University of Virginia | School of Engineering & Applied Science

Far Infrared and Terahertz Receiver Laboratory

Millimeter-Wave “Reflectionless” Filters and Diplexers based on Silicon Micromachining

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01471

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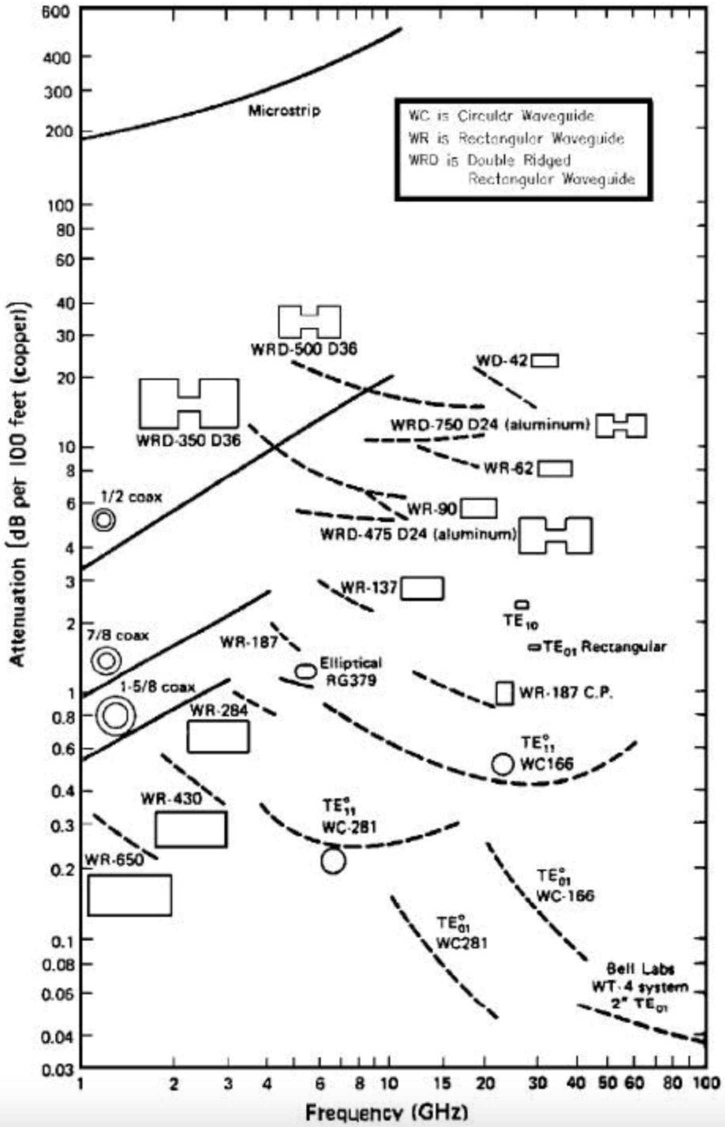
AGENDA

- Motivation: Waveguide as a Medium for Millimeter/Submillimeter-Wave Systems
- Multiband Waveguide Systems Incorporating Diplexers
  - 0-220 GHz s-Parameter Measurement Systems
  - Diplexer Architectures
- Reflectionless Filter and Diplexer Architecture
  - Morgan's Lumped-Element Reflectionless Filter
  - Practical Implementation of a Prototype 0-220 GHz Diplexer
  - Design and Simulation
- Reflectionless Filter Implementation
  - SOI-based Micromachined Diplexer
  - Test Fixture Design
  - Measurement and Assessment
- Reflectionless Diplexer Implementation
  - SOI-based Micromachined Diplexer
  - Test Fixture Design
  - Measurement and Assessment
- Summary

Waveguide Media for Millimeter/Submillimeter-Wave Applications



Courtesy RF Cafe

- **Predominant Medium for > 100 GHz**
- **Commercially-Available Instruments designed for Standardized Waveguide Bands**
- **Advantages (+)**

  Low Loss
  - Planar Transmission Lines: > ~1 dB/cm
  - Rectangular Waveguide: < ~0.01 dB/cm

  Shielded (Non-Radiative, High Isolation)

  Robust, Repeatable Interfaces
  - IEEE Standards for Rectangular Waveguide and Interfaces (P1785).
- **Disadvantages (-)**

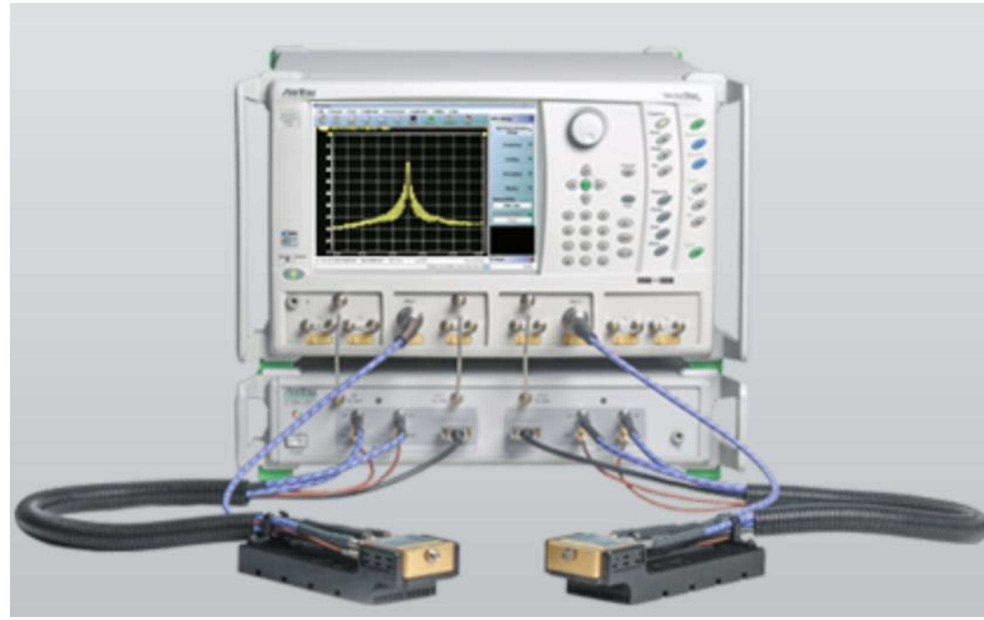
  Geometry, Size, and Weight
  - Considerably Larger than Circuits Housed

  Limited Bandwidth for Single-Mode Propagation
  - Approximately 40% Bandwidth

Example – Millimeter-Wave Measurement Systems

Agilent PNAX VNA

- Coaxial Medium to 110 GHz
- Schottky Diode-based Extenders to Up- and Down-Convert to Bands > 110 GHz using Mixers and Harmonic Multipliers
- Extenders Band-Limited by Rectangular Waveguide

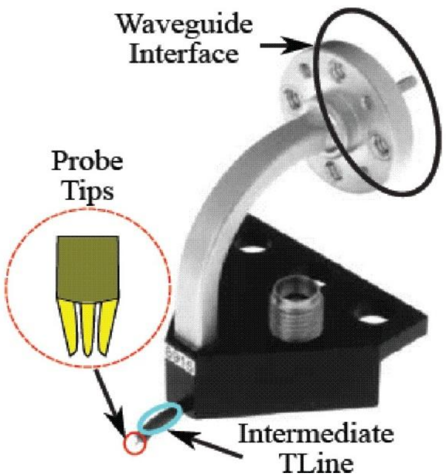


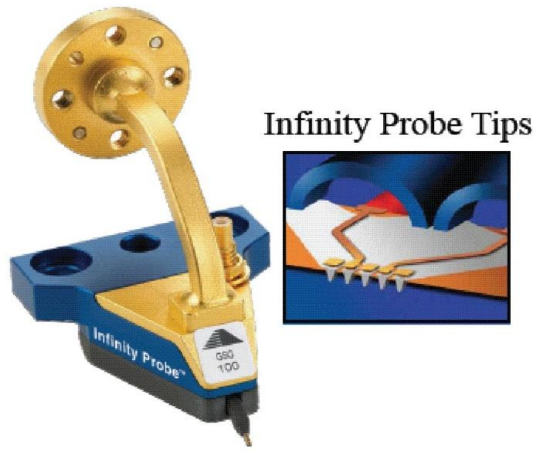
Anritsu VectorStar ME7838 VNA

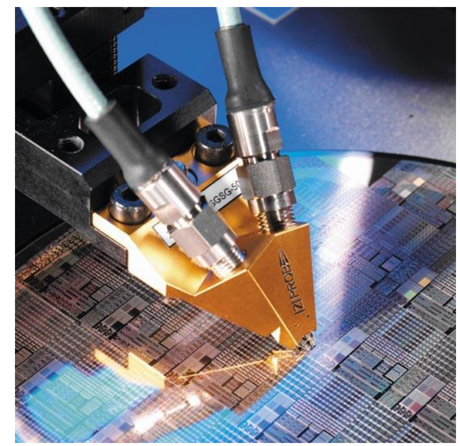
- Single-Sweep 70 kHz to 220 GHz Measurements
- NLTL/Shockline Harmonic Generators and Samplers
- Transmission Line Medium (0.5 mm Coax)

Micromachined On-Wafer Probe Concept

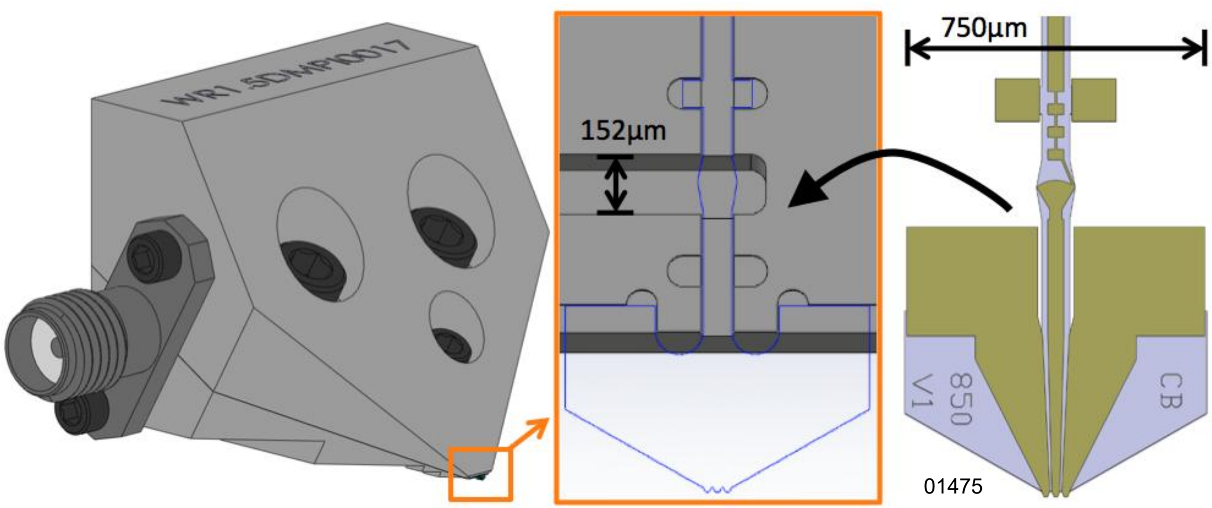
Commercial Wafer Probes



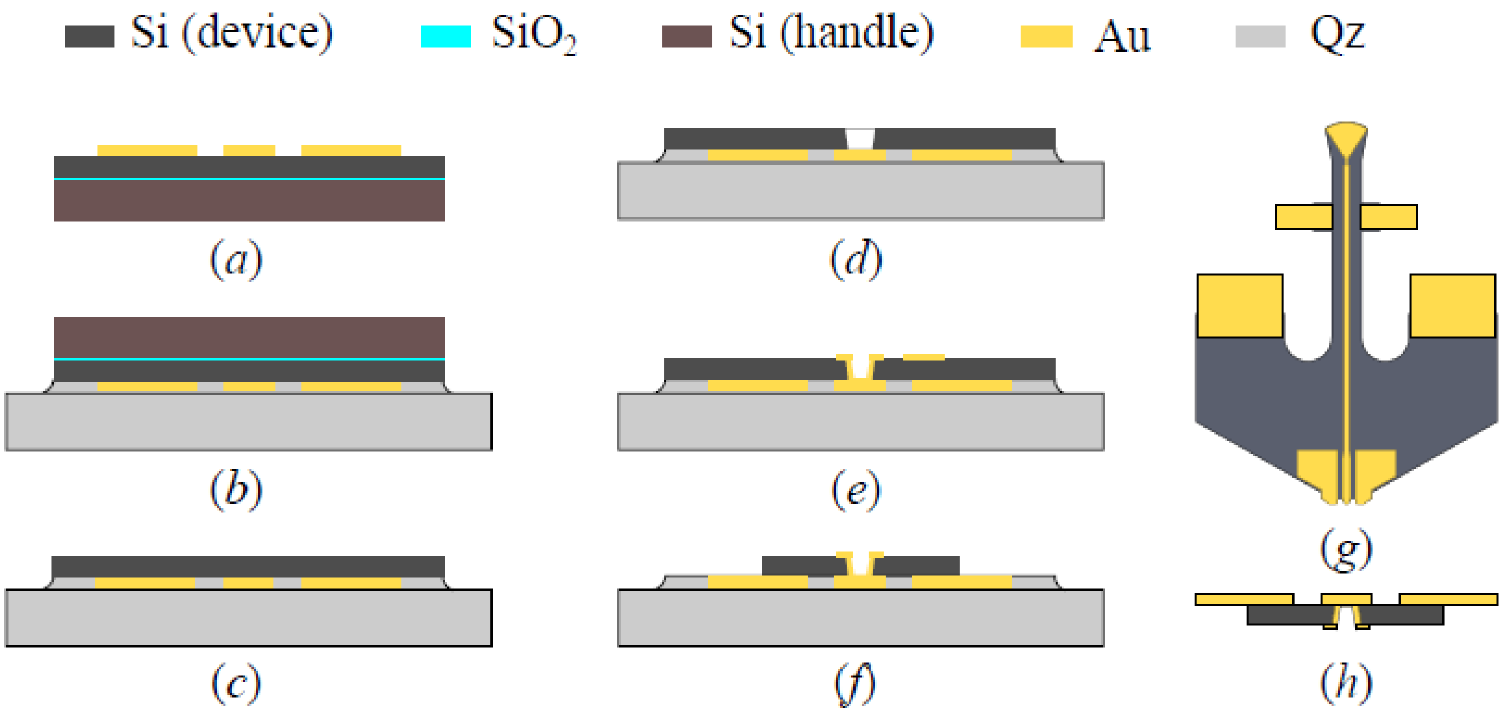




Micromachined Wafer Probe Assembly

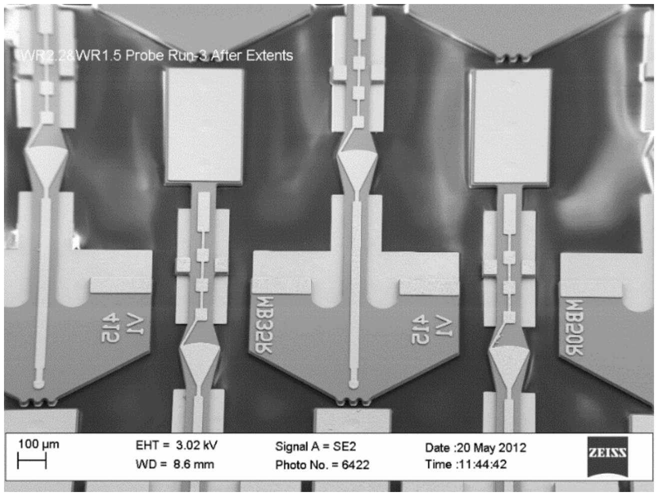


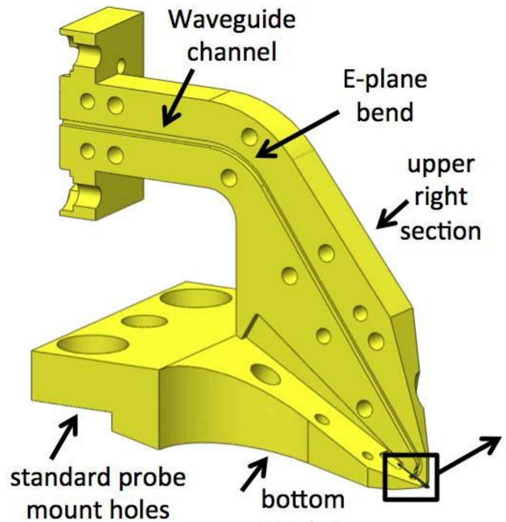
Micromachined On-Wafer Probe Fabrication

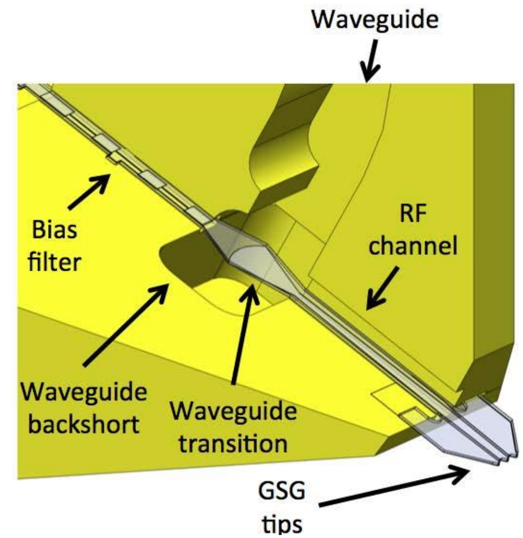


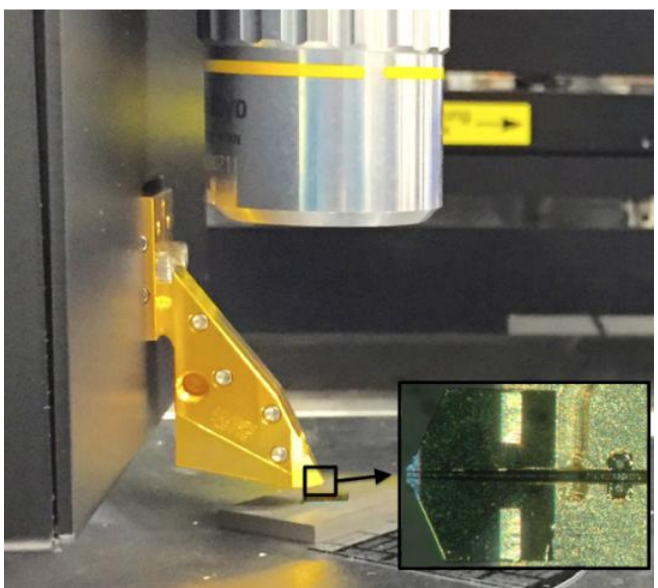
Process Flow of Micromachined SOI Chip Fabrication

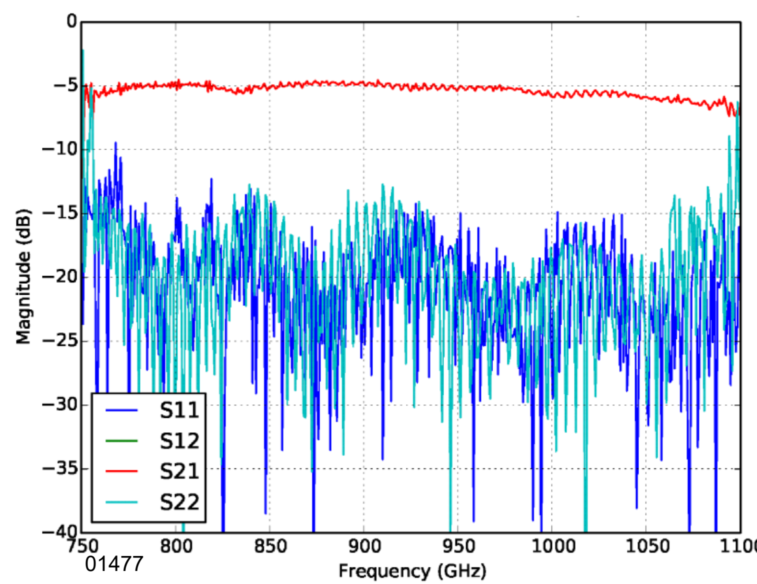
Micromachined On-Wafer Probe Implementation



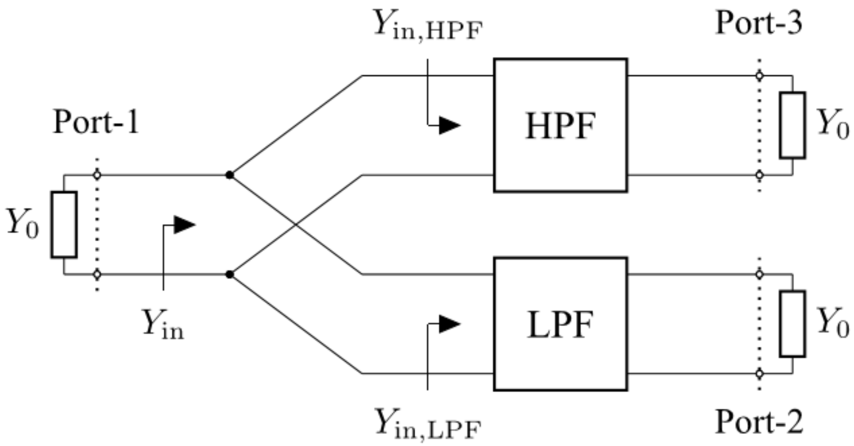




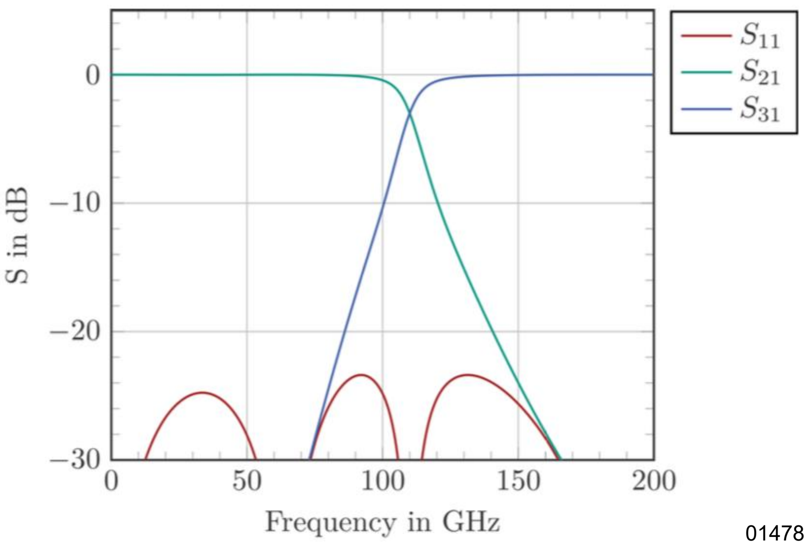




Extending the Operating Bandwidth of Waveguide Systems : Diplexers



- Passive diplexer features a high-pass filter (HPF) and low-pass filter (LPF) in parallel
- HPF and LPF are designed to be *complementary*, providing a broadband match
- Must be integrated into broadband transmission system (i.e., planar transmission line or probe)



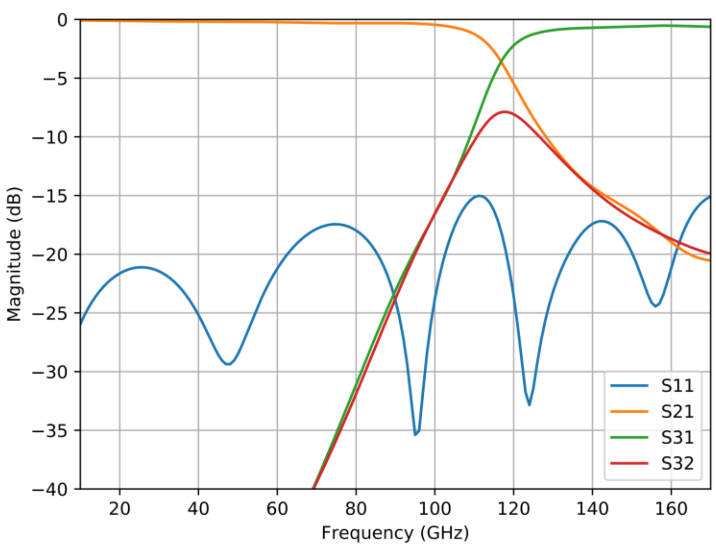
$$\Re(Y_{\text{in,LPF}}) + \Re(Y_{\text{in,HPF}}) = Y_0$$
$$\Im(Y_{\text{in,LPF}}) + \Im(Y_{\text{in,HPF}}) = 0.$$

Prototype Dual-Band Wafer Probe

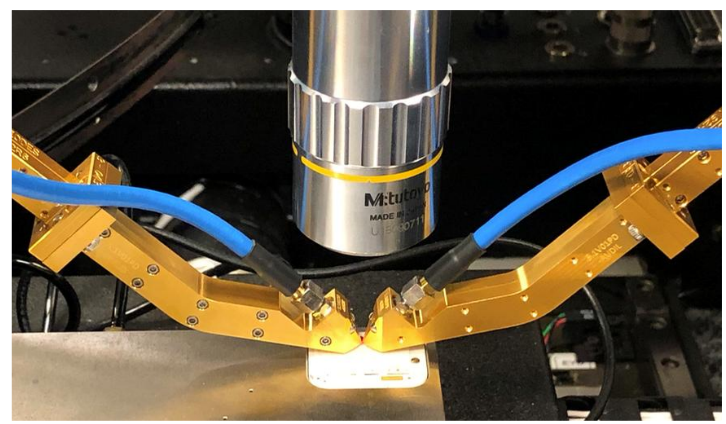
Port 2 - LPF

Port 3 - HPF

Port 1 – Combined



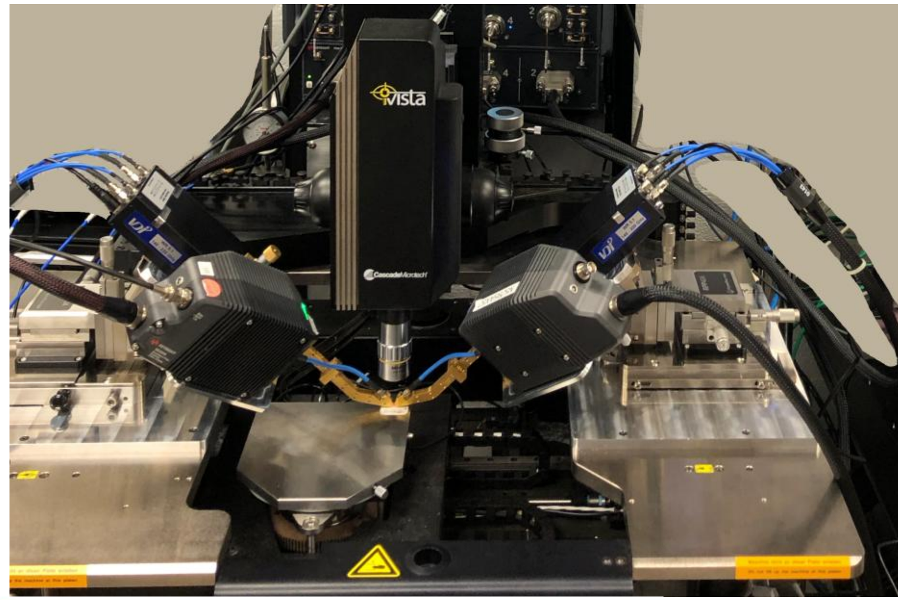
- Design flow described in detail in [1]
- Stepped Impedance LPF (N=5)
- Capacitively coupled resonator HPF (N=5)
- Connected in shunt using tee junction for combined output to probe tips
- 1.0 mm coax DC-130 GHz
- WR-5.1 input 130 – 220 GHz

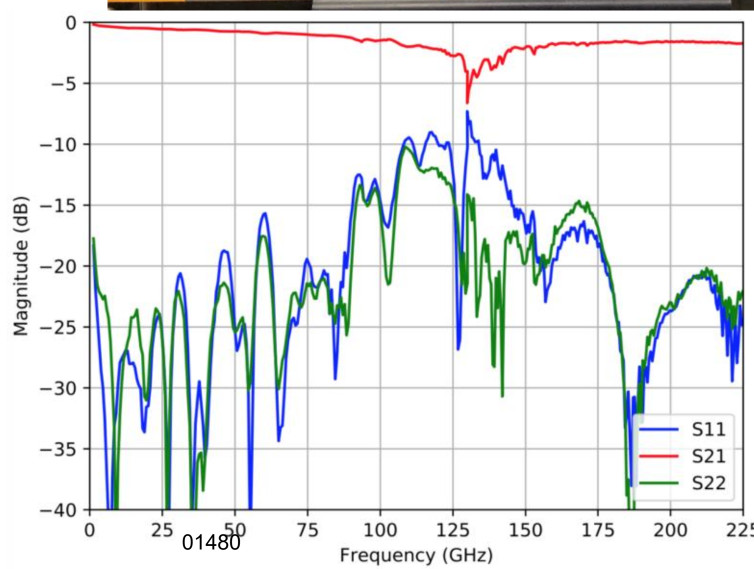


[1] F. Boes, G. Gramlich, M. Kretschmann, S. Marahrens and T. Zwick, "Ultrabroadband Diplexers for Next-Generation High-Frequency Measurement Applications," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 6

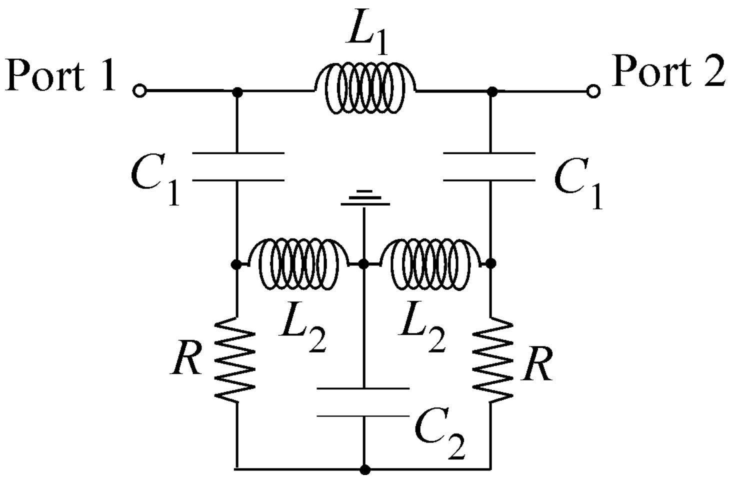
Measurement Setup

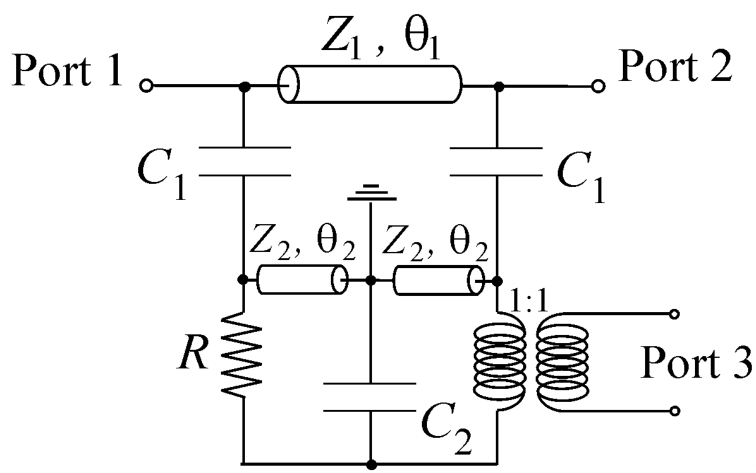
- FormFactor PA200 station
- Keysight N5245B PNAX
- Keysight N5292A Controller
- Keysight Broadband Modules (130 GHz, 13cm cables)
- VDI WR-5.1 Extended Modules (130 – 220 GHz)
- DMPI 220 GHz Broadband Probe (50 um pitch)





The Reflectionless Filter/Diplexer





- **Complementary Filter Diplexer is Lossless 3-Port Network**
  - Impossible to Simultaneously Match All Ports
  - Input Ports Not Isolated Near Crossover Frequency
- **Alternative Topology – Morgan's Reflectionless Filter**
  - Symmetric Network
  - Even and Odd Equivalent Circuits are Identical Duals ⟶
  - Out-of-Band Power Absorbed in Filter Internal Resistor
  - Converting Internal Resistor to Port ⟶ Reflectionless Diplexer
  - Inductive Elements Replaced with High-Z_0 Transmission Lines

$$R = Z_0$$

$$C_1 = \frac{1}{Z_0^2}\frac{L_1}{2}$$

$$L_2 = Z_0^2 C_1$$

$$C_2 = \frac{2L_2}{Z_0^2}$$

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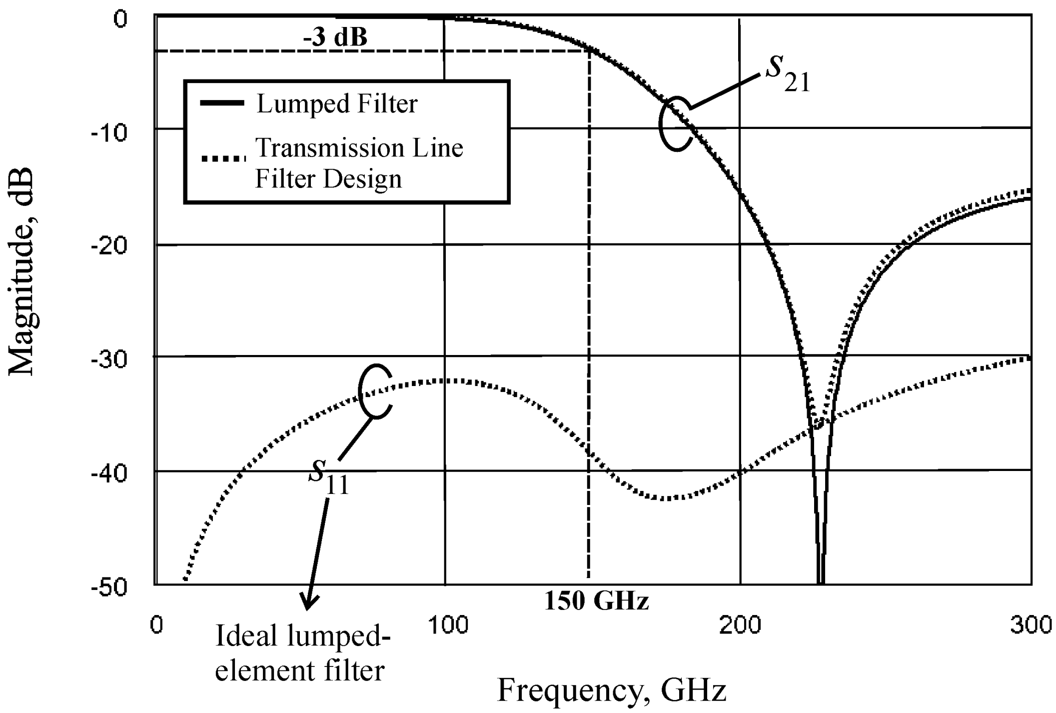
Reflectionless Filter Performance (Simulation)



- Comparison of insertion and return loss for ideal lumped-element reflectionless filter and
- "quasi-reflectionless" filter incorporating high-impedance transmission line elements.

- Return loss for deal lumped-element filter is infinite.

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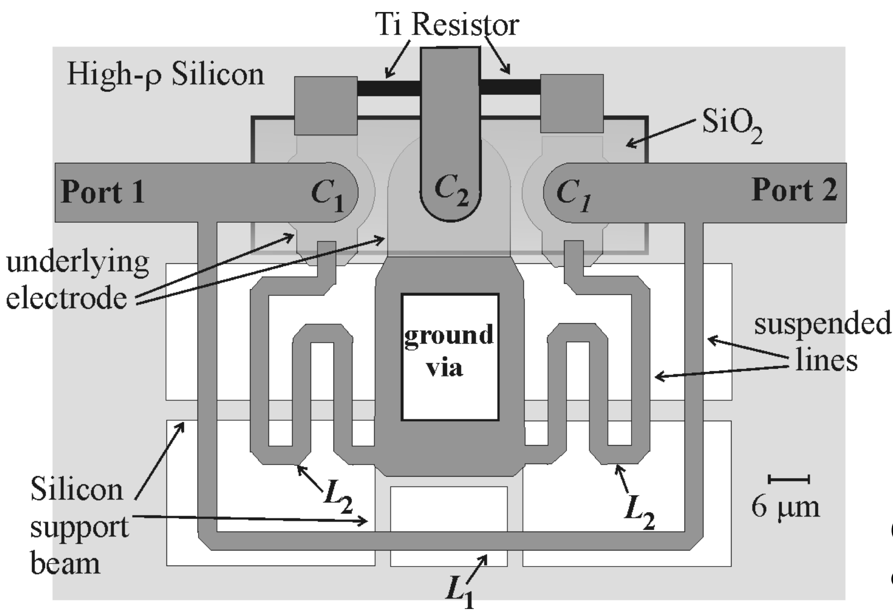
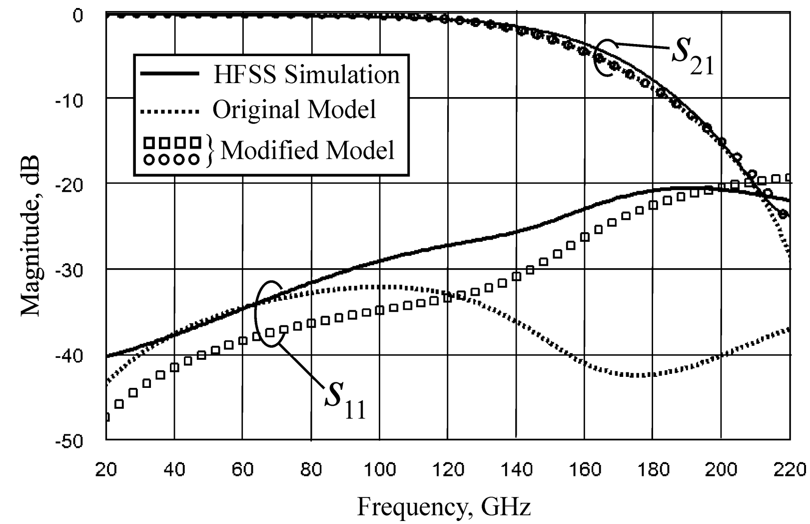
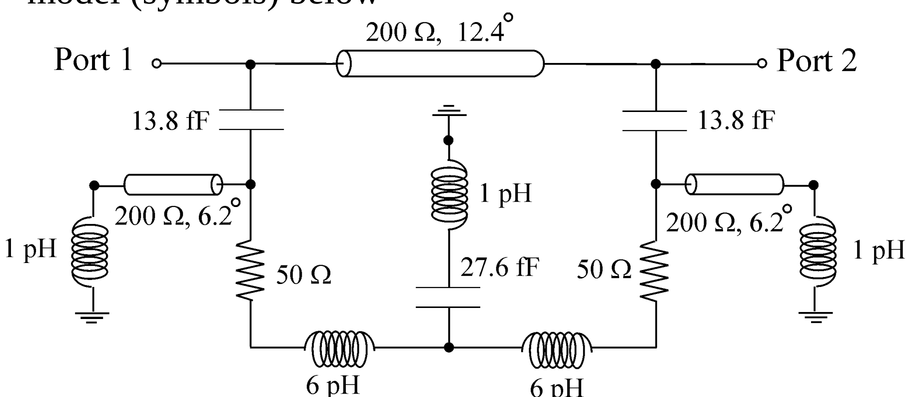
Filter Implementation and Simulation



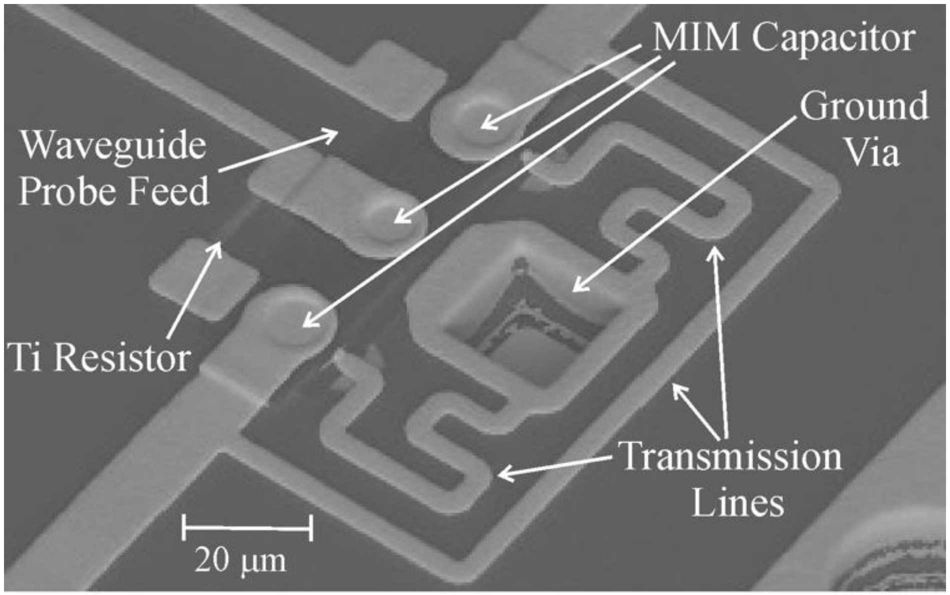


Comparison on an HFSS simulation (solid line) with the original circuit model (dashed line) and "modified" circuit model (symbols) below



- Suspended microstrip lines to realize the inductive elements, L_1 and L_2.
- 15 μm thick high-resistivity (>20kΩ-cm) silicon substrate.
- Thin-film titanium resistors (width of 2 μm, length of 10 μm and thickness 50 nm)

Filter Fabrication and Measurement



Scanning electron micrograph of a SOI-implemented reflectionless filter prior to backside processing and release

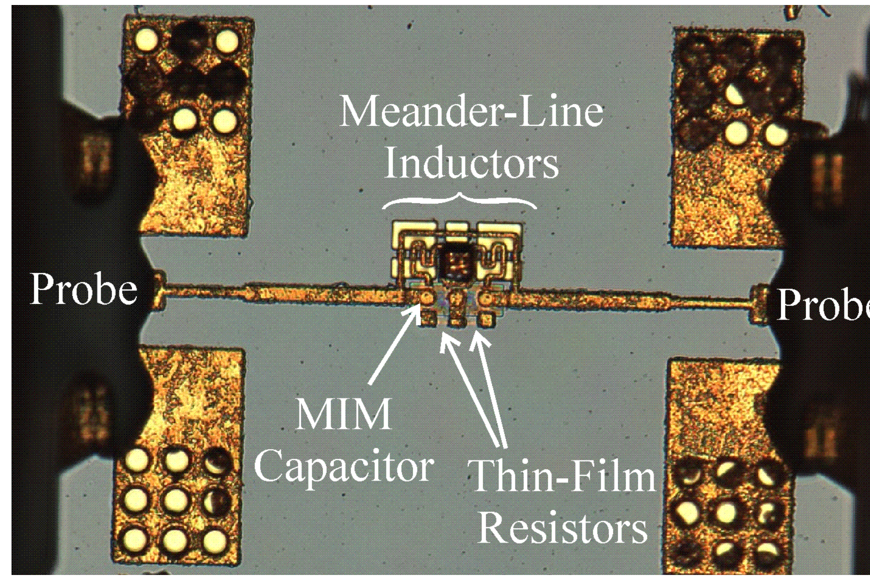
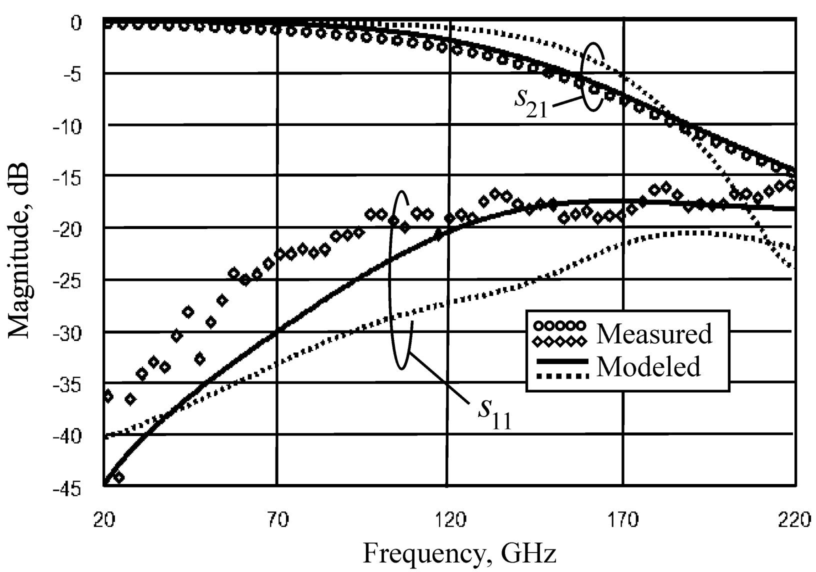
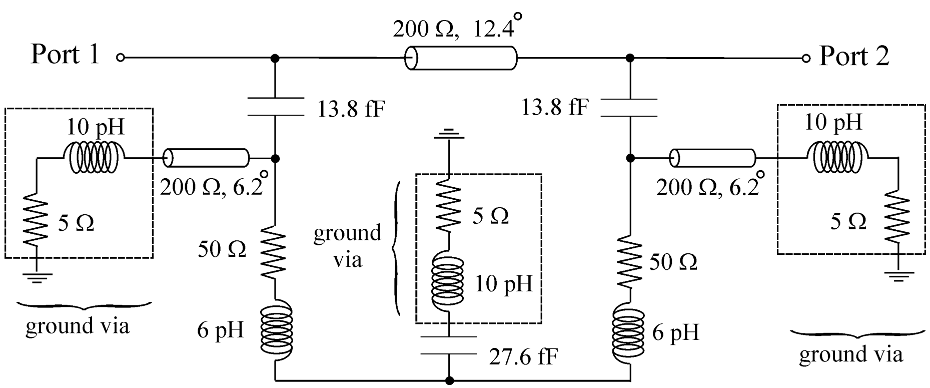


Image of a quasi-reflectionless filter during measurement over the 0—220 GHz range using dual-band wafer probe

Measurement and Model

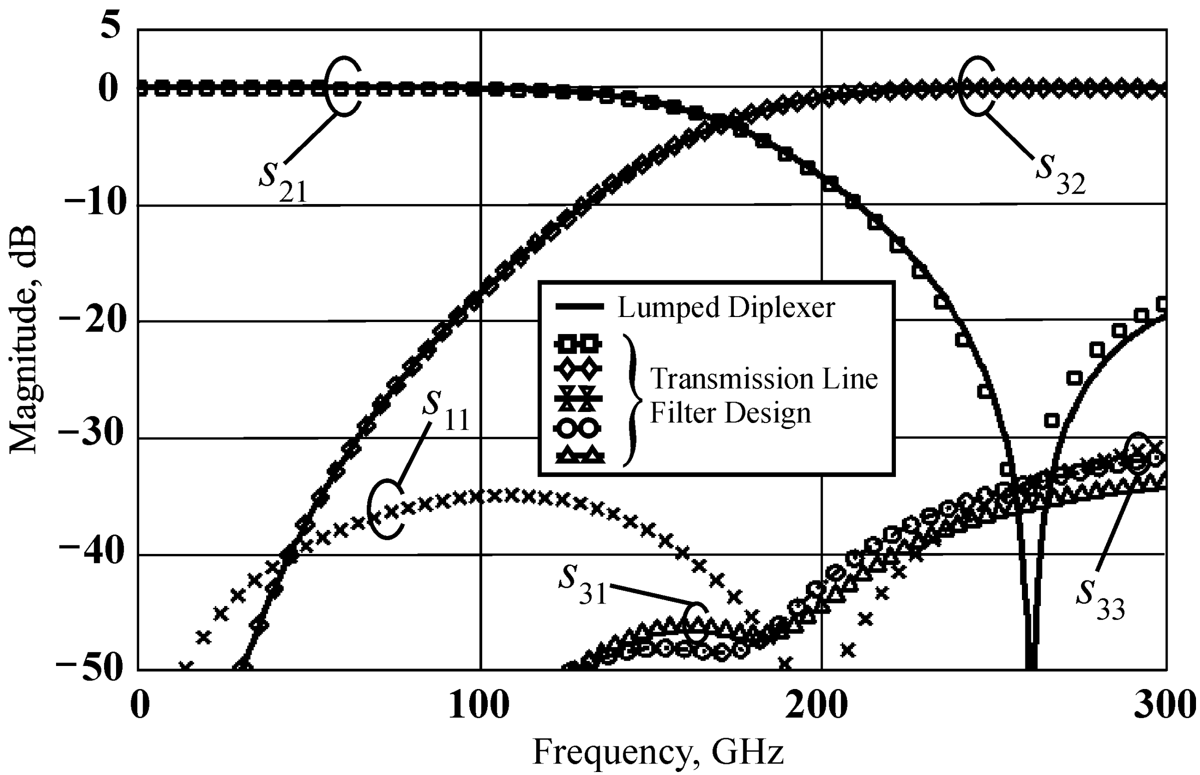




- Anticipated filter characteristic with a “soft” roll-off
- Shift in 3 dB corner frequency
- Absence of the expected null
- Return loss remains higher than 15 dB over the full measurement band.
- Response can be modeled by including additional parasitic elements where the filter connects to ground
- Possible non-uniform plating of the via
- Discontinuity of filter ground plane and measurement system ground

Reflectionless Diplexer

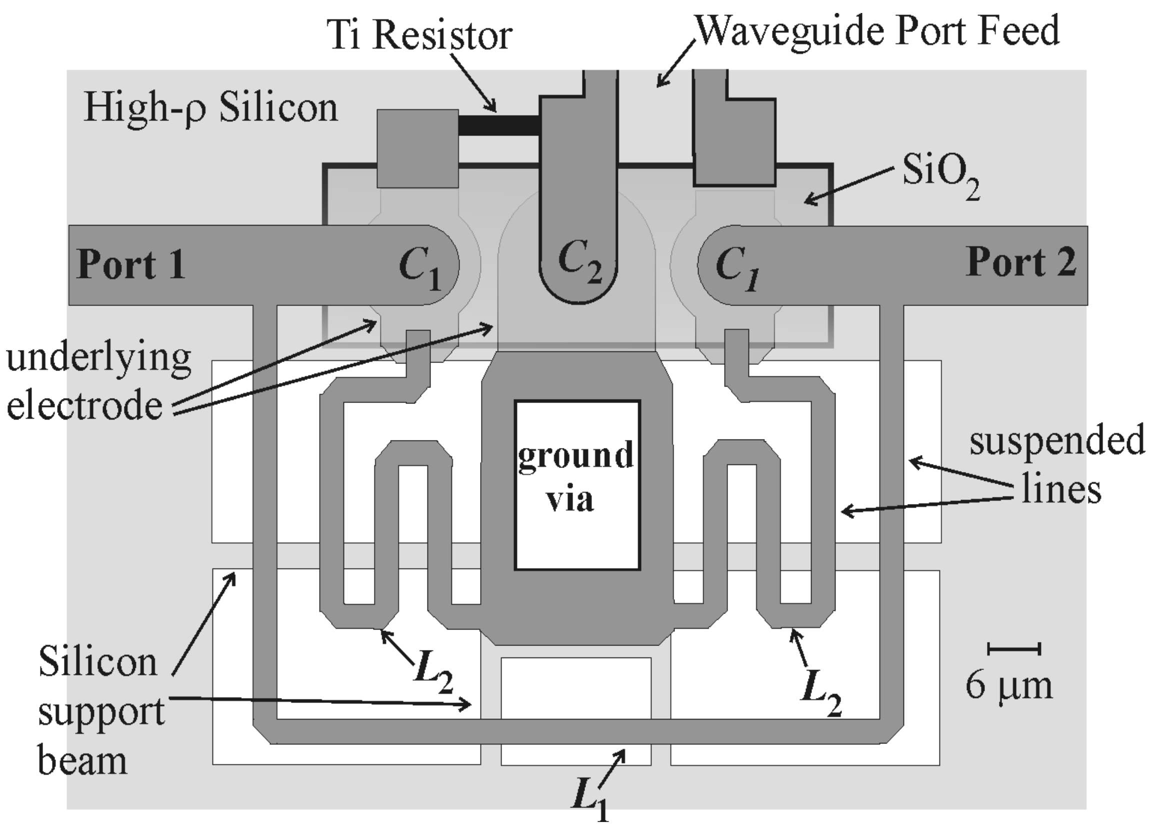
Reflectionless Diplexer Performance (Simulation)



- Comparison of s-parameters for an ideal reflectionless diplexer and "quasi-reflectionless" diplexer incorporating high-impedance transmission line elements.
- Insertion loss responses (s_{21} and s_{32}) of the two diplexer architectures overlap one-another. The return loss and isolation for the ideal lumped-element diplexer are infinite

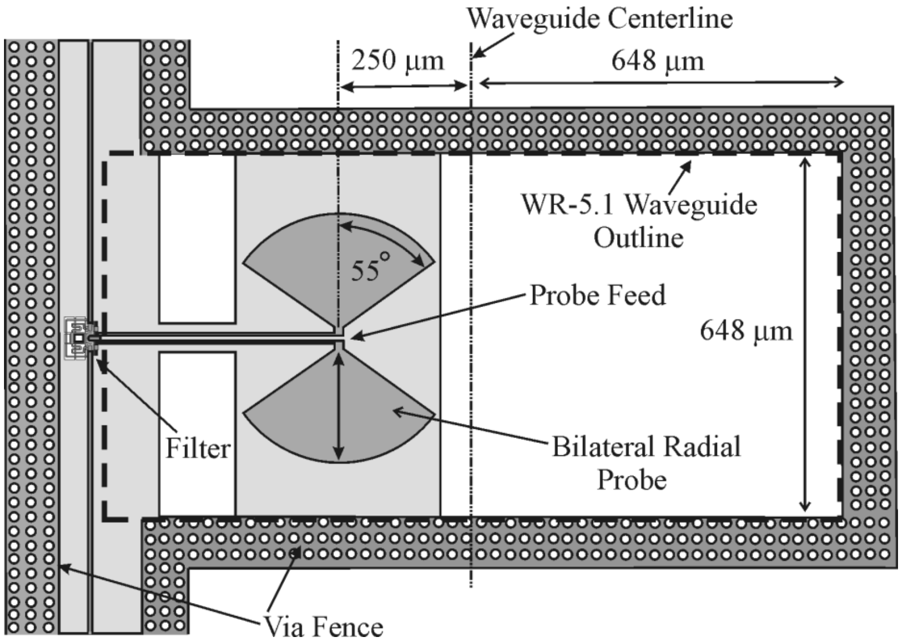
Transmission Lines (Inductors) are 200 Ω with electrical lengths of 11° (θ_1) and 5.5° (θ_2) at 100 GHz, respectively

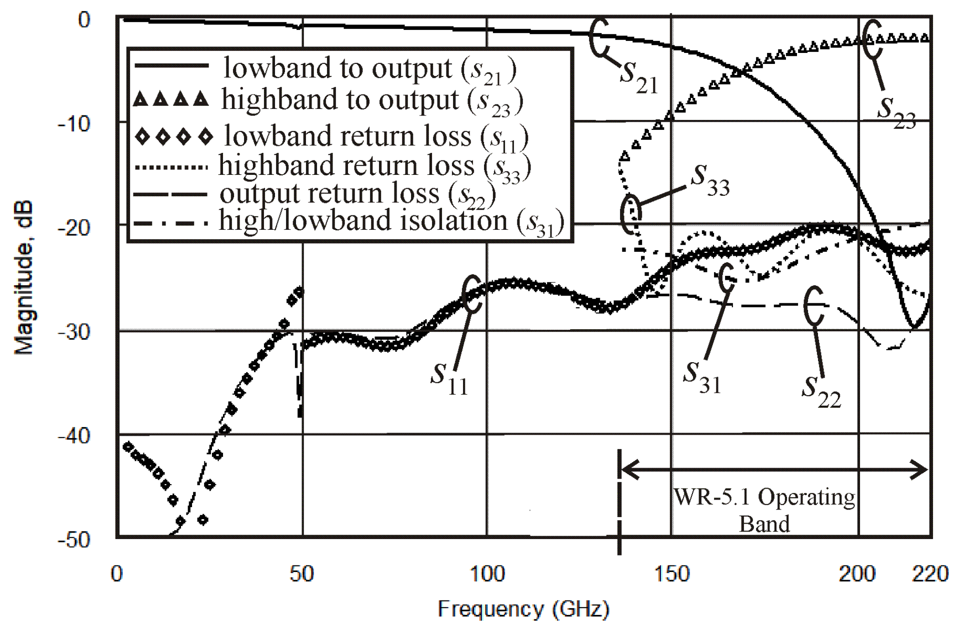
Implementation and Layout



- Microstrip transmission lines and integrated lumped components
- 15 μm thick high-resistivity silicon substrate
- Meandered suspended high-Z lines replace inductive elements
- C_1 and C_2 are metal-insulator-metal structures with underlying contacts and shared SiO_2 insulating layer
- Thin Film Ti Resistor (2 μm wide, 10 μm long, 50 nm thick)
- Common Ground Via

Implementation and Layout



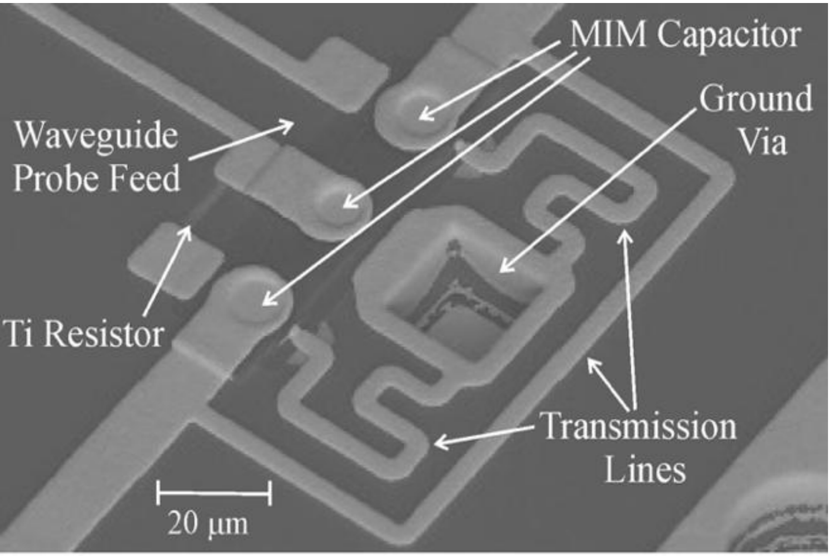


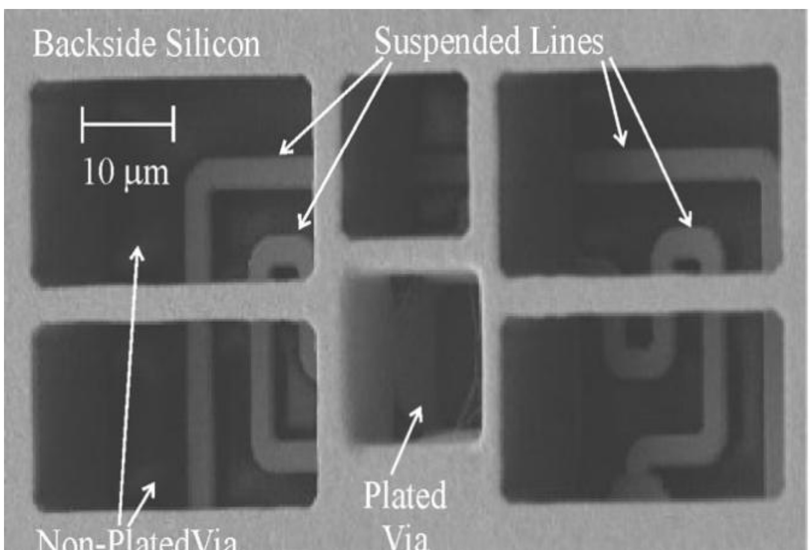
- Diplexer Internal Port feeds differential waveguide probe
- Probe Offset from Center to Eliminate Even Mode Resonance
- Via fence for Electrical Continuity

HFSS simulation results showing the diplexer performance with the waveguide probe geometry.

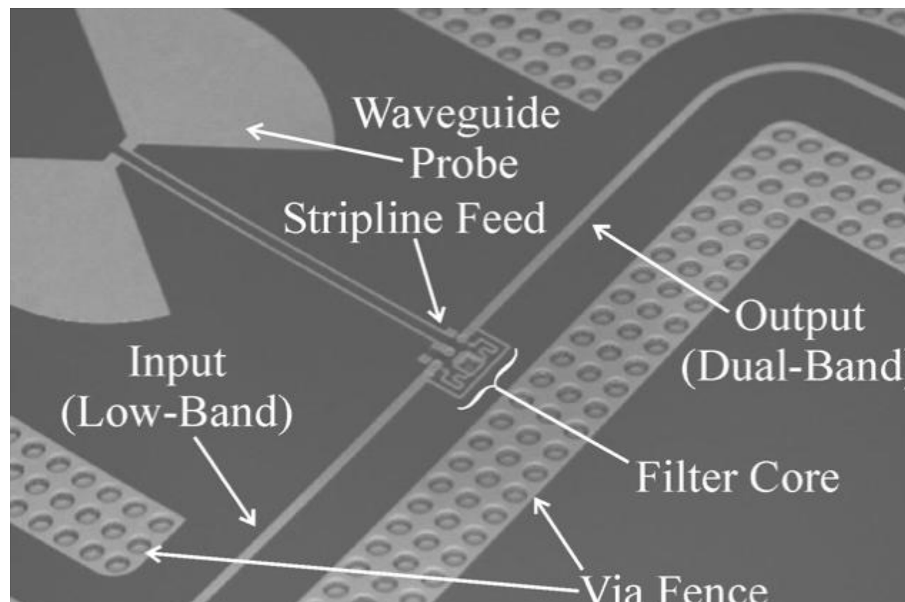
Port 1 corresponds to the low-band (< 170 GHz)
Port 3 to the high-band (>170 GHz)
Port 2 to the output (dual band).

Implementation – Fabrication

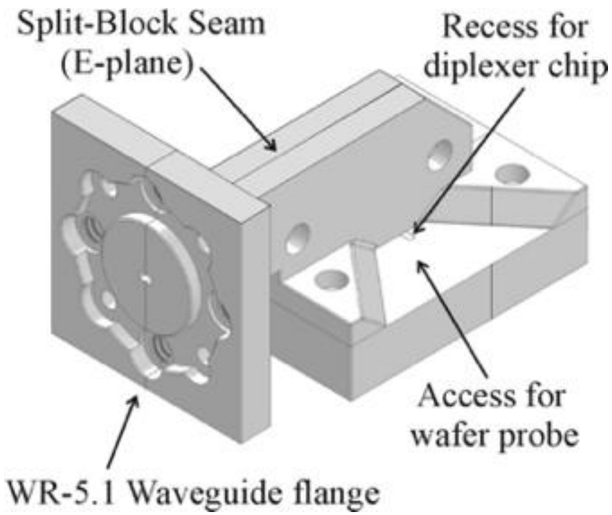


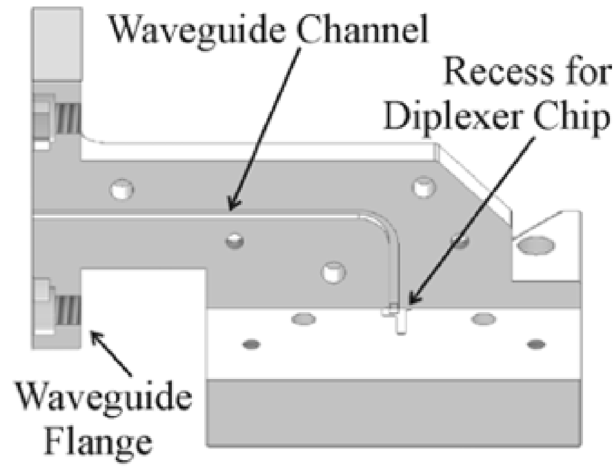


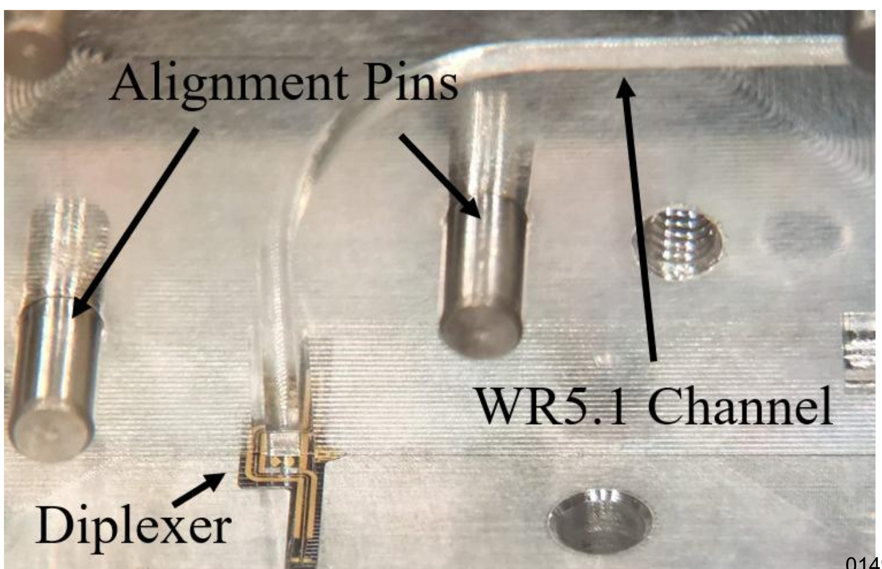
- Silicon-on-Insulator (SOI) micromachining process
- Frontside lithography, deposition and electroplating
- ICP reactive ion etching forms ground via, via fence, and alignment structures for backside processing
- Wafer bonded topside-down to a temporary carrier for backside processing



Measurement Fixture







- Split-block, 3-piece assembly
- Un-Plated Aluminum
- WR-5.1 (WM 1295) waveguide channel, split along the E-plane
- UG-387 flange and Recesses for access of wafer probes

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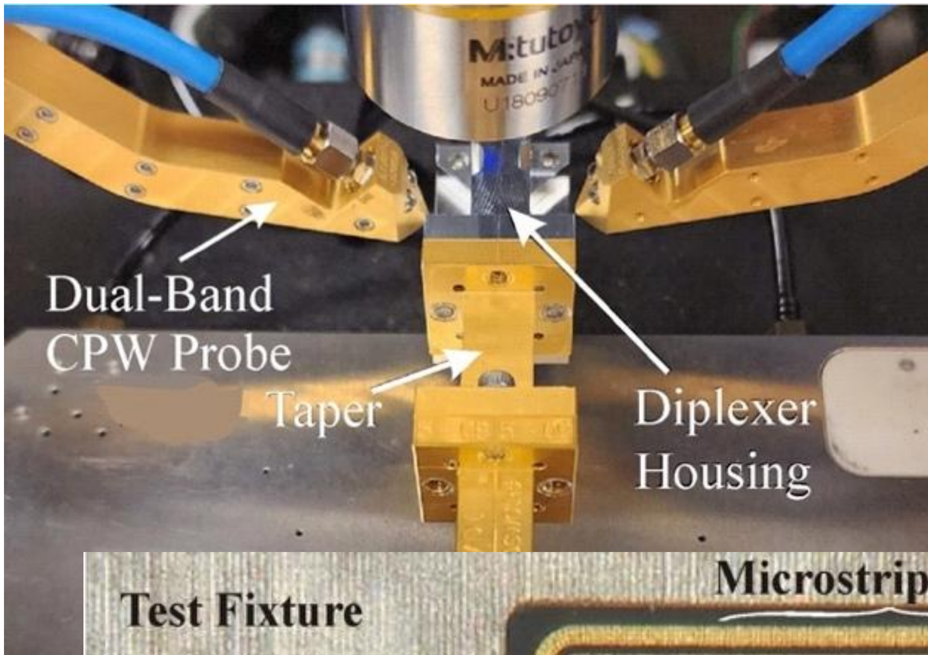
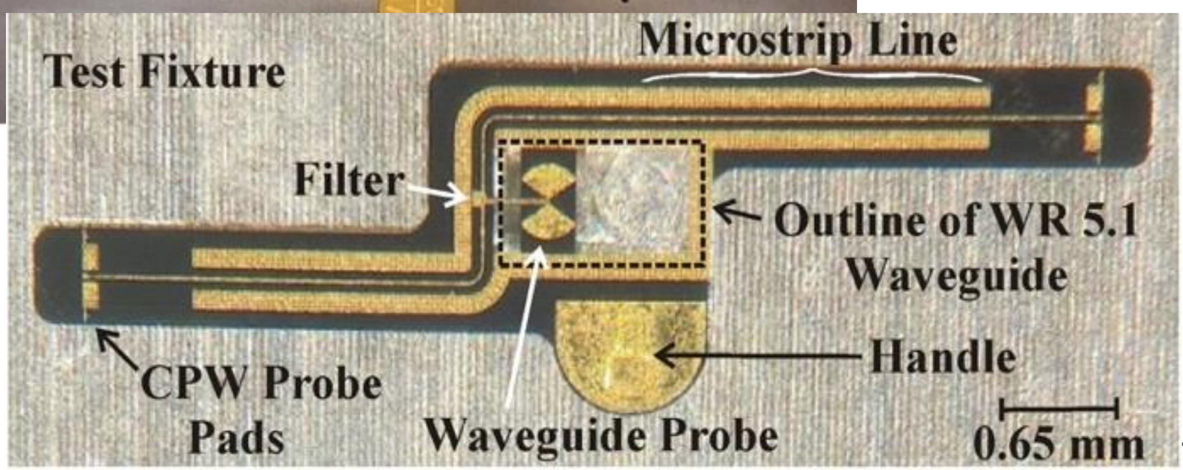
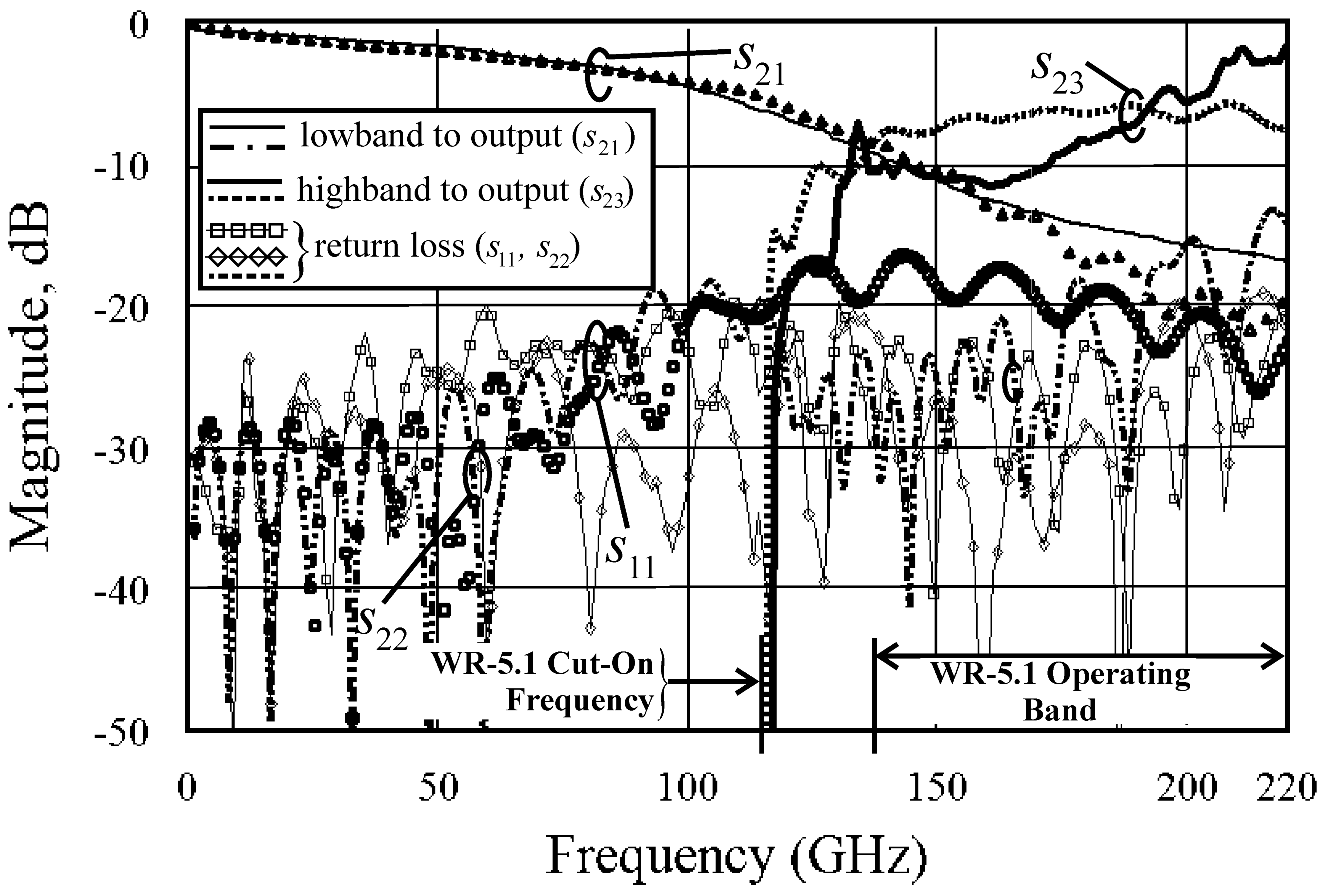
Assembly and Measurement Setup

- Low-band and dual-band output microstrip ports measured with coplanar wafer probes\
- Two-port multi-line TRL calibration
- Reference plane set at the probe landing pads
- Power coupled to the waveguide (high-band) port monitored with a power meter (Erickson PM5)



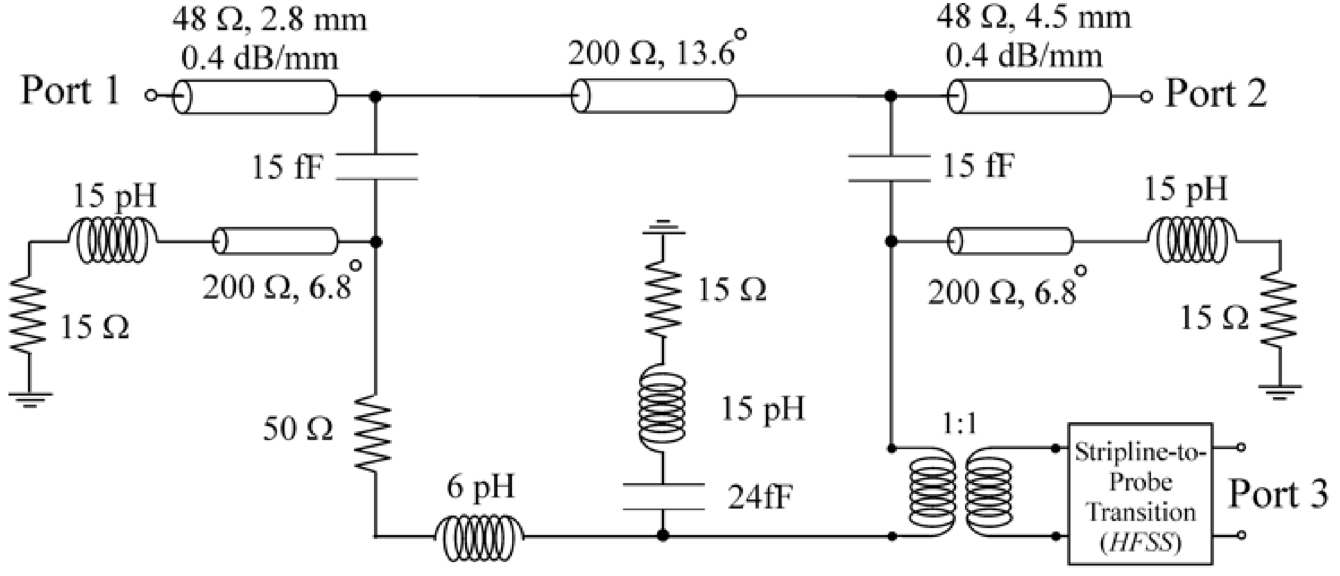


Measurements



- Measured (solid lines and solid lines with symbols)
- Modeled (symbols without lines)
- Coupling to waveguide (port 3) is found as the ratio of output power measured at port 3 to the available input power measured at port 2

Modeling



- Parasitics associated with the circuit ground via have significant influence on performance.
  - Softer roll-off characteristic for lowband response
  - Lower the cross-over frequency from nominal designed value to 140 GHz
- Via parasitics appear at each of the nodes connected to ground (same fitted values of 15 Ω and 15 nH)
- Quality and coverage of plated metal on the ground via sidewalls is suspect
- Interface between the microstrip ground metallization of the diplexer chip and the (aluminum) conductor of the circuit housing

Summary

- Demonstrated Prototype ”Quasi-Reflectionless” Filter and Diplexer from 0-220 GHz
- Developed Test Fixture with CPW Probe and Waveguide Interfaces to Characterize Diplexer
- Ground/Packaging Via Parasitics Appear to Play Significant Role in Measured Performance
- Initial Step towards Expanding Operating Bandwidth of Waveguide and Band-Limited Instruments for Millimeter/Submillimeter-Wave Systems