cannot Take the Integrated Circuit for Granted at mmWaves

Next 15 Years of Wireless Manufacturing by Country

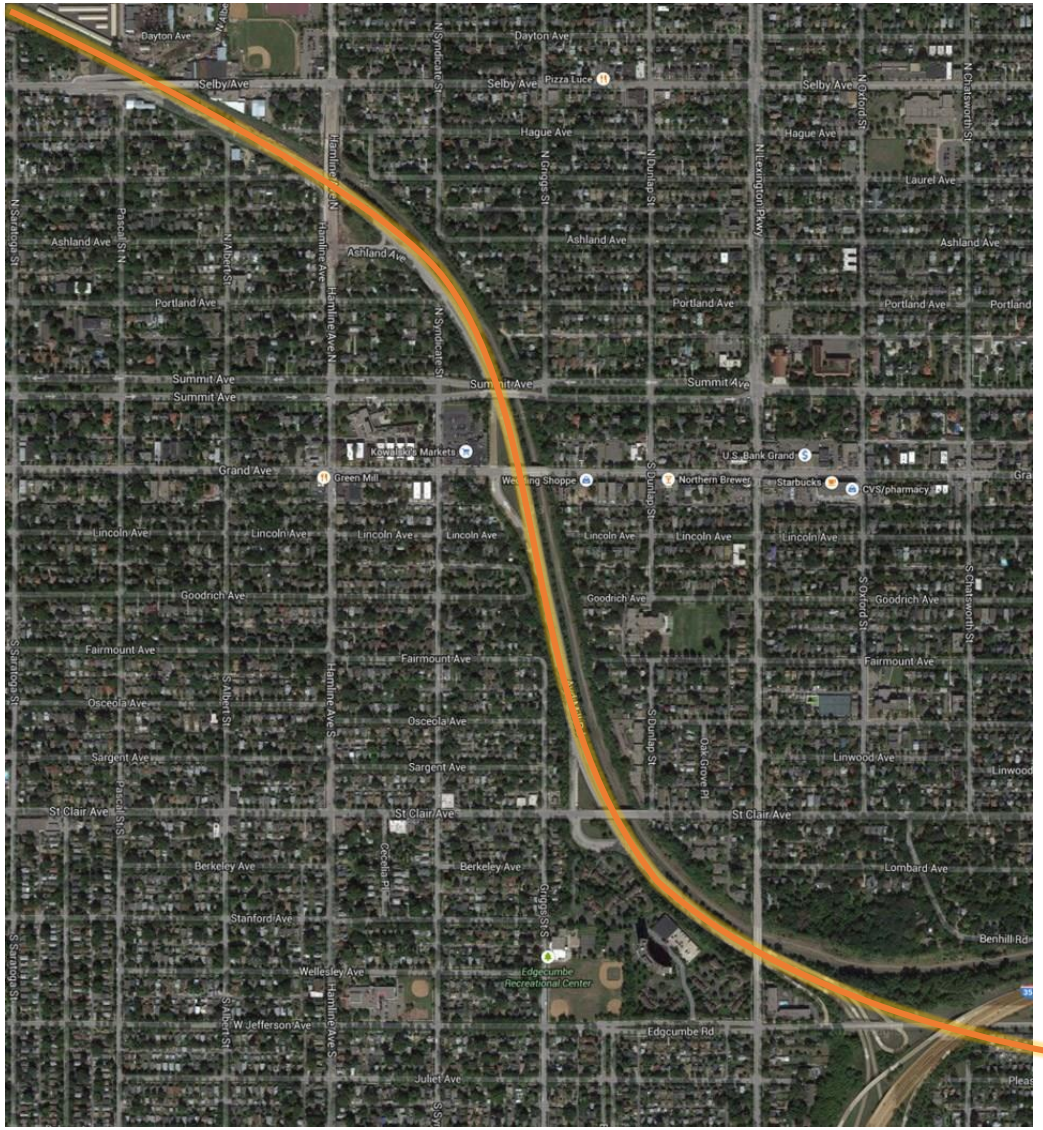
The United States still dominates mmWave manufacturing



Notes: K = thousand, M = million, B = billion, T = trillion
Source: IHS

Enables $12.3T in Total Economic Growth (2020-2035)

Communication Providers Want Speed of Fiber on Your Phone



Federal Communications Commission **FCC 19-30**

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Use of Spectrum Bands Above 24 GHz For Mobile Radio Services	)	GN Docket No. 14-177
	)	

FIFTH REPORT AND ORDER

Adopted: April 12, 2019 **Released: April 15, 2019**

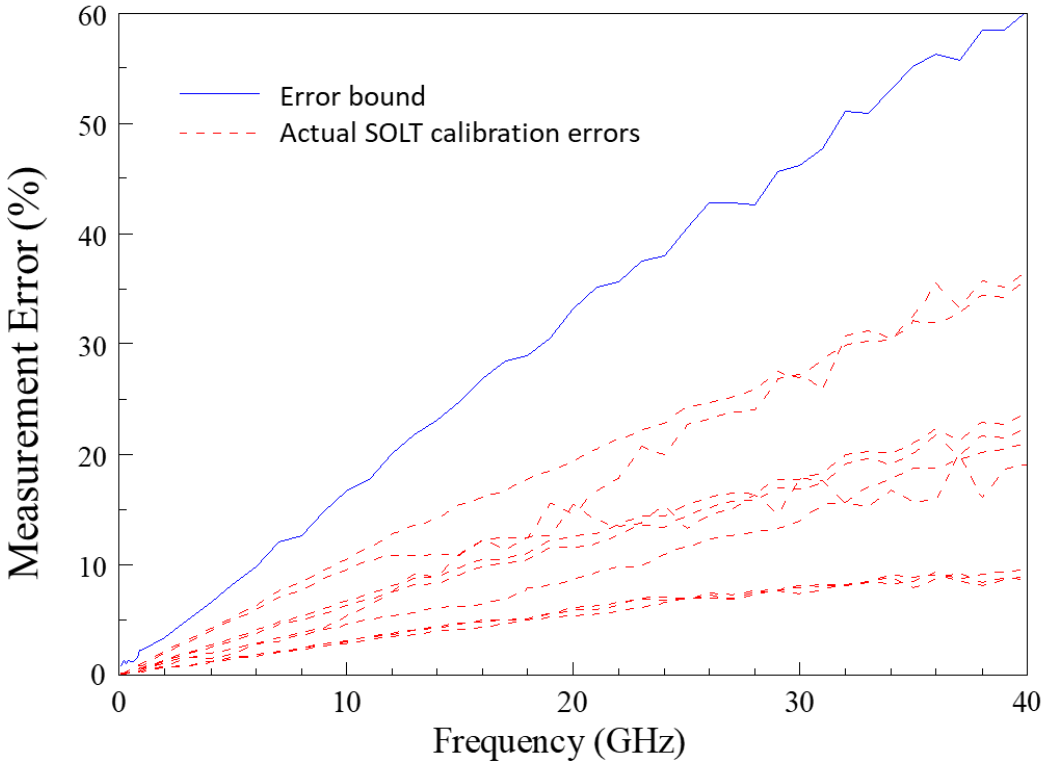
By the Commission: Chairman Pai and Commissioners O'Rielly and Carr issuing separate statements; Commissioners Rosenworcel and Starks approving in part, dissenting in part, and issuing separate statements.

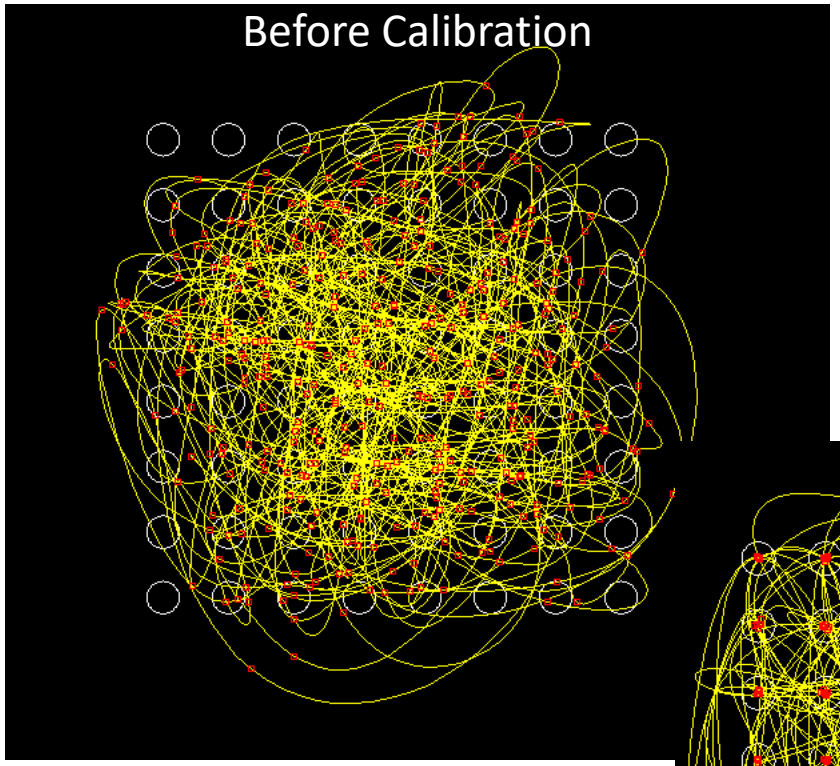
I. INTRODUCTION

1. Today, we take two actions that continue our efforts to make available millimeter wave (mmW) spectrum, at or above 24 GHz, for fifth-generation (5G) wireless, Internet of Things, and other

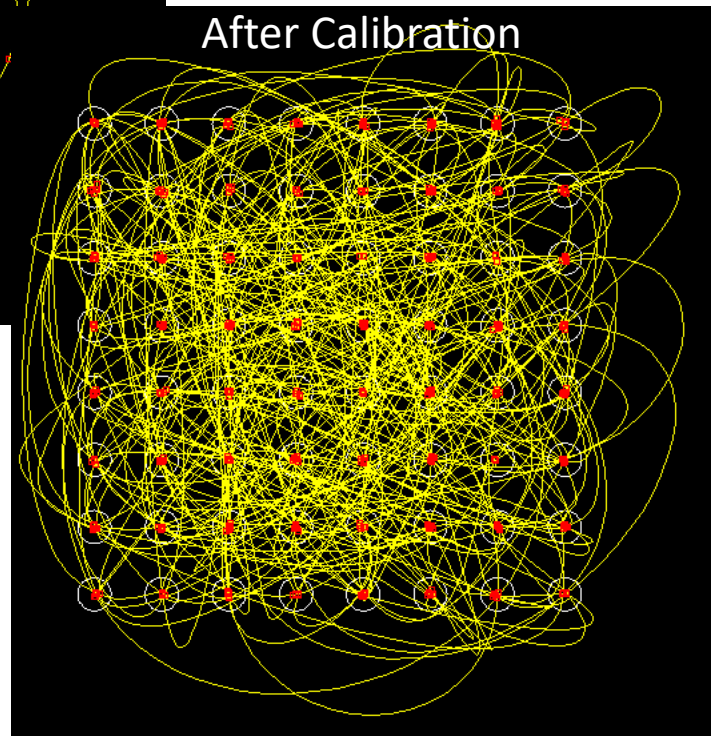
Millimeter-Waves *are* the Next Wireless Frontier

Measurements and Calibrations Matter at mmWaves

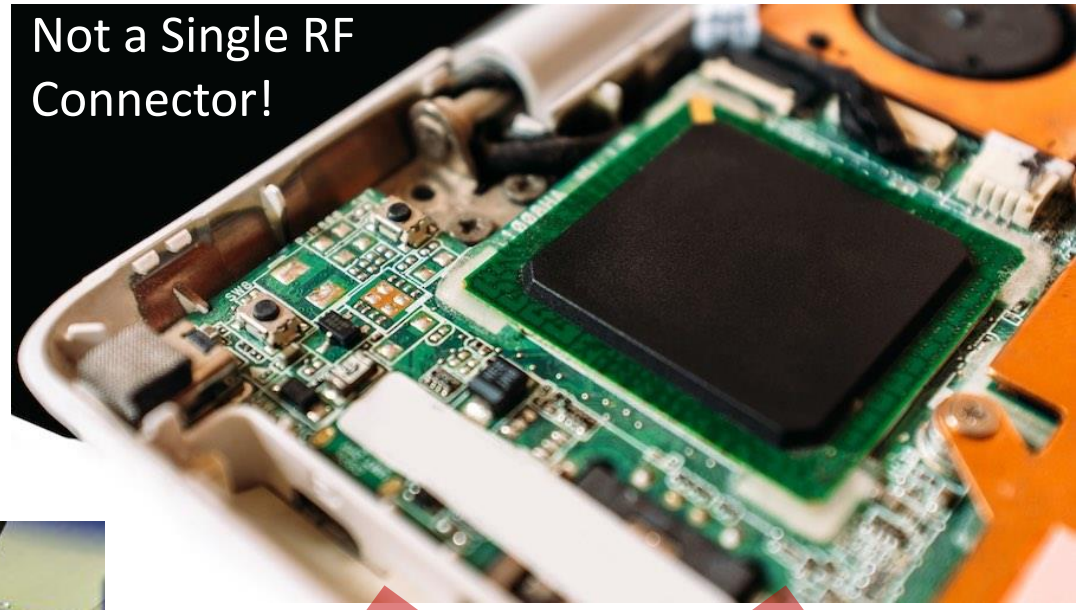


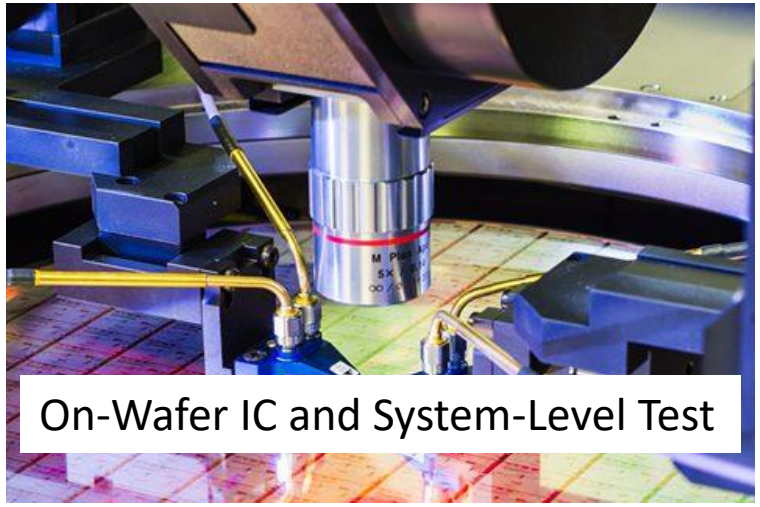


64 QAM at 44 GHz



mmWave Measurement Challenge of our Era





Transistor models IC Test System-Level Test End-to-End Verification

On-Wafer → Connectorized ← Free-Space

Goals for Vector Network Analysis in CTL

Project Calibration Reference Planes On-Wafer and to OTA Test

On-Wafer Measurements

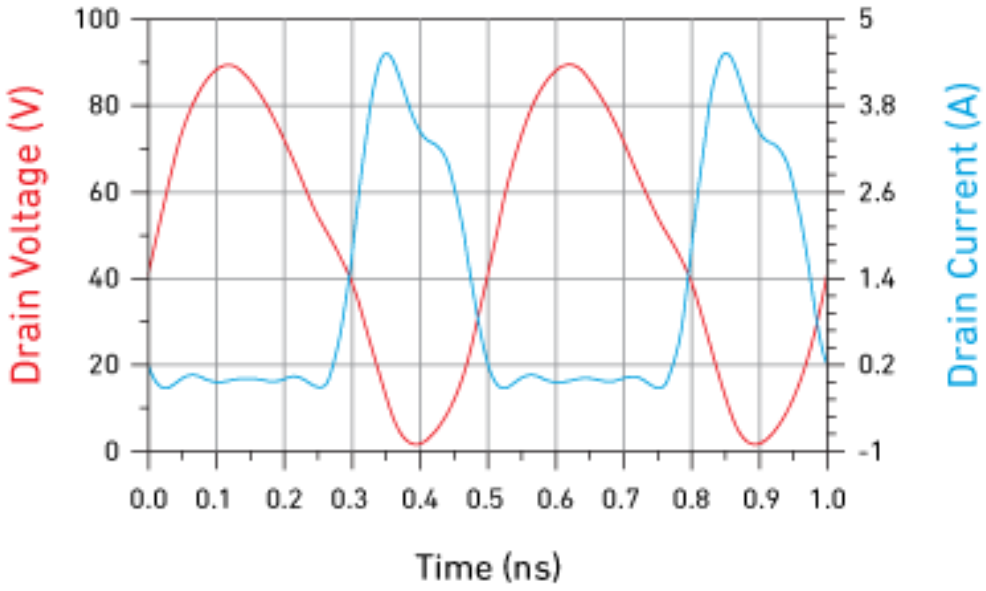
- Innovations in Calibration
- Support Device Models to System-Level Test
- State-Of-The-Art Instruments for US mmWave NR Manufacturers

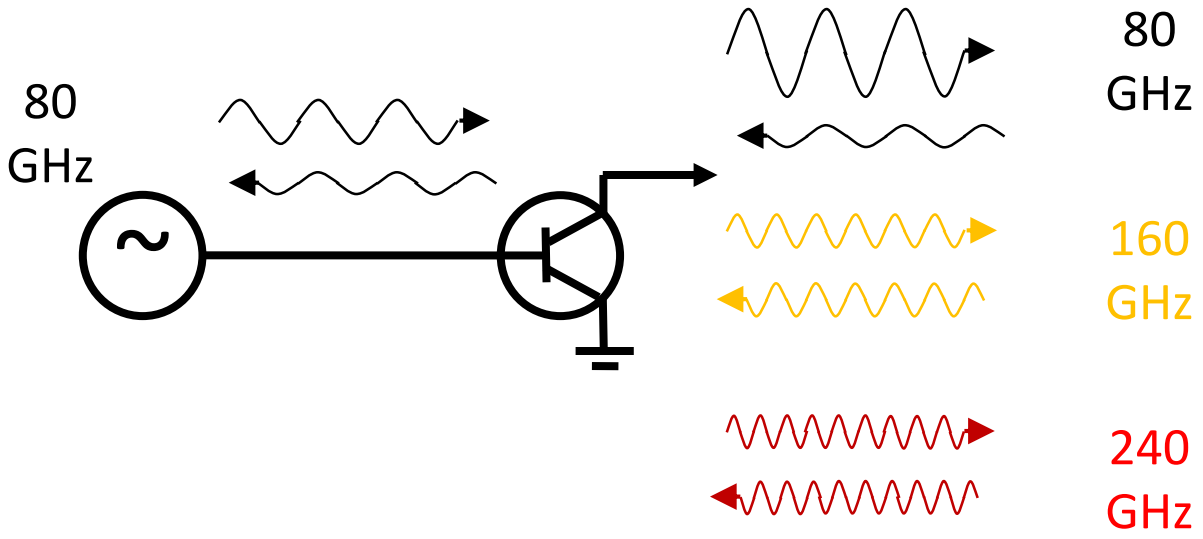
Vector Network Analysis

- Platform for Traceable System-Level Tests Across CTL
- Close the Connector-Less Gap

mmWave Design Extremely Complex

Accurate measurements are a must



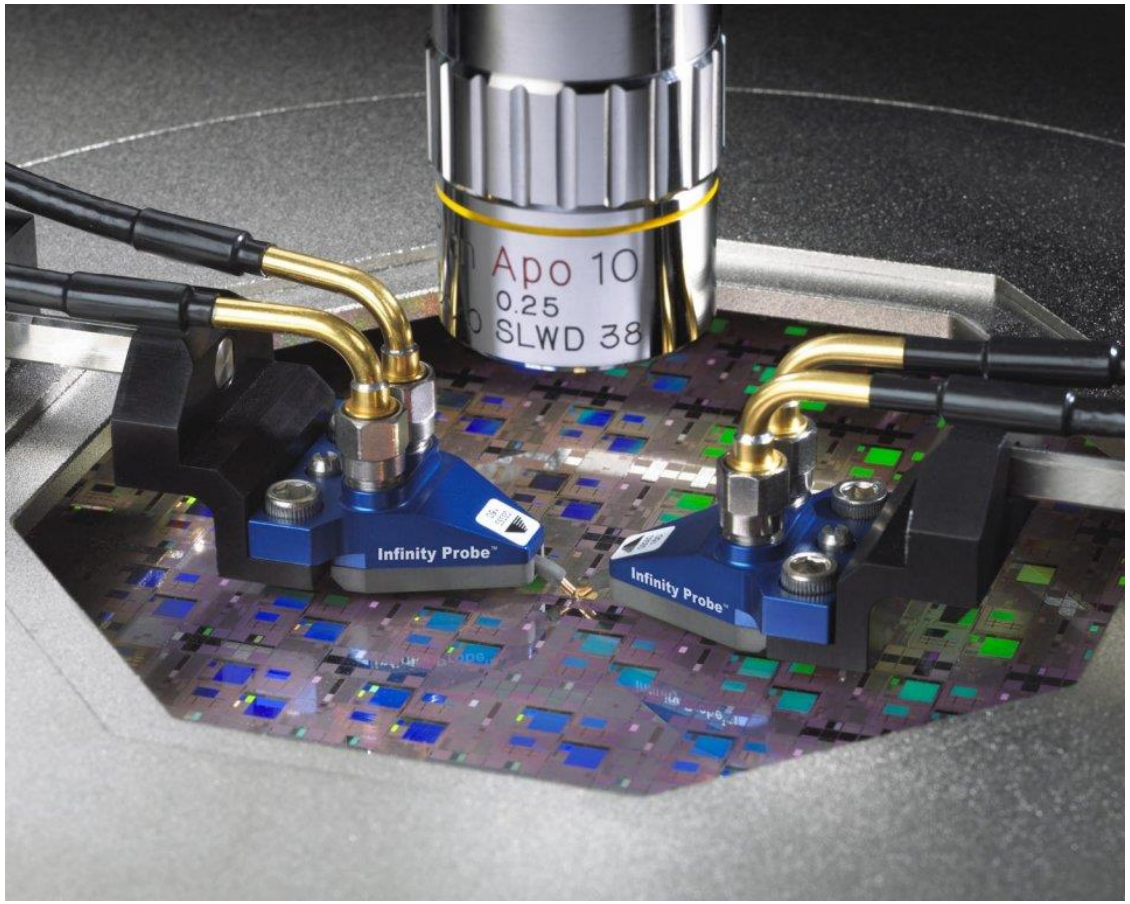


- Highly nonlinear operating states required for efficiency
- Characterize, capture, control and reuse harmonics
- Must maintain linearity

On-Wafer Measurement the Only Way to Test ICs

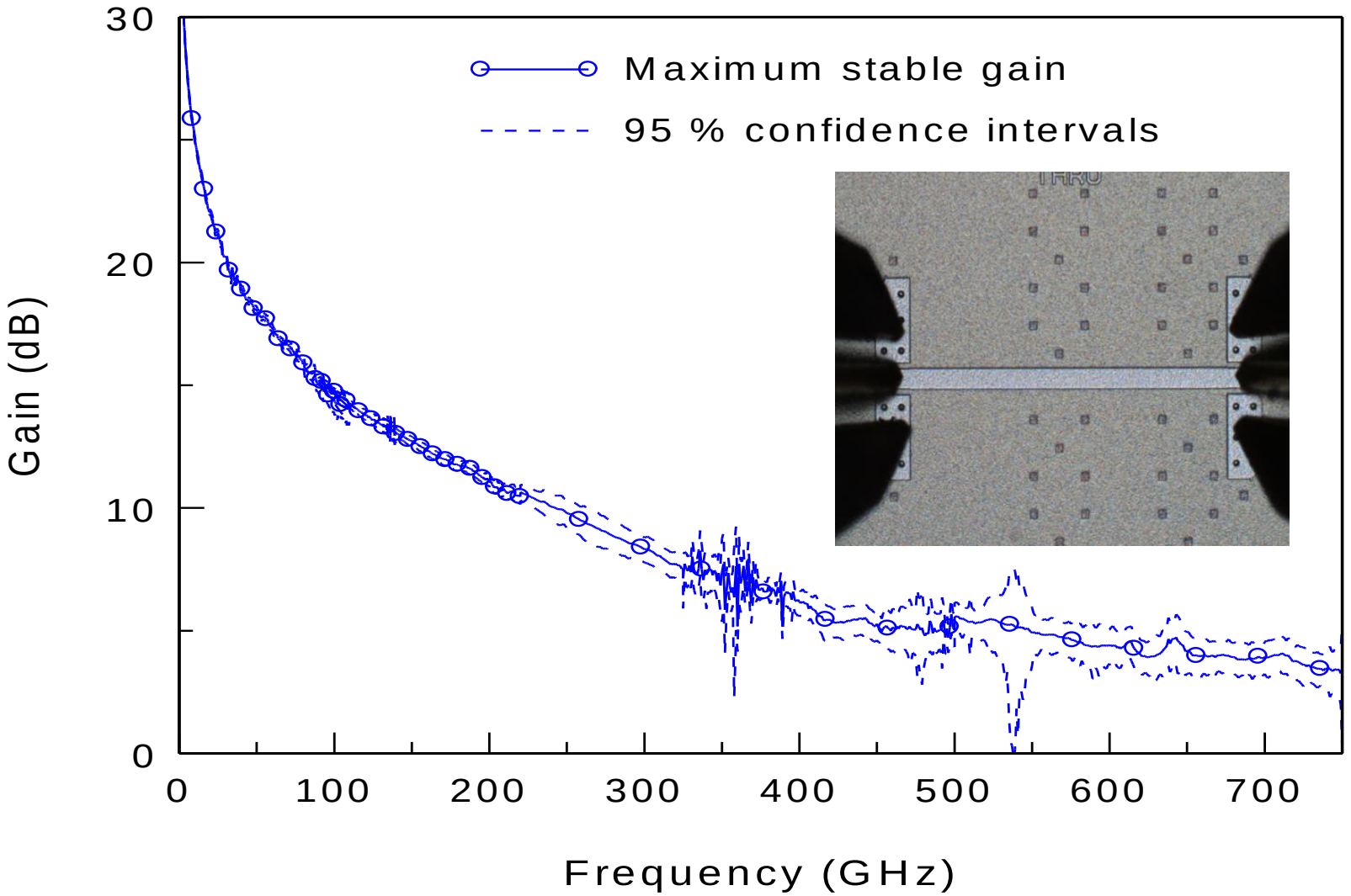
Yesterday

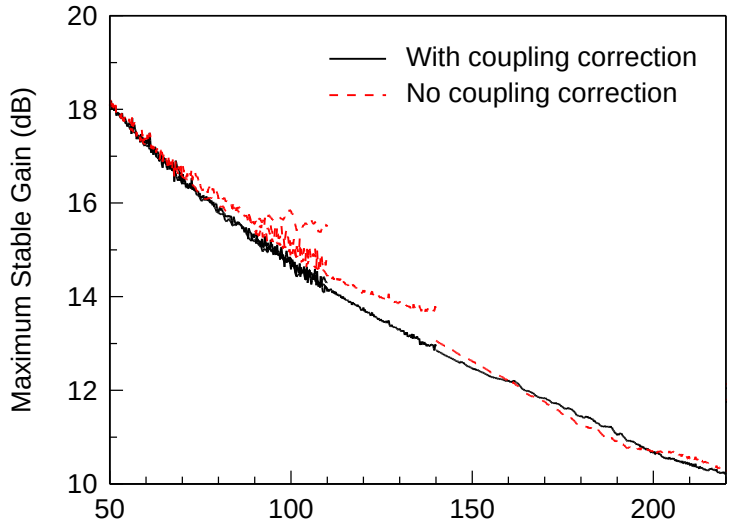
Today

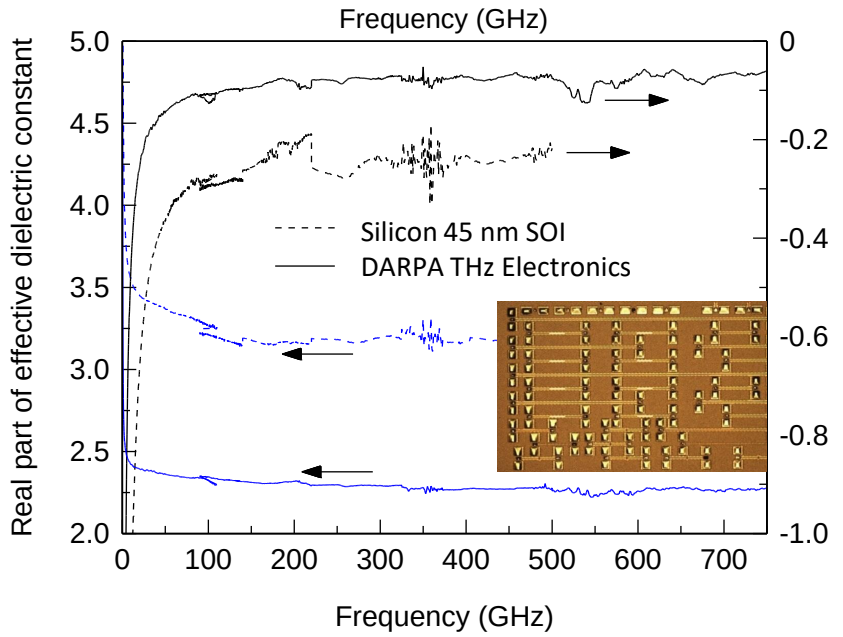


CTL On-Wafer Accomplishments

NIST On-Wafer Approaches Firmly Established as *the* Methods of Reference

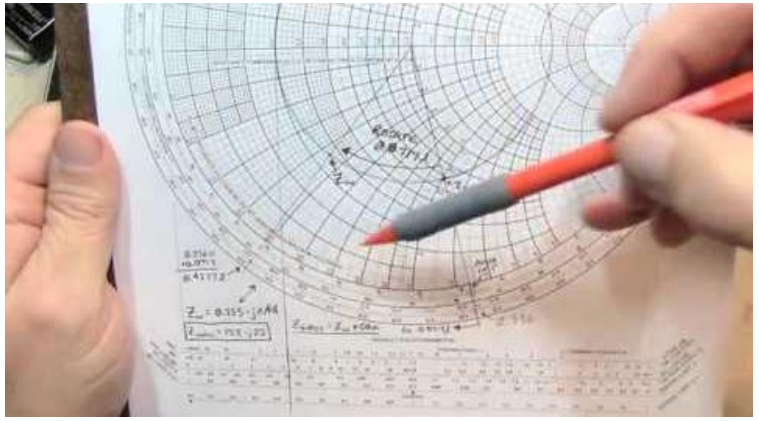






Microwave Design Strategy Evolved Greatly

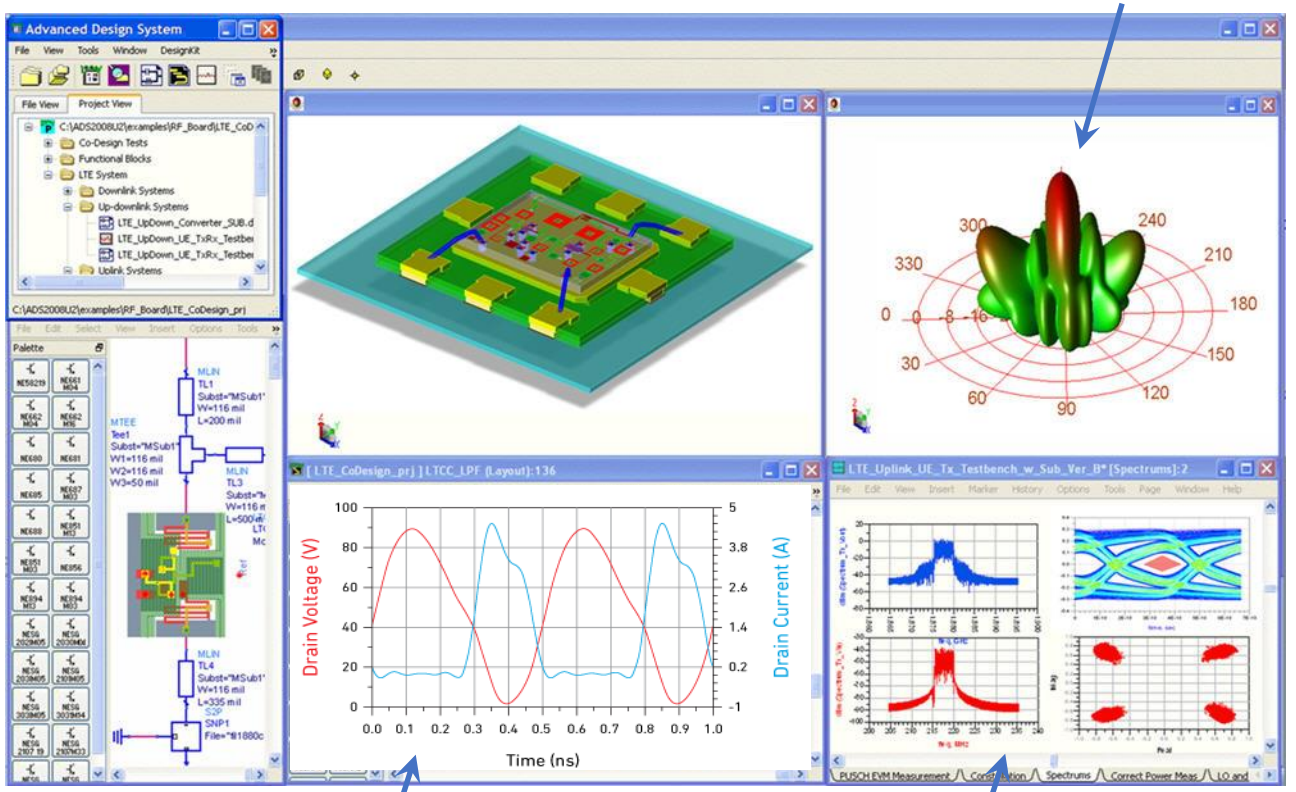
CTL Has Been Evolving Vector Network Analysis



Impedances, reflections and waves

50 Years Later

OTA
system-level behavior



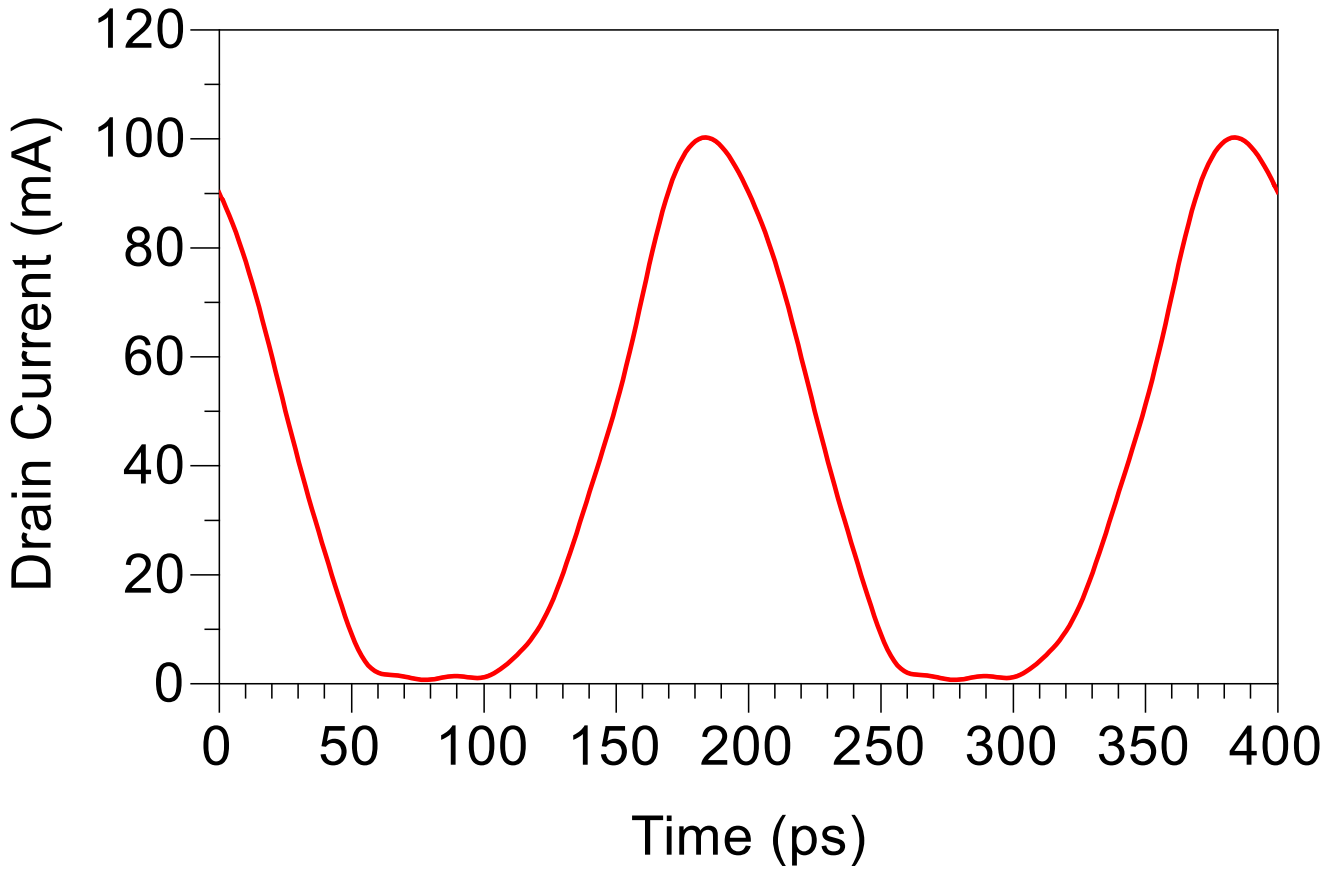
On-wafer
voltages and currents

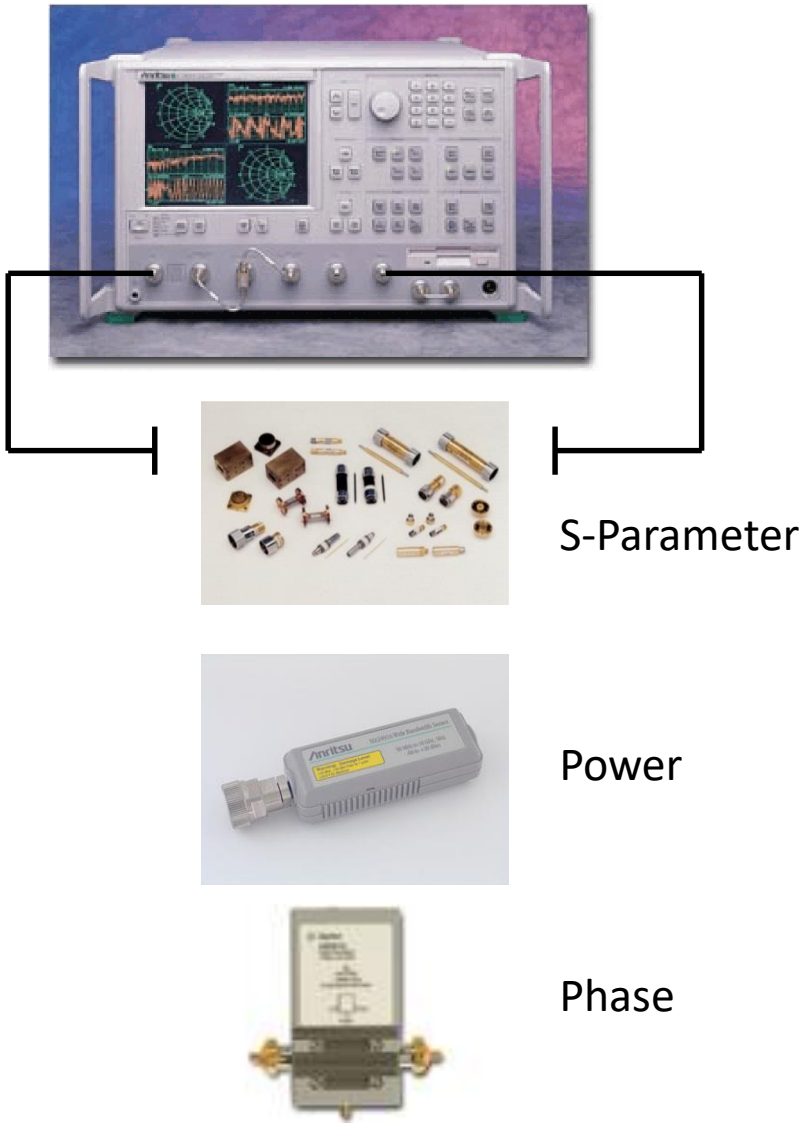
On-wafer
system-level behavior

Vector Network Analysis Today

Same network analyzer

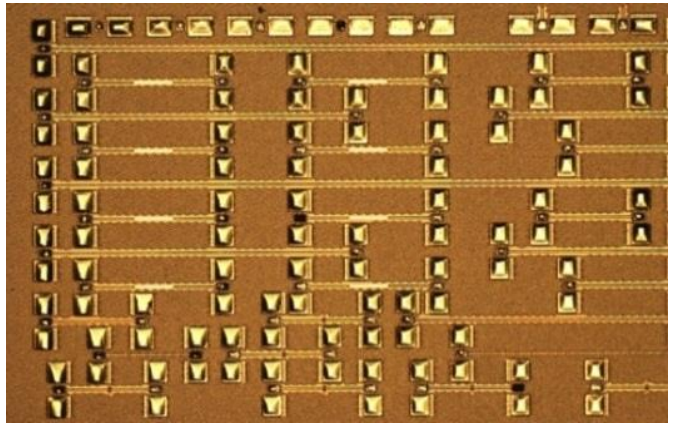
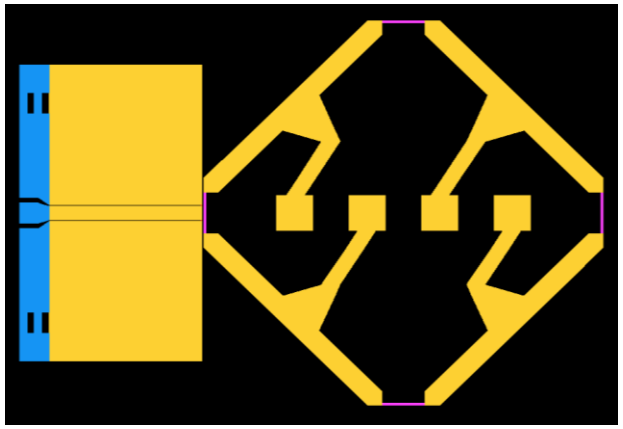
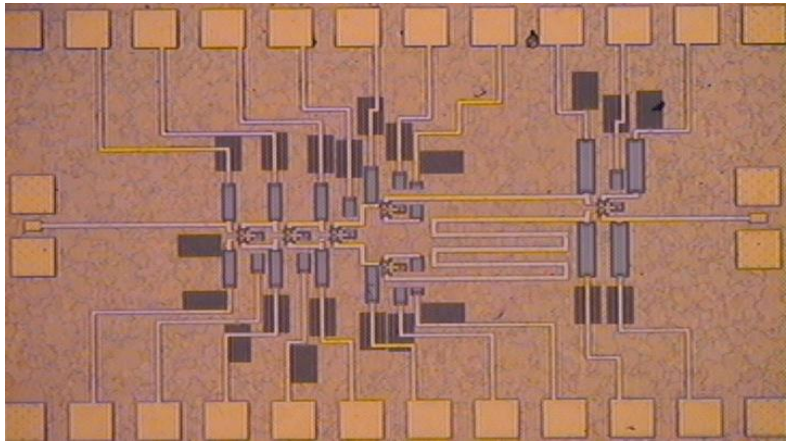
- S-parameter calibration
- **Add Power and Electrical-Phase calibration**





The Future of On-Wafer Vector Network Analysis

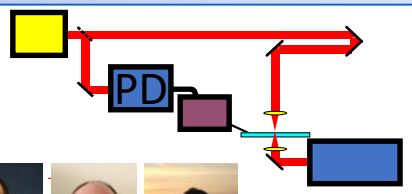
CTL Innovating in S-Parameters, Power and Electrical Phase

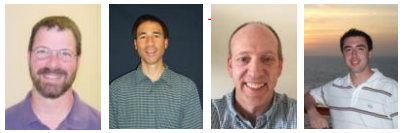
	Scattering-Parameter Calibration Kit	Power Meter	Electrical Phase Reference
Today			
Tomorrow			

A Conduit for Traceability Inside and Outside CTL

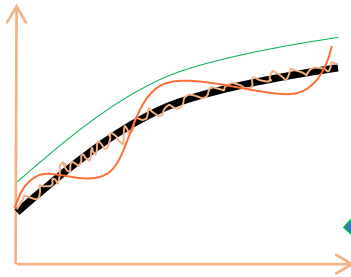
Vector Network Analysis Brings Power, Electrical Phase, Impedance and Waveforms to Remote Reference Planes

NIST Waveform Services



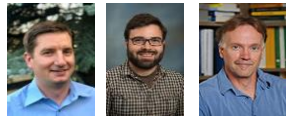


Electrical Phase



Correlated Uncertainty

$$\sum_Y = J \sum_X J^{\mathrm{T}}$$



Uncertainty

Microwave Power Services

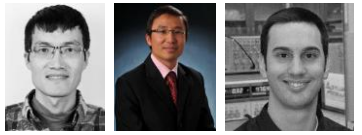
S-Parameter Services

Impedance

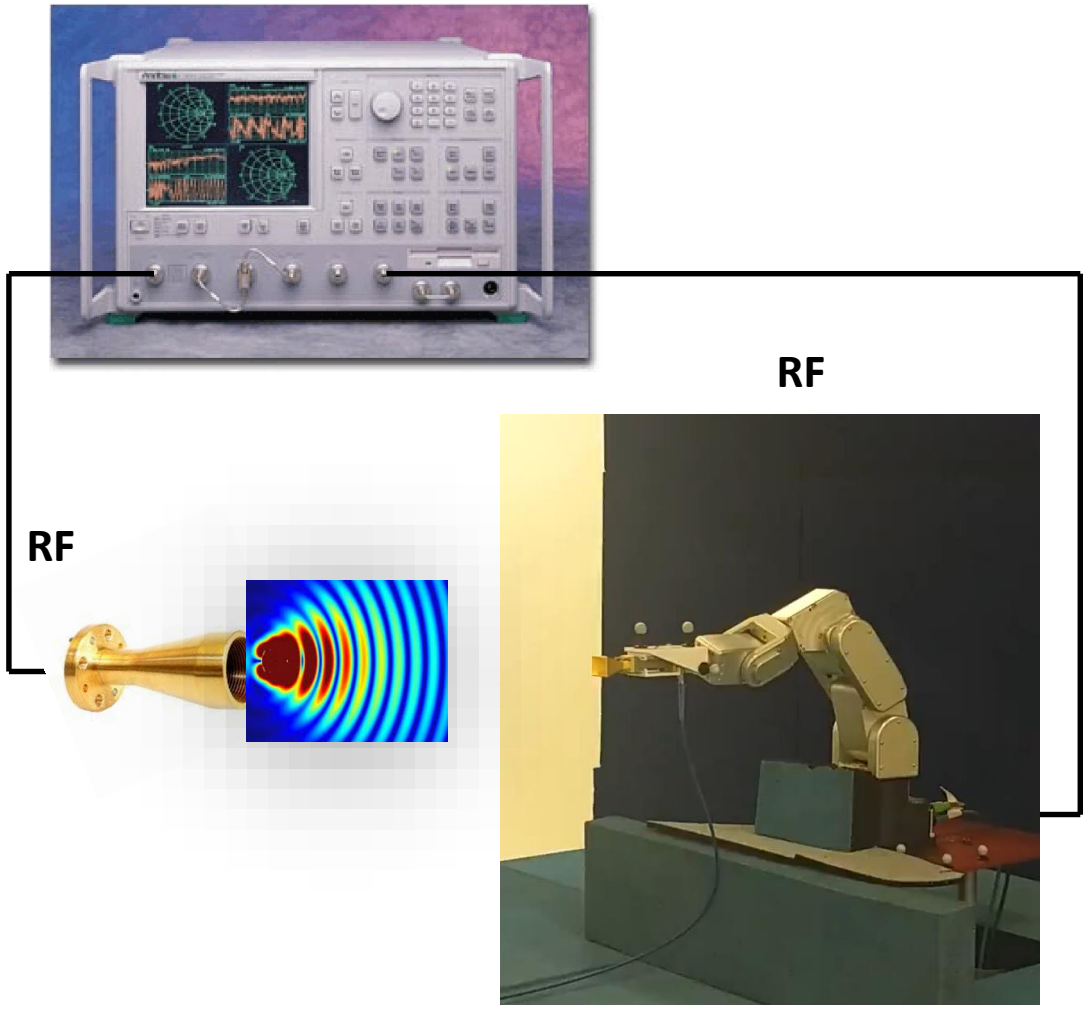
Vector Network Analyzer

Power

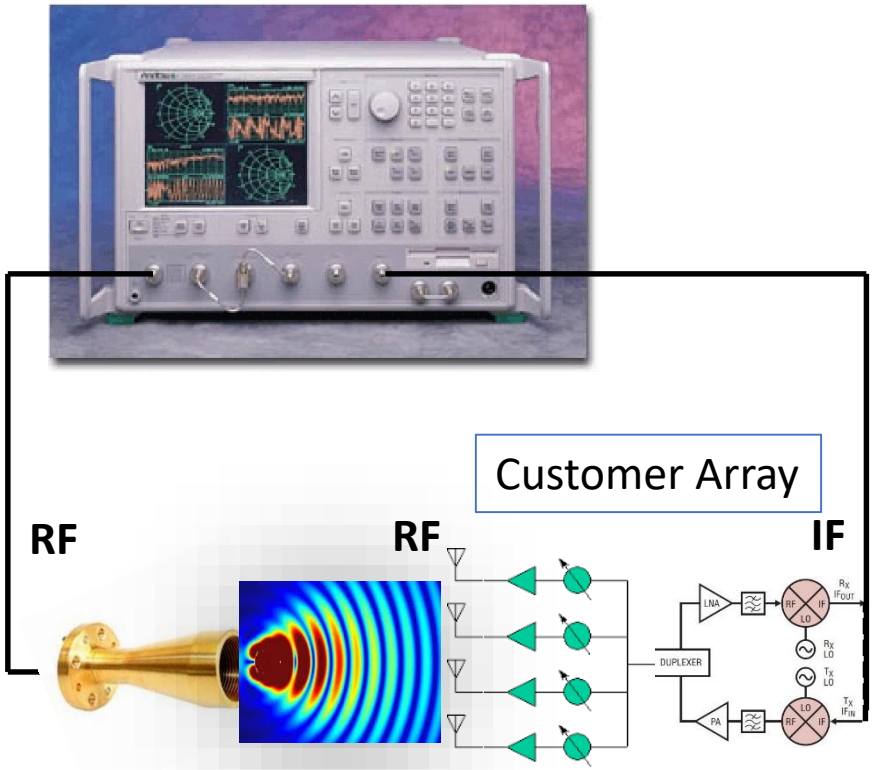
Microwave IC Design
Modulated Signal Quality
Free-Field Test



OTA System-Level Measurements



Characterize Fields



OTA Measurements

VNA Traceability For:

- Channel Distortion, AoA and Polarization
- Flexible RF-RF and RF-IF Measurements
- Multiple Traceable Modulated Signals

Some Outcomes of CTL Vector Network Analysis

On-Wafer Measurements

- On-Wafer Device-Modeling Capability with Uncertainty
  - GaN manufacturer asks for models with uncertainty
- On-Wafer Impedance-Power-Phase Calibration Kits
  - Power Standard with 100 GHz BW
  - Fabricated experimental on-wafer phase reference
- On-Wafer Instruments in a Probe
  - Self-calibrating, connector-less, 1 THz BW

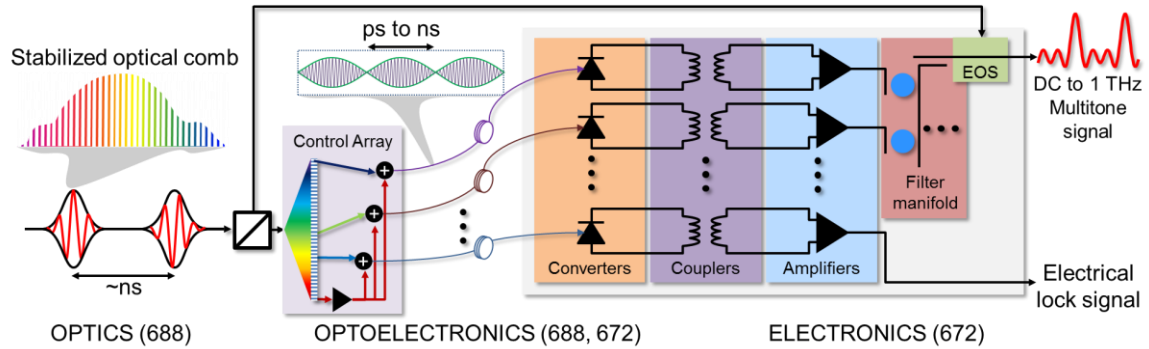
VNA Measurement Methods

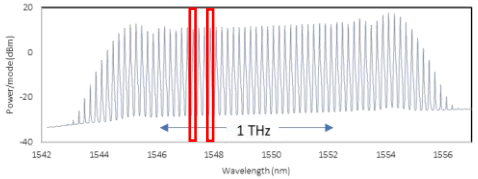
- Improved VNA Synchronization for Accurate Modulated-Signal Measurement
  - Using similar technique Keysight announces accurate EVM measurements with VNA
- Traceable Characterization of any Signal AWG can Generate
  - Arbitrary frequency grid, dramatically improved sync/SNR
- Investing in Calibration Services
  - 4 New Staff Members
  - Waveform calibrations report both conventional and correlated uncertainties
  - Power and Scattering-Parameter Services migrating toward VNA transfers and correlated uncertainties

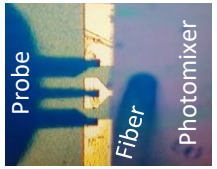
Impact on Instrument Makers

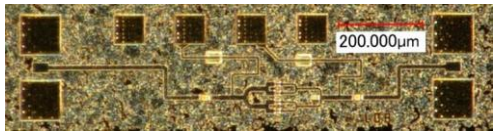
- Keysight adopts calibrated NIST Photodiodes for oscilloscope and electrical-phase traceability
- Instrument Maker adds electrical phase reference and asks for NIST traceability
- Instrument Maker announces 220 GHz VNA with no Coaxial Calibration Kit
  - Joint experiments to investigate direct NIST photodiode calibrations
  - Need 220 GHz calibration kits supporting on-wafer impedance-power-phase

The Future of Vector Network Analyzers

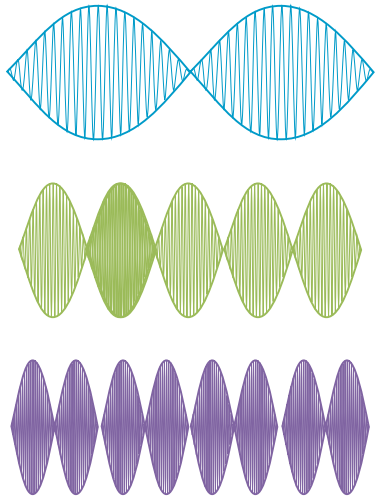




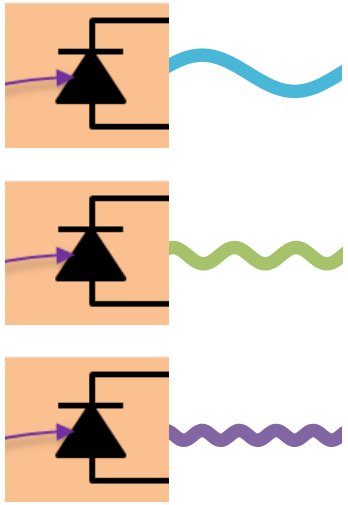




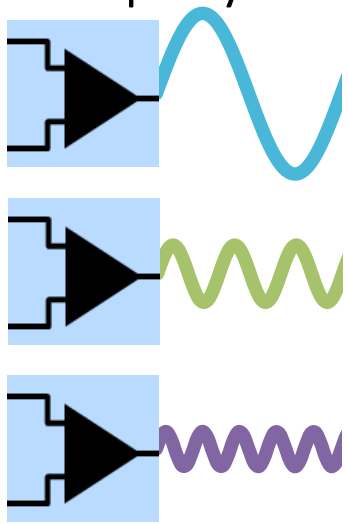
1. Control



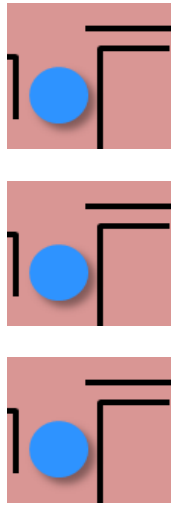
2. Convert



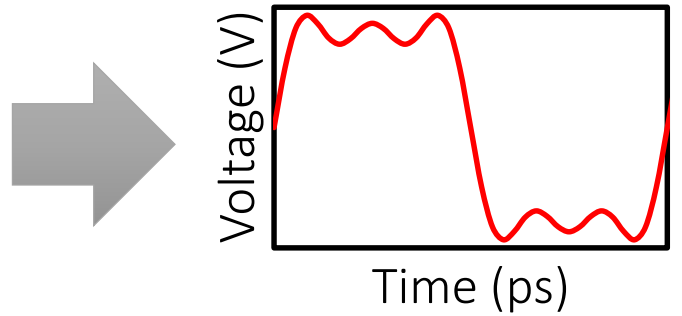
3.1 Amplify



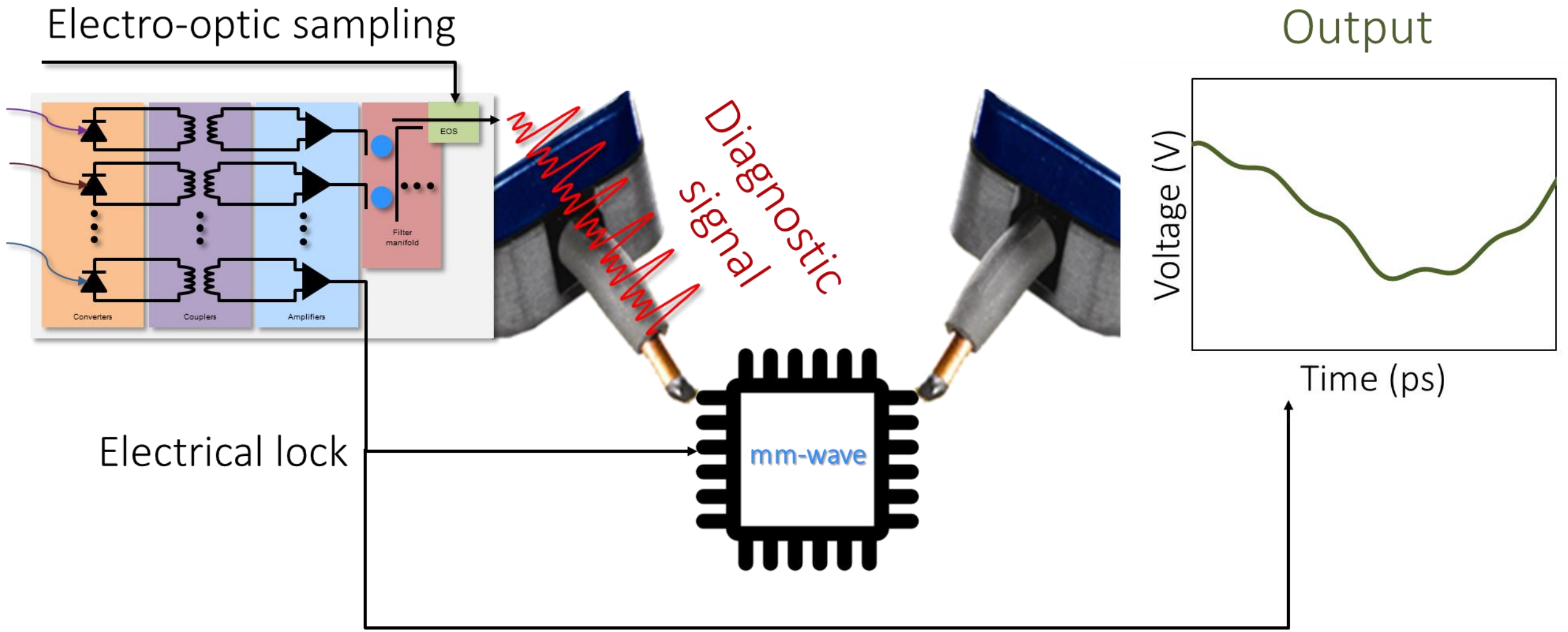
3.2 Combine



Diagnostic Signal

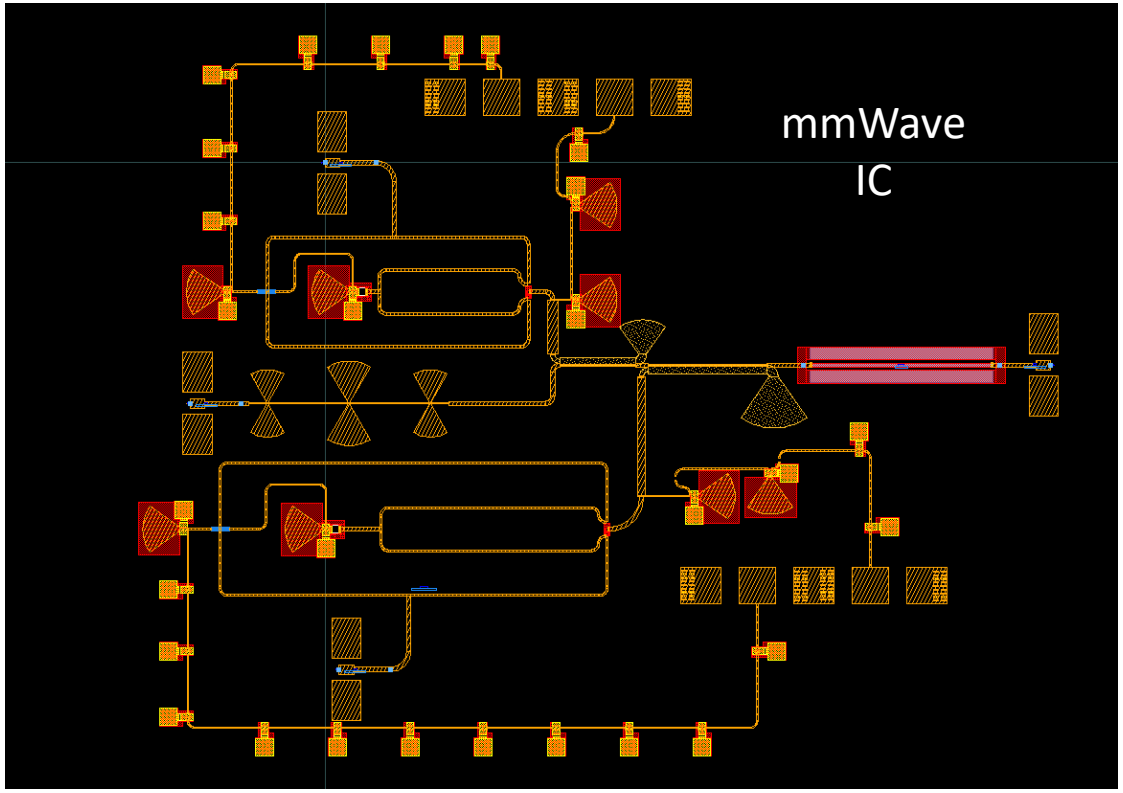


Everything in a Probe to Measure mmWave ICs

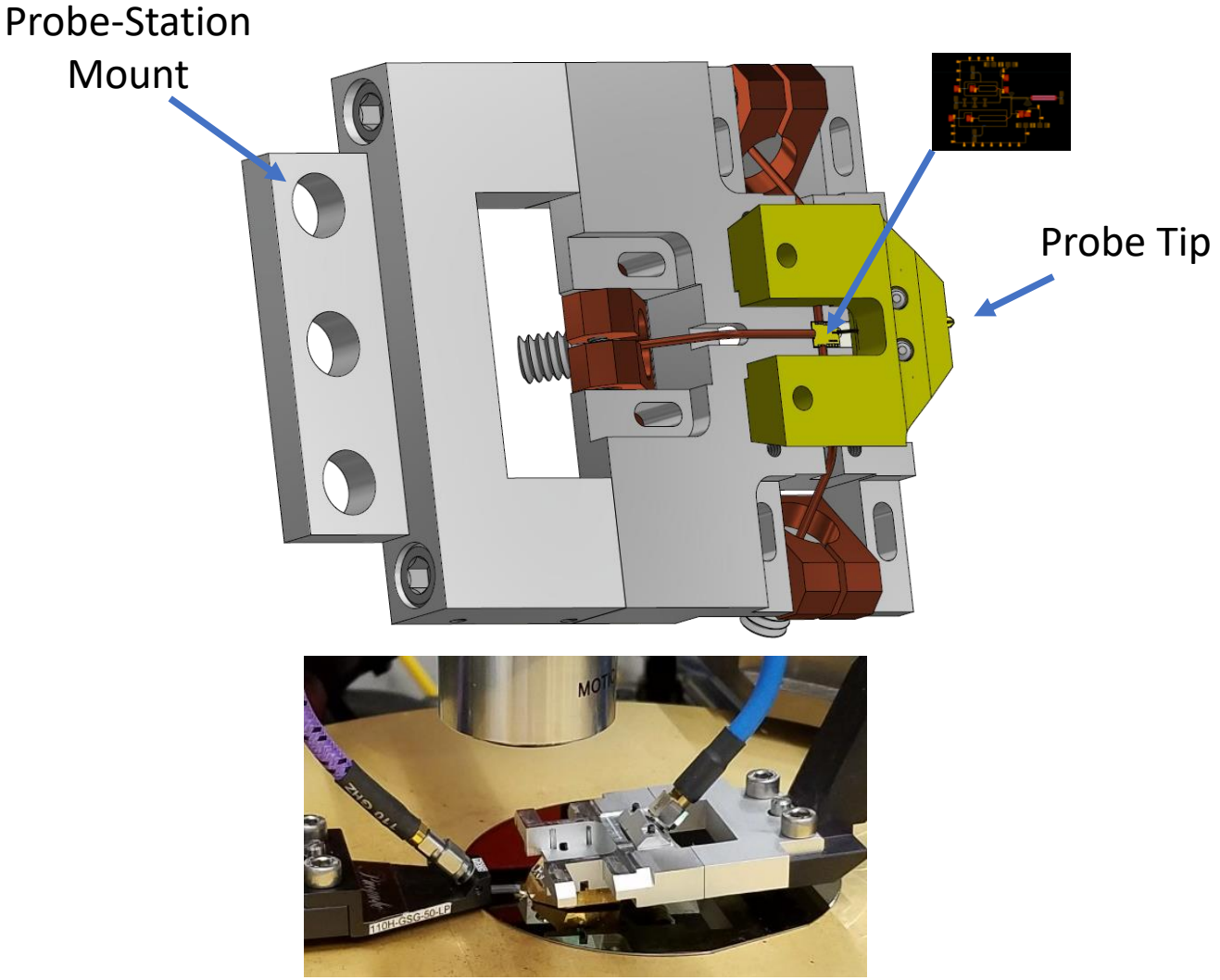


Vector Network Analyzer in-a-Probe

60 GHz – 270 GHz VNA-on-a-chip



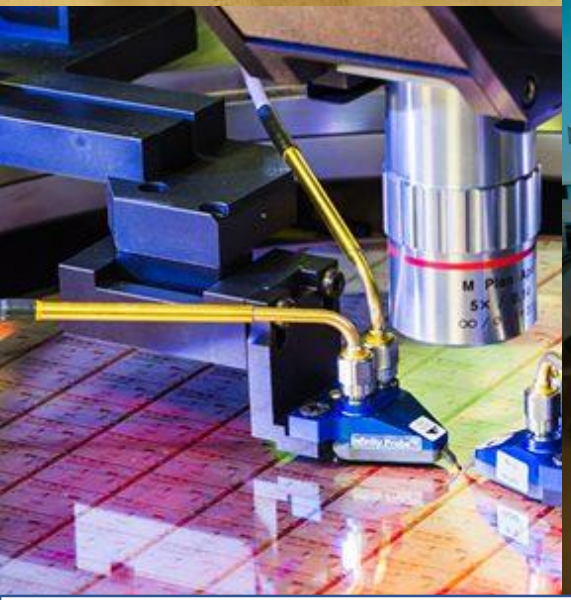
60 GHz – 270 GHz VNA-in-a-probe

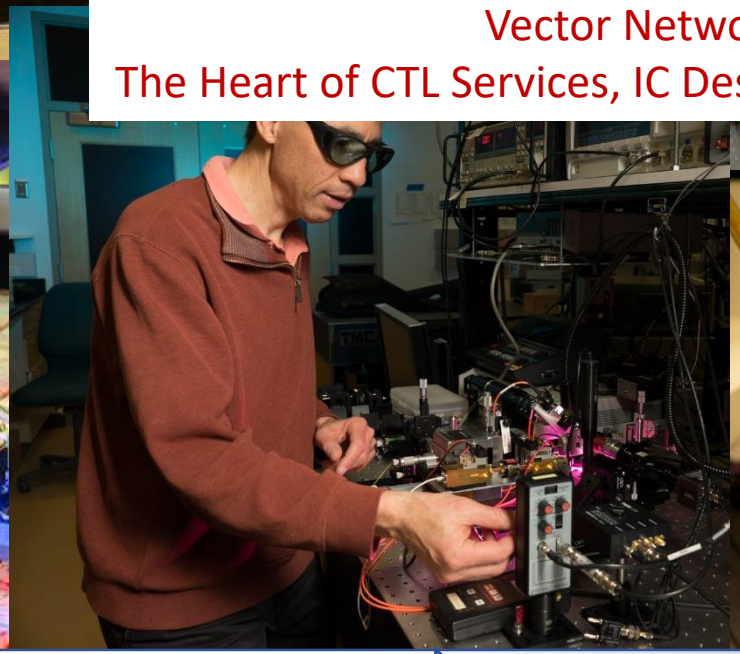


CTL at Cutting Edge of On-Wafer-to-OTA Test

mmWaves are the Wireless Frontier

Vector Network Analysis
The Heart of CTL Services, IC Design *and* OTA System-Level Test





On-Wafer → System-Level Test ← Free-Space