Heterogeneous Integration and Micromachining Technologies for Integrated Terahertz Devices and Components

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002041

AGENDA

Overview of Terahertz Device Research and Applications

Terahertz Metrology, Packaging/Assembly and Micromachined On-Wafer Probes

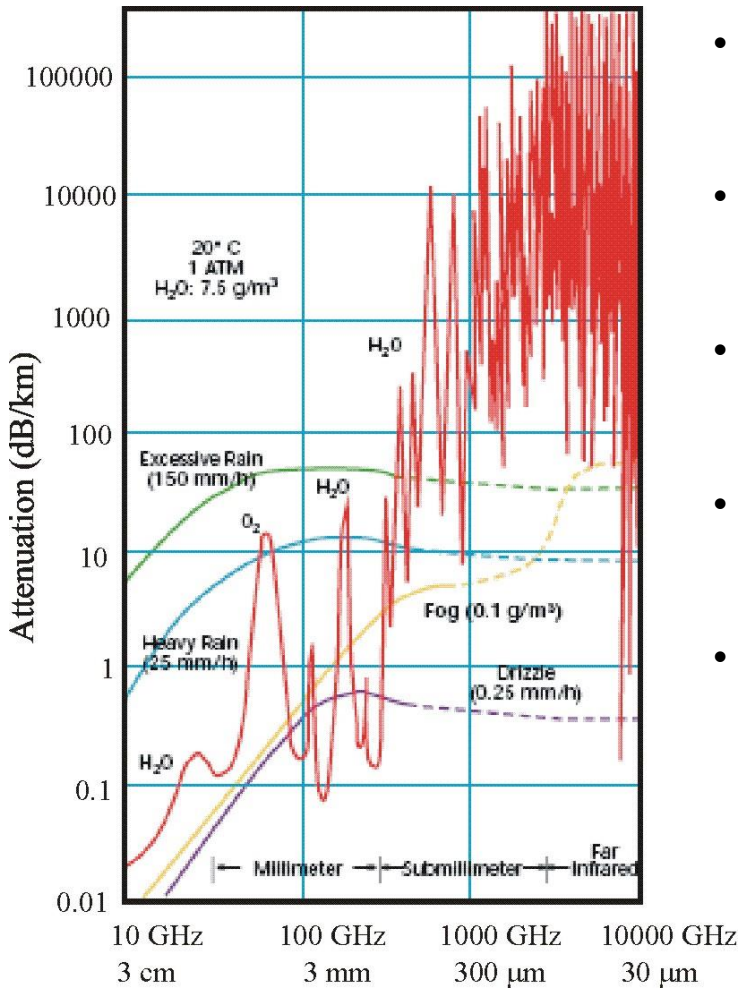
- Context and Need
- Micromachined On-Wafer Probe Concept and Design
- Probe Fabrication and Assembly
- Probe Characterization
- Current Efforts and Future Directions

Heterogeneous Integration for Assembly/Packaging of Submillimeter-Wave Components

- Integrated Quasi-Vertical Schottky Diodes
- Integrated High-Order Multipliers

Summary

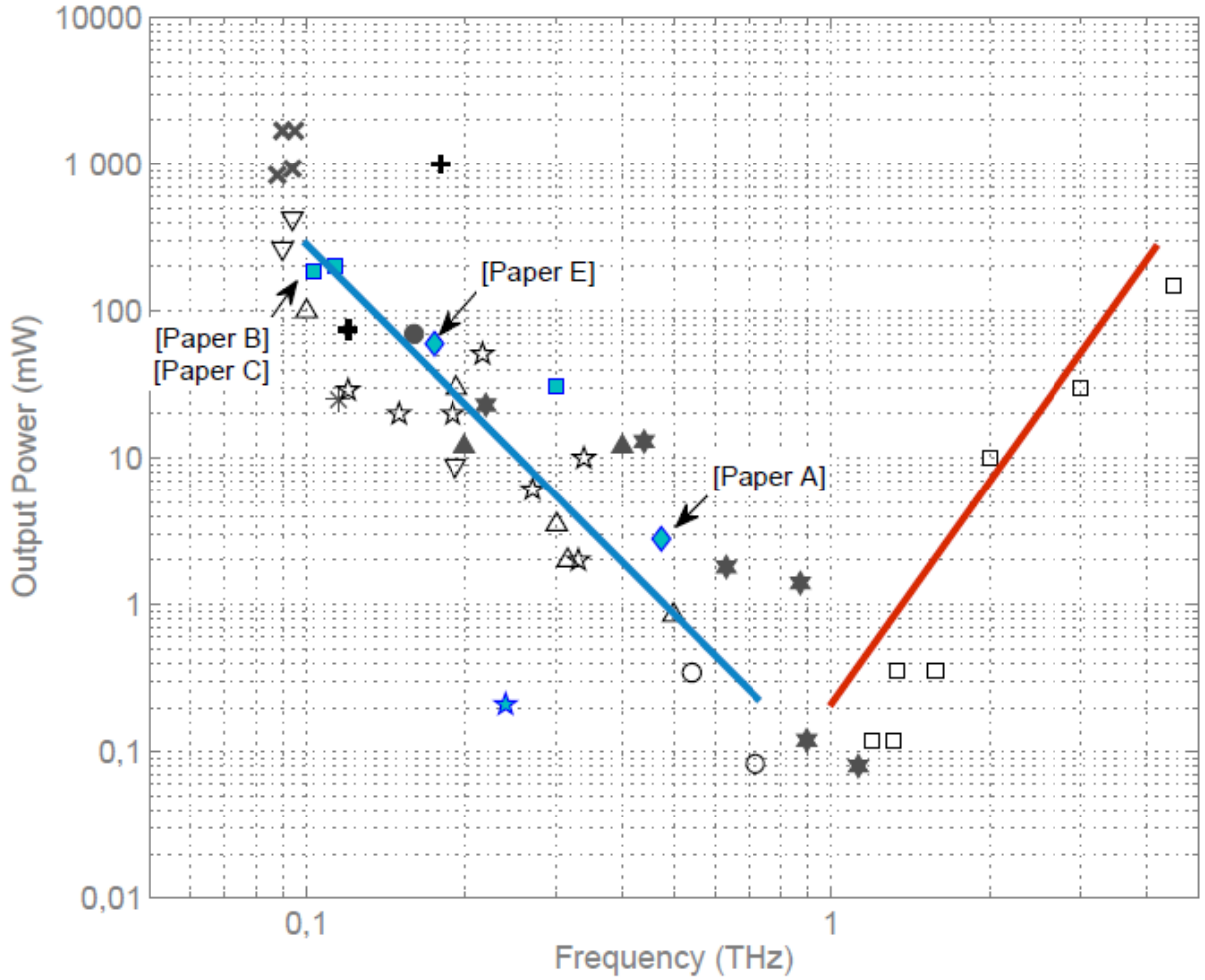
The Terahertz (Submillimeter-wave) Spectrum



Courtesy of F. DeLucia

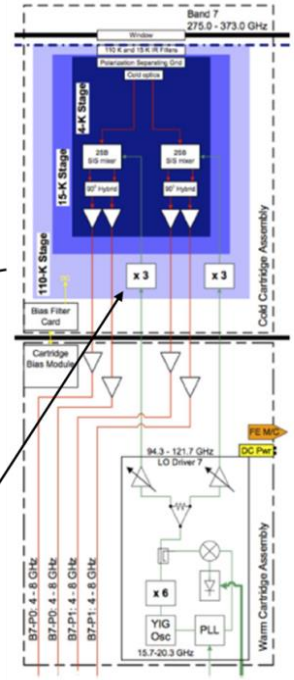
- **Spectral Region is rich in molecular rotational and vibrational modes**
- **Represents a "Transition Region" between Electronics and Photonics**
- **Corresponds to "transition" between Traditional Machining and Lithography**
- **Measurement instrumentation is scarce and expensive.**
- **Lack of compact, tunable sources**

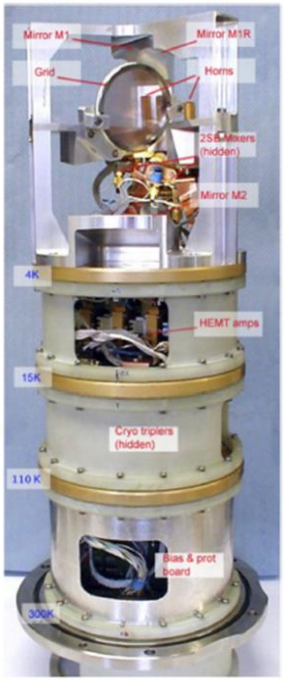
The Terahertz (Submillimeter-wave) Spectrum
(survey of sources)



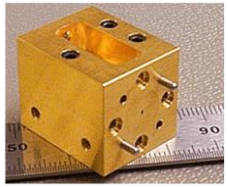
Atacama Large Millimeter/Submillimeter Array

- **Located in the Atacama Desert of Chile (5000 meters elev.)**
- **66 twelve-meter diameter radio telescopes**
- **Frequency coverage from 84 to 950 GHz (detect CO, HCN, SiO, H_2, etc.)**
- **Interstellar media and planetary atmospheres**
- **Schottky diodes and SIS Junctions essential for sub-millimeter-wave radio receivers**



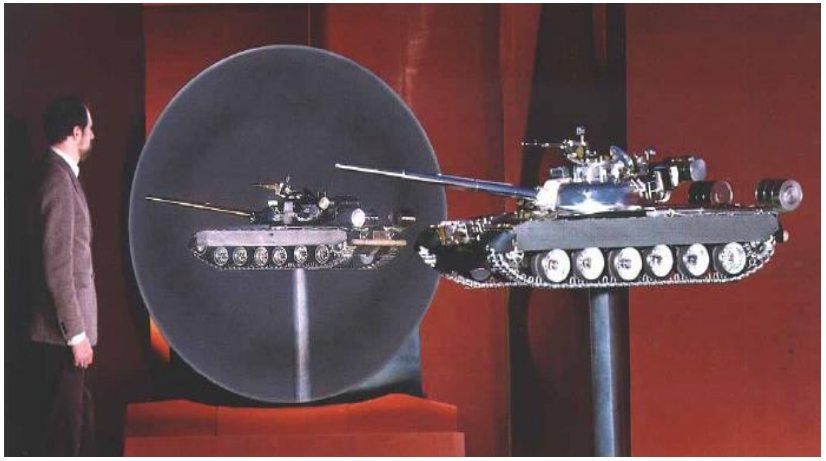


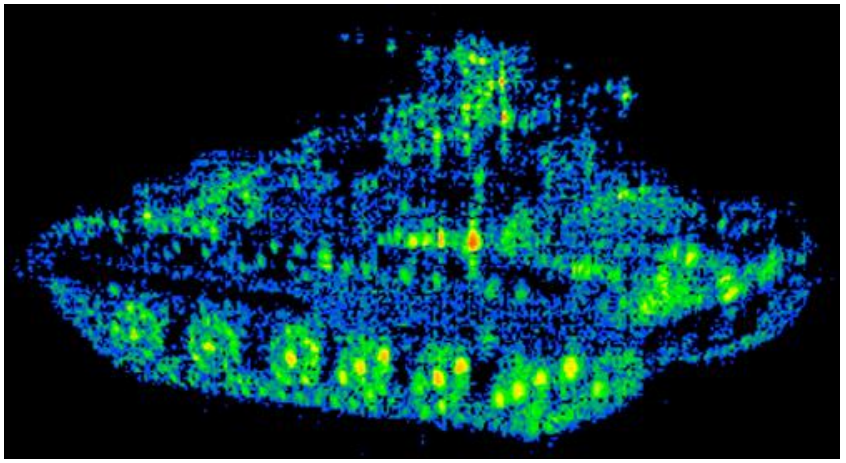
Location of 280-360 GHz Triplers



G.H. Tan, 2008

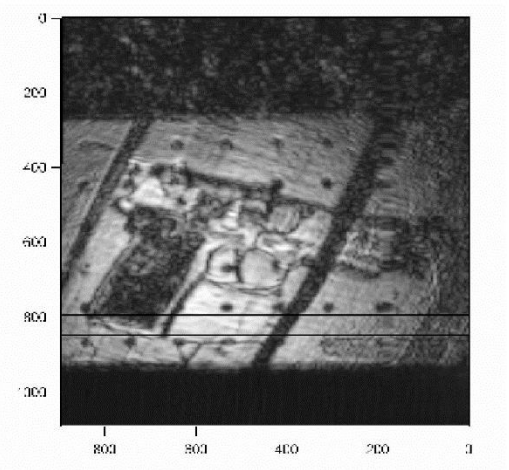
Compact Radar Range Systems and Imaging





Scaled Radar Systems (Tank image taken at 1.6 THz).

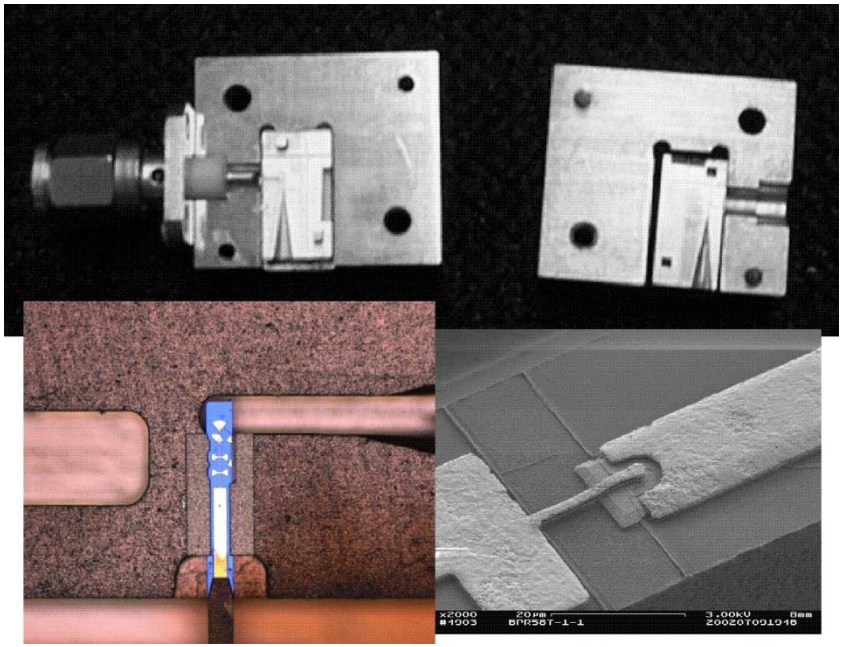
Courtesy of the National Ground Intelligence Center, Charlottesville, VA



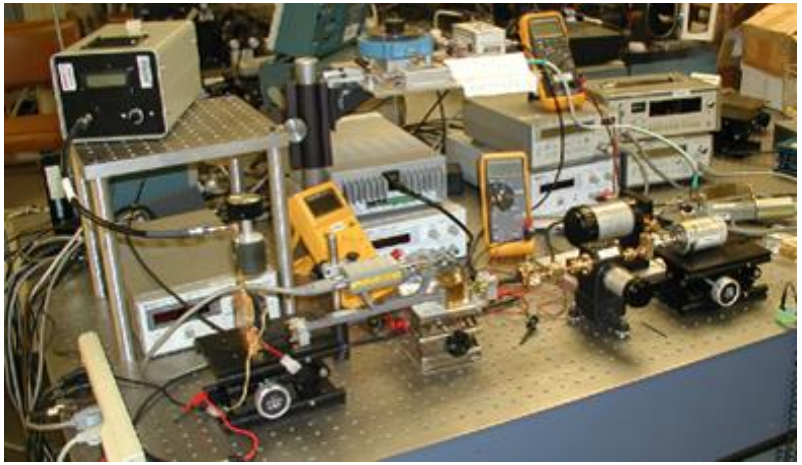
Examples of millimeter-wave (left, 94 GHz and right, 650 GHz) images

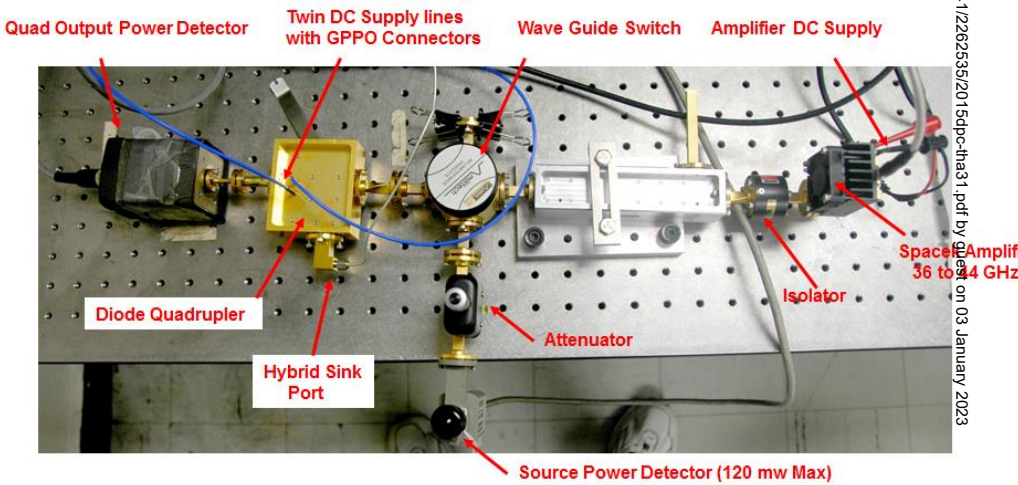
Terahertz Metrology, Packaging/Assembly and Micromachined On-Wafer Probes

Metrology and Assembly/Packaging at Terahertz Frequencies



- Waveguide-Based Media
- Specialized Measurement Systems
- Characterization of global parameters (noise temperature, conversion loss)
- No standardized interfaces
- No traceable standards





Metrology and Assembly/Packaging at Terahertz Frequencies

Network Analyzer Frequency Extenders (Virginia Diodes, Inc.)

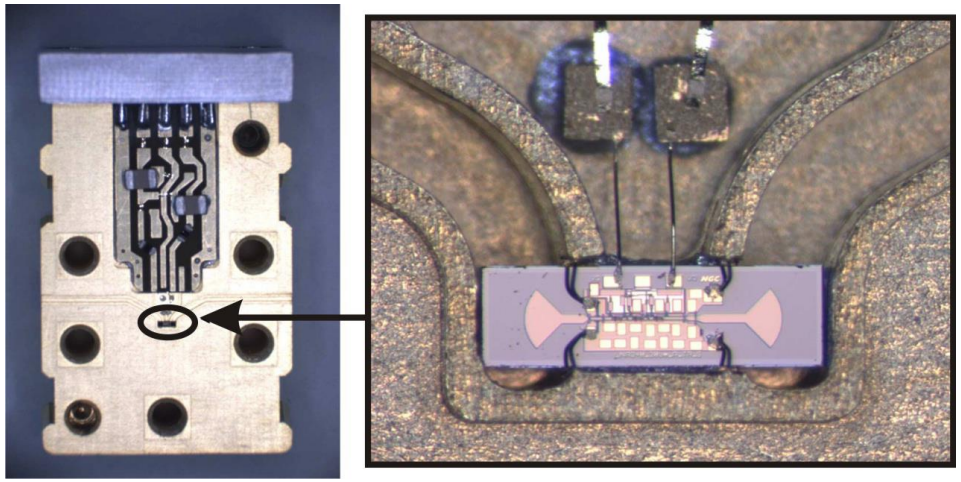
WR2.2 (330-500 GHz) VNA System

Image Courtesy of Anritsu

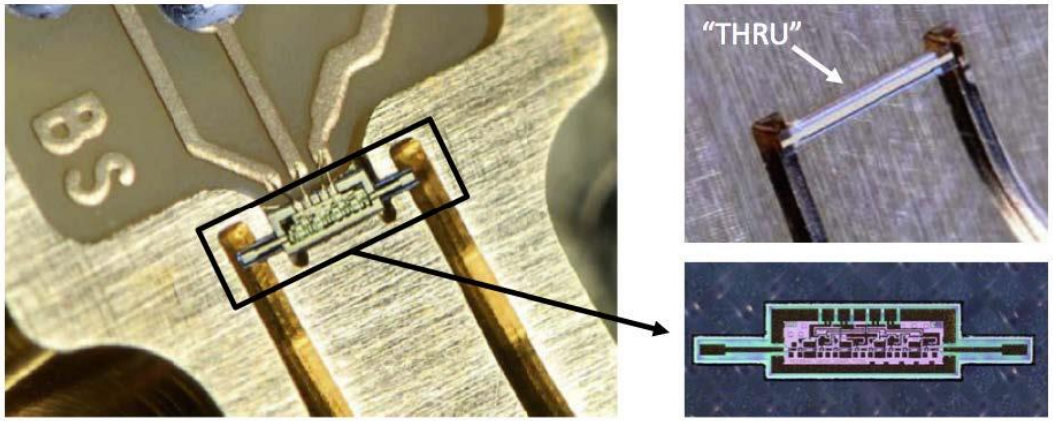
VDI					
Waveguide Band (Ghz)	WR 3.4 220-330	WR 2.8 260-400	WR 2.2 325-500	WR 1.5 500-750	WR 1.0 750-1100
Dynamic Range (BW = 10 Hz, dB)	115	100	100	100	60
Dynamic Range (BW = 10 Hz, min)	100	80	80	80	40
Magnitude Stability (dB)	0.3	0.5	0.5	0.8	1
Phase Stability (deg)	6	8	8	10	15
Test Port Power (dBm, typ)	-9	-16	-17	-25	-35

Metrology and Assembly/Packaging at Terahertz Frequencies

- **Dicing and Mounting Chips**
- **Test Fixture with Flanges**
- **Calibration and De-embedding**



LNA mounted in a waveguide fixture (courtesy of Northrup Grumman Aerospace Systems, IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 20, NO. 5, MAY 2010, pp. 289-291)



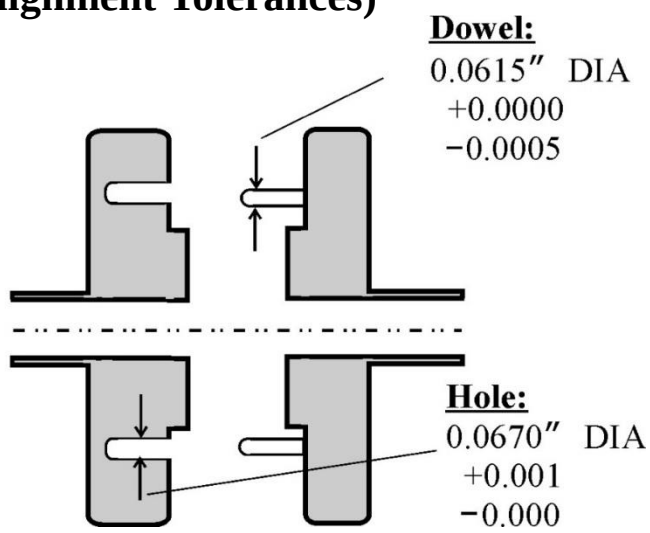
A. Tessmann, et al, "Metamorphic HEMT MMICs and modules operating between 300 and 500 GHz," Solid-State Circuits, IEEE Journal of, vol. 46, no. 10, pp. 2193–2202, Oct 2011.

Metrology and Assembly/Packaging at Terahertz Frequencies

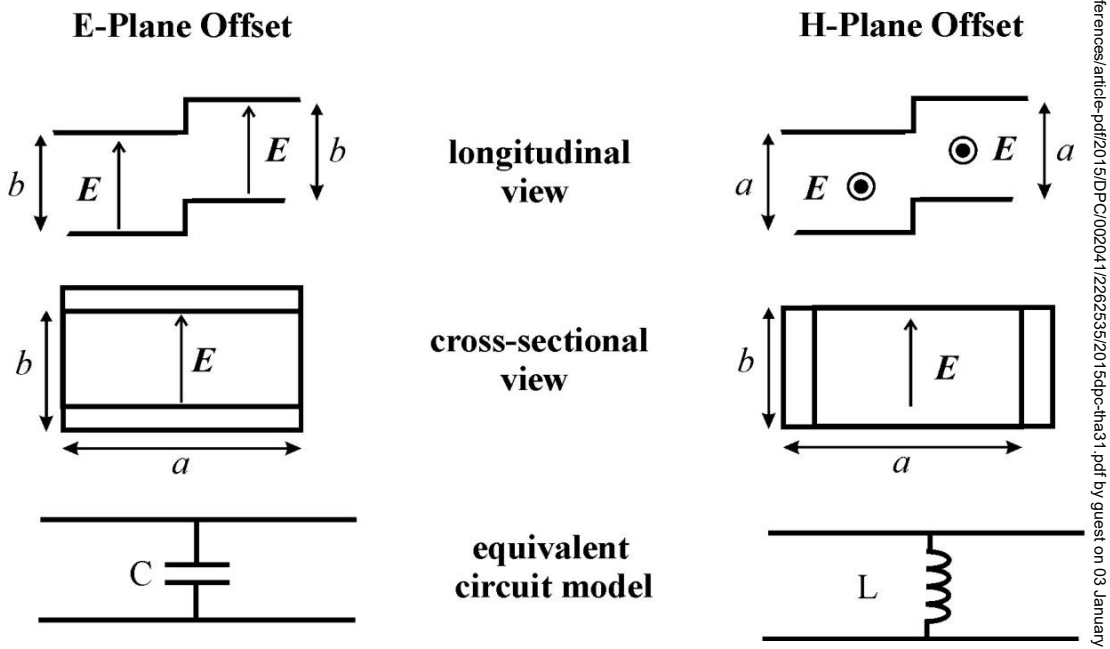
Effects of Waveguide Misalignment

- **Result of Machining Tolerances on Alignment Dowels/Holes**
- **Electrically Results in Unknown Shunt Susceptance at Junction**
- **Introduces Biased Error in Return Loss Measurements**
- **Effects More Severe as frequency → 1 THz**

MIL 3922/67C (UG-387) Flange (Alignment Tolerances)



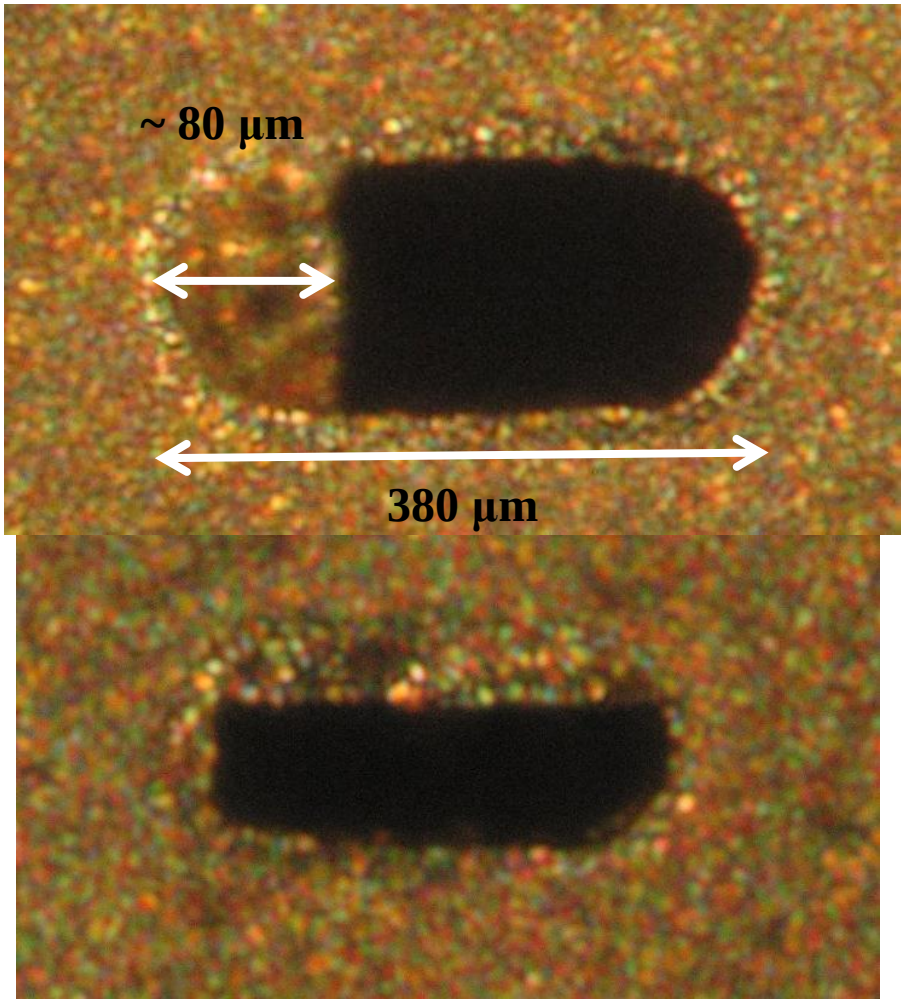
Maximum Waveguide Offset = 3.5 mils



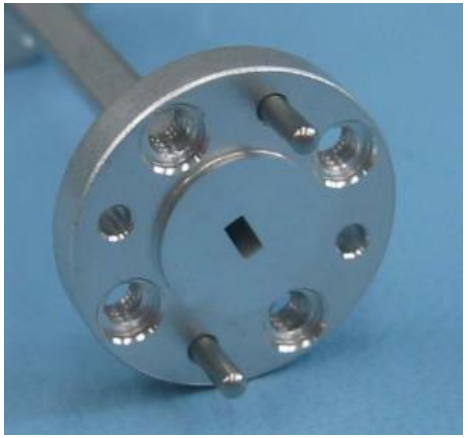
Metrology and Assembly/Packaging at Terahertz Frequencies

Test Port Flange Misalignment (UG-387)

WR 1.5 or WM 380 (500–750 GHz)

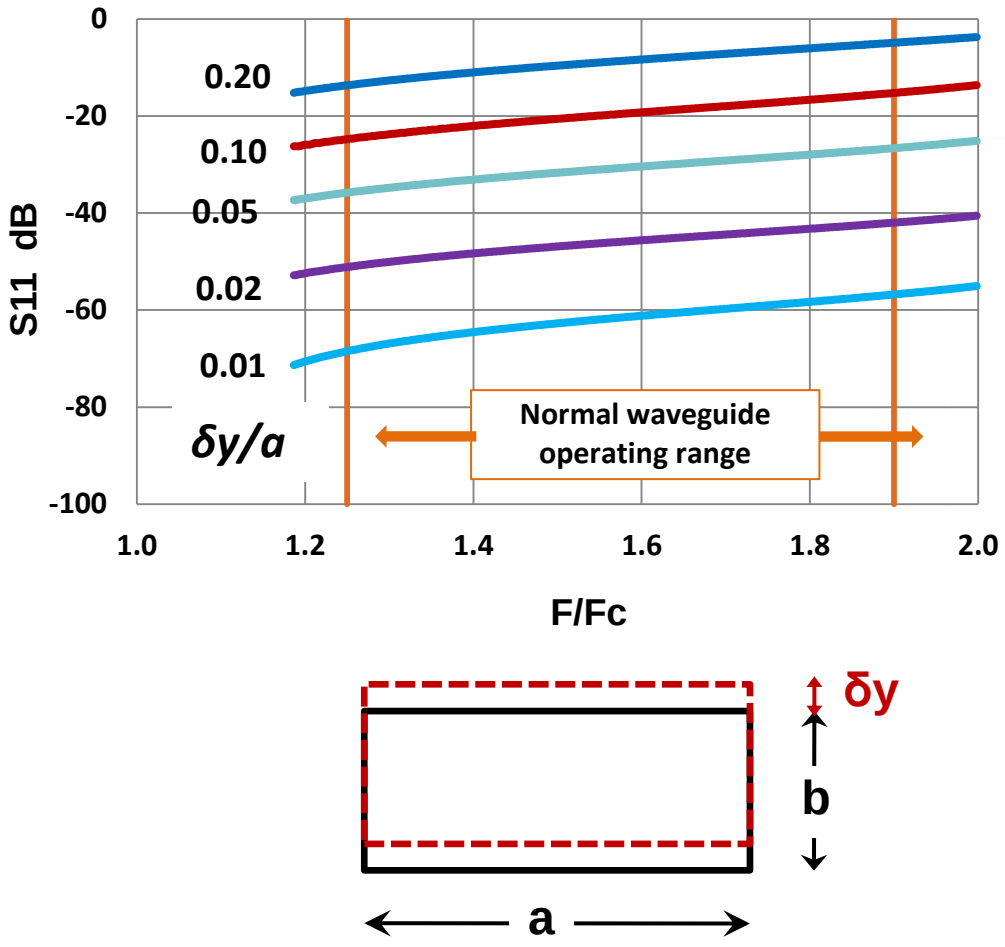


VDI Waveguide Test Port Seen Through Milled Waveguide Shim



Metrology and Assembly/Packaging at Terahertz Frequencies

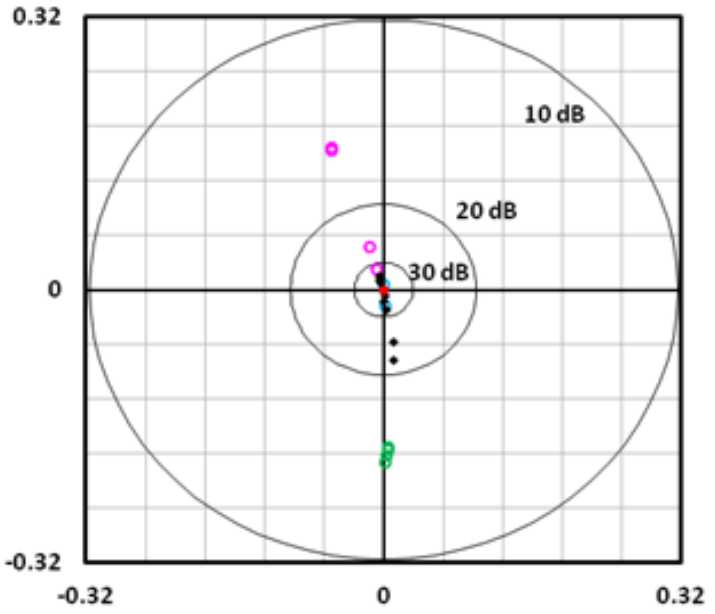
Effects of Waveguide Misalignment



(A. R. Kerr, EDTN 215)

Flange Repeatability (625 GHz)

- Initial Measurement
- 13 Reconnections
- Flange pushed East-West (H-plane)
- Flange pushed North-South (E-plane)

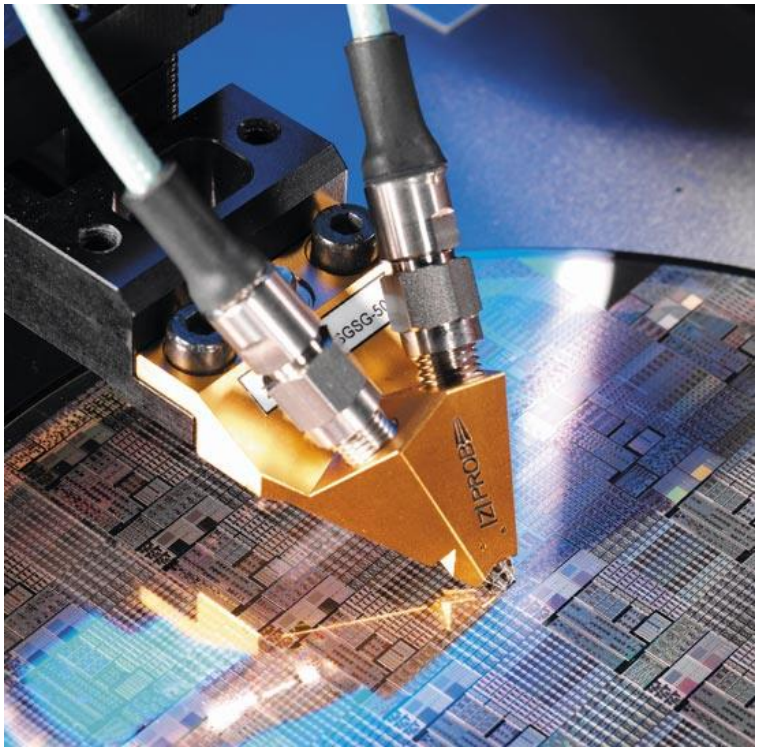


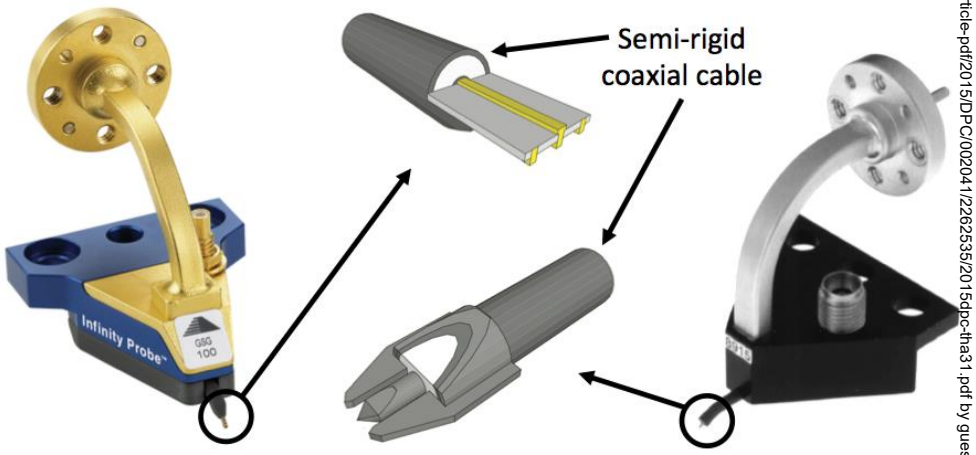
Standard UG-387 Flange

Metrology at Terahertz Frequencies

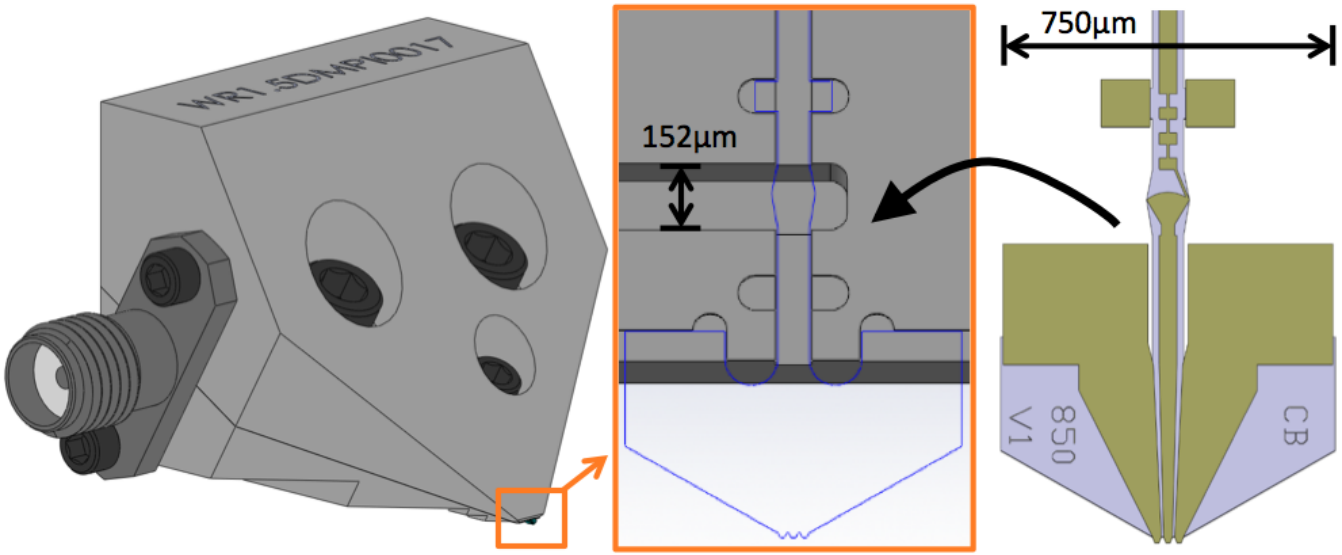
- Transistors have recently reached 1 THz operating frequencies
- Current Characterization Methods based on Fixturing Components
- Need for Direct On-Wafer Measurement

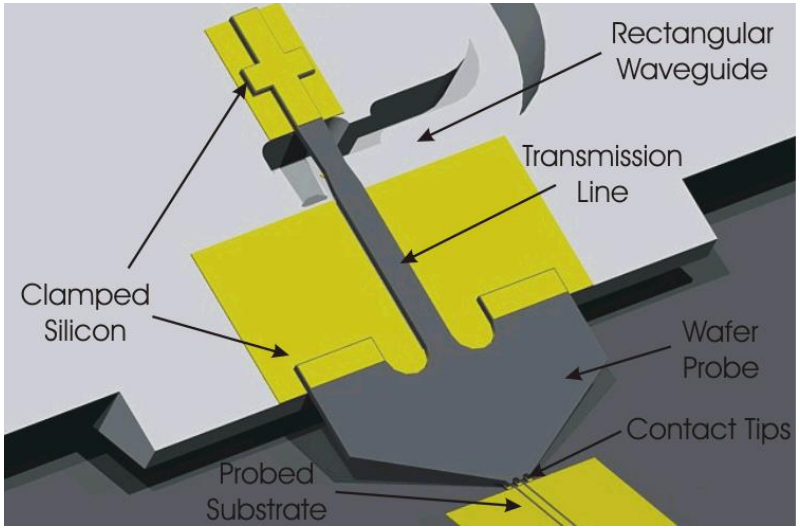
  - No De-embedding of Fixture
  - Rapid Measurement/Assessment
  - Development of Device Models





Micromachined On-Wafer Probe Concept



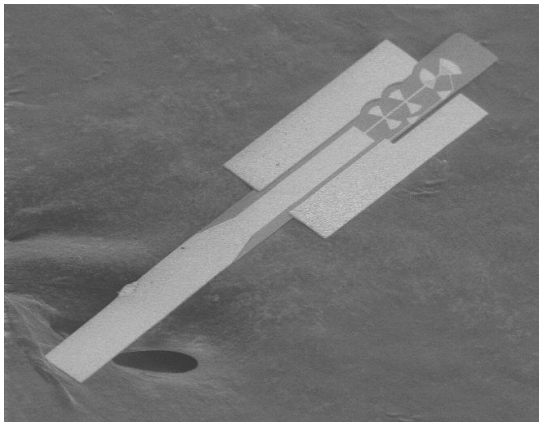


Design Features/Requirements:

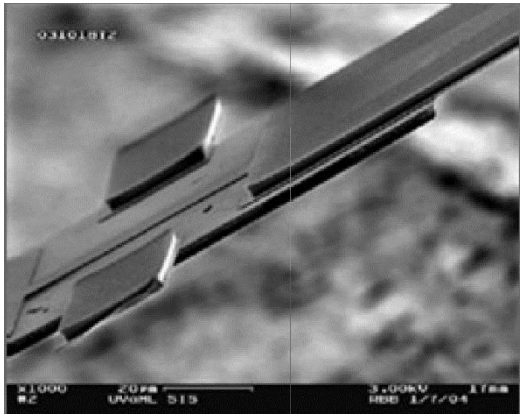
1. Waveguide Interface and Housing
   - Compatible with VNA Front-Ends
   - Split Block Design
   - Waveguide-CPW/Microstrip Transition
   - Waveguide Twist to Convert Polarization
2. Integrated Probe Chip
   - Single Drop-In Module
   - Fabricated using SOI Beamlead Process
   - Mechanical Robusness/RF Performance
   - Amenable to DC Biasing

Micromachined On-Wafer Probe Technology

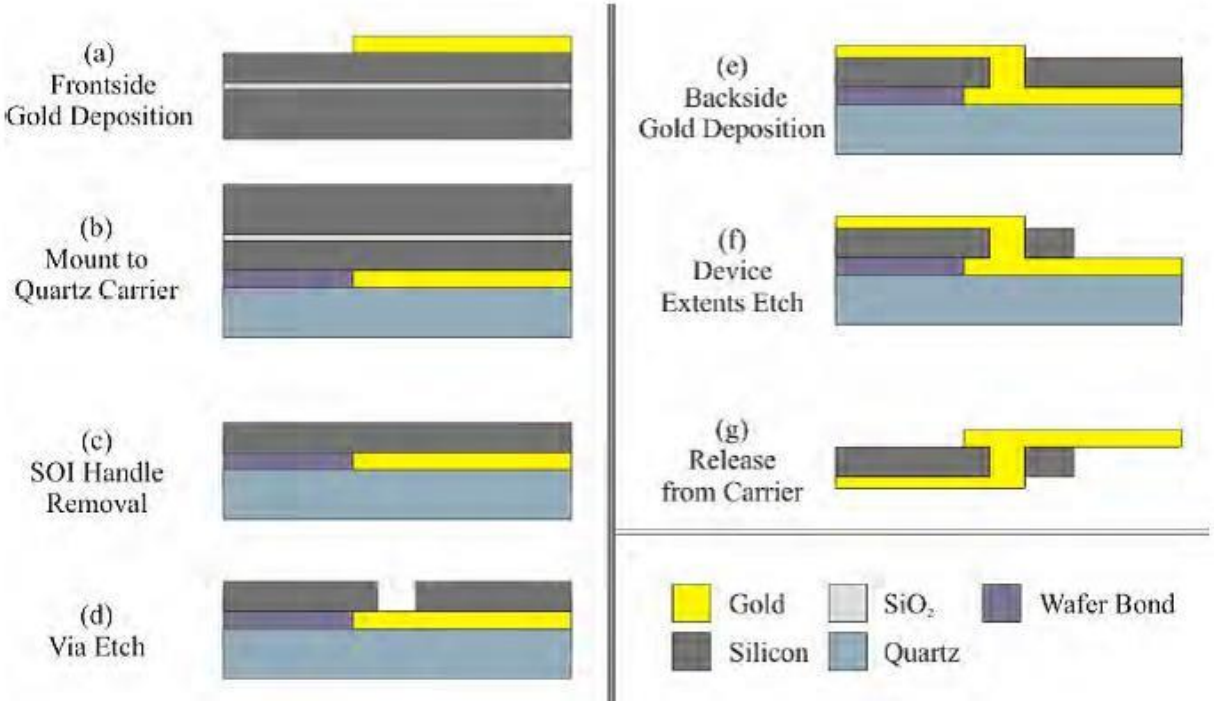
- Silicon Micromachining of SOI
- Top and Backside Processing
- Beamlead and Via Formation
- Thickness of 3 μm to 15 μm



1.6 THz HEB mixer on SOI



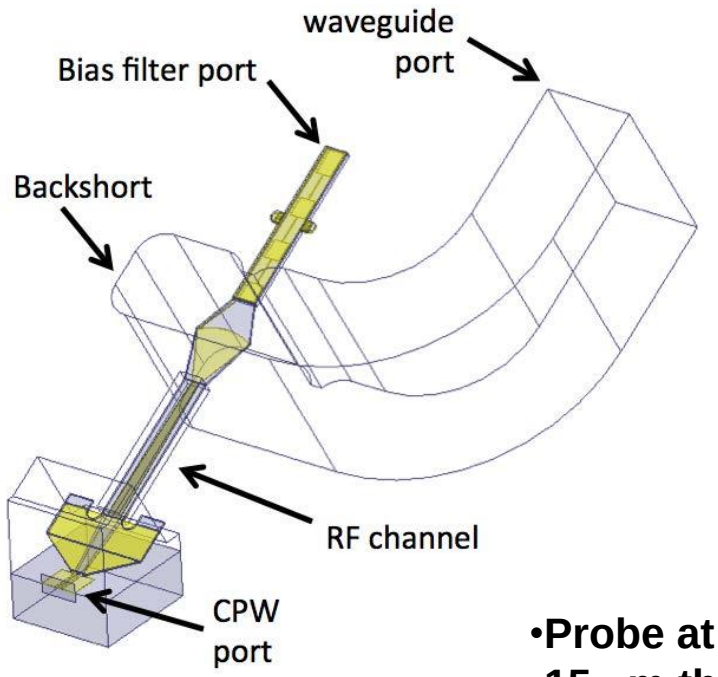
Close-Up of 3 μm silicon carrier



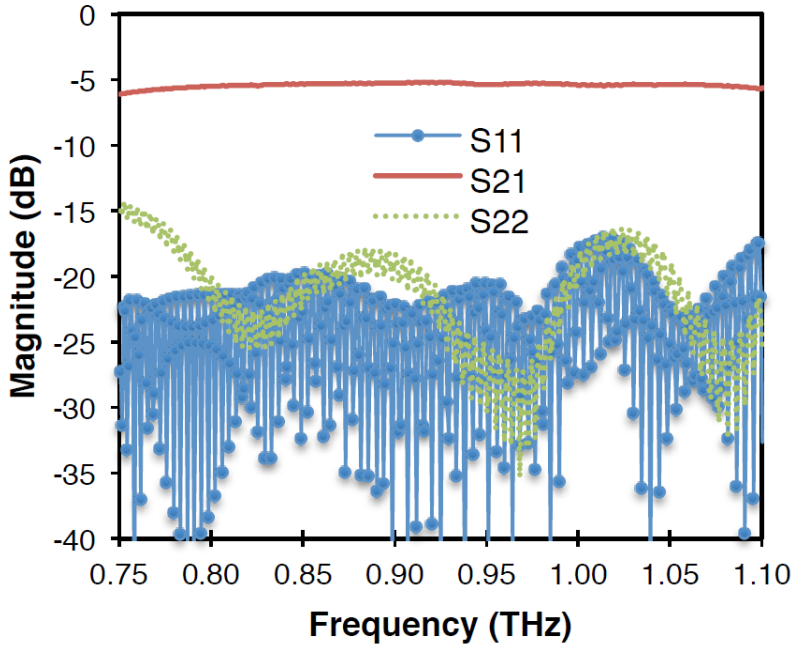
Process Flow of Micromachined SOI Chip Fabrication

Micromachined On-Wafer Probe
RF Design

- Use of Electromagnetic Finite-Element Solvers (HFSS)
- Two Primary Transitions (Waveguide-to-Probe and Probe to Substrate)
- Incorporation of Bias Feed/Filter
- Minimize Insertion Loss/Maximize Return Loss



Simulated Scattering Parameters

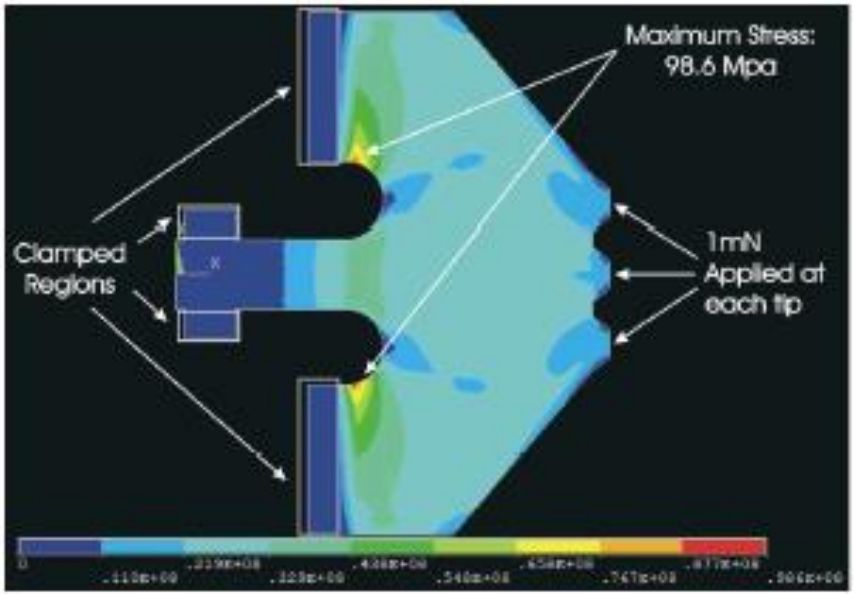


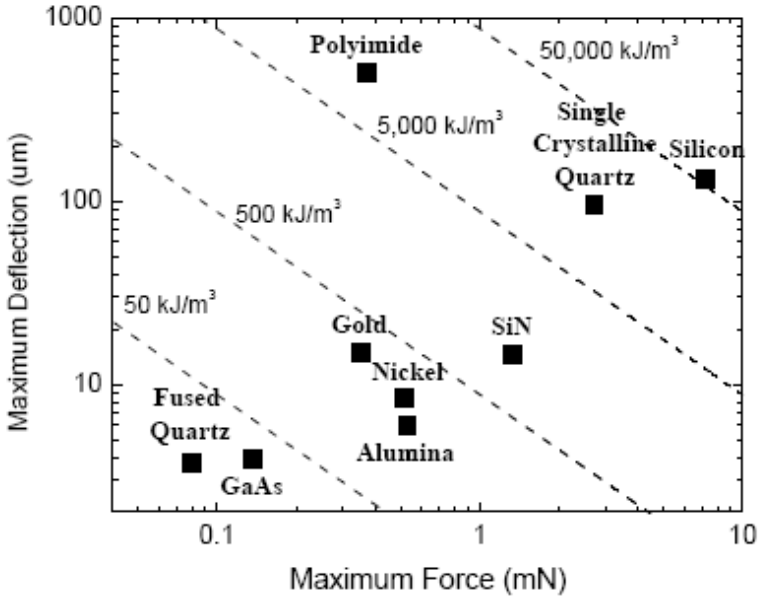
- Probe at 30° angle
- 15 μm thick Si, ρ > 10kΩ·cm (5 μm thick Si for WR 1.2)
- 25 μm probe pitch
- 4 μm plated Gold conductor
- 0.8 inch waveguide loss included

Micromachined On-Wafer Probe

Mechanical Considerations

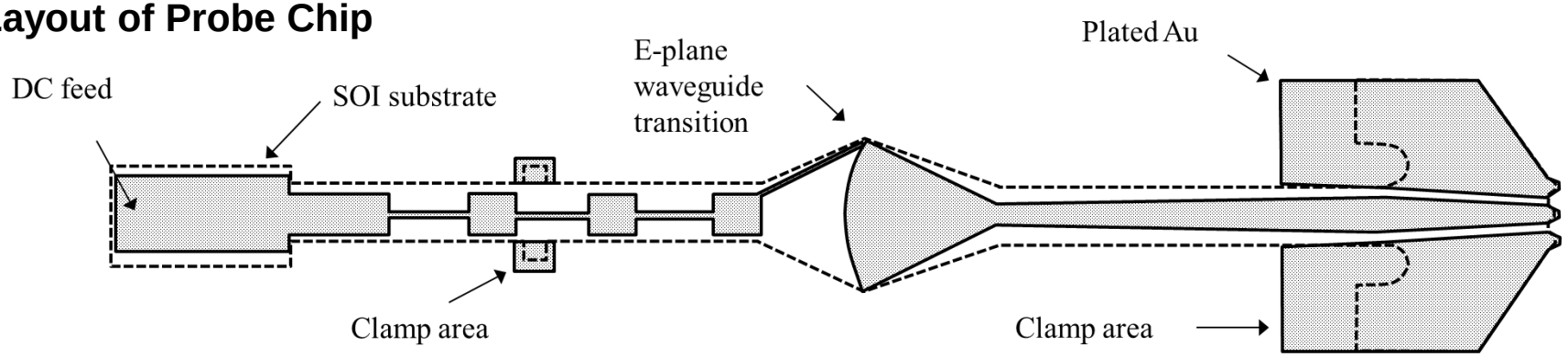
Material	E (GPa)	σ^{yeild} (MPa)	ϵ_r	Modulus of Resilience (kJ/m^3)
Gold [54]	80	220	N/A	302
Nickel [55]	207	320	N/A	447
Fused Quartz [56]	73	50	3.8	17
Gallium Arsenide [57] [58]	118	85	12.9	30
Alumina [59]	300	330	9.1	181
Silicon Nitride [60]	310	830	5-8	1,111
Kapton HN Polyimide [61]	2.5	230	3.2	10,580
Single Crystalline Quartz [62]	97	1700	4.6	14,897
Silicon [63][64]	185	4500	11.9	54,730

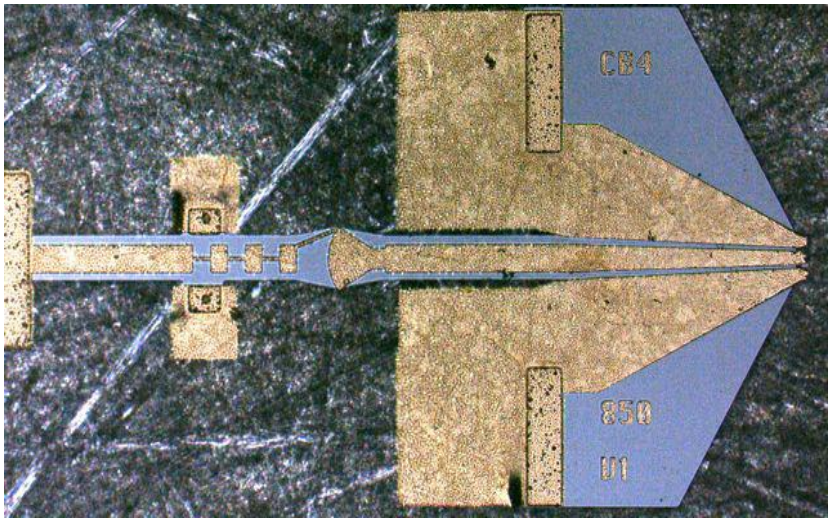




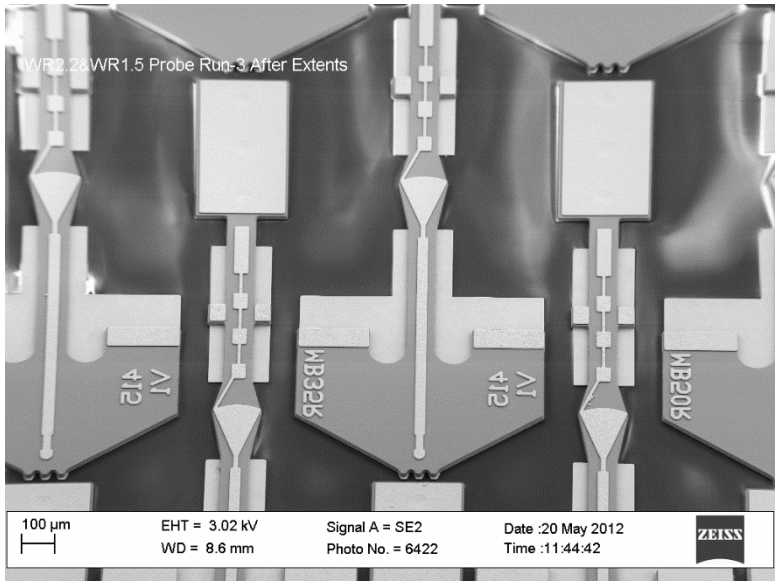
Micromachined On-Wafer Probes
Design and Implementation

Layout of Probe Chip



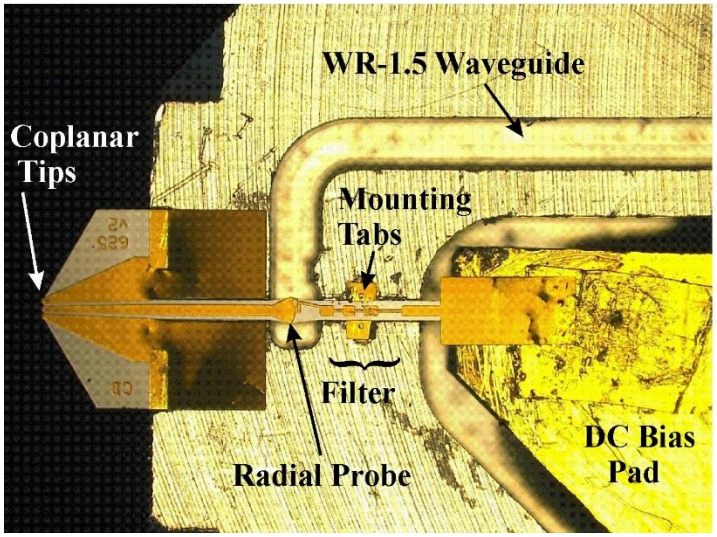


Completed Probe Chip

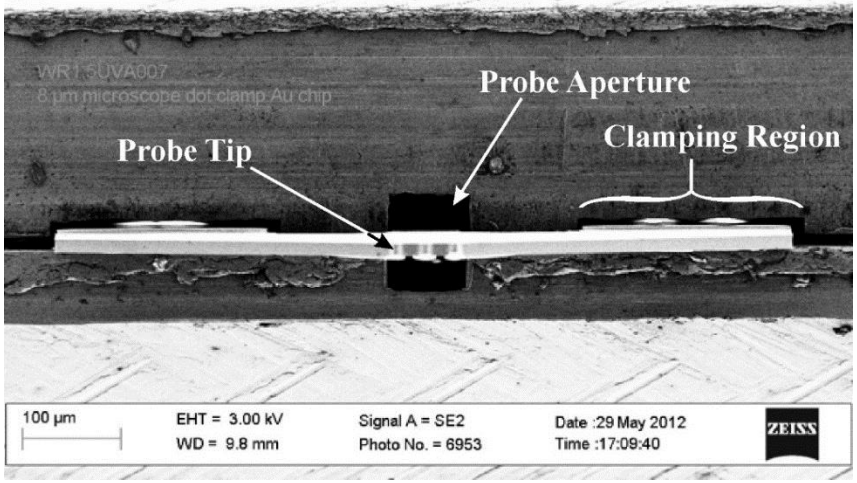


Probe Chips Before Separation

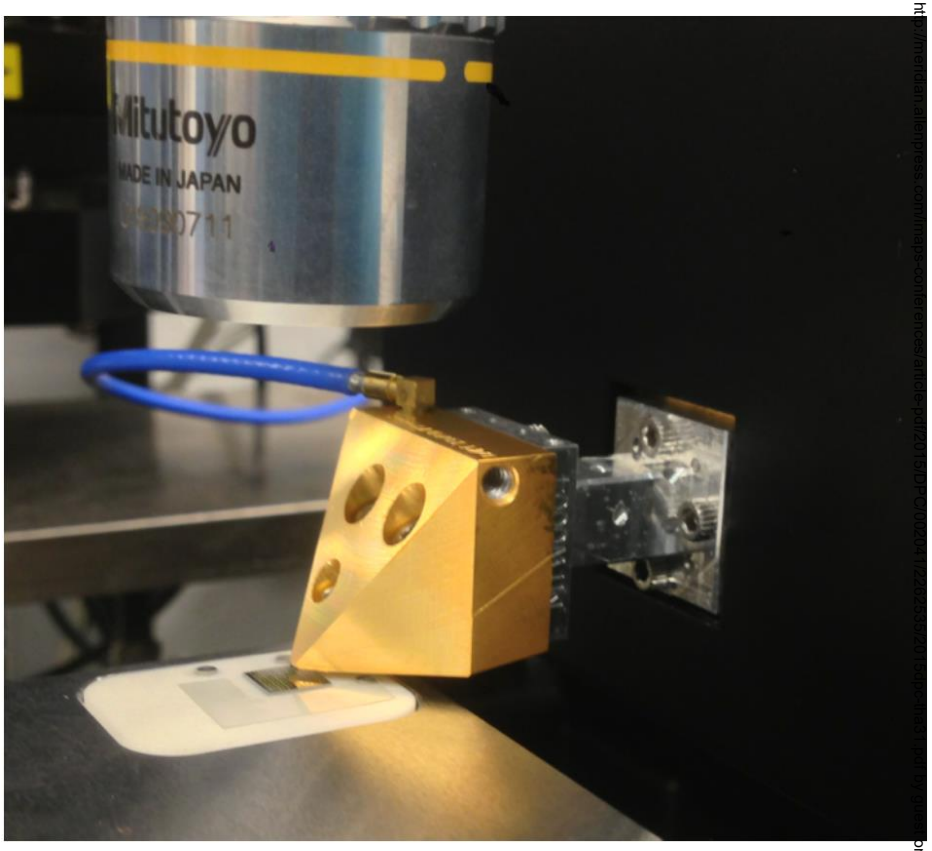
Micromachined On-Wafer Probes
Packaging and Assembly



Mounted Coaxial Probe with Bias



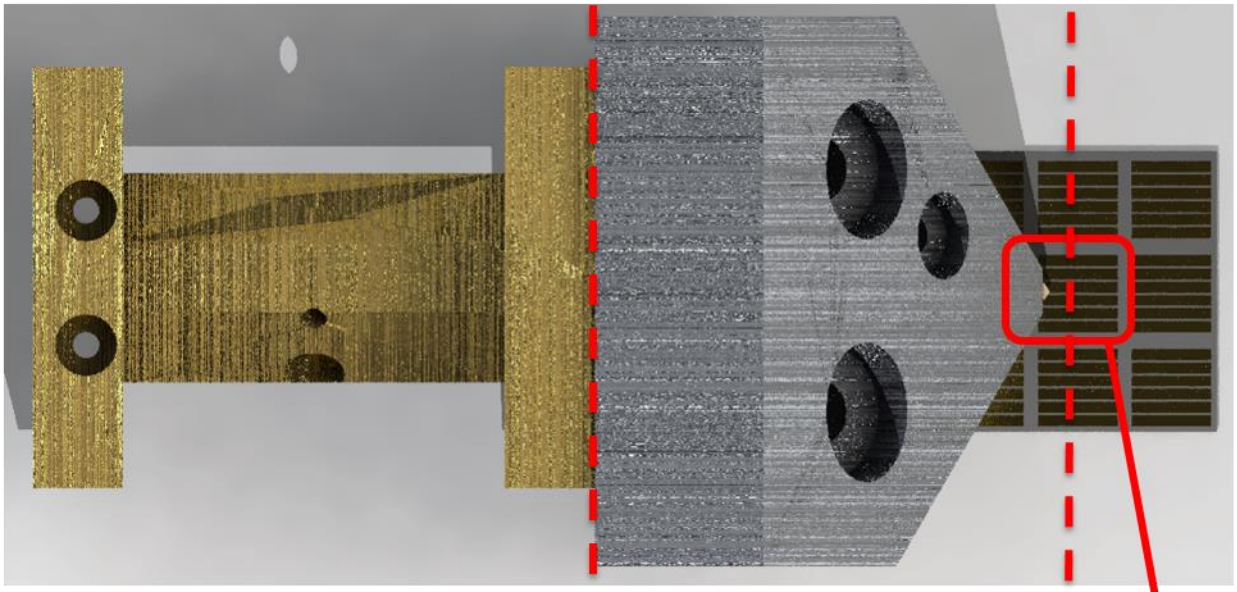
End View of Chip Clamping



WR-1.0 Probe Mounted to VDI Module and Cascade PA200 Probe Station

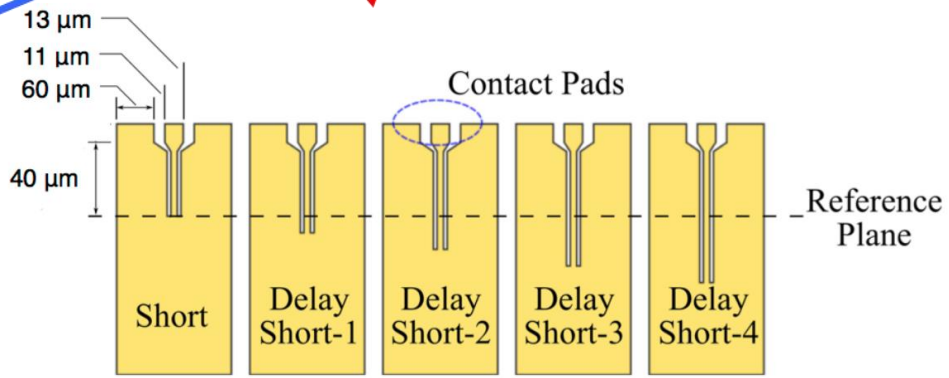
Micromachined On-Wafer Probes

RF Characterization



- **Two-Tier Calibration**
- **Offset CPW Short Standards**
- **Over-Determined System**

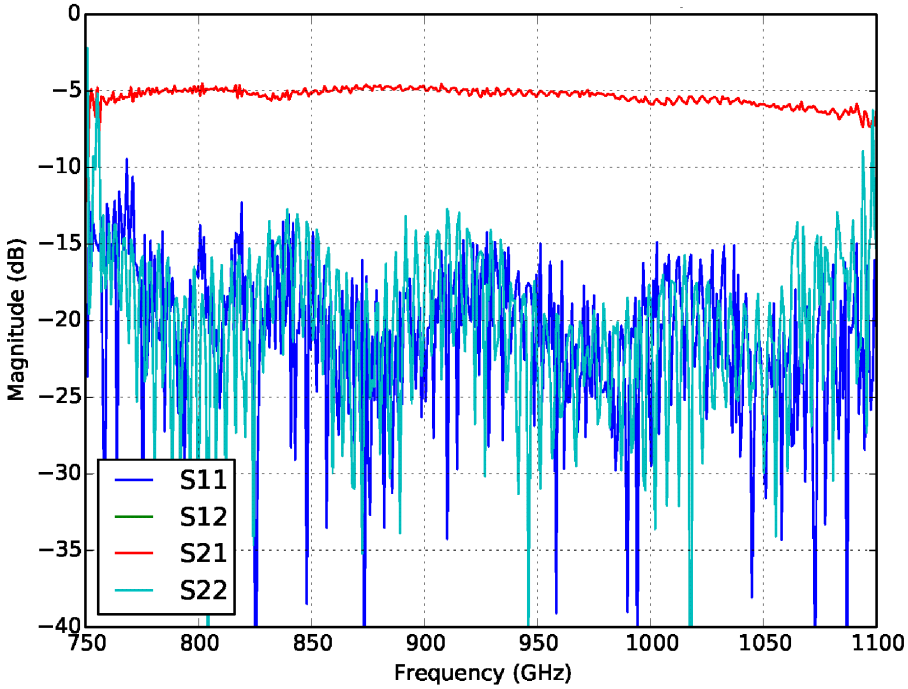
$$\Gamma^M = e_{11} + \frac{e_{21}e_{12}\Gamma_l}{1 - e_{22}\Gamma_l}$$



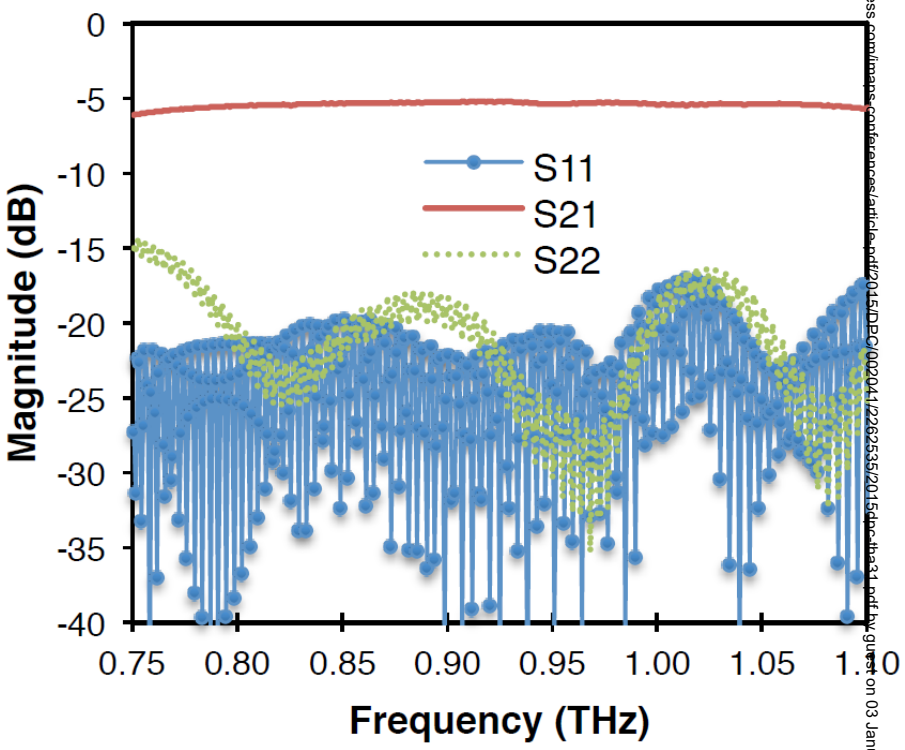
Micromachined On-Wafer Probes
RF Characterization

Measured and Modeled Probe Scattering Parameters

Measured Probe S-Parameters



Electromagnetic Simulation



WR-1.0 Probe (750-1100 GHz)

- **Implemented in 15μm Silicon**
- **Nickel-Plated Probe Tips**

Micromachined On-Wafer Probes
RF Characterization

Measured Coplanar Transmission Lines

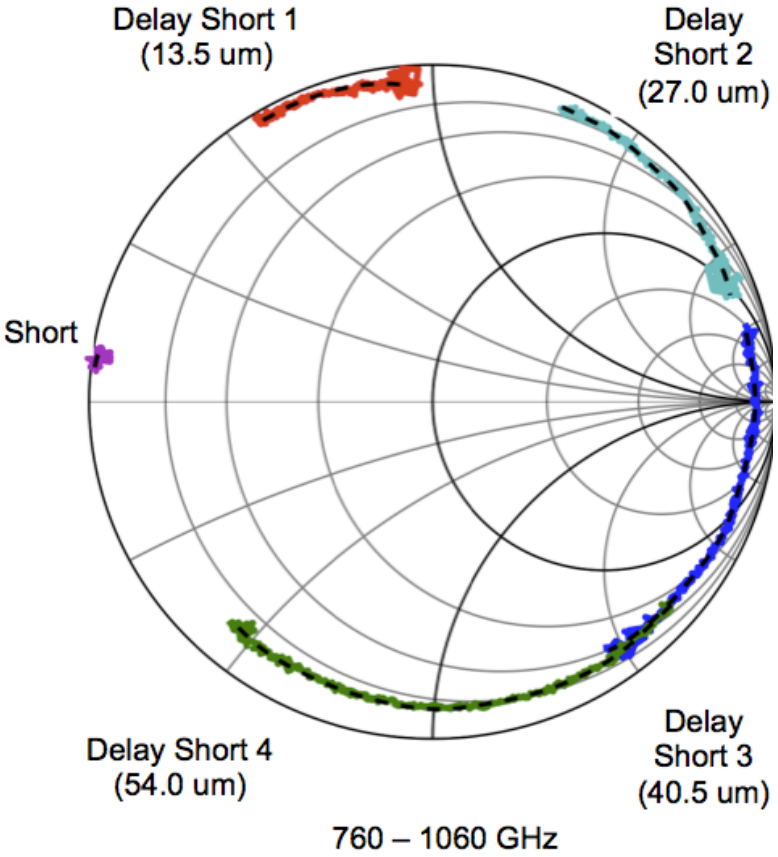
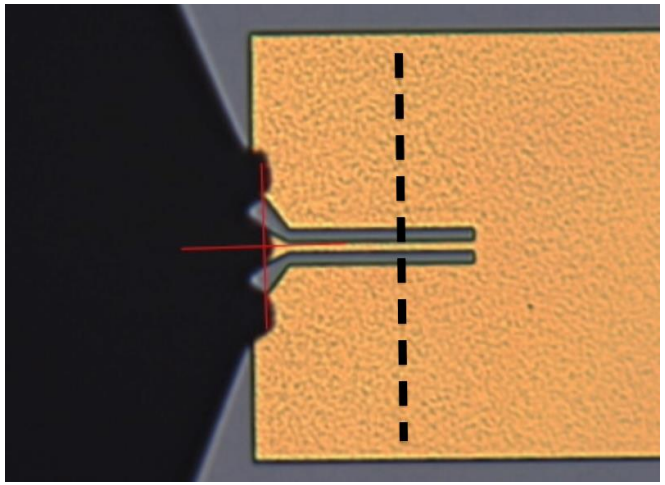
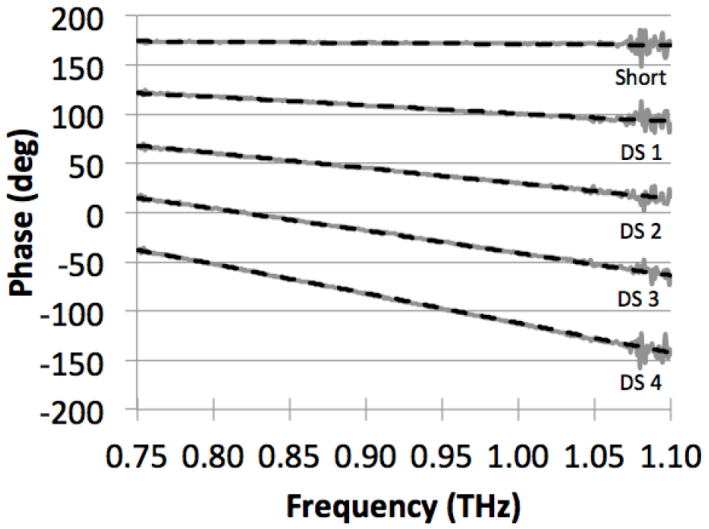


Image of On-Wafer Standard





Metrology at Terahertz Frequencies

First Terahertz Transistor

Northrup Grumman Aerospace

EE Times Connecting the Global Electronics Community

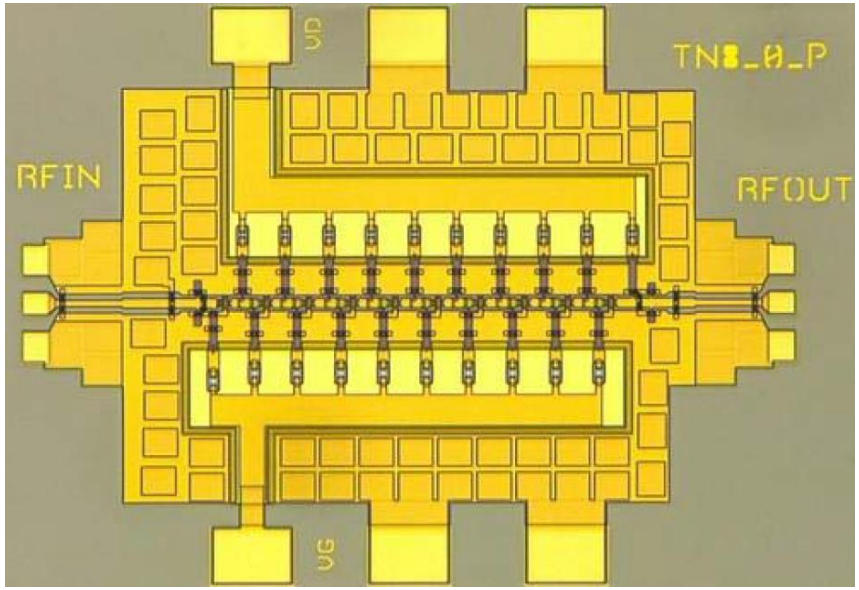
designlines PROTOTYPING

News & Analysis

DARPA Gets Guinness Record for World's First THz Amp

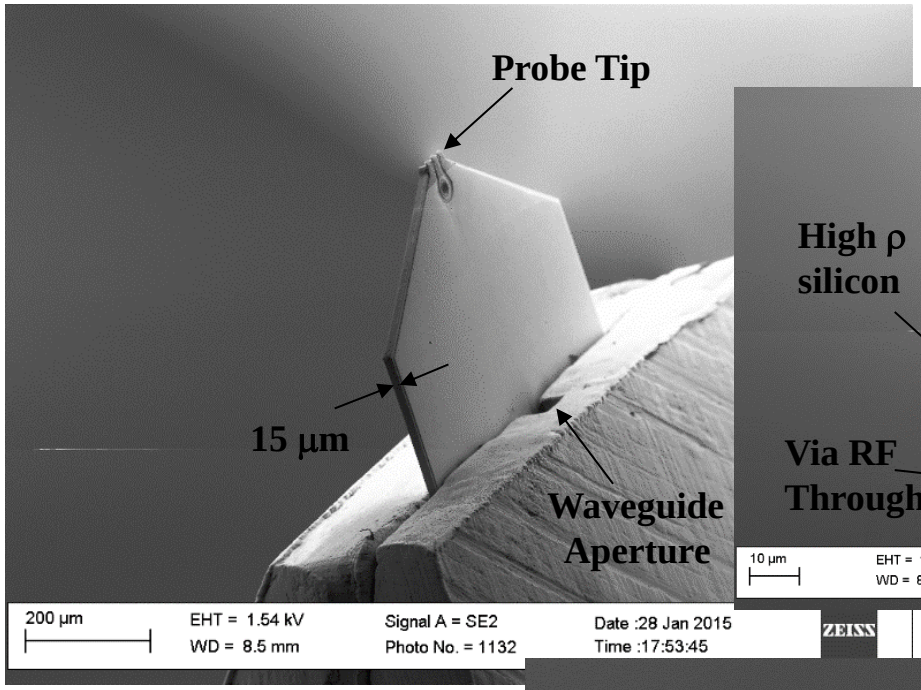
R. Colin Johnson

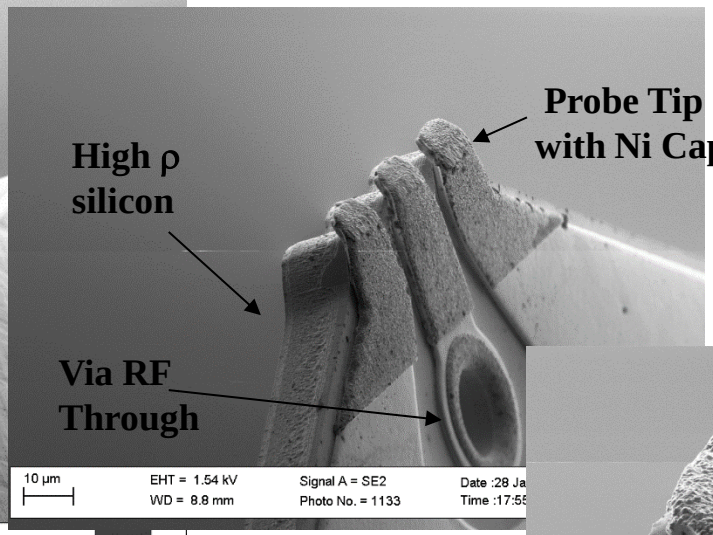
11/3/2014 07:43 PM EST

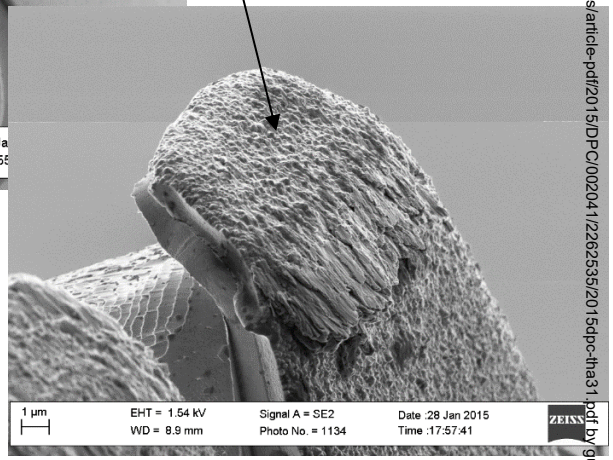


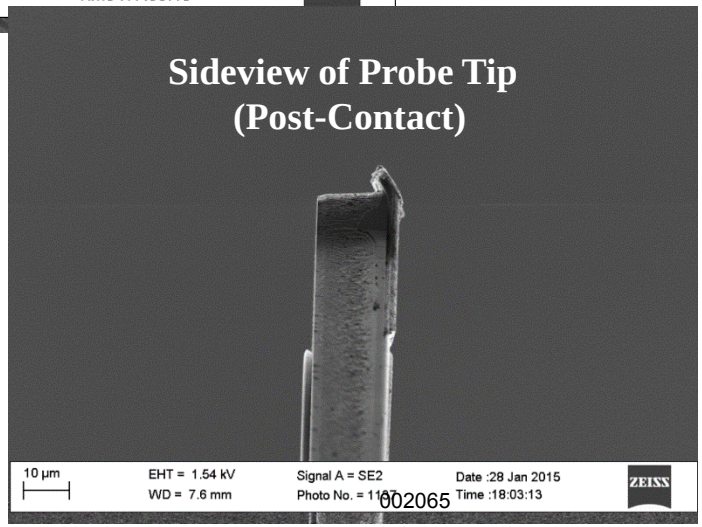
Micromachined On-Wafer Probes

Tip Deformation Post-Contact





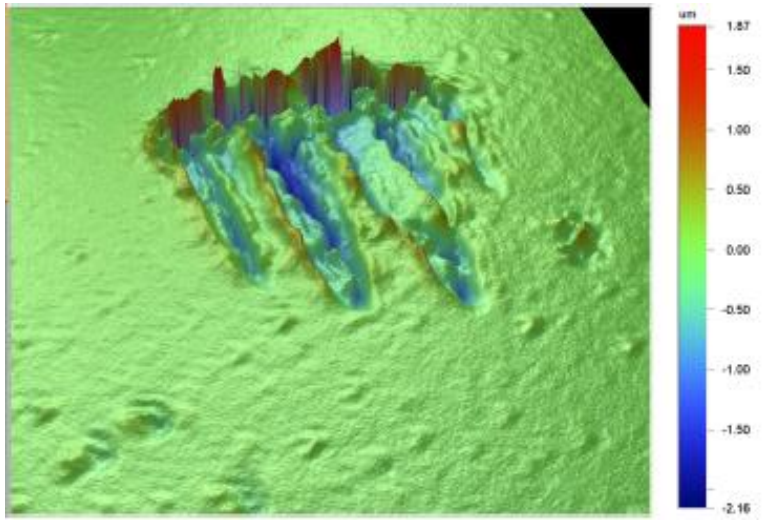




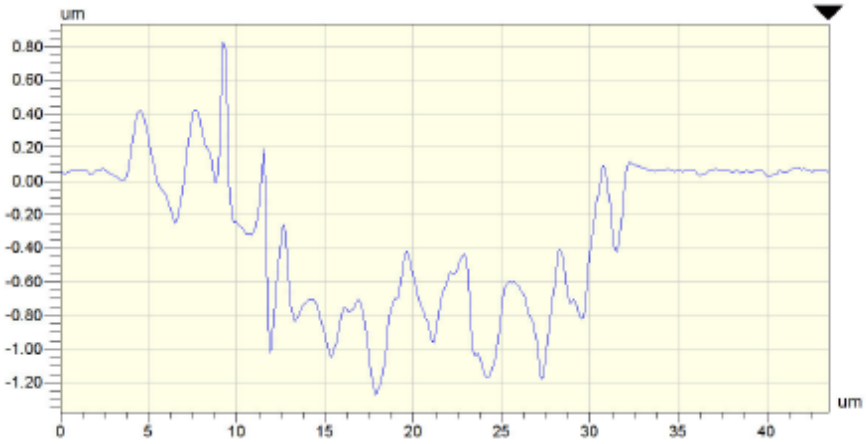
Micromachined On-Wafer Probes

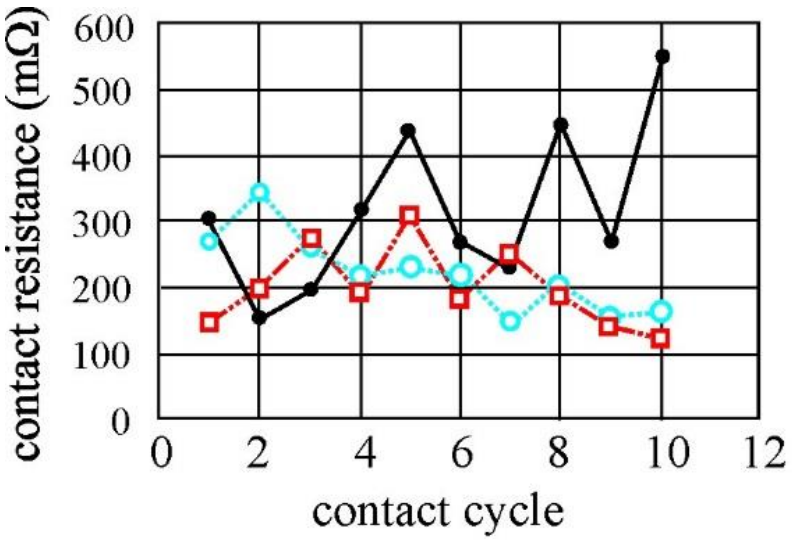
Skating Mark Characteristics and Contact Resistance

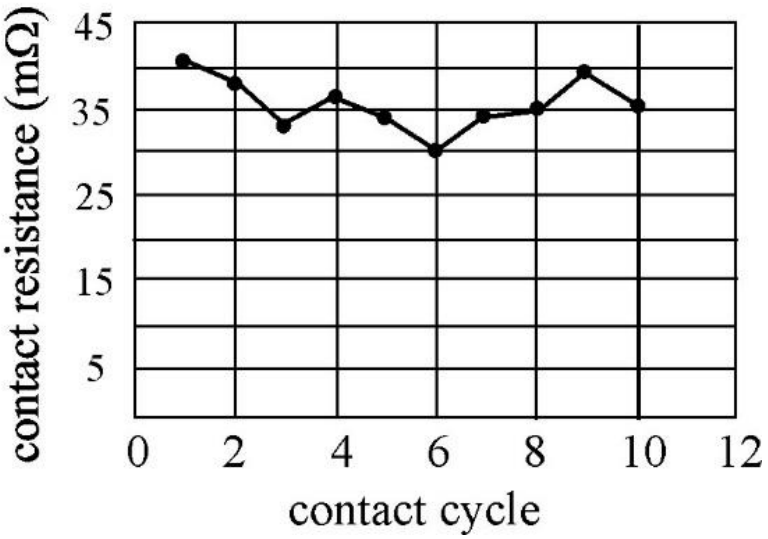
Micromachined Probe Skate Mark



Micromachined Probe Skating Profile







Heterogeneous Integration for Assembly/Packaging of Submillimeter-Wave Components

Micromachined W 1.5 Probe with Integrated Strain Sensor

Probe Layout:

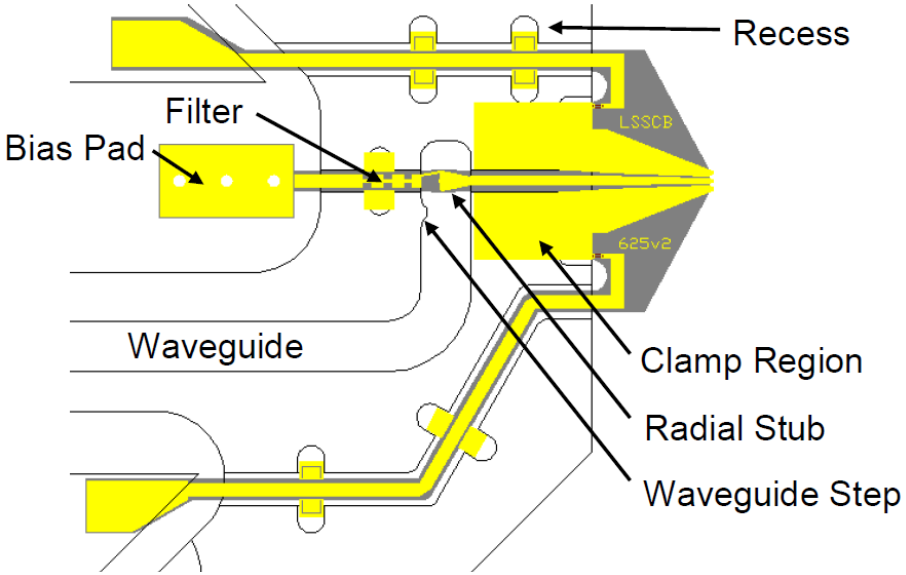
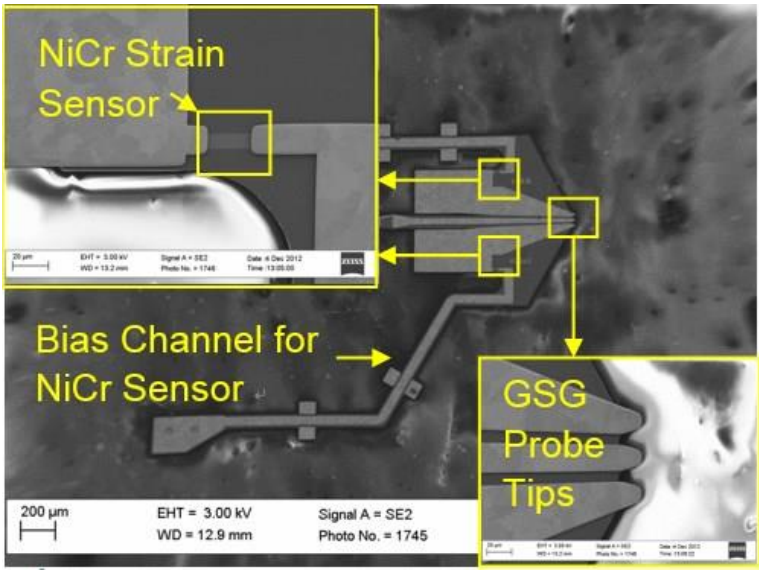
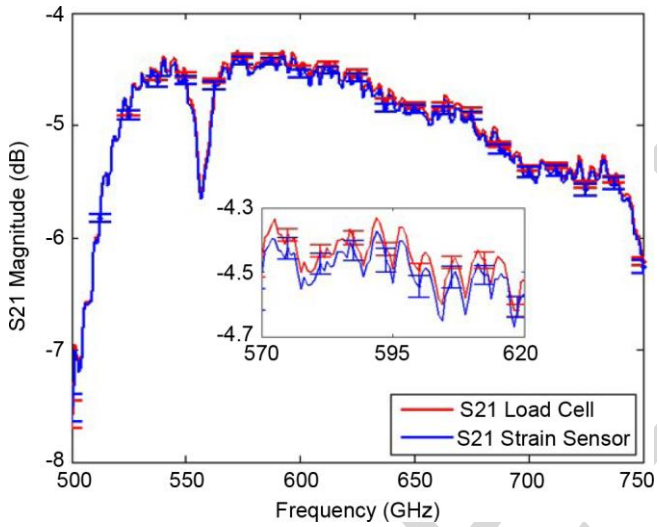
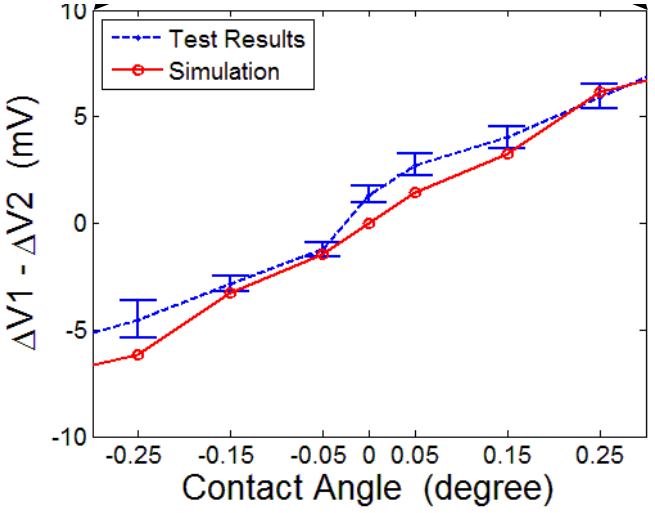


Image of Completed Probe:

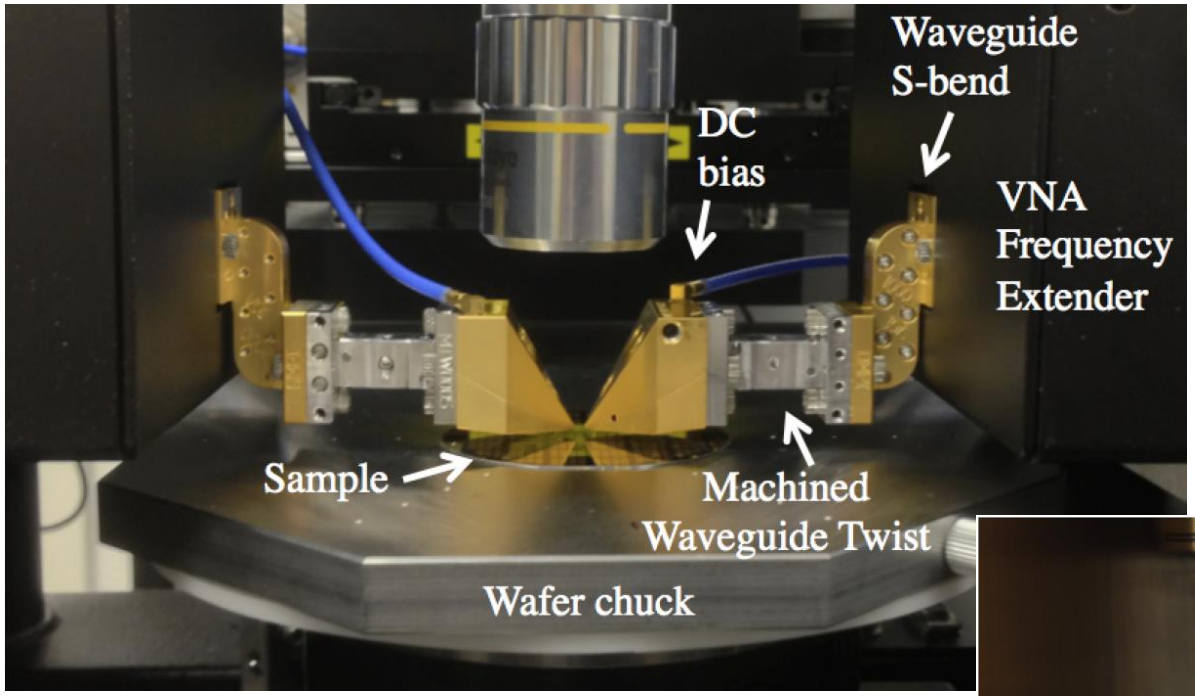






Metrology at Terahertz Frequencies

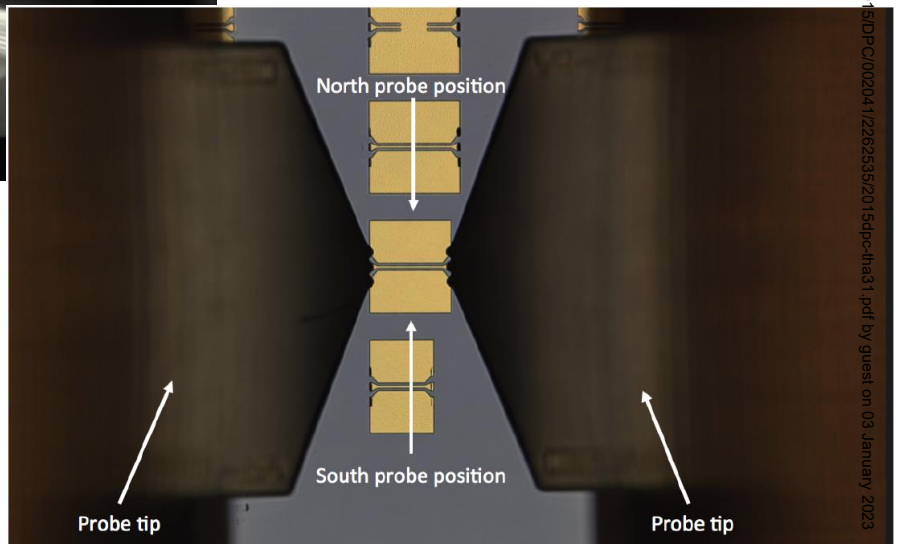
Two-Port Measurement Setup



Probe Set-Up for Two-Port Measurement

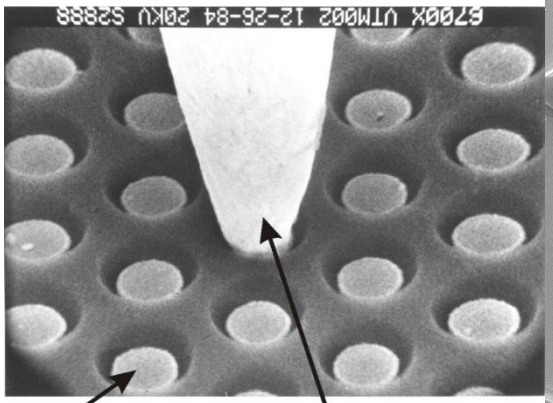
- **Waveguide Twist Section**
- **WR-1.0 S-Bend**
- **Large-Area Micropositioner**

Image of Probes Contacting TRL Standard

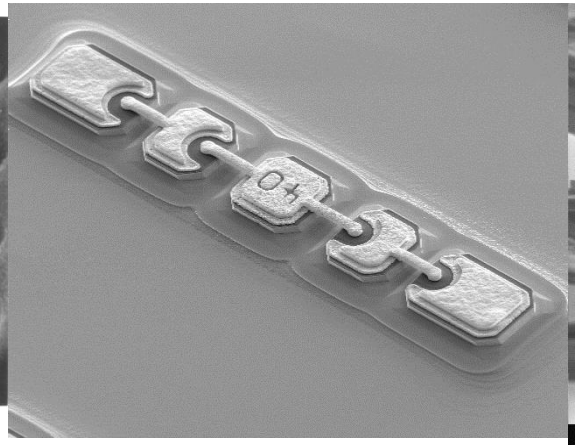


Schottky Diodes for THz/sub-mmW Wavelengths

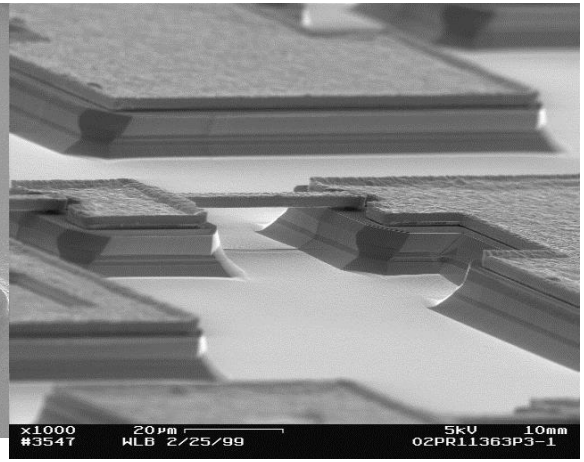
Evolution of the Schottky Diode:



~ 1980

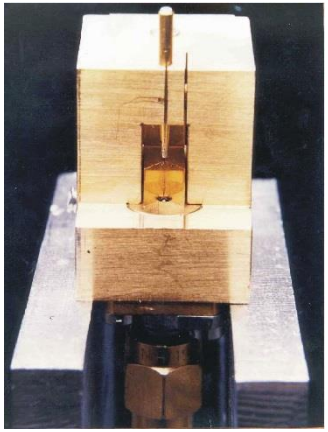


~ 1995

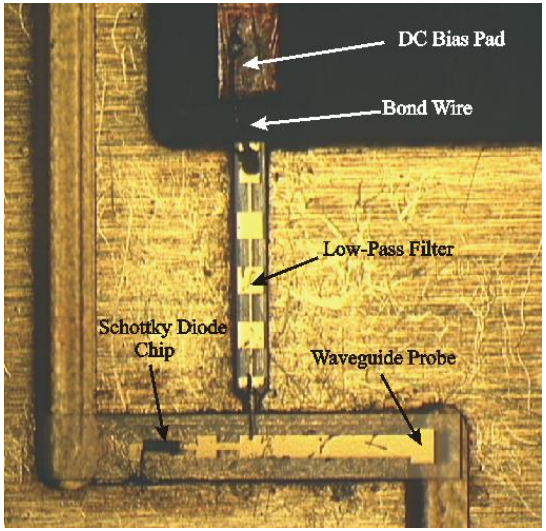


~ 2000

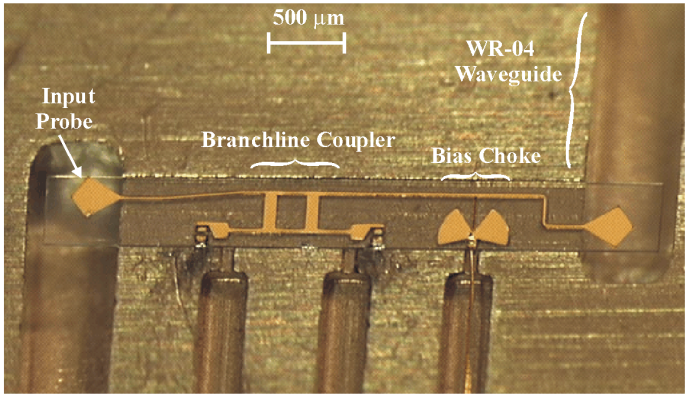
Diode-Based Circuits Circuits:



Cornercube Mixer



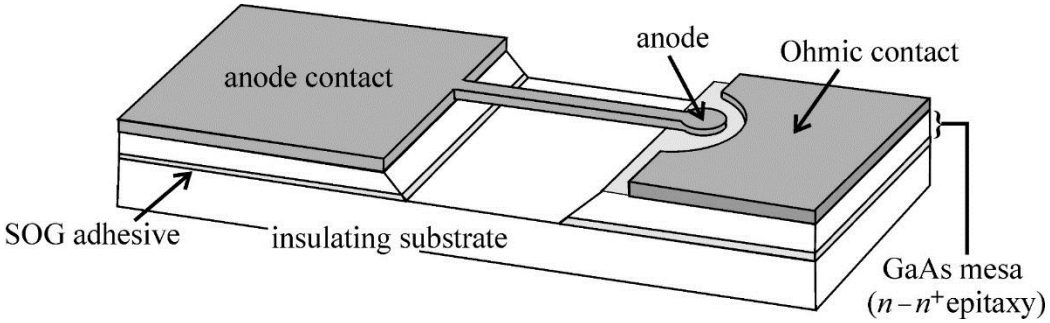
Flip-Chip Mounted Diodes

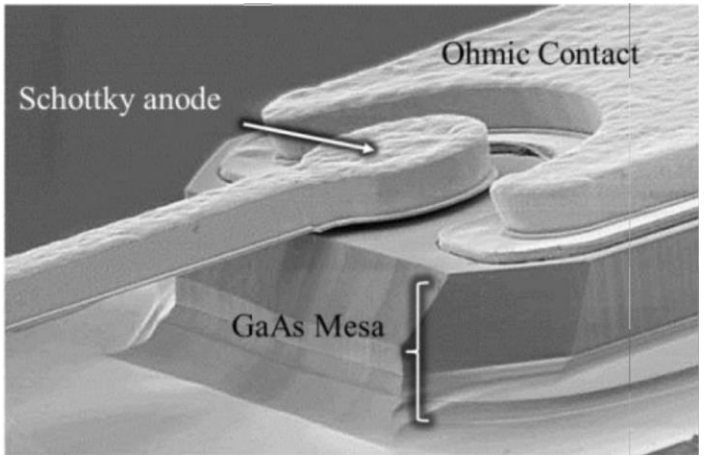


Phase Shifter

Quasi-Vertical vs. Planar Diodes

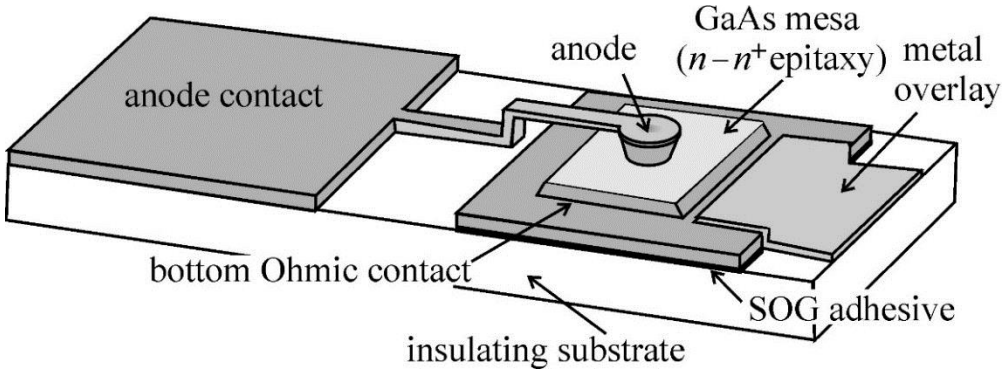
Planar Diode:

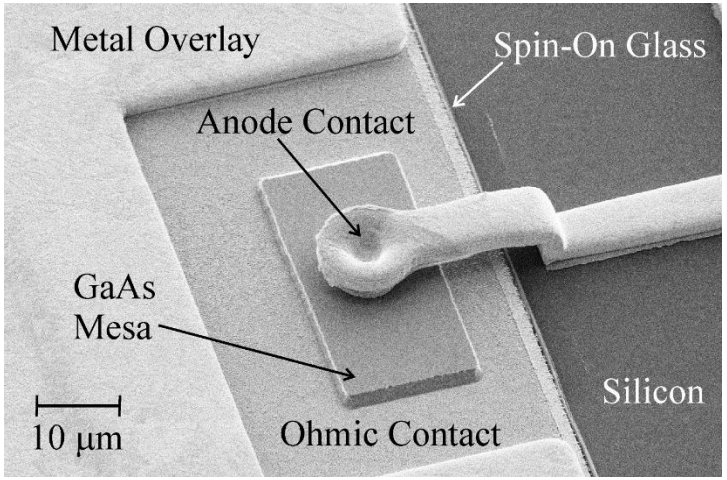




- **Coplanar anode/ohmic contacts**
- **Lateral current flow**
- **Partially-encircled anode**

Quasi-Vertical Diode:

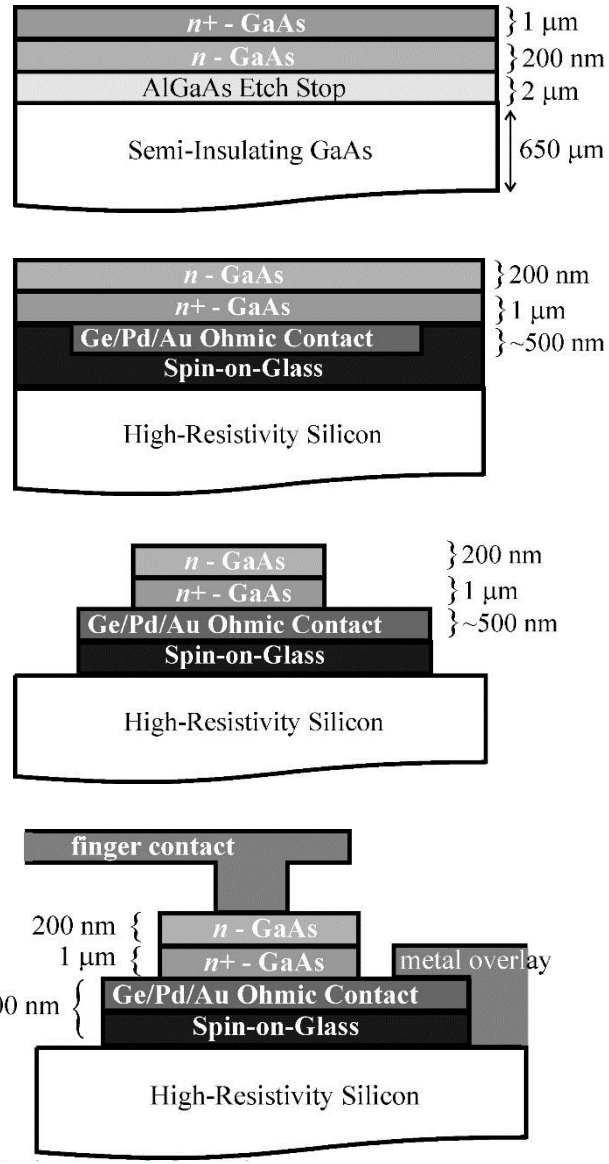




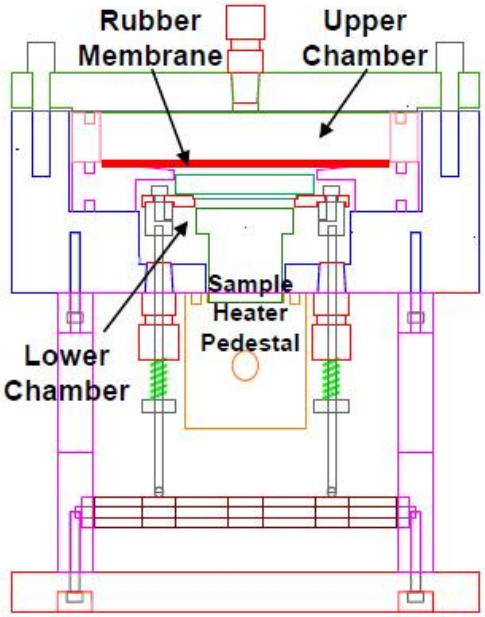
- **Ohmic contact beneath Anode contact**
- **Bulk current flow (through thin ~ 1 μm GaAs mesa)**
- **Large-area Ohmic contact**

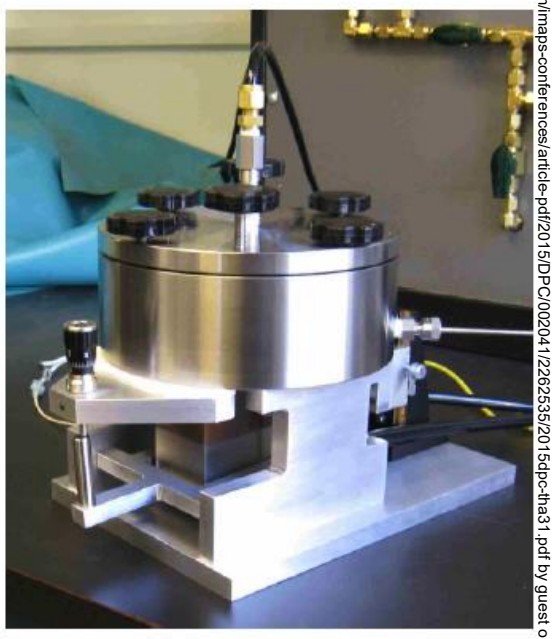
Quasi-Vertical Diode Fabrication

Basic Process Steps:



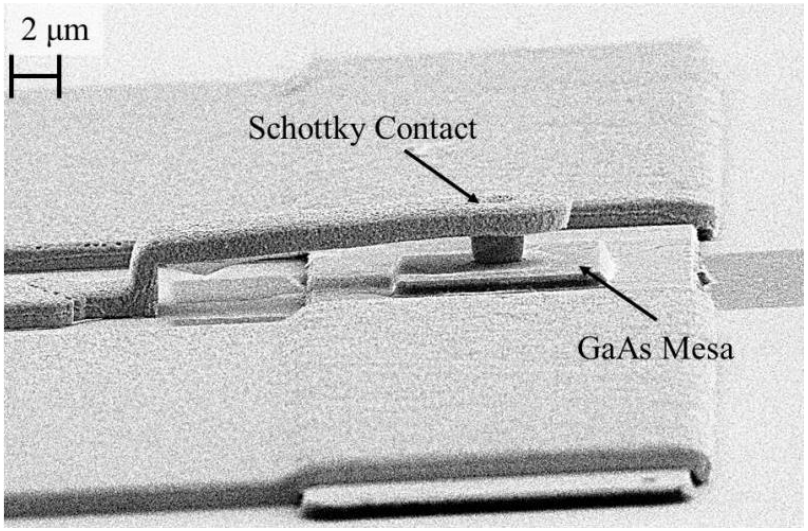
Wafer Bonding Press:



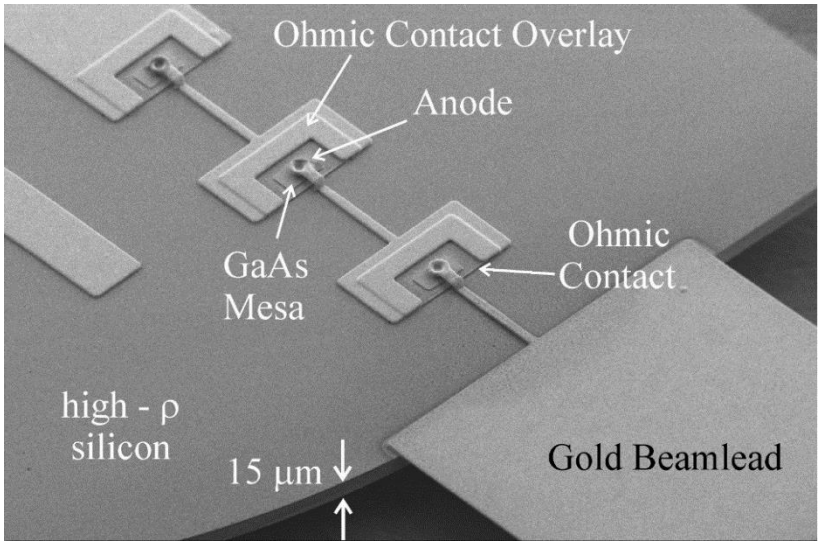


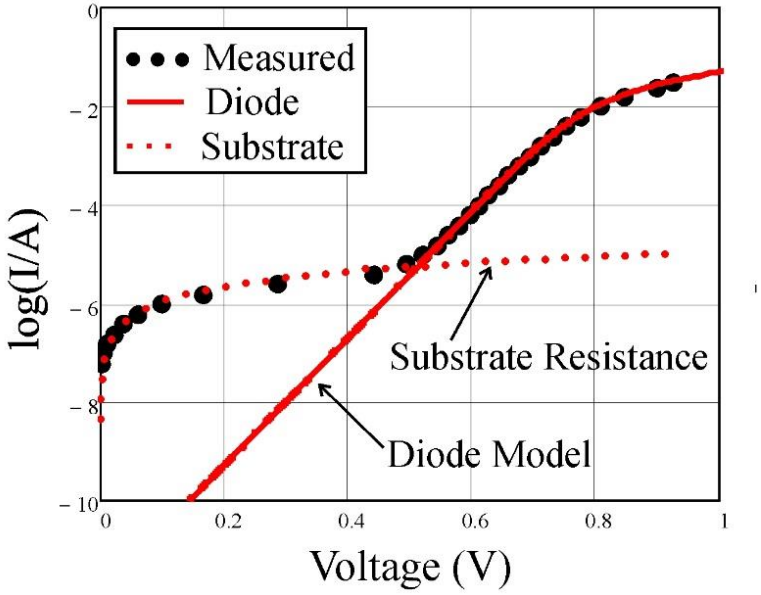
Quasi-Vertical Diode DC Characteristics

Side View of Diode:



QVD Array on 15 μm silicon:





MEASURED DC PARAMETERS OF QUASI-VERTICAL DIODES

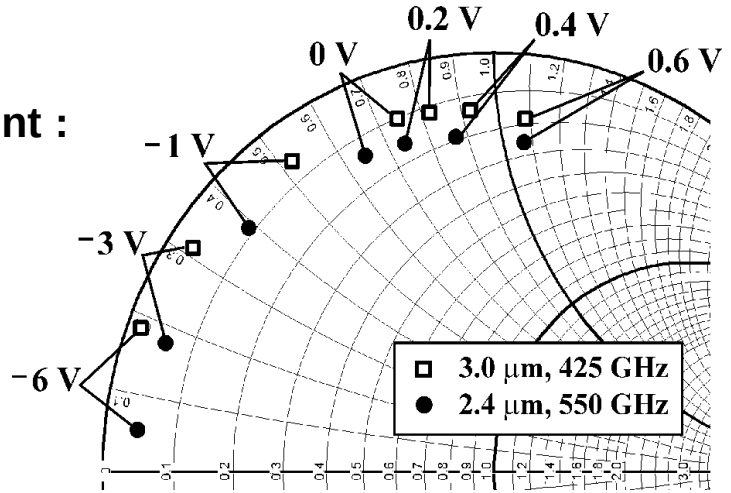
Anode diameter (nominal), μm	Ideality factor	Resistance (Ω)	Saturation Current (pA)
3.0	1.35	3.7	1.4
2.4	1.28	4.5	0.4
1.8	1.25	6.0	0.1

Metrology at Terahertz Frequencies

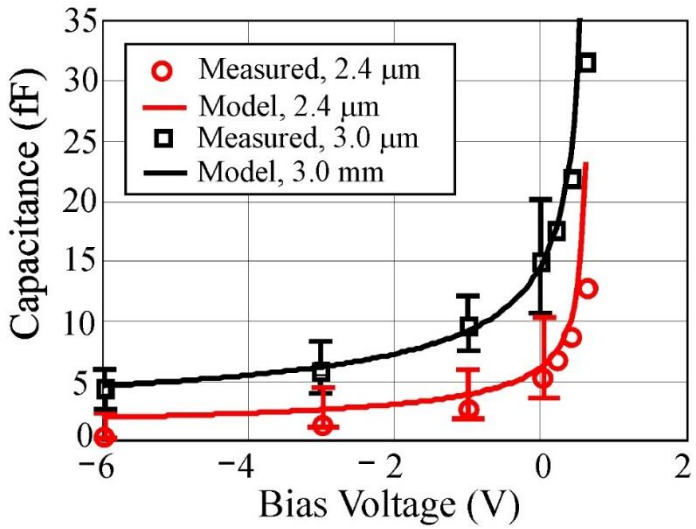
On-Wafer Characterization of Schottky Diodes

On-Wafer Measured Reflection Coefficient :

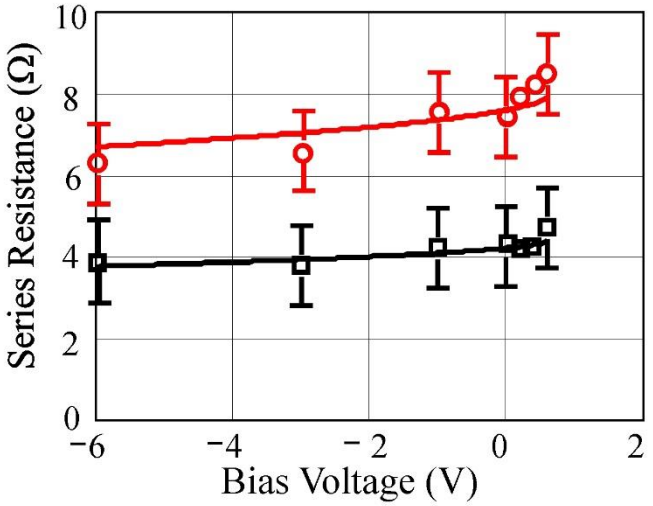
- **WR-2.2 and WR-1.5 Bands**
- **S_{11} vs. Diode Bias**
- **3.0μm and 2.4 μm devices**



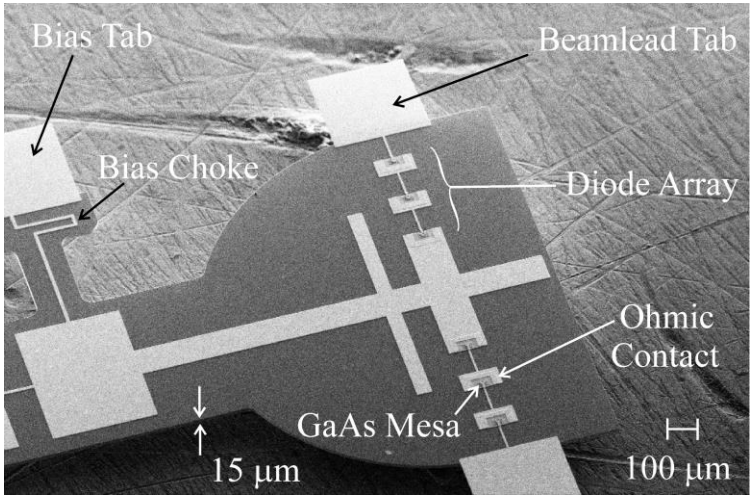
Extracted Capacitance



Extracted Series Resistance



Application of Quasi-Vertical Diodes
High-Order Frequency Multipliers



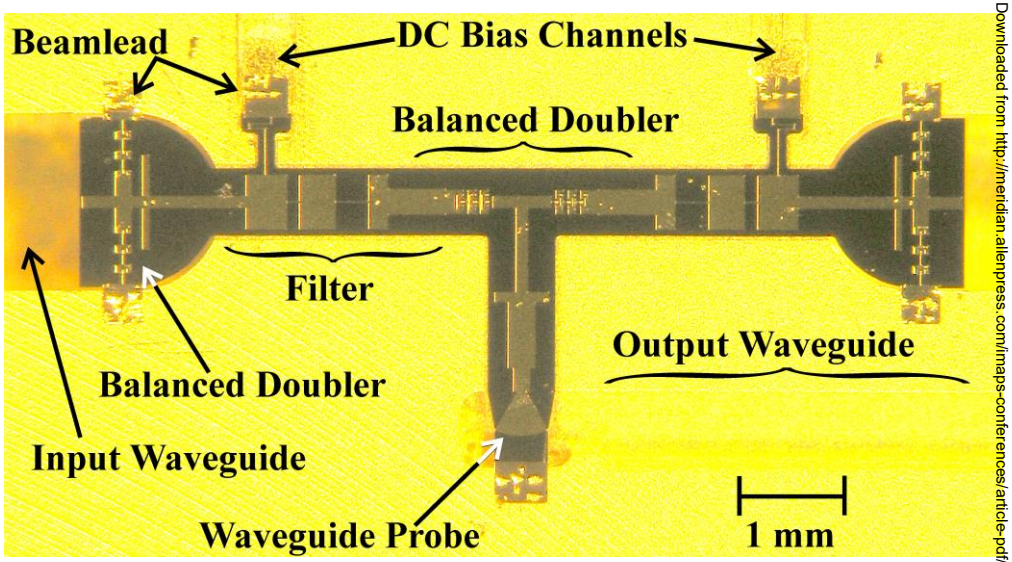
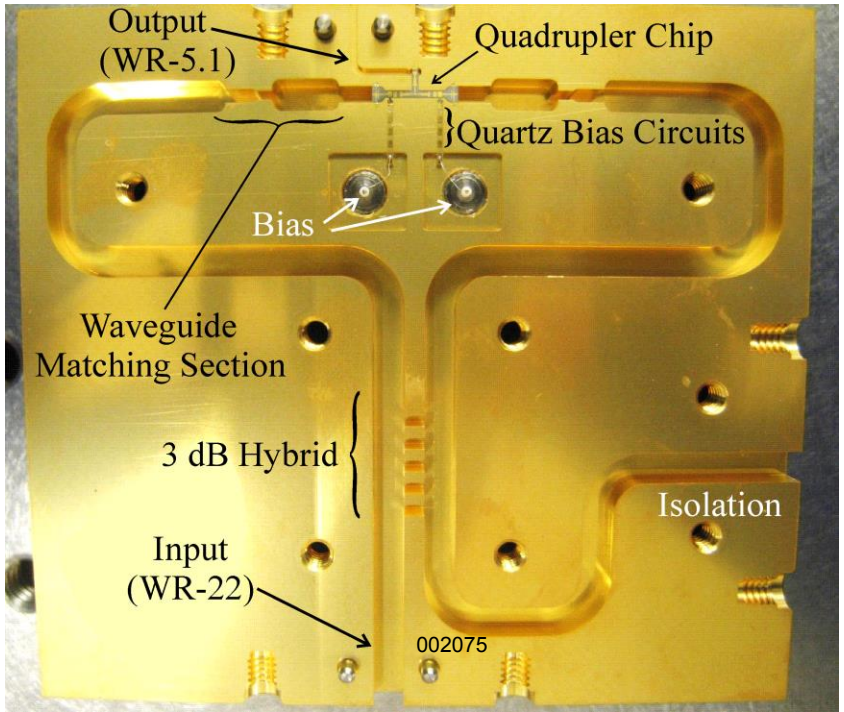


Image of Quadrupler Housing with Mounted Chip

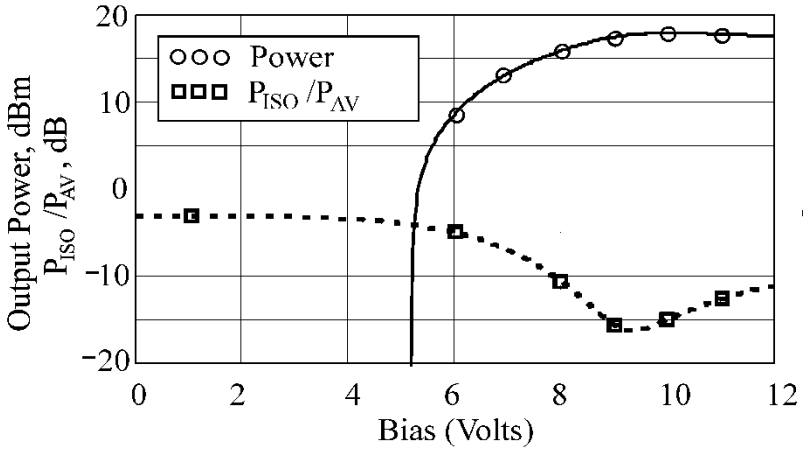


Integrated Quadrupler Chip

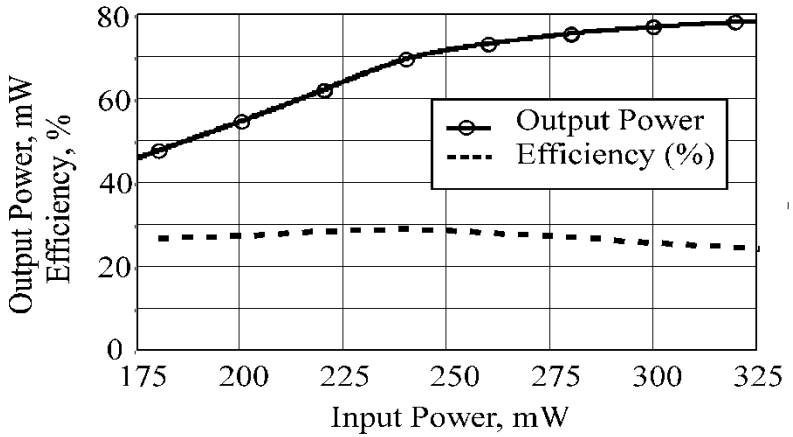
- **18 Varactor Diodes**
- **Filter/Matching Networks**
- **Alignment/Mounting Tabs**
- **Bias Tabs**

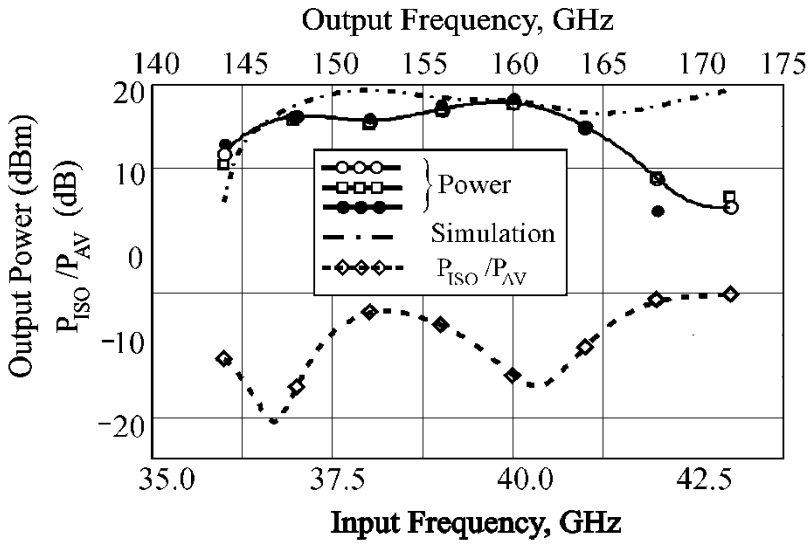
Application of Quasi-Vertical Diodes
High-Order Frequency Multipliers

Output power vs. Bias



Output power vs Input Power





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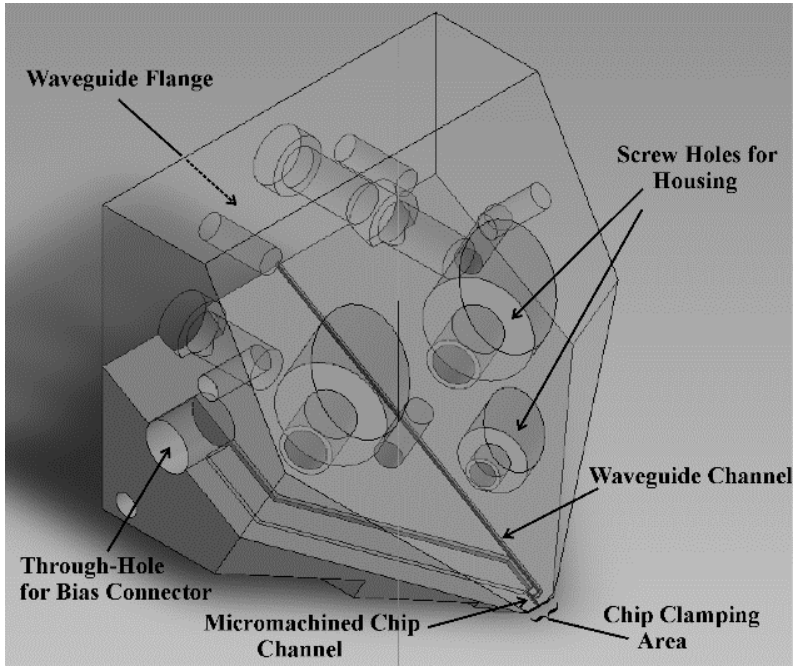
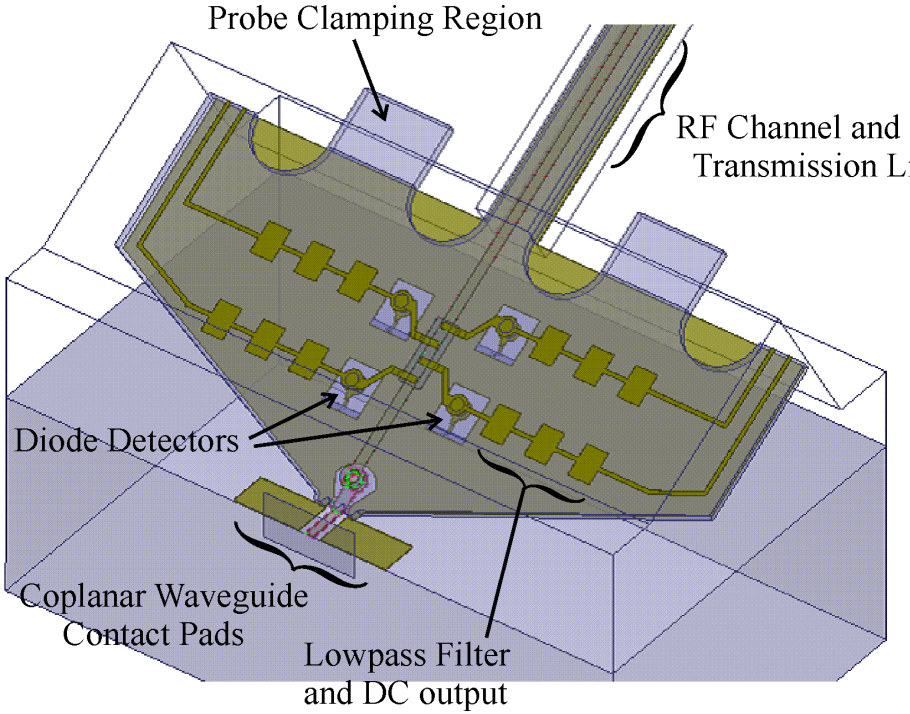
- **Bandwidth ~ 13%**
- **Output Power, 79 mW**
- **Max Effiiciency, 30%**
- **Diode Temperature ~ 40° C**

Some Research Directions

- **Micromachined Probes with Integrated Sensors (Detectors/Mixers)**
- **Incorporation of Front-End RF Electronics into Probe Housing**
- **Development of Integrated Six-Port Reflectometer**





SUMMARY

- On-Wafer Measurements now possible up to 1.1 THz
  - **Probe Pitches of 25 μm — 100 μm**
  - **1.5—6 dB Insertion Loss**
  - **Probe Lifetime Measured > 20,000 contacts**
  - **Bias Design permits > 100 mA DC current**
  - **Commercially-Available through Cascade-Microtech/DMPI**

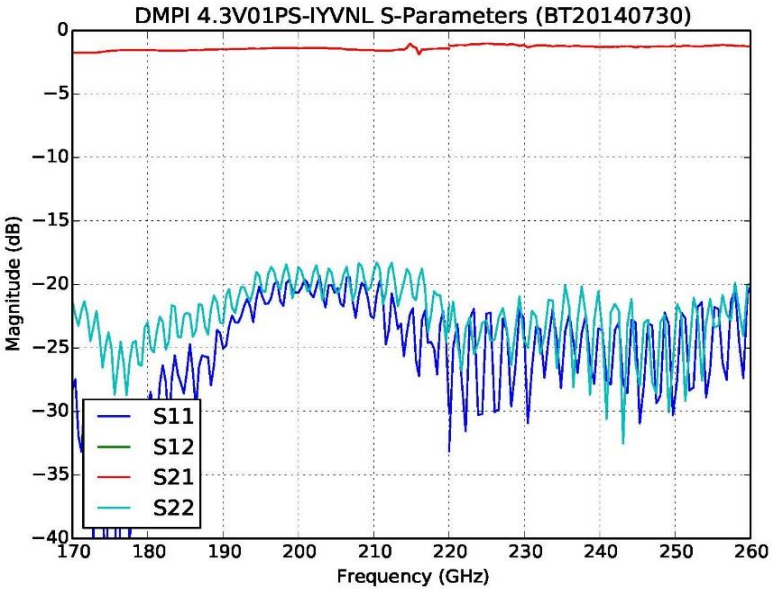
- Current Efforts Focused on Robust Tips and Integration of Sensors/Components
  - **Engineering Hard-Metal Probe Tips**
  - **Integrated Stain Sensors**
  - **On-Chip Balun for Differential Circuits**
  - **Integrated Schottky Diodes for Detection/Signal Generation**

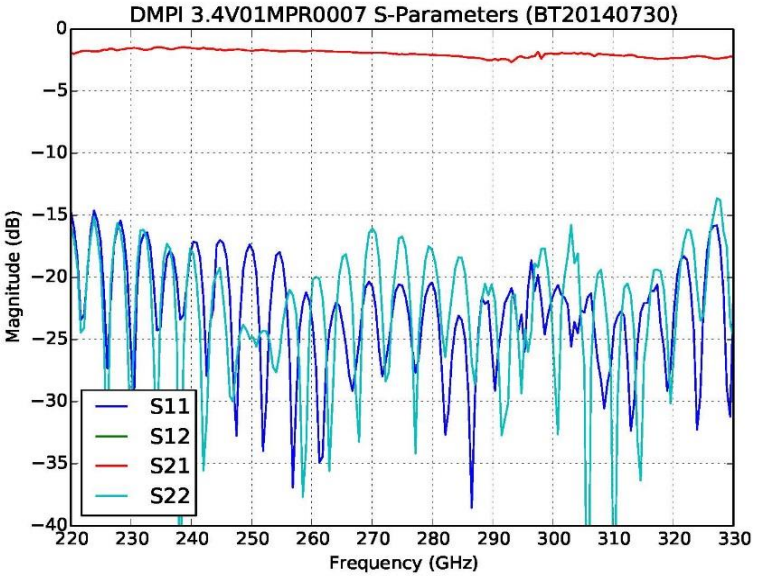
- Heterogeneously-Integrated Electronic Devices
  - **Terahertz Operation with Low Parasitics**
  - **Mechanically-Robust, Thin Support Membranes**
  - **Chip Geometry Tailored for Housing/Application**
  - **Fully-Integrated, Low Profile Instrumentation**

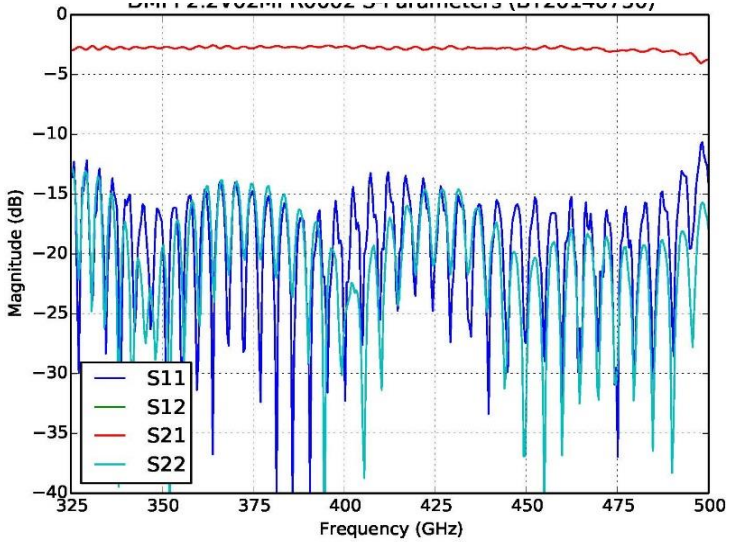
Questions …?

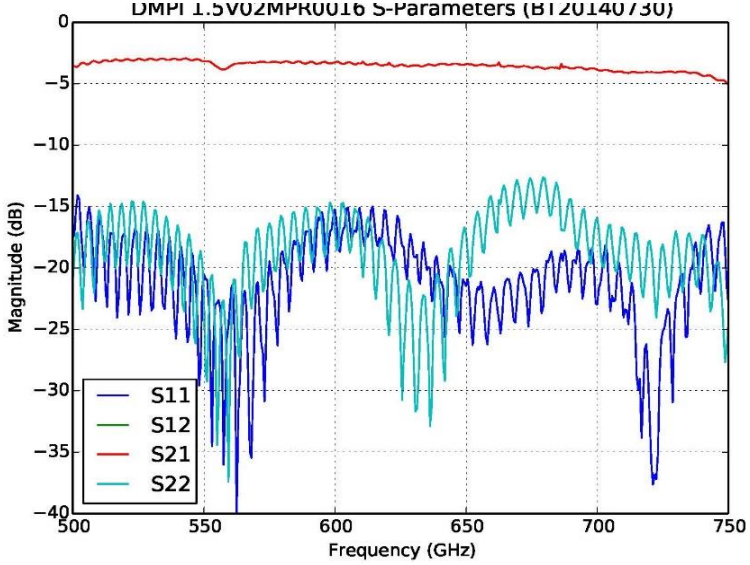
Submillimeter-Wave Micromachined Probe Performance

Overview

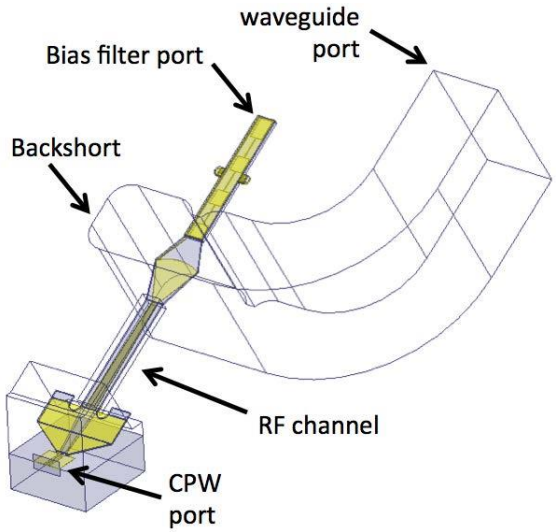




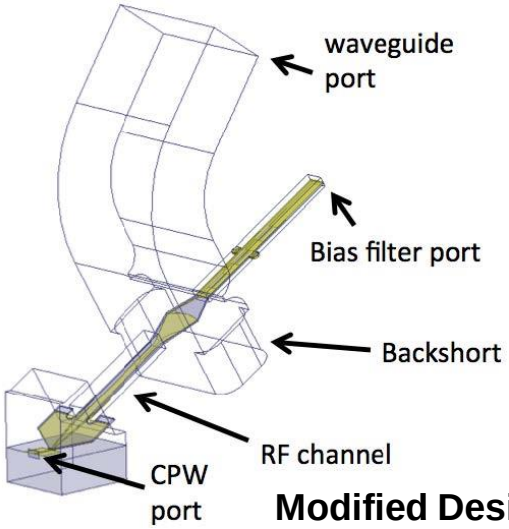




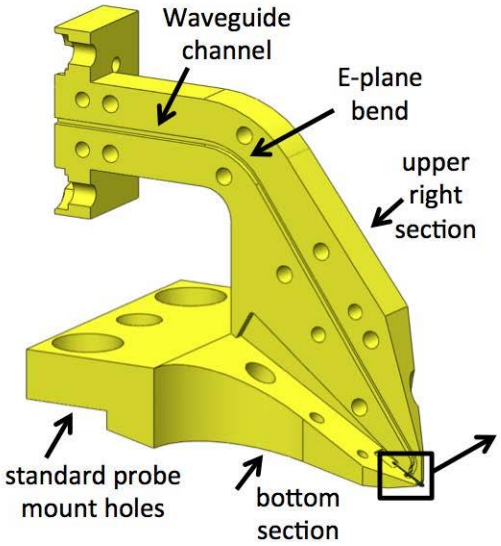
Evolution of the Probe Design

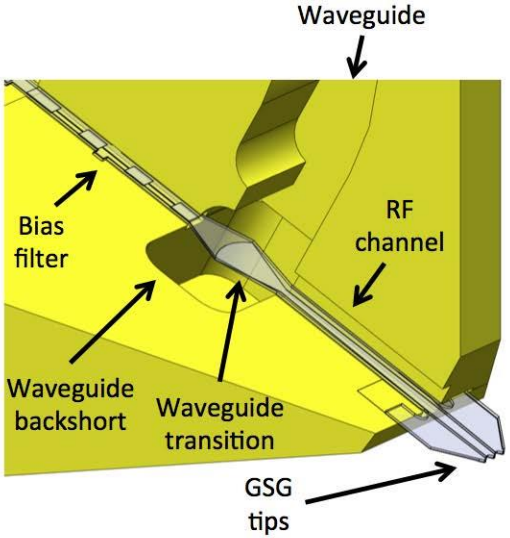


Initial Design Approach



Modified Design





Details and Implementation