Development of Low-Mass, Low-Power, High-Frequency Microwave Radiometers with Internal Calibration to Provide High-Resolution Wet-Tropospheric Path Delay Measurements for the SWOT Mission

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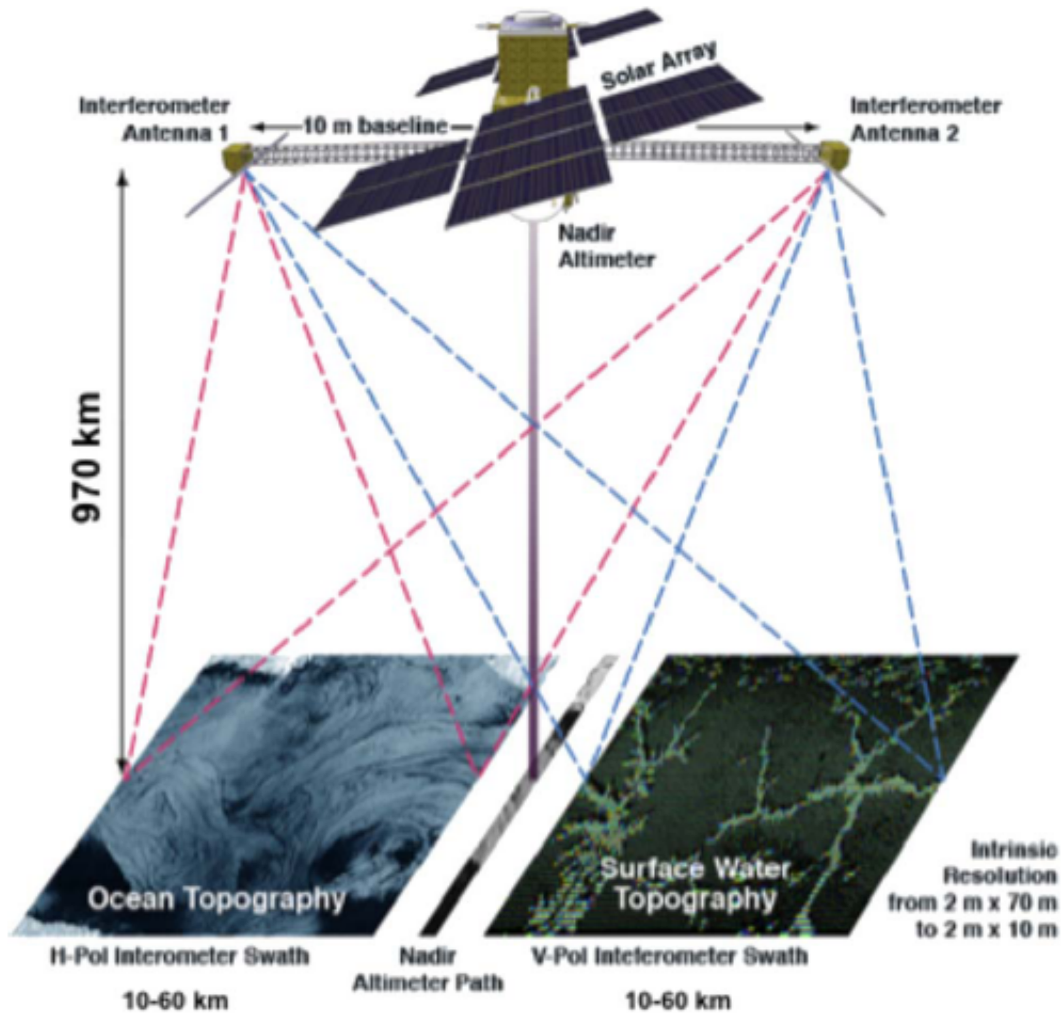
Surface Water and Ocean Topography (SWOT) Mission

Accelerated Tier-2 U.S. National Research Council Earth Science Decadal Survey Mission planned for launch in 2020 (NASA/CNES partnership)

- **Oceanography Objectives:**
  - Characterize ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and larger (1-cm ht. precision required)
    - Kinetic energy / Heat and carbon air-sea fluxes
    - Climate change and ocean circulation
    - Coastal and internal tides
- **Hydrology Objectives:**
  - To provide global height measurements of inland surface water bodies with area greater than 250 m^2 and rivers with width greater than 100 m
  - To measure change in global water storage in these inland water bodies and river discharge on sub-monthly to annual time scales

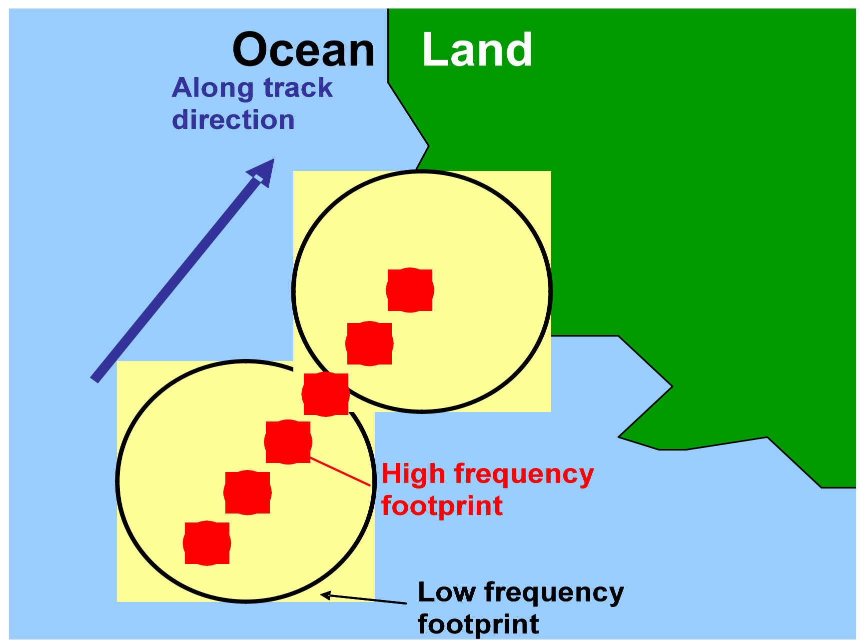
SWOT Ka-band Radar Interferometer (KaRIN)



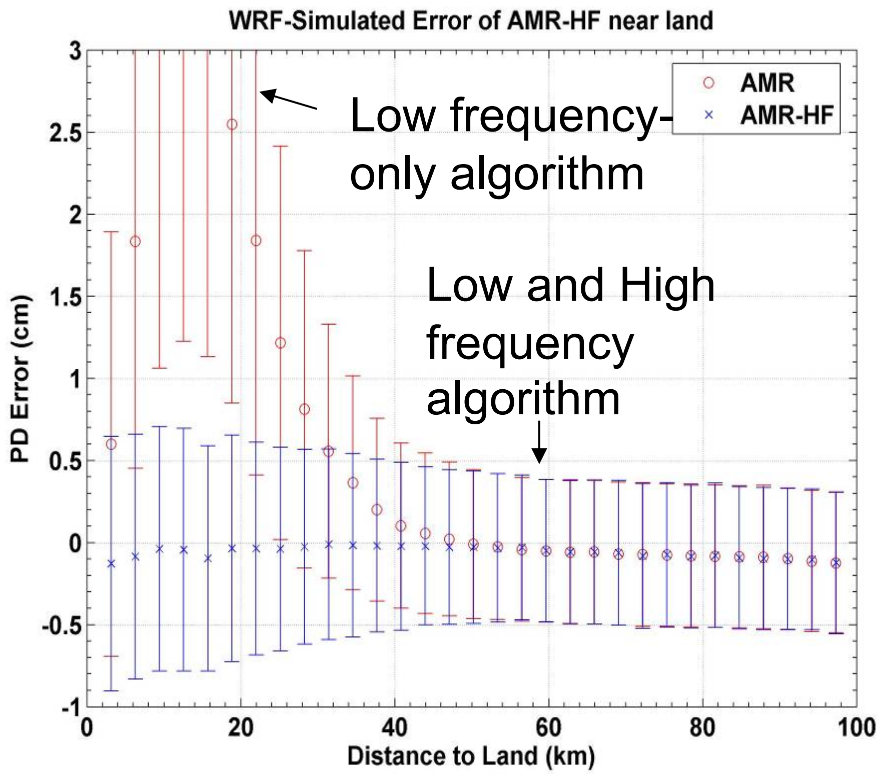
M. Durand et al., "The Surface Water and Ocean Topography Mission: Observing Terrestrial Surface Water and Oceanic Submesoscale Eddies," *Proc. IEEE*, Jul. 2010.

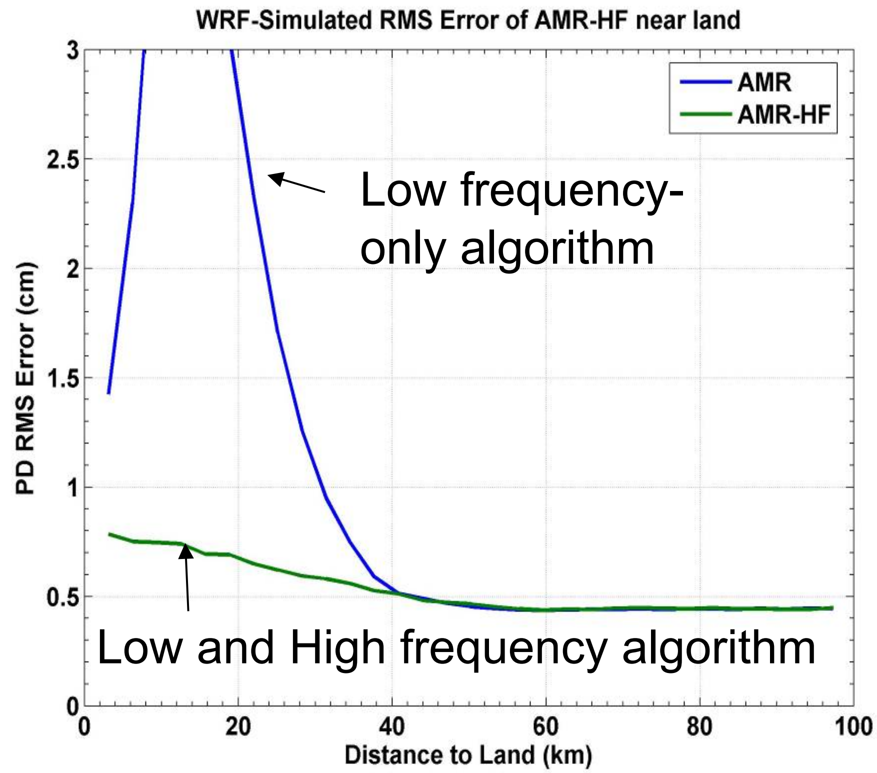
Scientific Motivation

- Current satellite ocean altimeters include a nadir-viewing, co-located 18-34 GHz multi-channel microwave radiometer to measure wet-tropospheric path delay. Due to the large diameters of the surface instantaneous fields of view (IFOV) at these frequencies, the accuracy of wet path retrievals begins to degrade at approximately 40 km from the coasts.
- Conventional altimeter-correcting microwave radiometers do not provide wet path delay over land.
- In order to meet these needs, higher-frequency microwave channels (90-170 GHz) are part of the trade space of the SWOT mission to improve retrievals of wet-tropospheric delay in coastal areas and to increase the potential for over-land retrievals.



SWOT Mission Concept Study



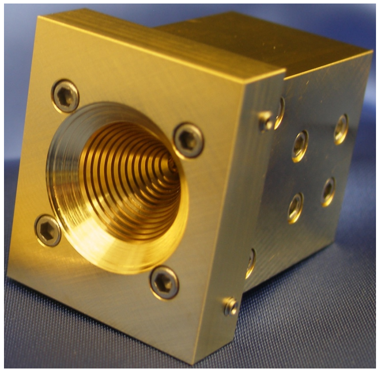


High-resolution WRF model results show reduced wet path-delay error using both low-frequency (18-34 GHz) and high-frequency (90-170 GHz) radiometer channels.

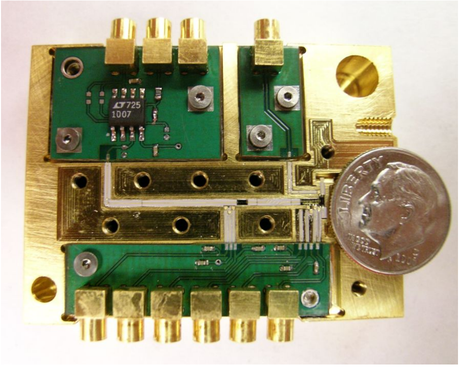
Objectives

- Develop low-power, low-mass and small-volume direct-detection high-frequency microwave receivers with integrated calibration sources covering frequencies from 90 to 170 GHz
- Design and fabricate a tri-frequency feed horn with integrated triplexer covering 90 to 170 GHz
- Design and fabricate PIN-diode switches and noise diodes for internal calibration from 90 to 170 GHz that can be integrated into the receiver front end
- Integrate and test components in MMIC-based low-mass, low-power, small-volume radiometer at 92, 130 and 166 GHz with the tri-frequency feed horn

Requirements



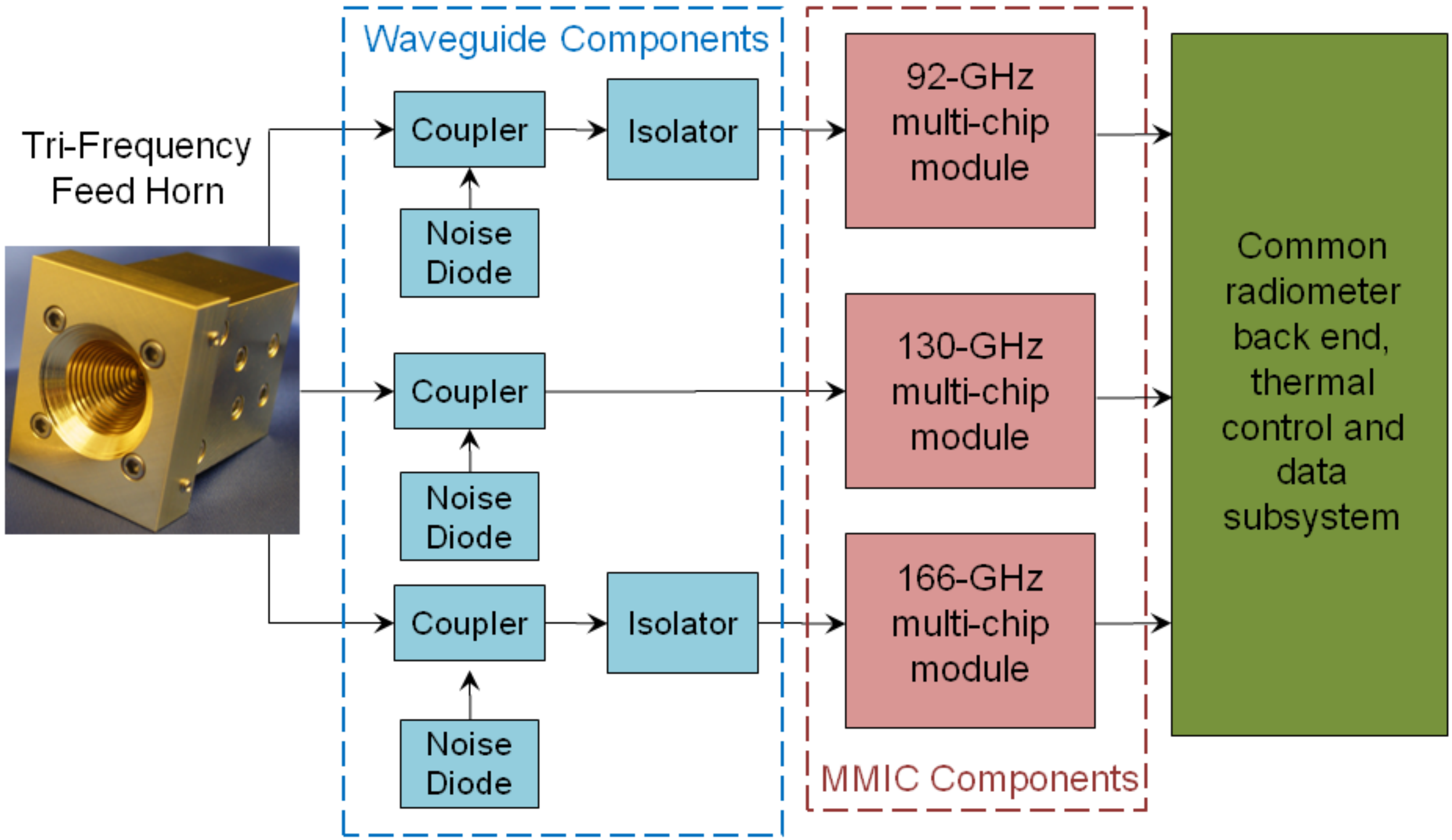
Key Antenna Subsystem RF Requirements	
Center frequencies	92, 130 and 166* GHz
Bandwidths	10 GHz
Port-to-port isolation	> 20 dB
Return loss	> 15 dB
Insertion loss	< 0.75 dB



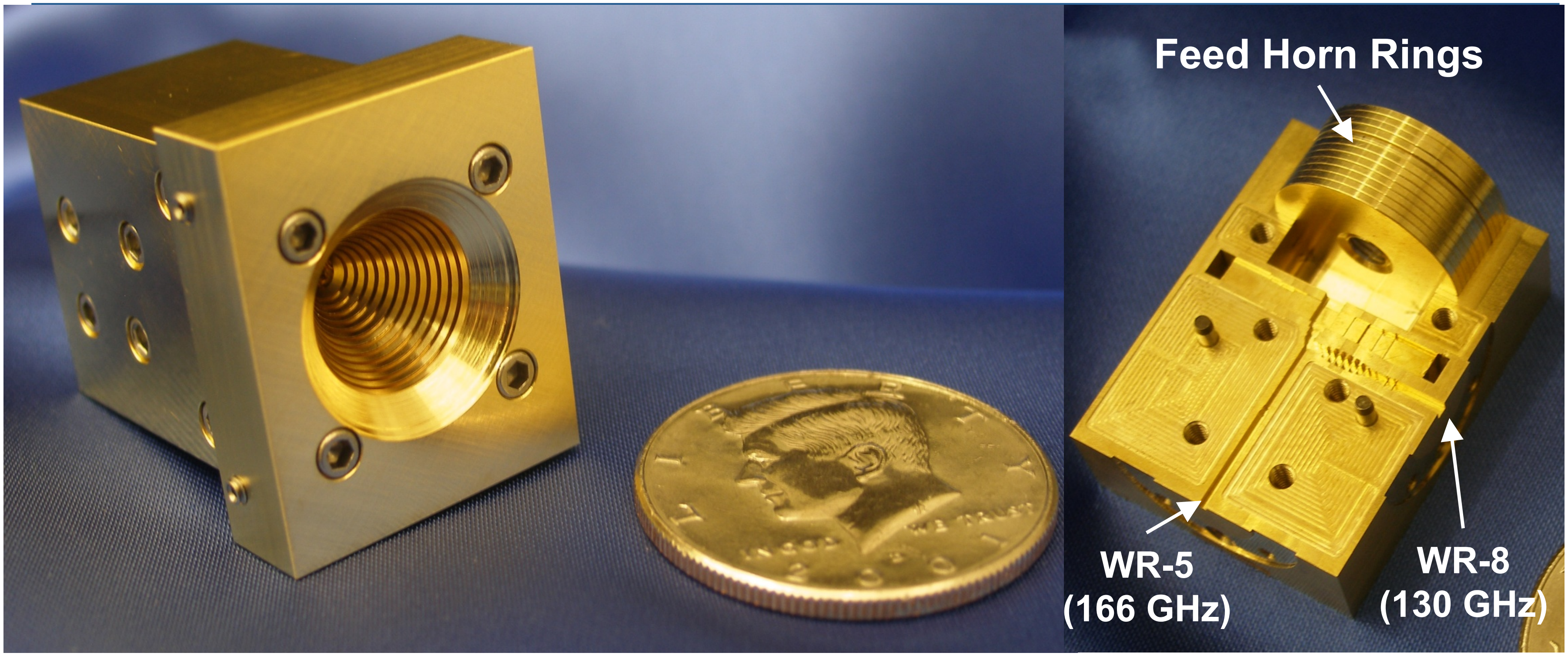
Key Receiver RF Requirements	
Center frequencies	92, 130 and 166 GHz
Bandwidths	5 GHz
Noise Temperature	< 1300 K
Return loss	> 15 dB
Calibration stability	0.1 K over 30 – 60 s

**Note: We will attempt to push all 166 GHz component designs to accommodate 183 GHz sounding channels as closely as possible.*

System Block Diagram

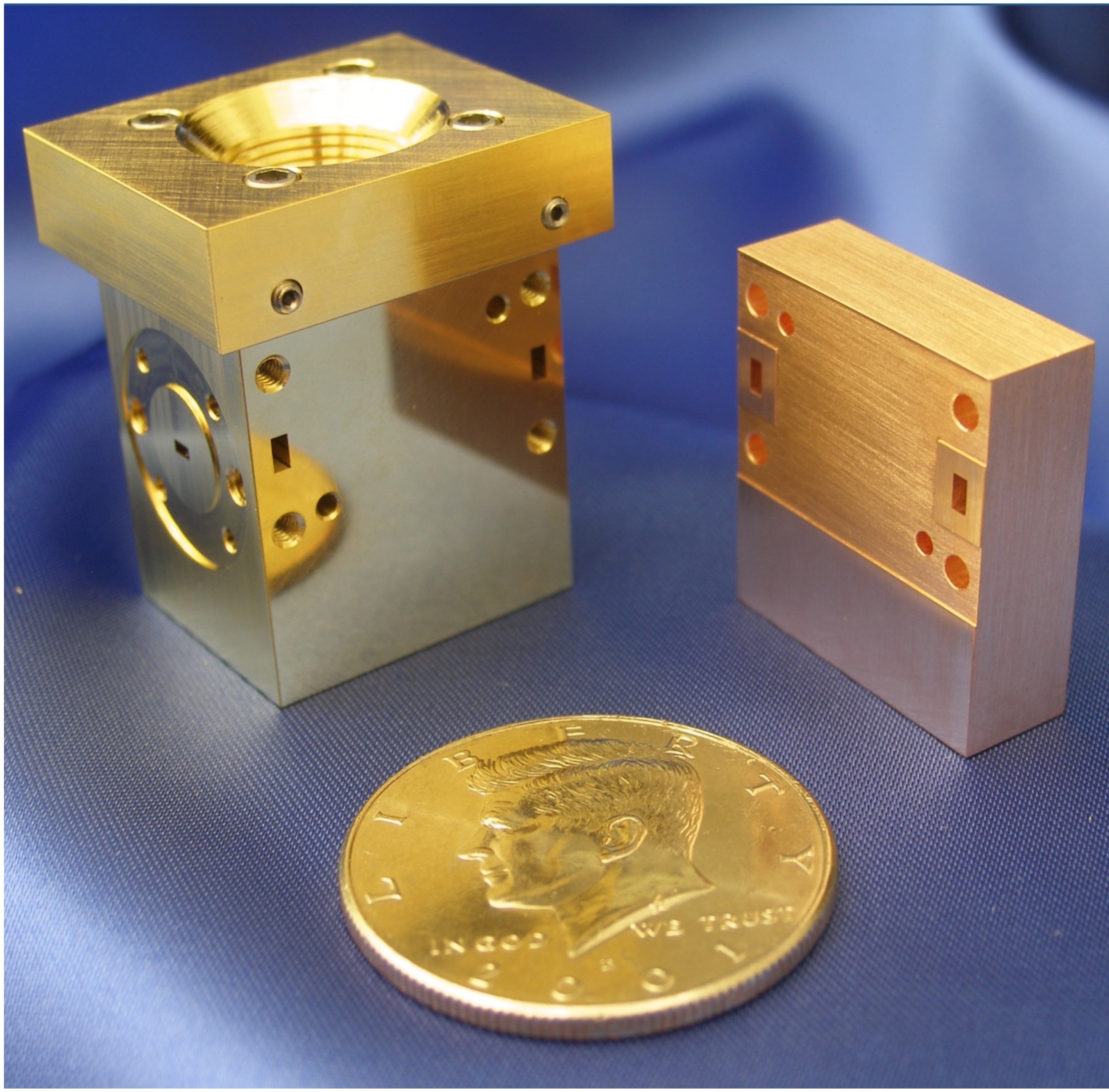


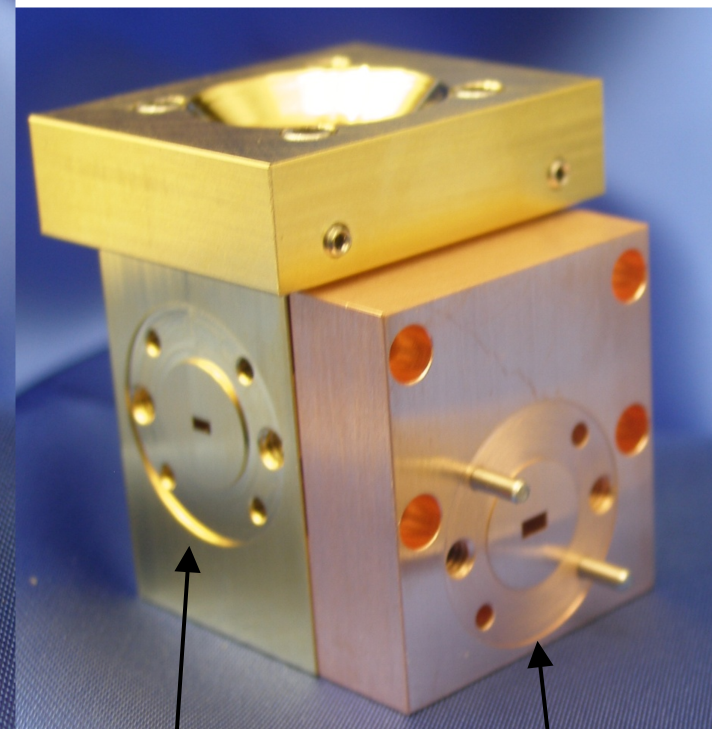
Tri-Frequency Horn Antenna



A single, tri-band feed horn and triplexer are required to maintain acceptable antenna performance, since separate feeds for each of the high-frequency channels would need to be moved further off the reflector focus, degrading this critical performance factor. The tri-frequency horn was custom designed and produced at JPL, with an electroform combiner from Custom Microwave, Inc. Measurements show good agreement with simulated results.

Tri-Frequency Antenna (Detail)



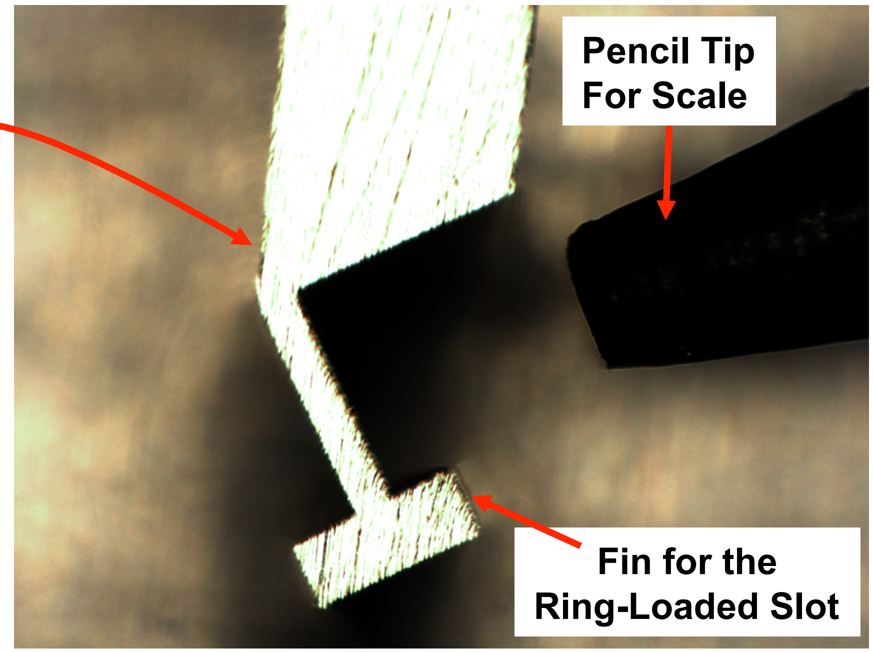


WR-8 Waveguide Port

WR-10 Waveguide Port

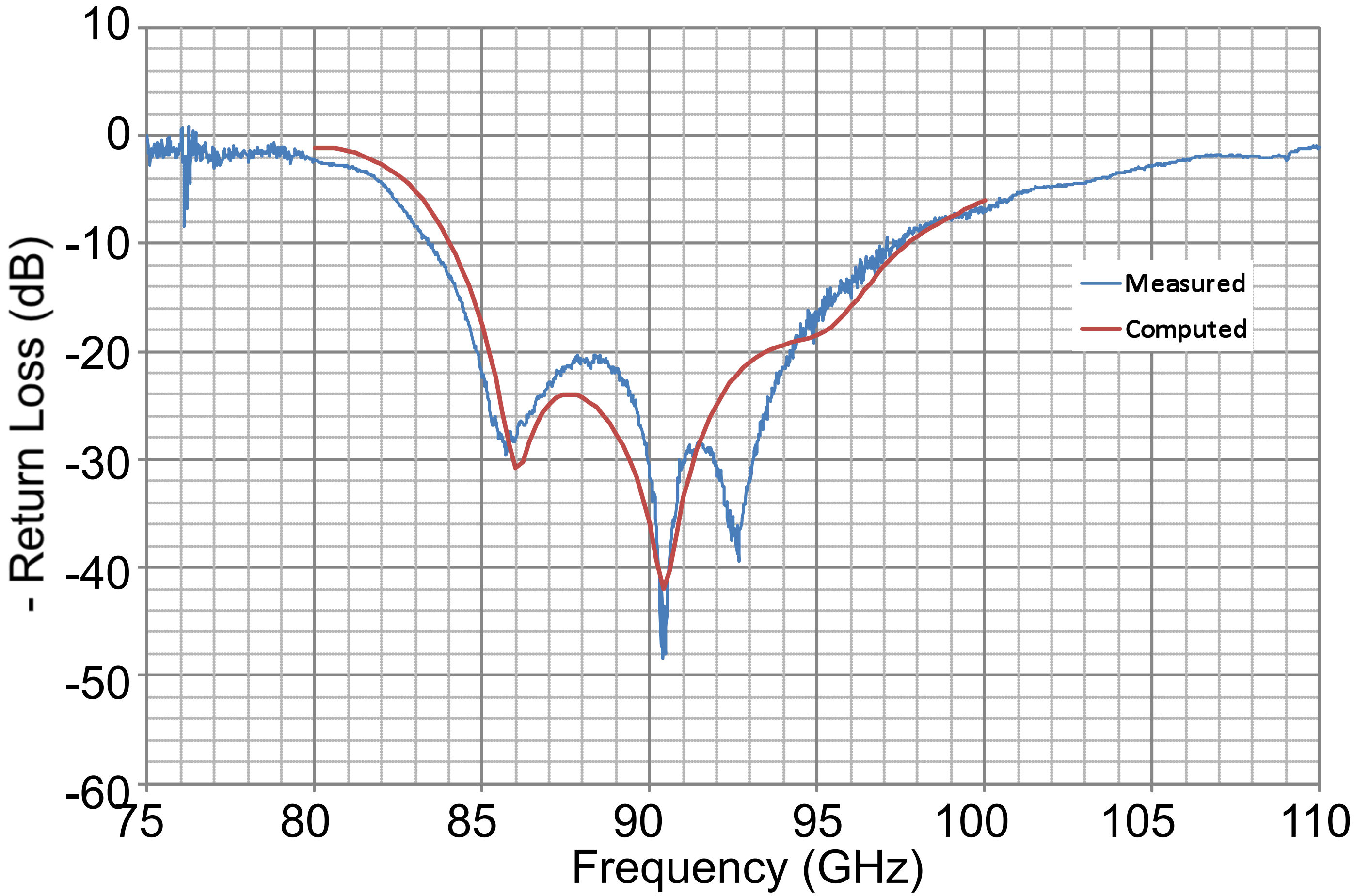
Detail of Feed Horn Rings

Ring Cross Section



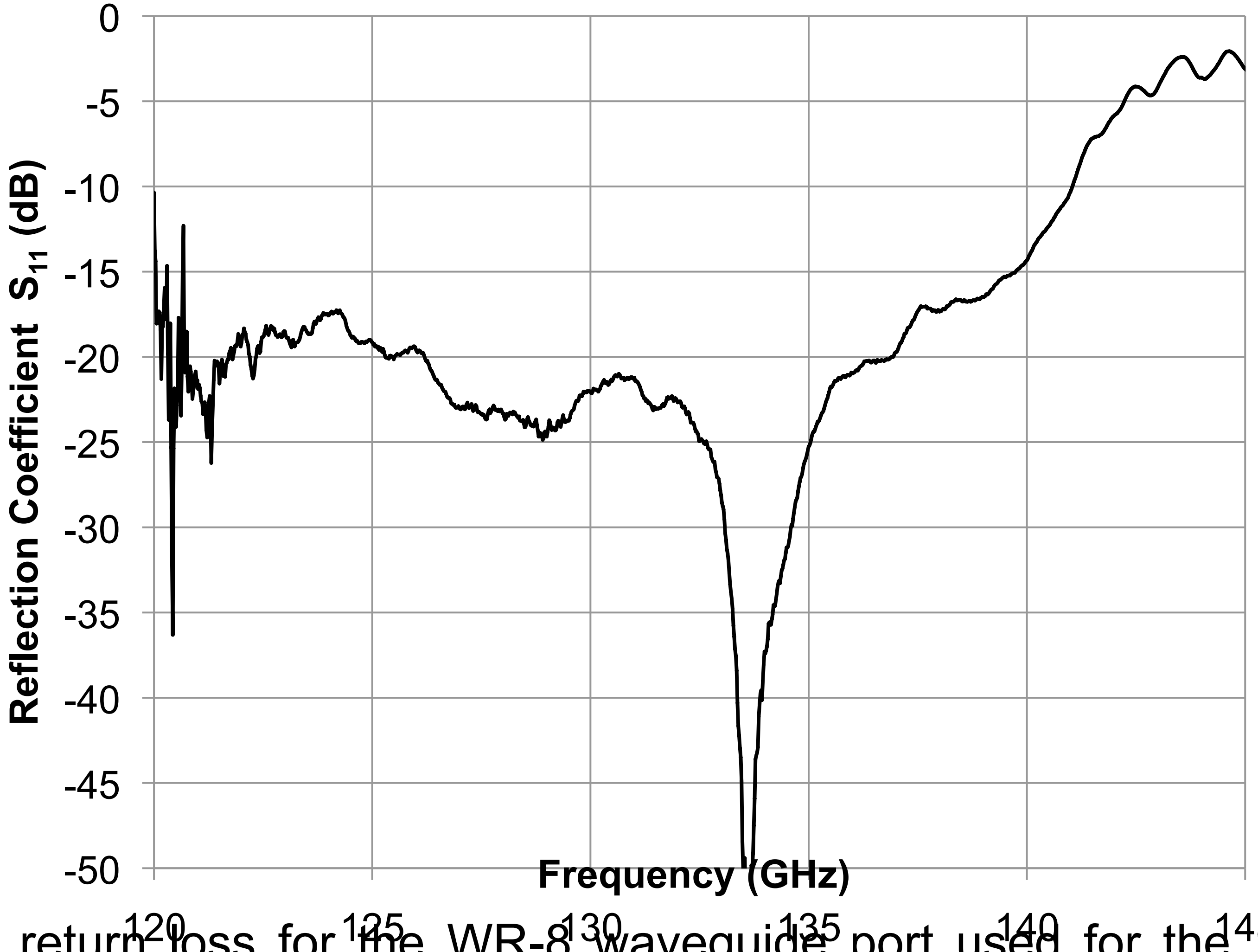
Example of a Ring to Produce Horn Corrugation

Horn Return Loss for WR-10 Port



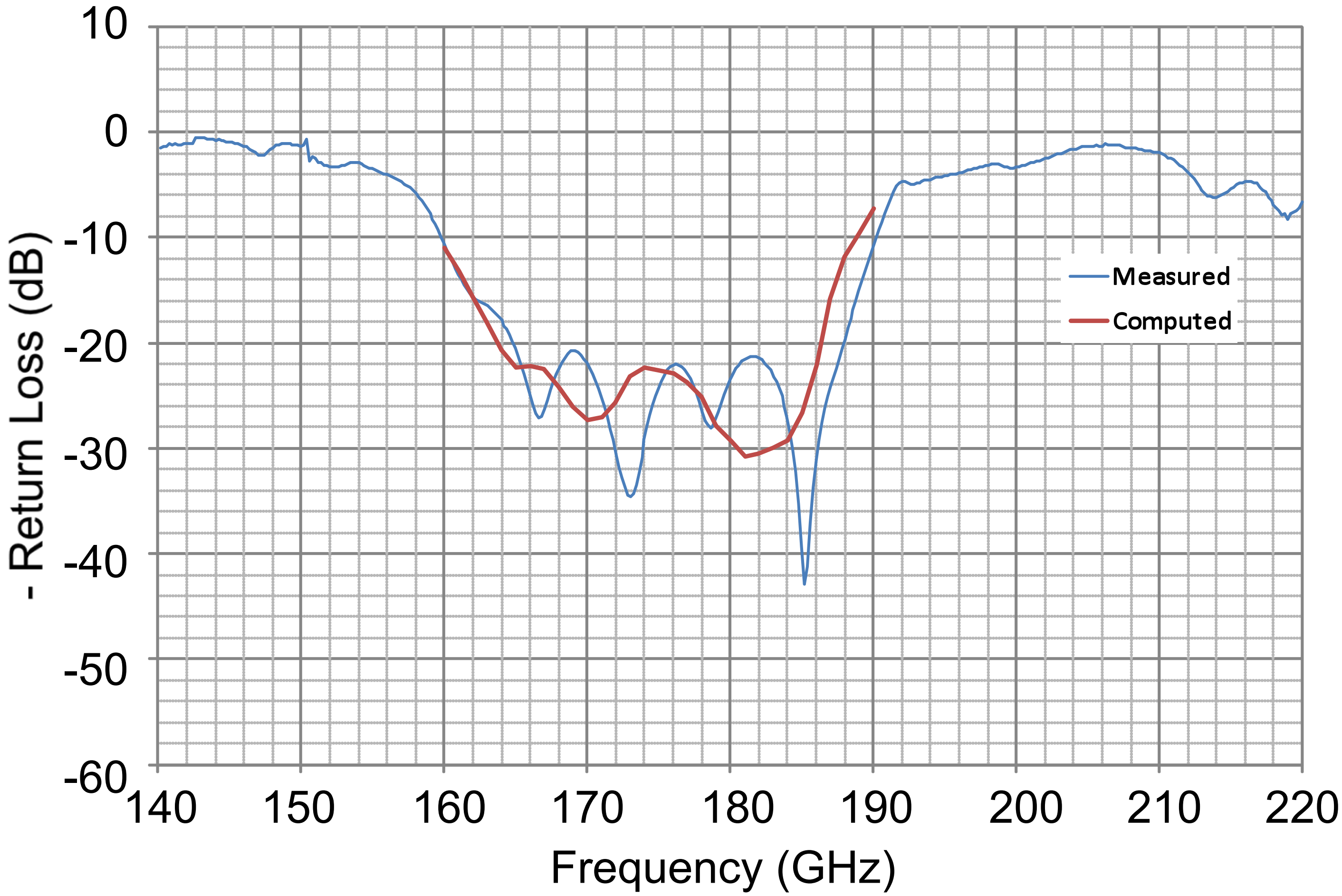
Comparison of measured and simulated return loss, shown in blue and red, respectively, for the WR-10 waveguide port used for the 92-GHz radiometer. The bandwidth is 11 GHz with 15-dB return loss or better.

Horn Return Loss for WR-8 Port



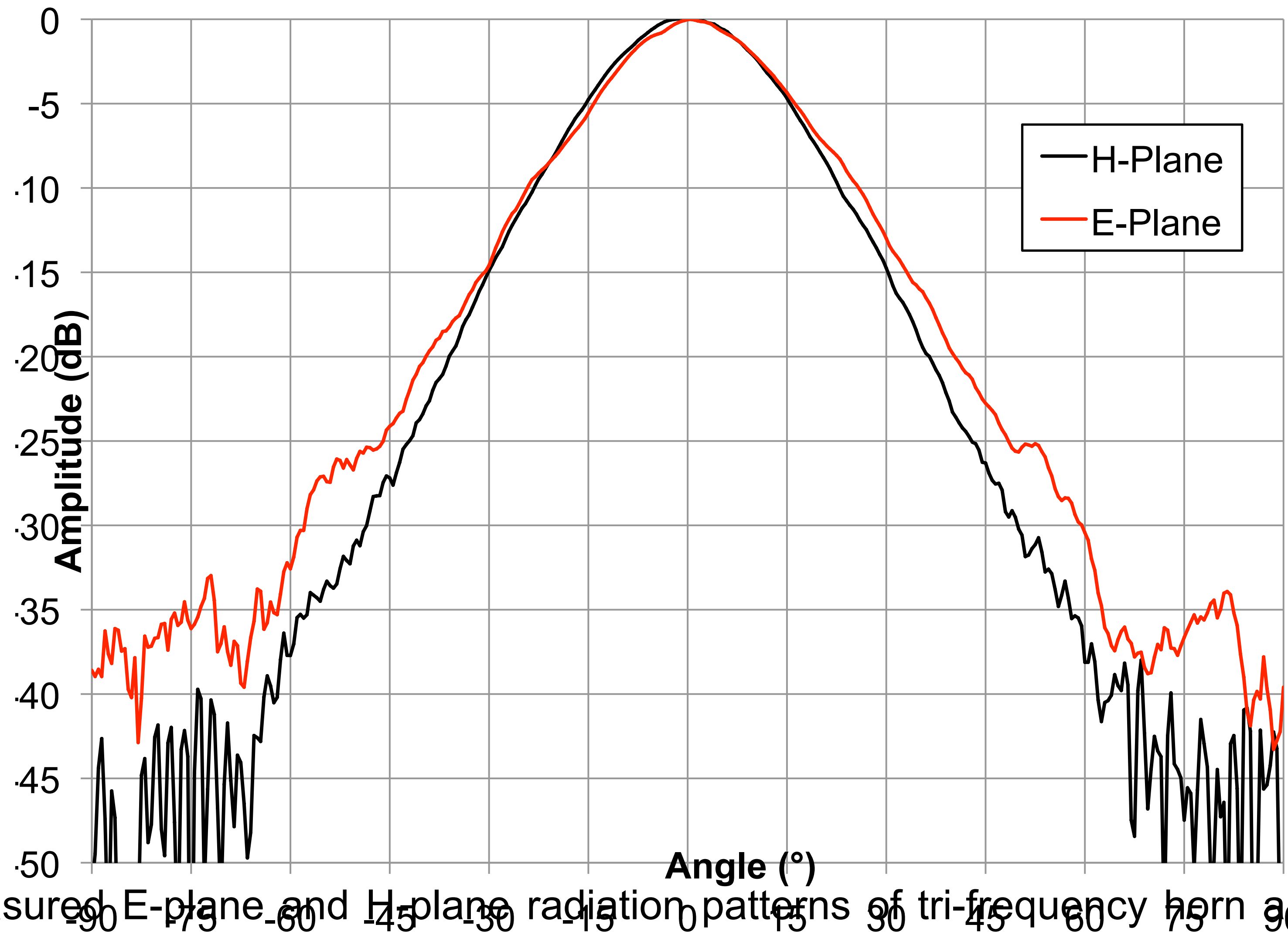
Measured return loss for the WR-8 waveguide port used for the 130-GHz radiometer. The bandwidth is 18 GHz with 15-dB return loss or better.

Horn Return Loss for WR-5 Port



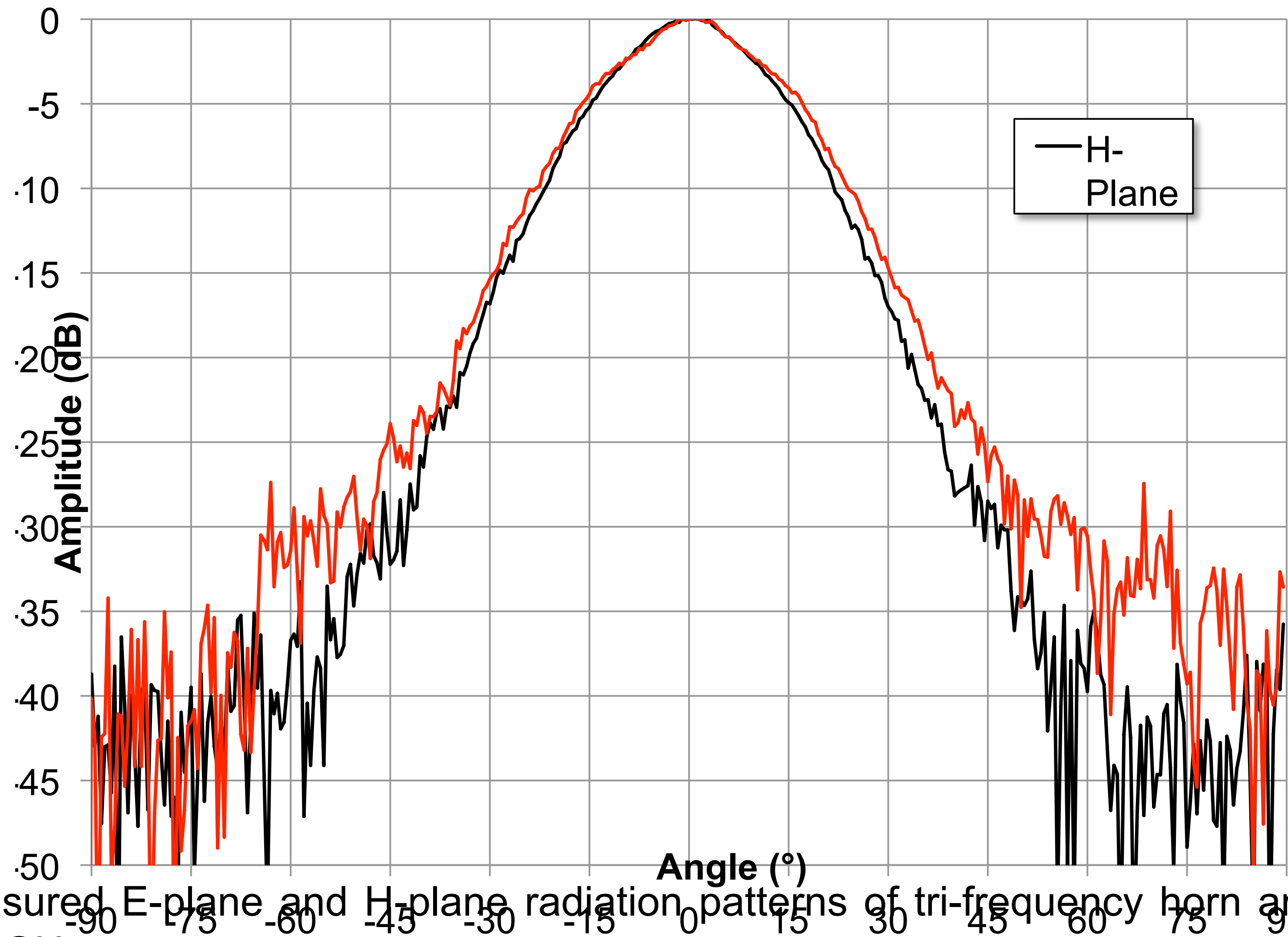
Comparison of measured and simulated return loss, shown in blue and red, respectively, for the WR-5 waveguide port used for the 166-GHz radiometer. The bandwidth is 26 GHz with 15-dB return loss or better, including the 183-GHz band.

Horn Antenna Pattern at 92 GHz



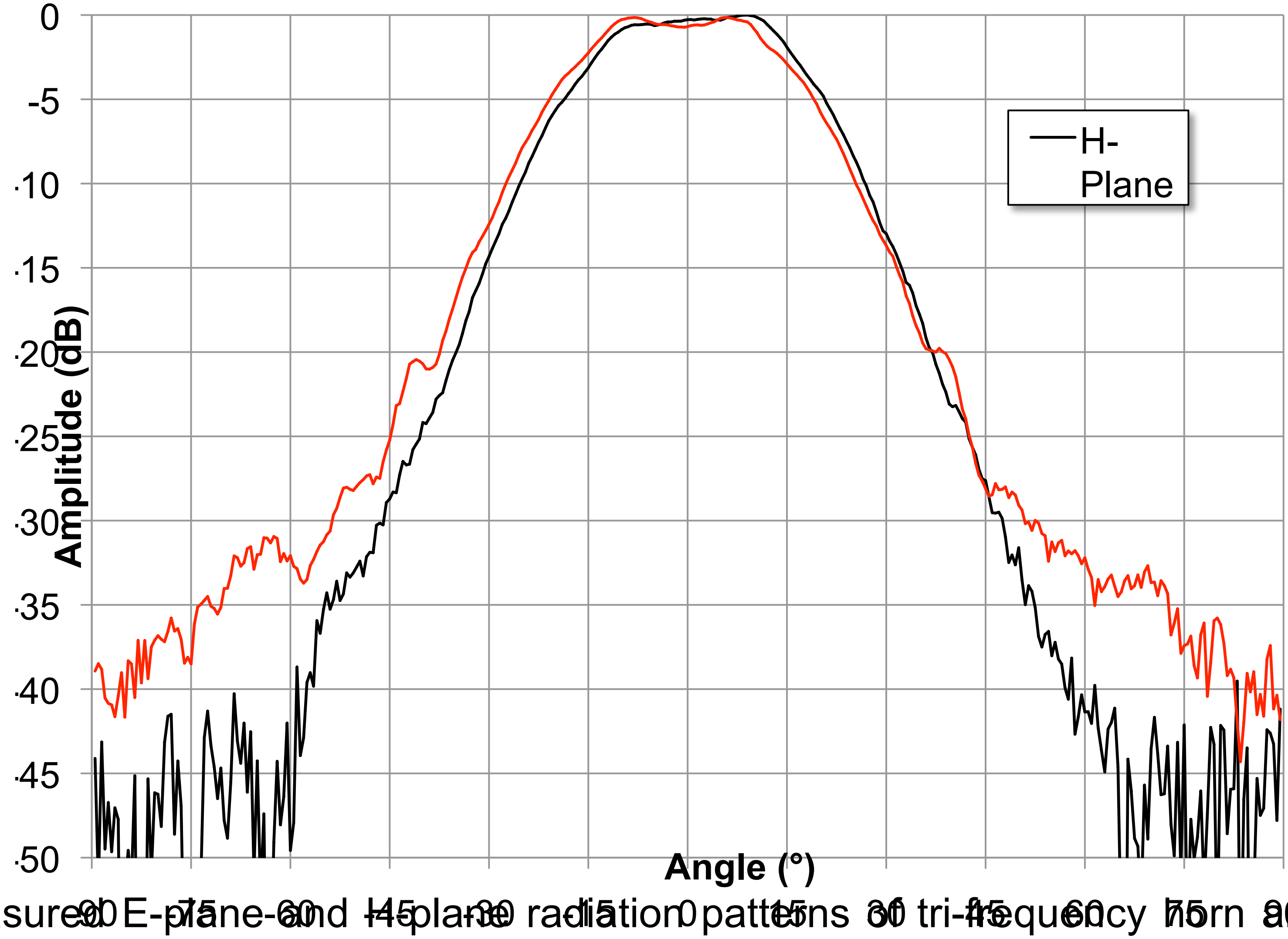
Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 92 GHz.

Horn Antenna Pattern at 130 GHz



Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 130 GHz.

Horn Antenna Pattern at 166 GHz

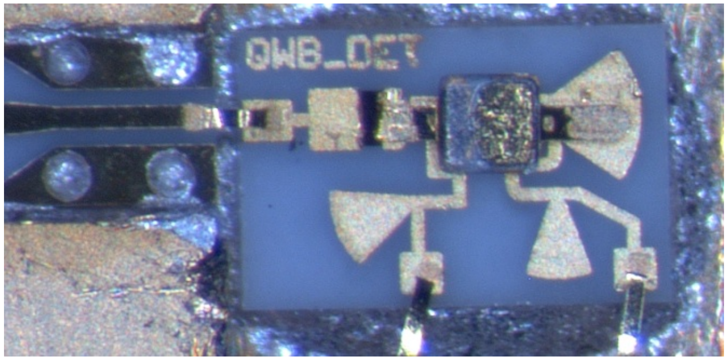


Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 166 GHz.

Noise Diodes for Internal Calibration

- Nadir-pointing radiometers are flown on altimetry missions with no moving parts, motivating two-point internal radiometric calibration, as on Jason-2. Highly stable noise diodes will be used to achieve one of these two points.
- **Radiometric objectives**
  - Provide an electronically-switchable source for calibrating the radiometer over long time scales, i.e. hours to days.
- **RF design objectives from radiometer requirements**
  - Noise diode output will be coupled into the radiometer using a commercially-available waveguide-based coupler.
  - Stable excess noise ratio (ENR) of 10-dB or greater, yielding equivalent noise of ~600 K for a 10-dB coupler.

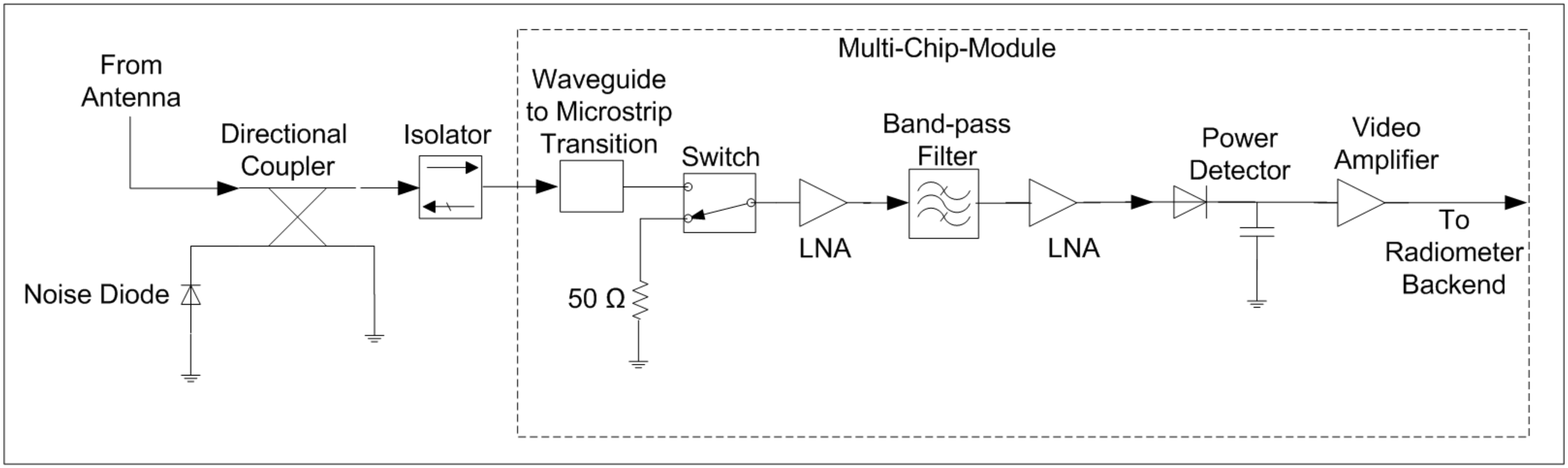
Noise Diode Measurements



Package Style	Manufacturer	ENR @ 92 GHz (dB)	ENR @ 135 GHz (dB)
Beam Lead*	**M-Pulse**	**13**	**8**
Bare Die (substrate bypass)	M-Pulse	11	--
Bare Die (wire bypass)	M-Pulse	10	--

*Noise diode manufactured for NASA/GSFC

92-GHz Radiometer Design

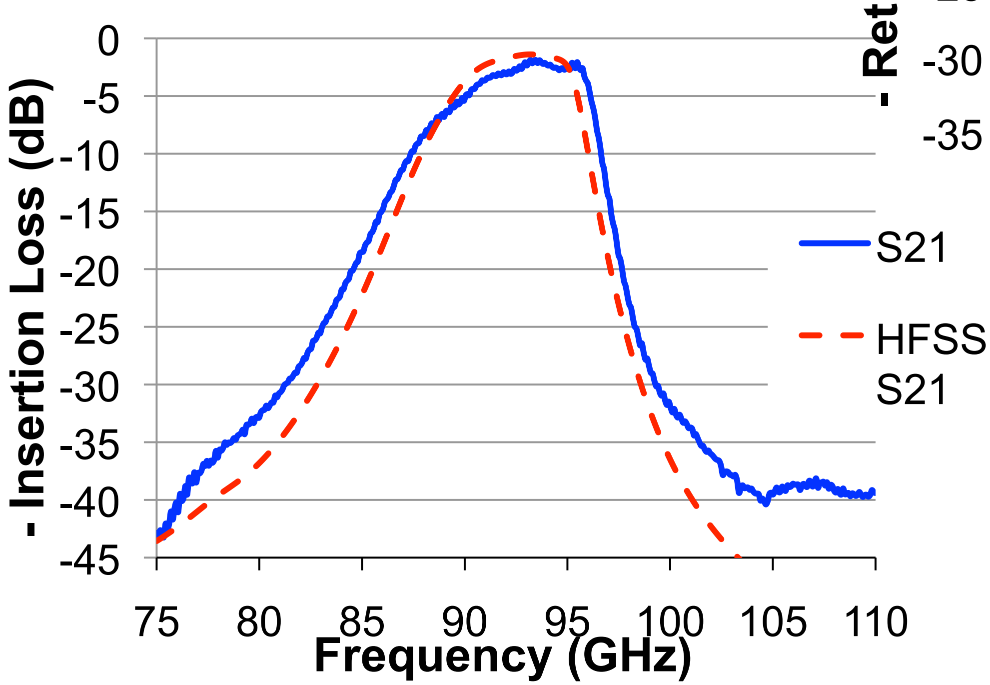


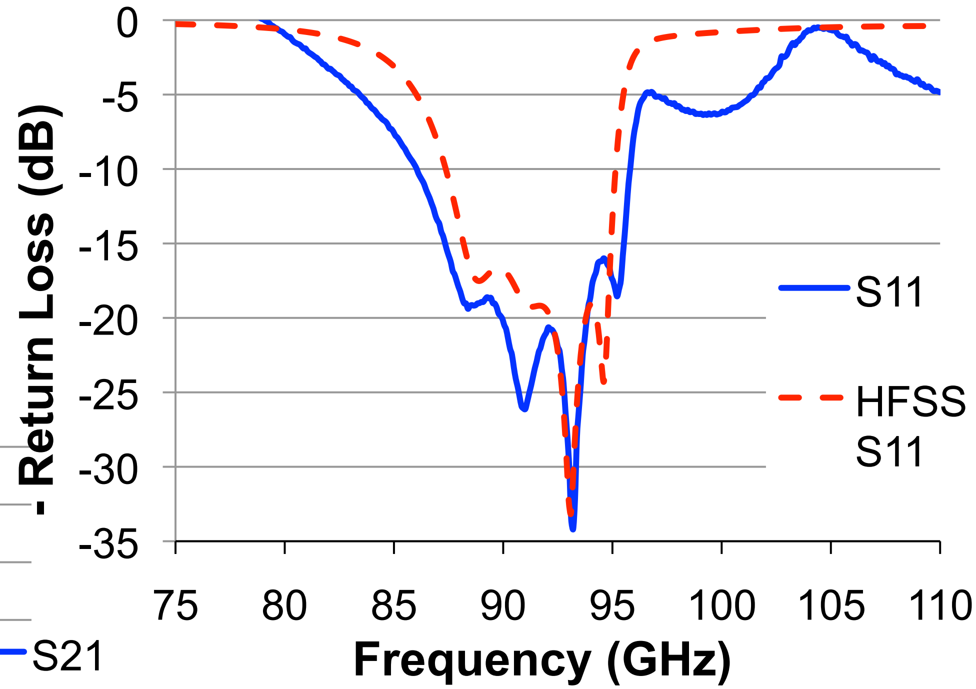
- This direct-detection Dicke radiometer uses two LNAs and a single bandpass filter for band definition.

- Direct-detection architecture is the lowest power and mass solution for these high-frequency receivers. Keeping the radiometer power at a minimum is critical to fit within the overall SWOT mission constraints, including the power requirements of the radar interferometer.

92-GHz Bandpass Filter: Modeled and Measured on Die

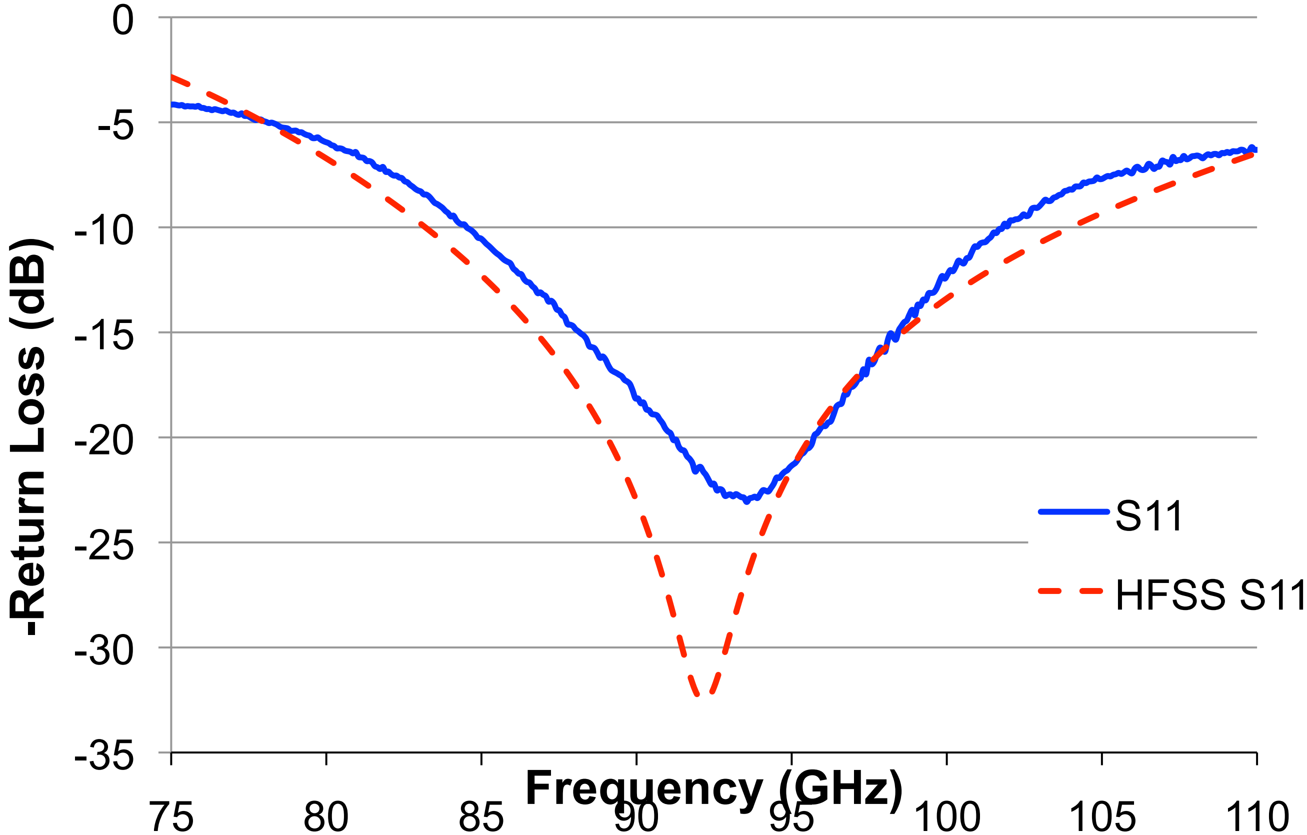
4.6 mm

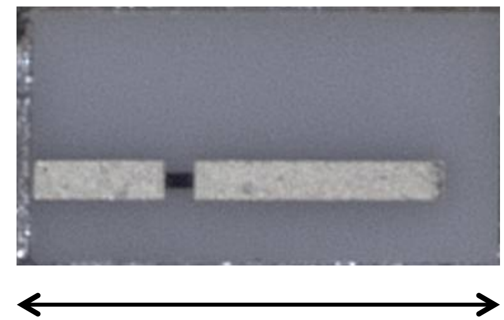




- 5-mil (125-μm) thick polished alumina substrate
- Measured using a probe station with WR-10 waveguides
- Modeled and measured in open air

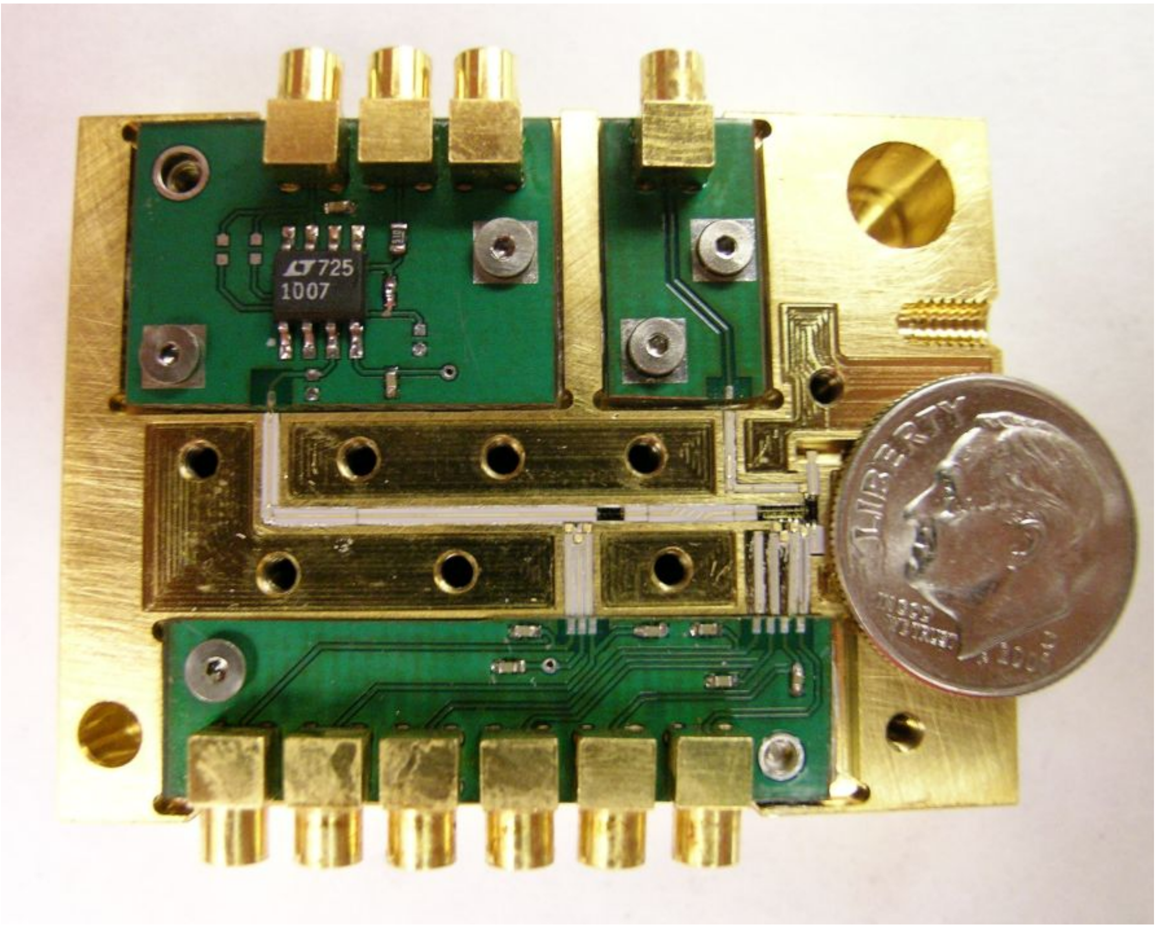
Matched Load for Calibration: Modeled and Measured Results





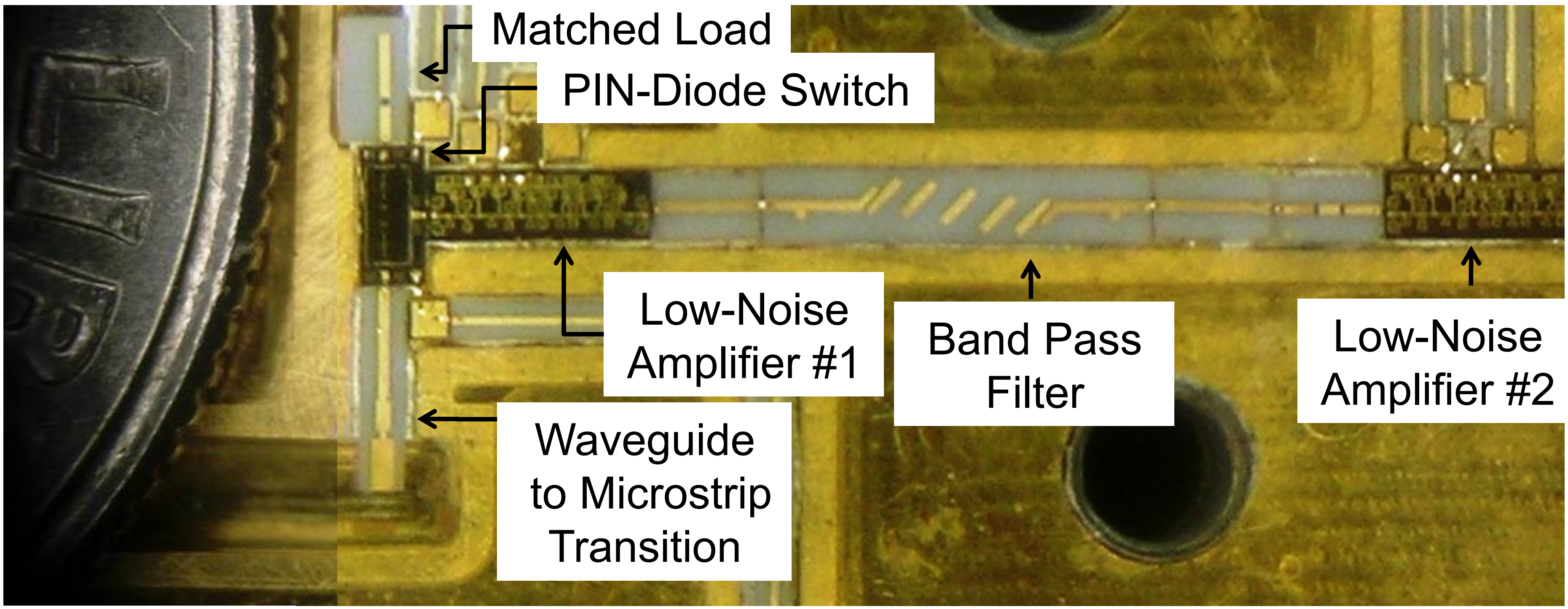
1.45 mm

92-GHz Multi-Chip Module

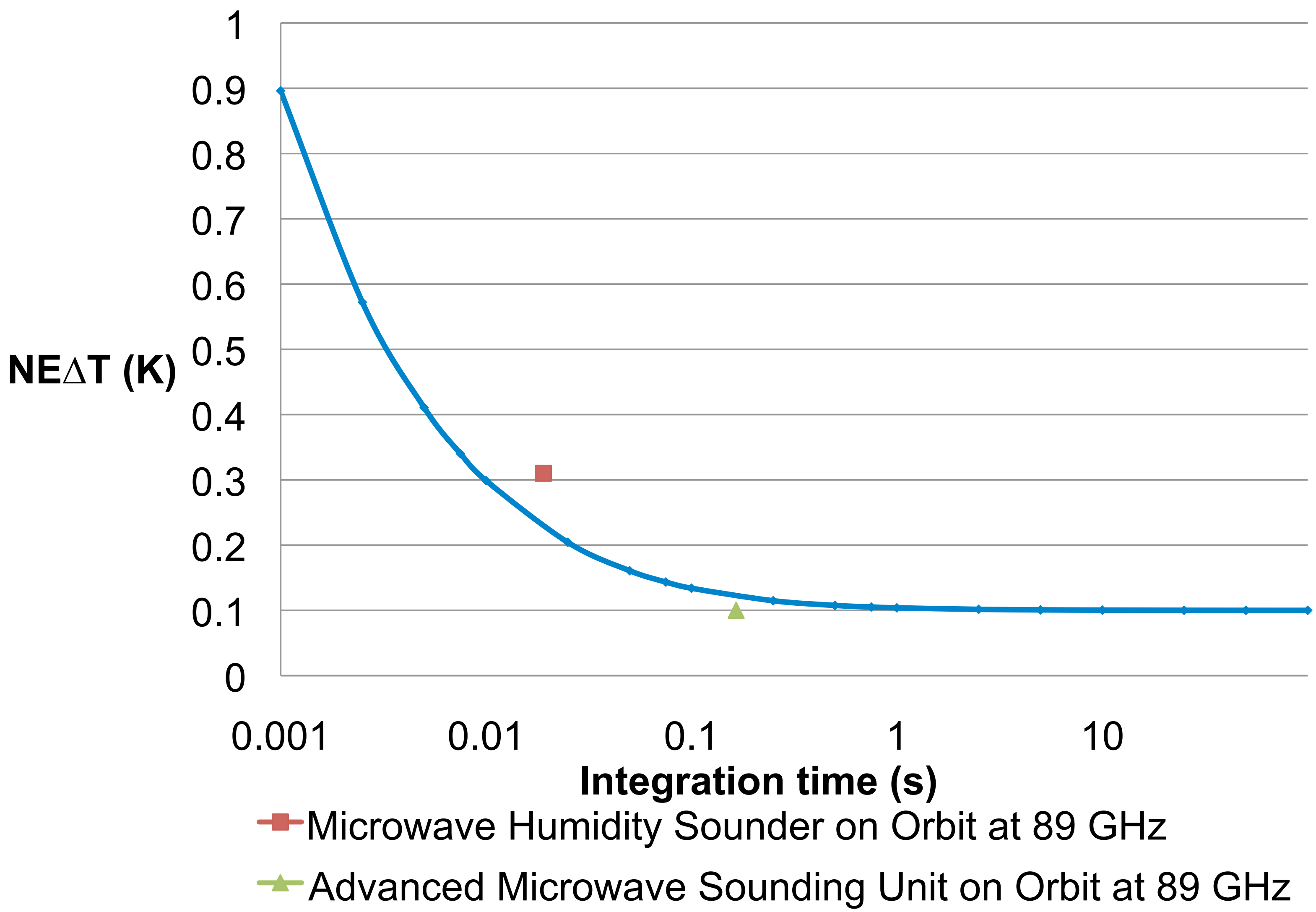


92-GHz direct-detection radiometer with Dicke switching and integrated matched load

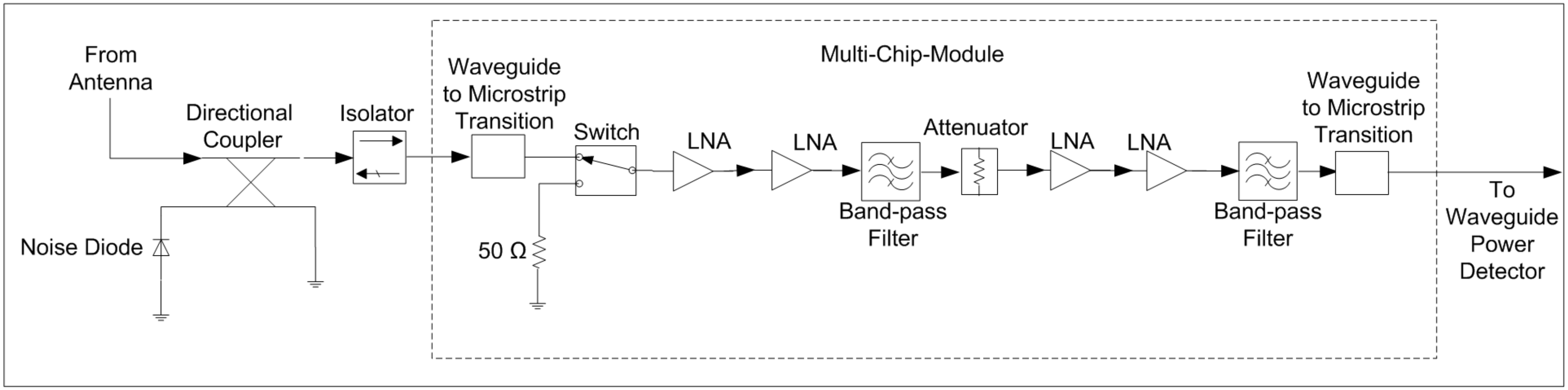
92-GHz Multi-chip Module (Close-up)



92-GHz Radiometer Performance Analysis



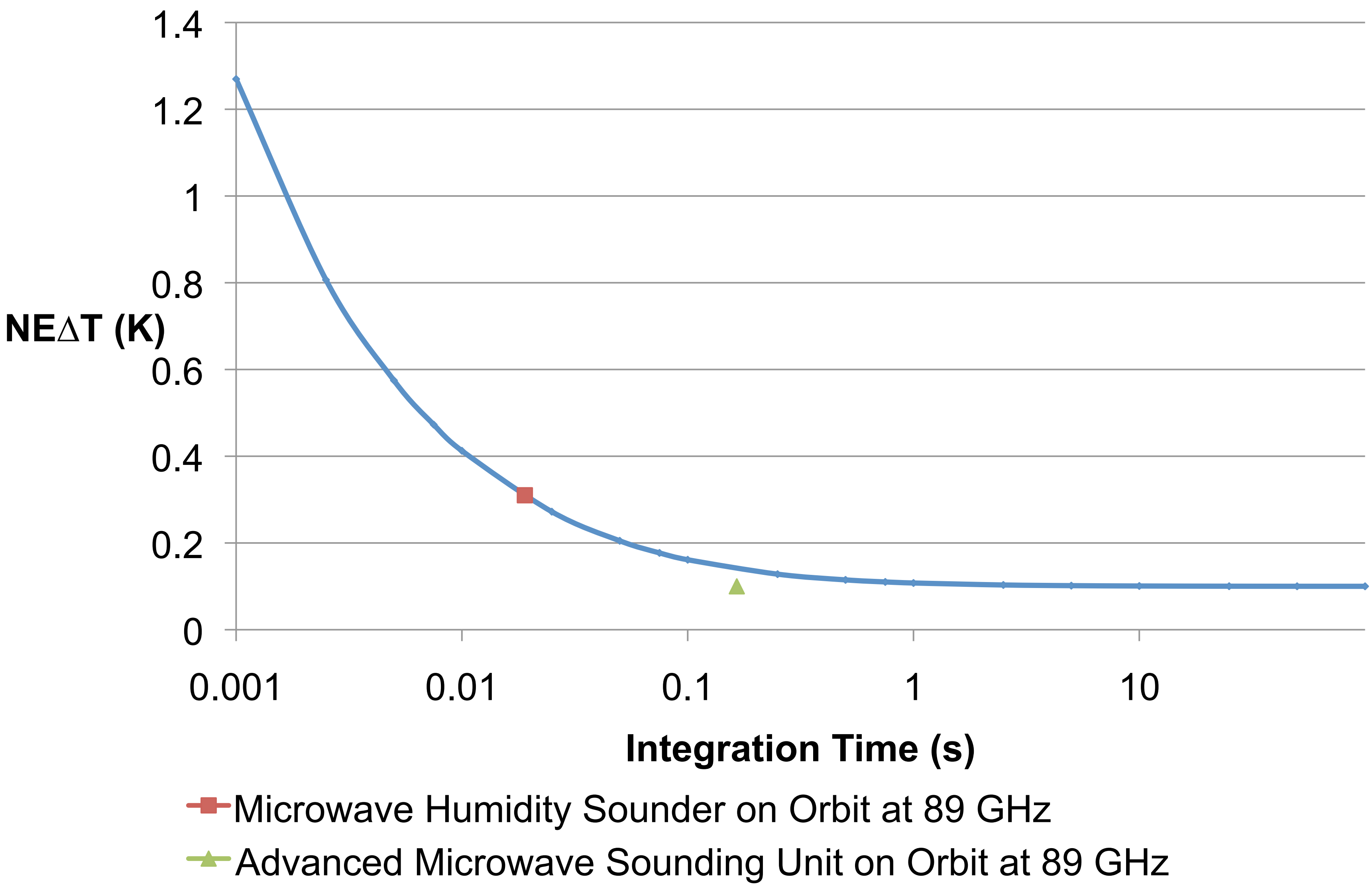
130- and 166-GHz Radiometer Design



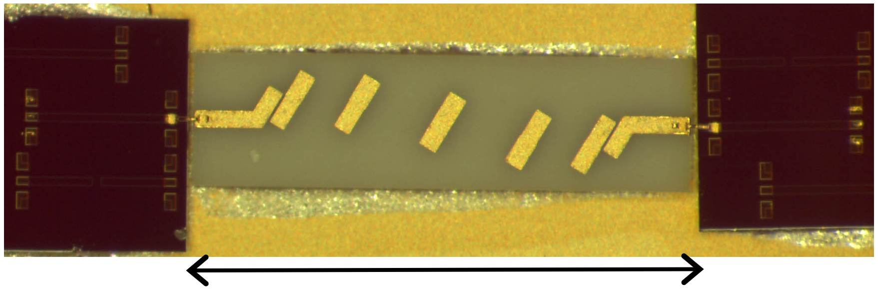
- These Dicke radiometers use four LNAs to provide sufficient signal level at the input to the detector.

- Direct-detection architecture is the lowest power and mass solution for these high-frequency receivers. Keeping the radiometer power at a minimum is critical to fit within the overall SWOT mission constraints, including the power requirements of the radar interferometer.

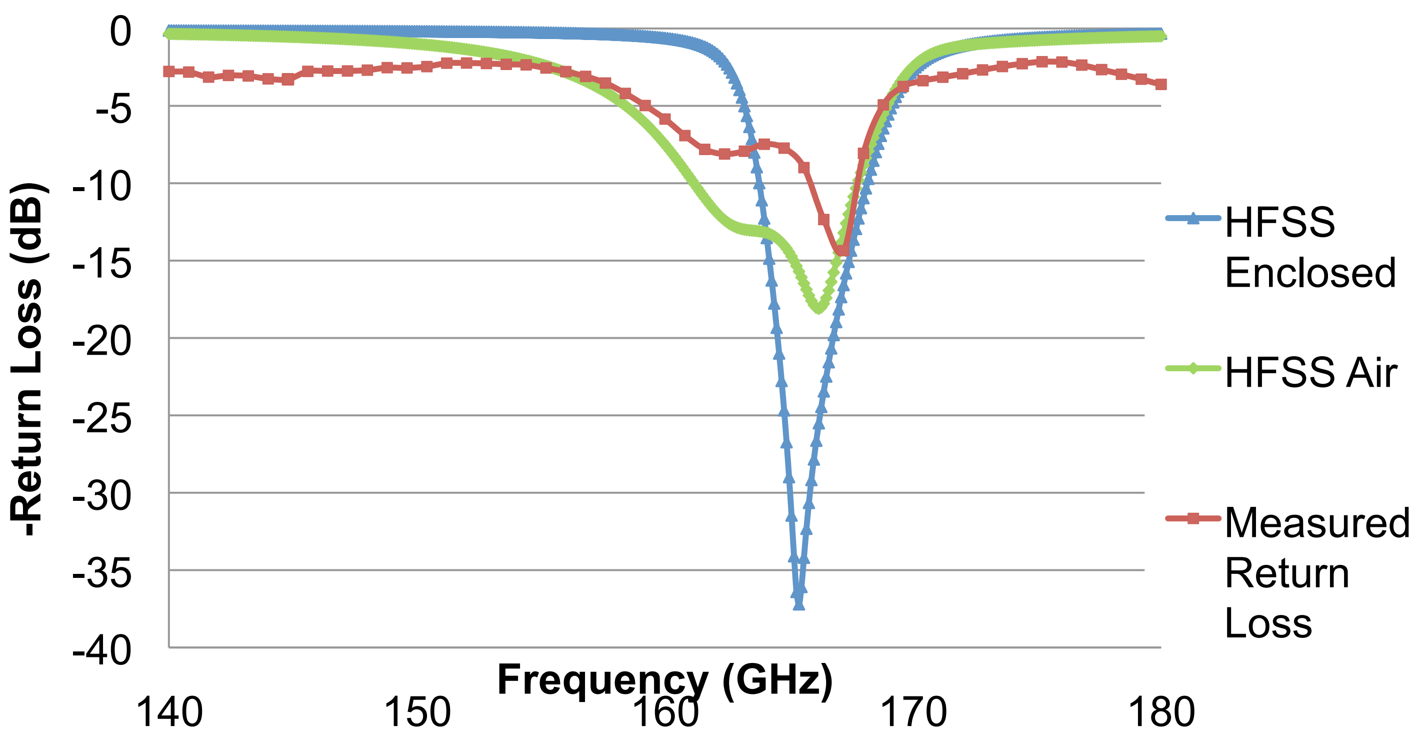
166-GHz Predicted Performance



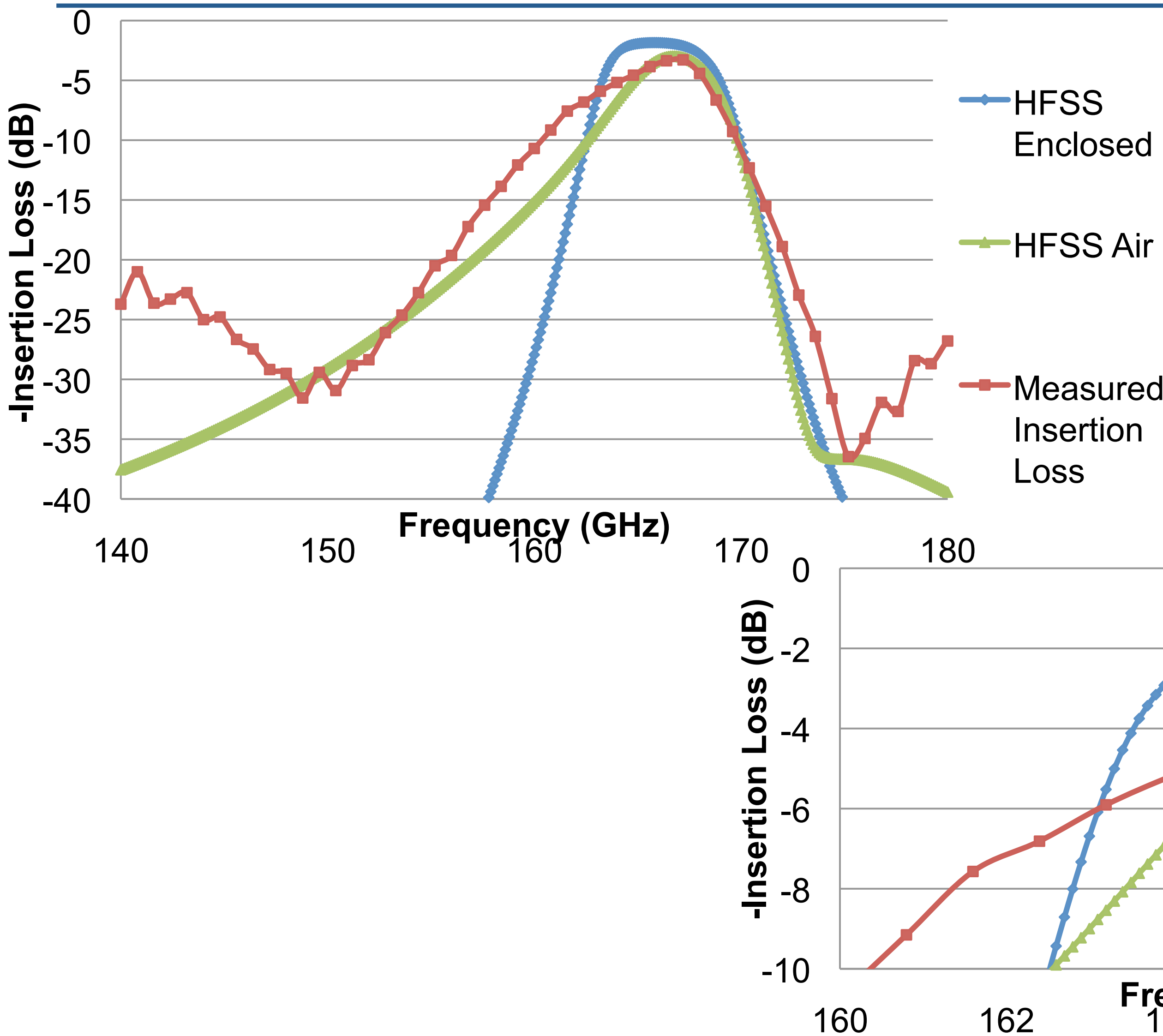
166-GHz Band Pass Filter: Return Loss



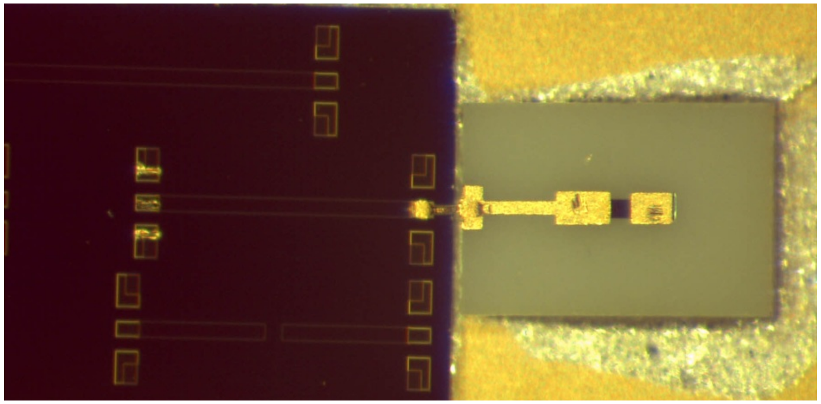
0.94” (2.4 mm)



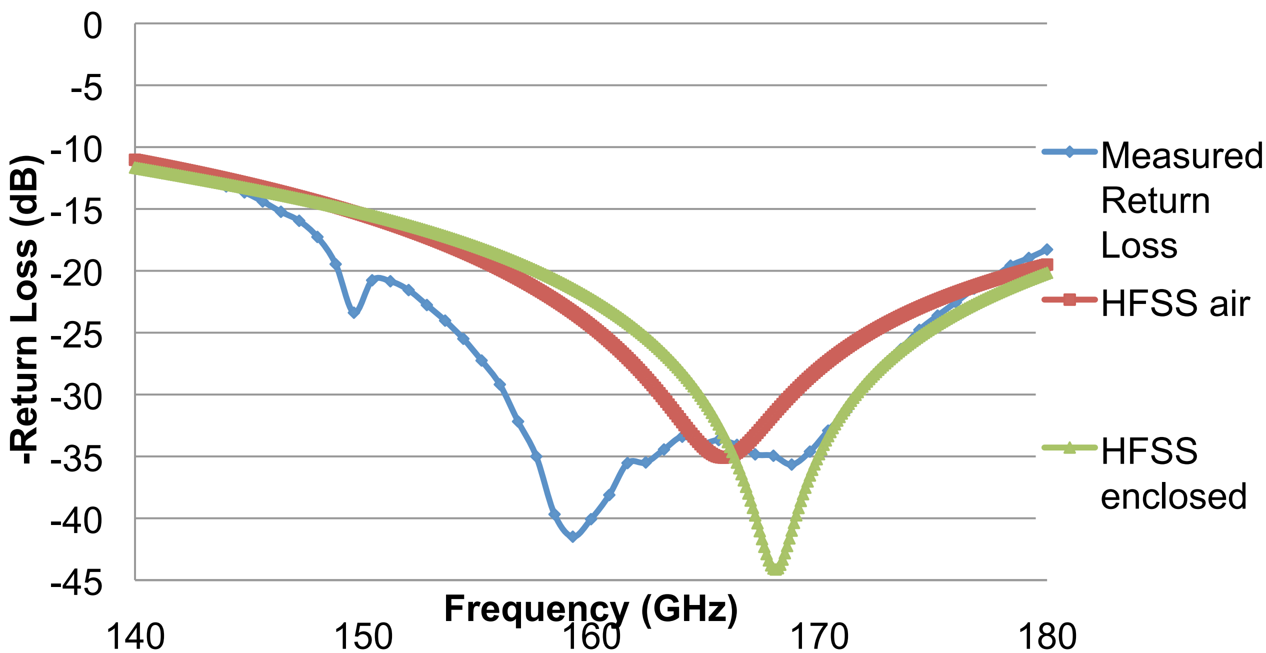
166-GHz Band Pass Filter: Insertion Loss



166-GHz Matched Load

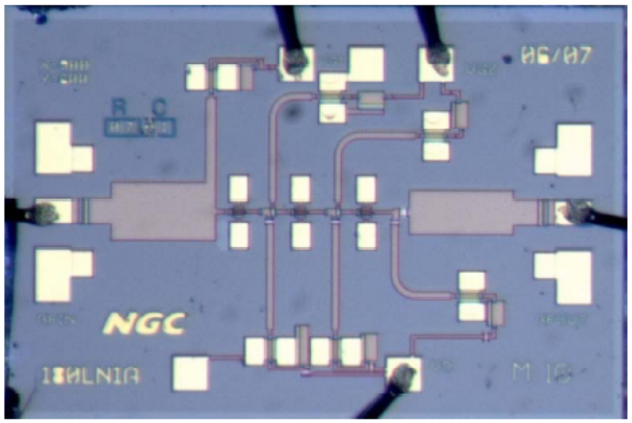


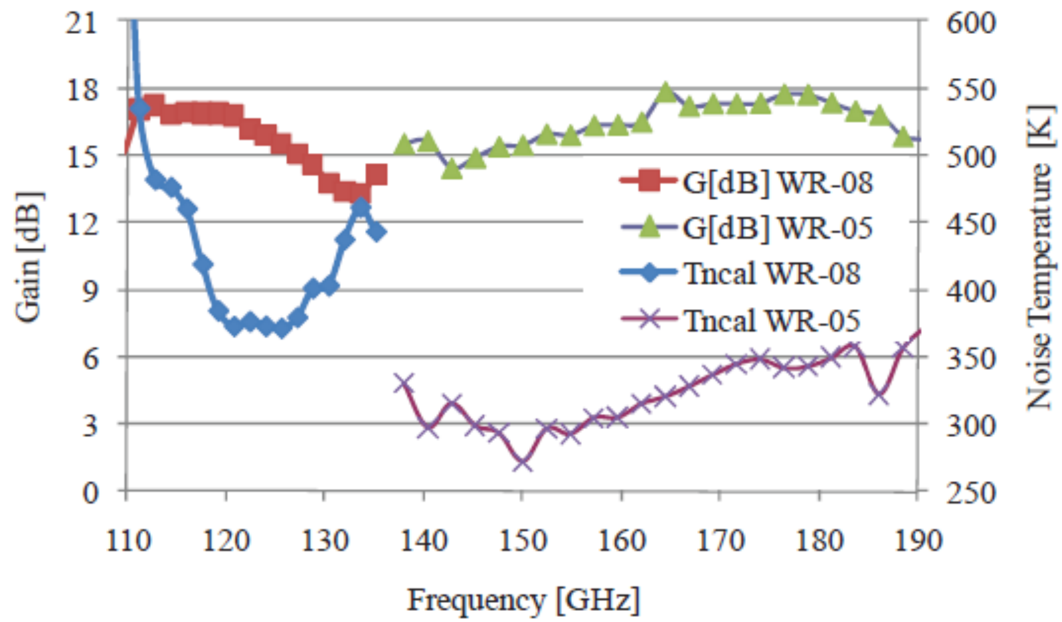
The passive high-frequency microwave components were designed and fabricated in microstrip technology on 3-mil (75 μm) thick alumina substrates.



166-GHz Low-Noise Amplifier

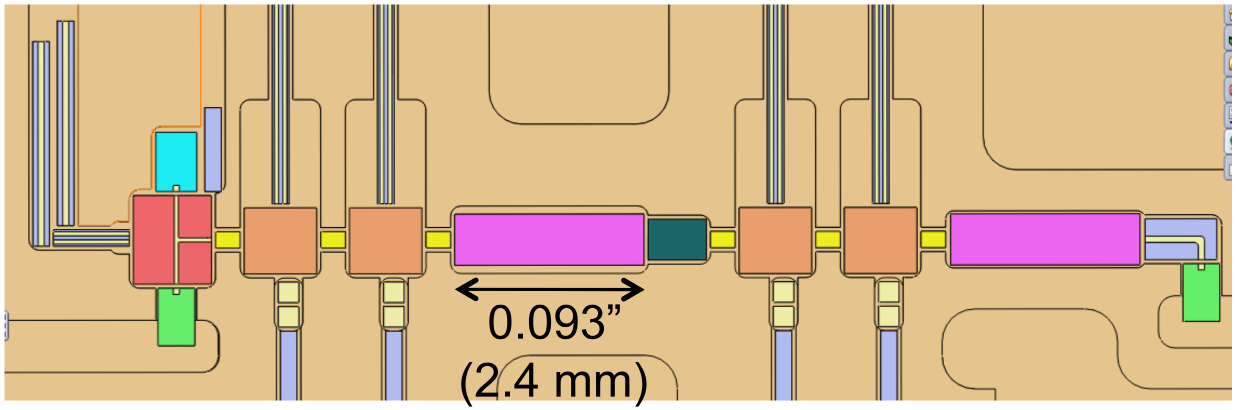
Low-Noise Amplifier Layout and Measured Response

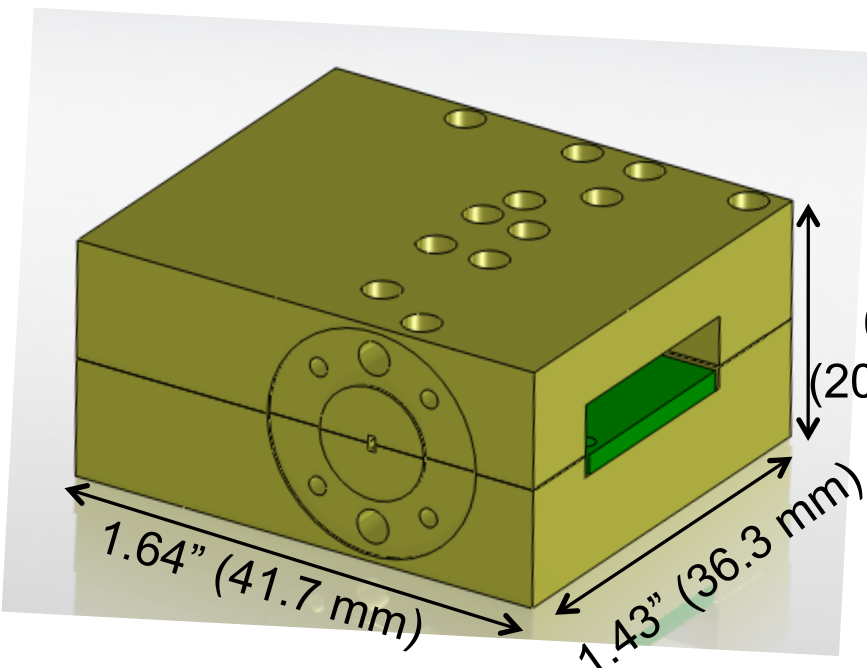


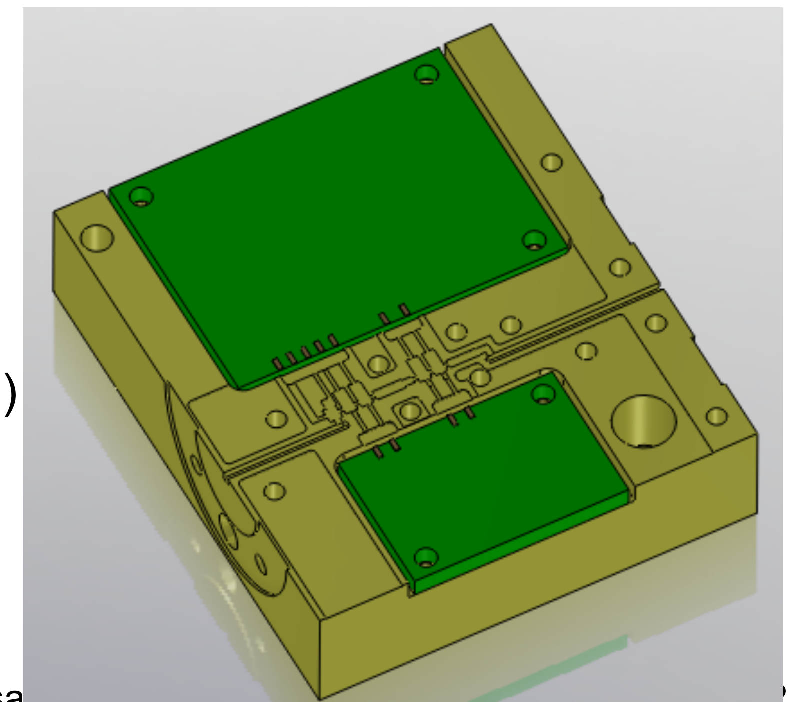


- 35-nm process InP HEMT
- Three-stage design with separate gate bias for the first stage to optimize low-noise performance
- Record low noise temperature of 300 K from 150 - 160 GHz
- Chip area of 900 x 560 $(\mu m)^2$
- The LNA was mounted in optimized WR-08 and WR-05 waveguide housings to test over a broad bandwidth.

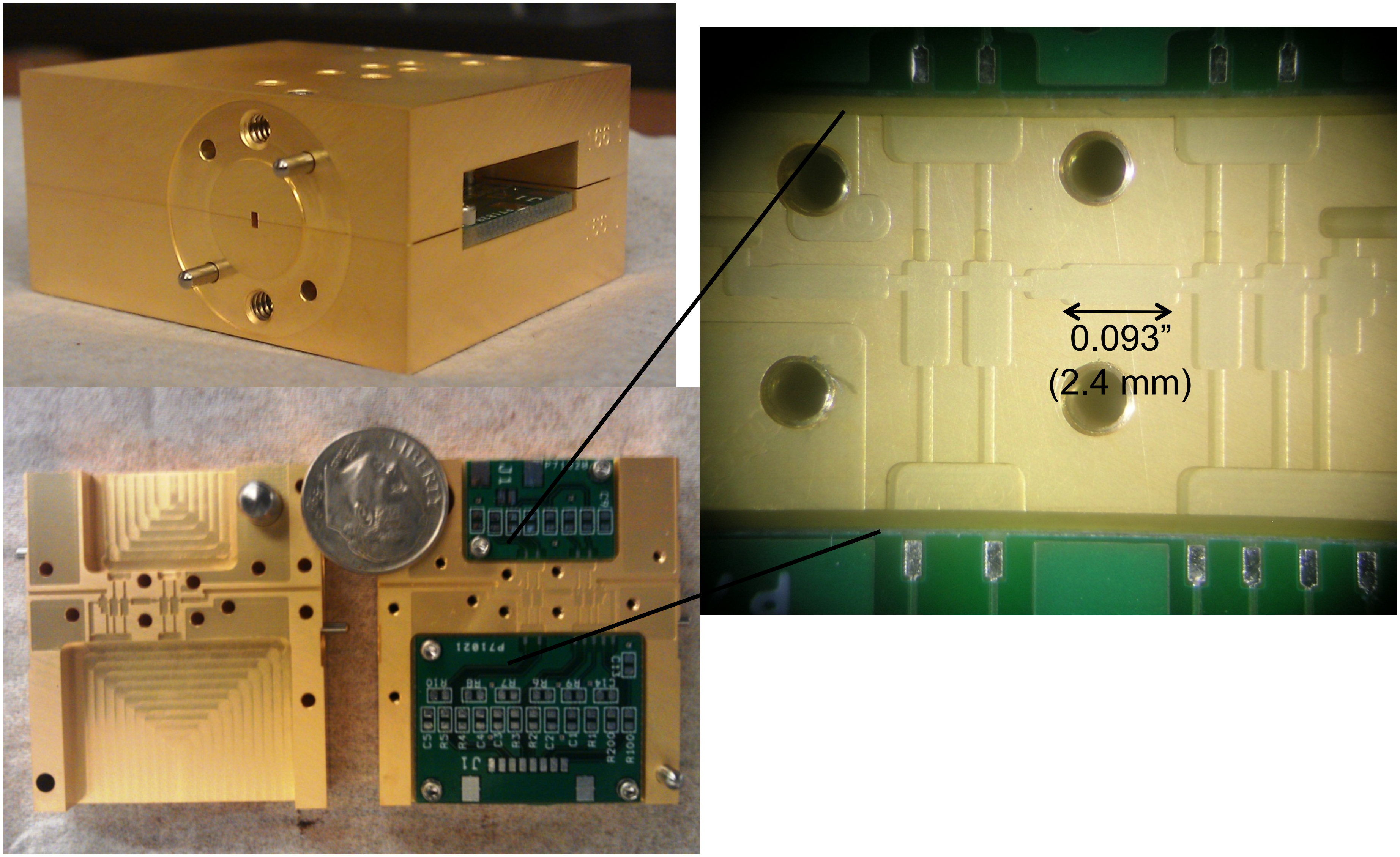
166-GHz Multi-Chip Module



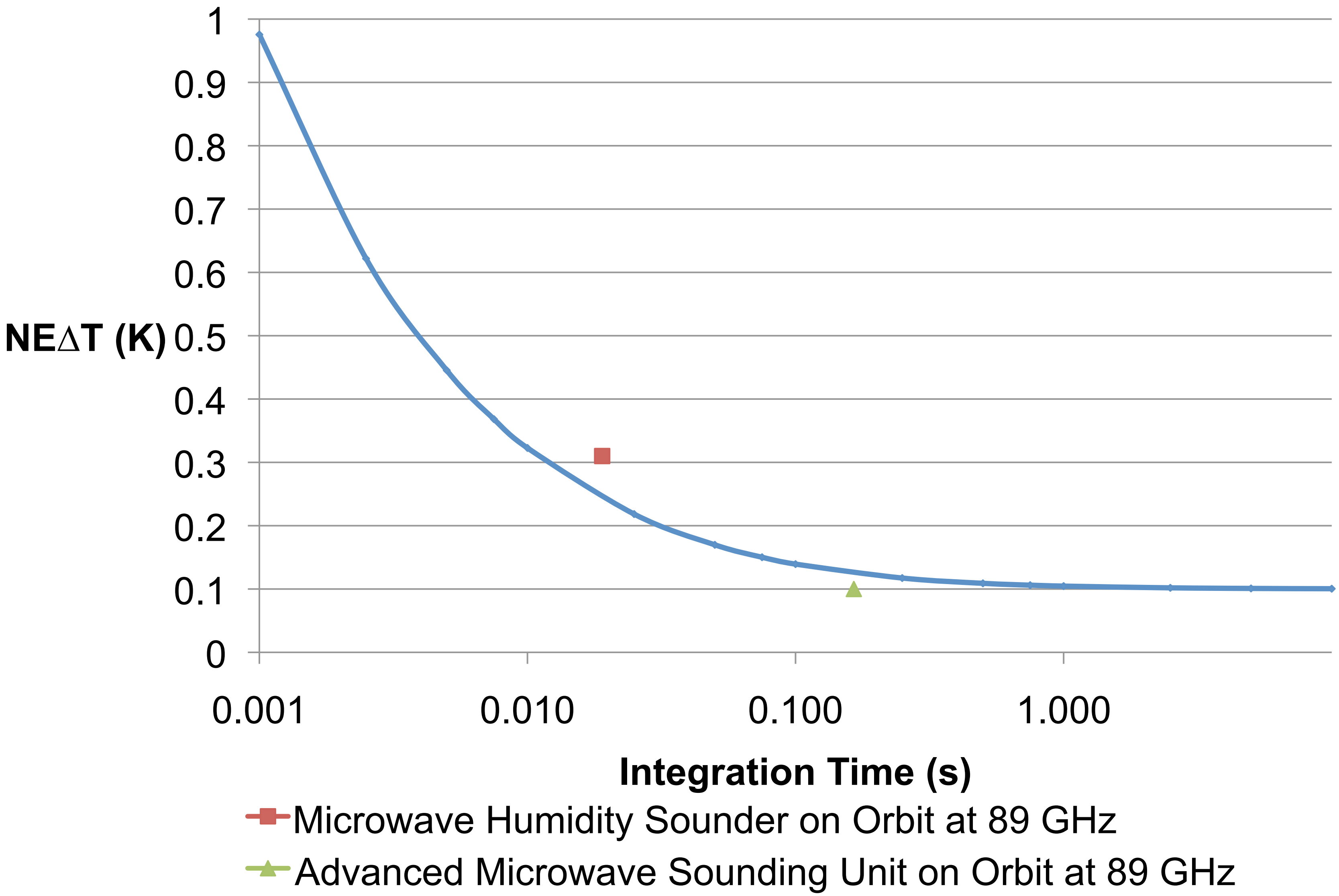




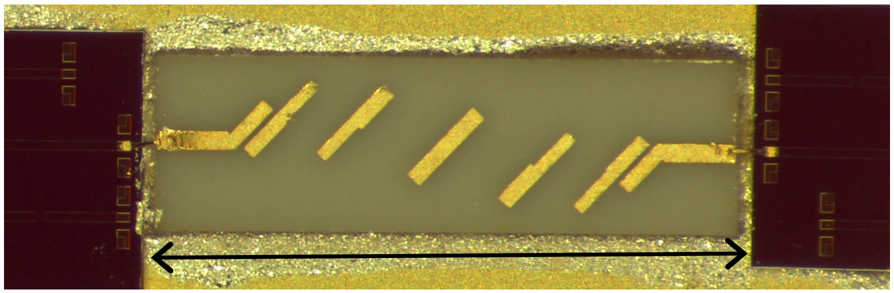
166-GHz Multi-Chip Module



130-GHz Predicted Performance

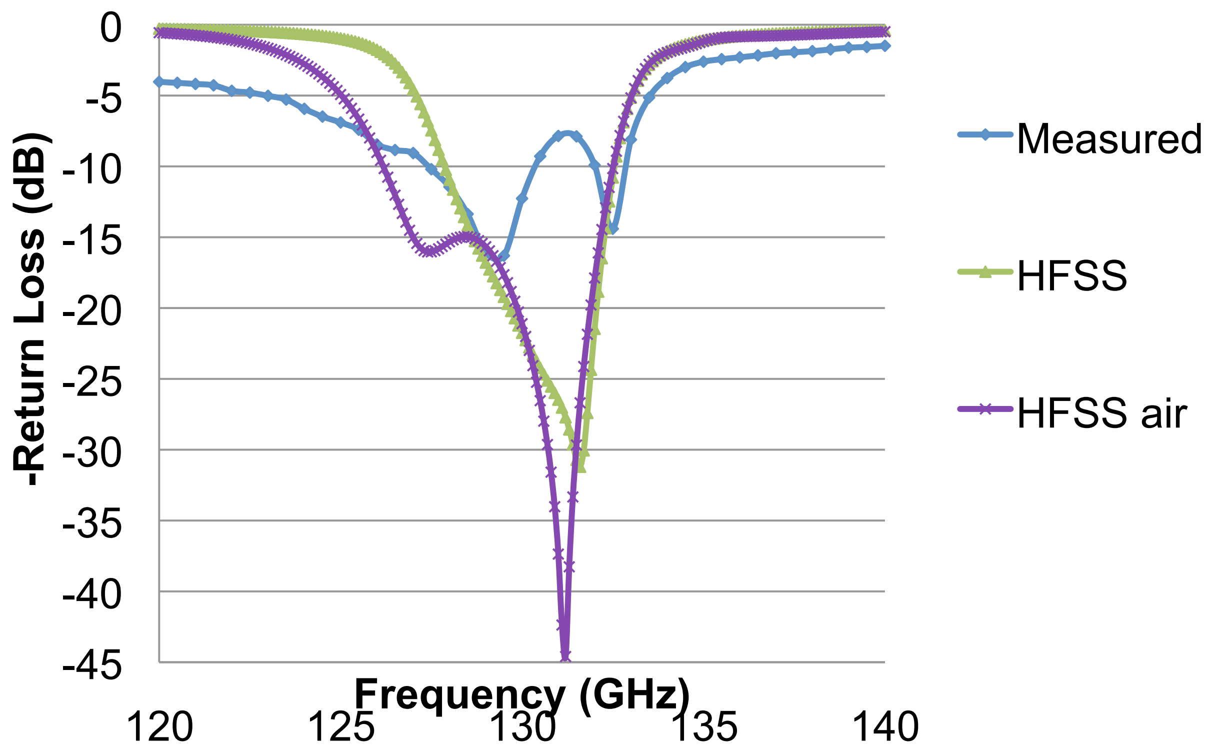


130-GHz Band Pass Filter: Return Loss

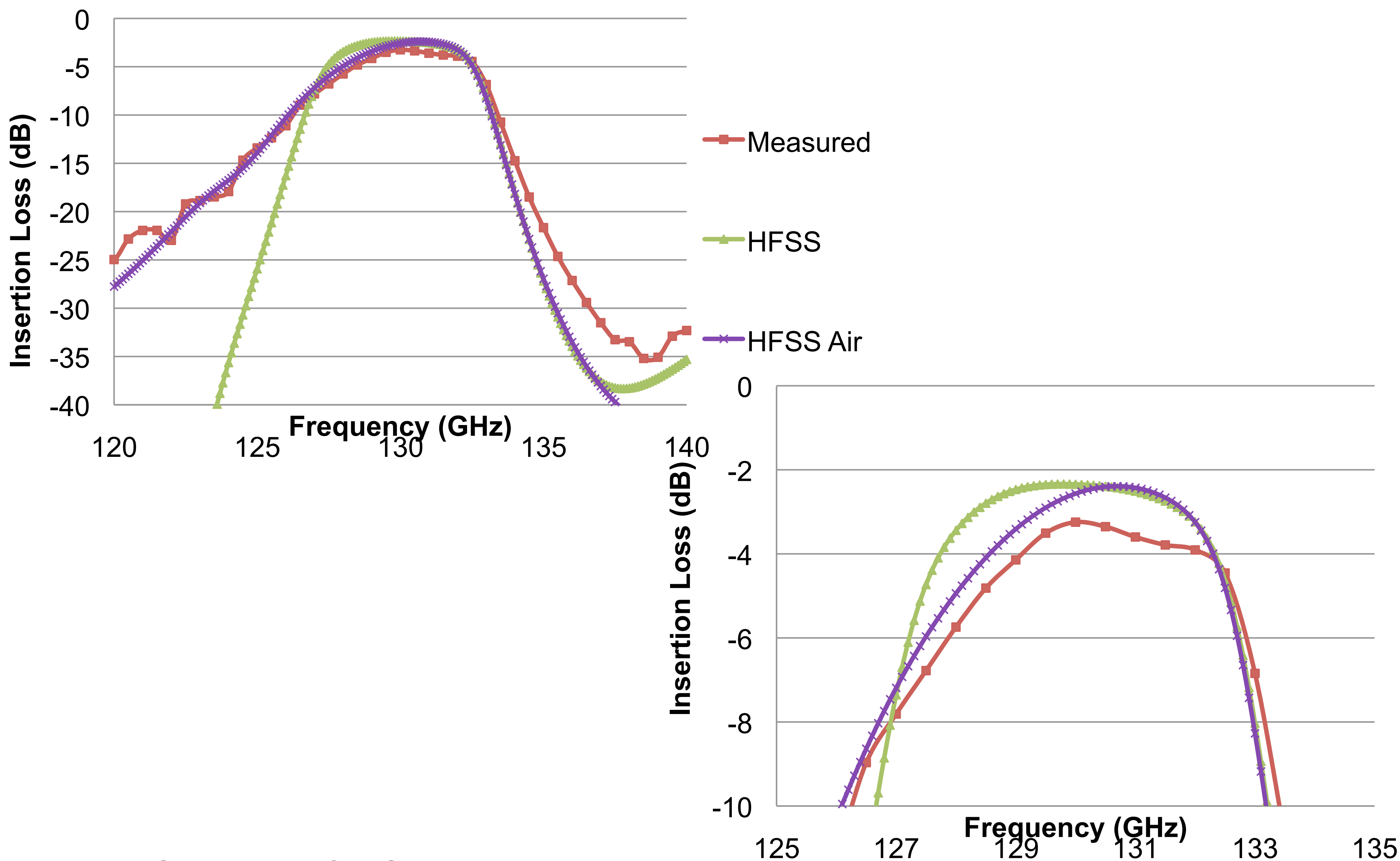


0.94” (2.4 mm)

The passive high-frequency microwave components were designed and fabricated in microstrip technology on 3-mil (75 µm) thick alumina substrates.

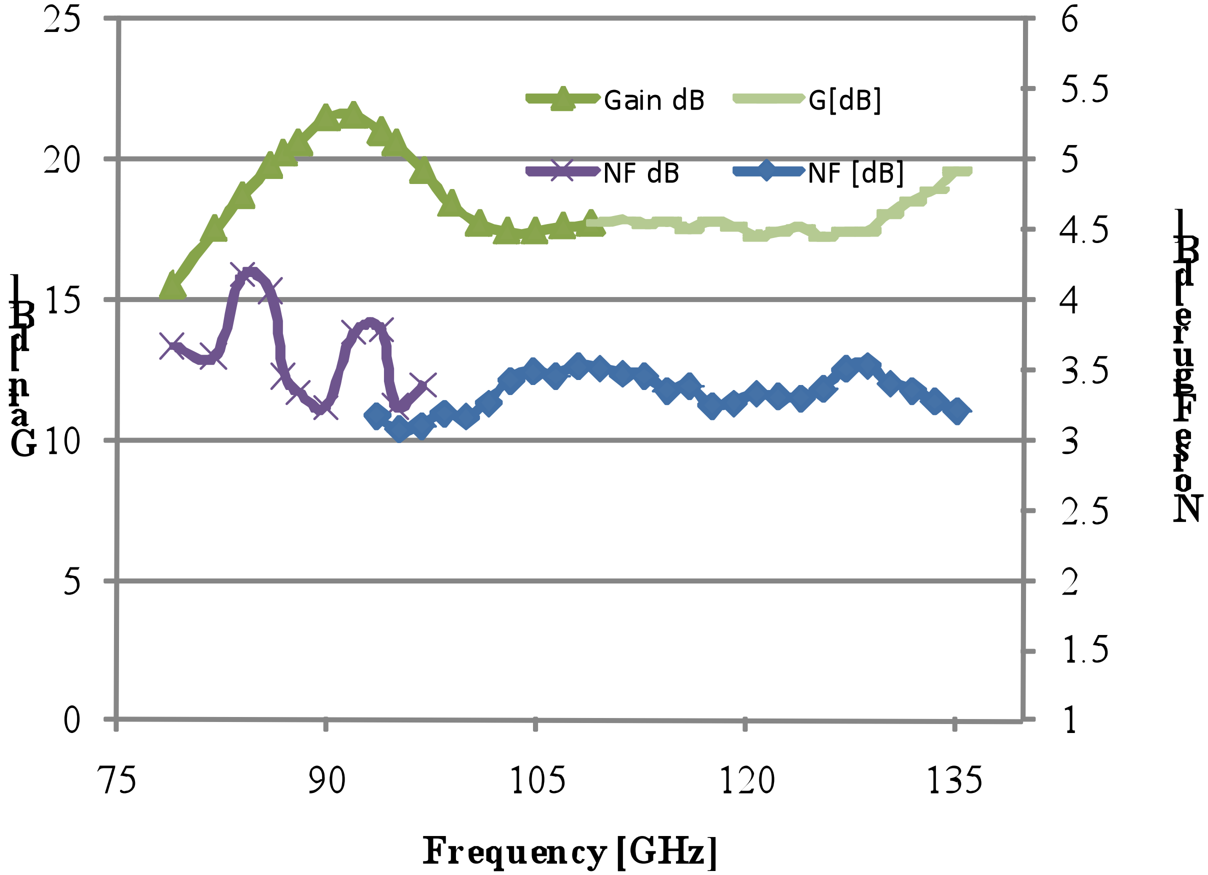


130-GHz Band Pass Filter: Insertion Loss



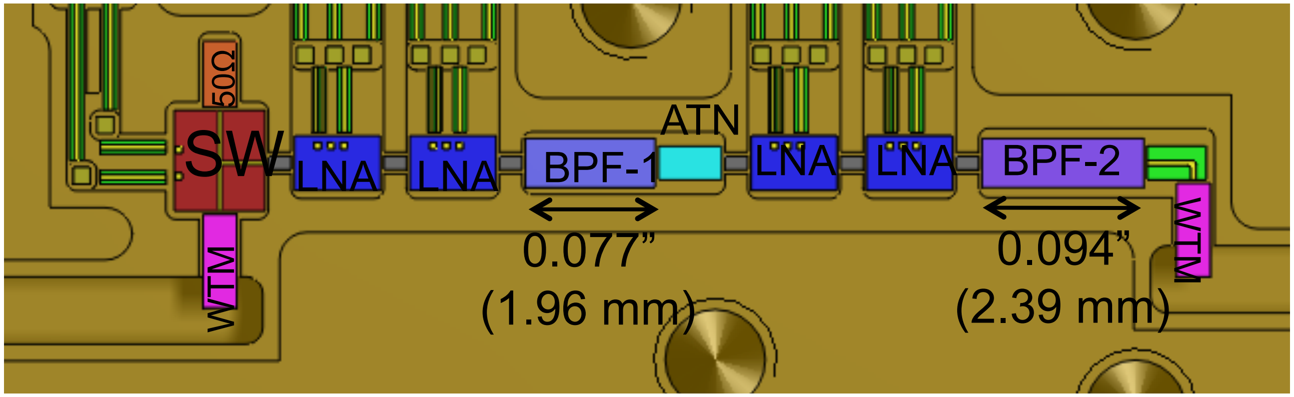
Note: Correction for CPW losses included.

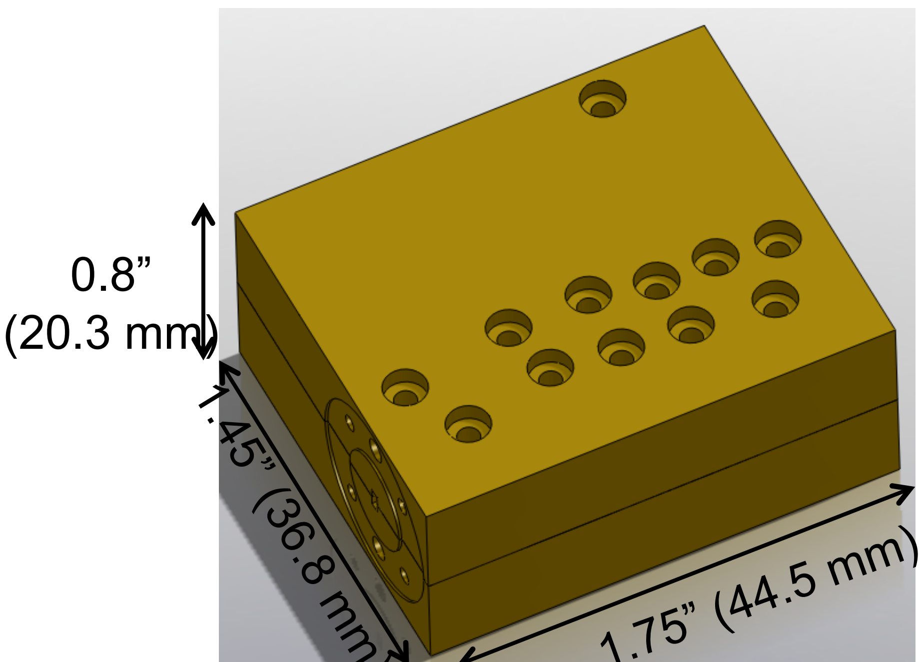
130-GHz Low-Noise Amplifier

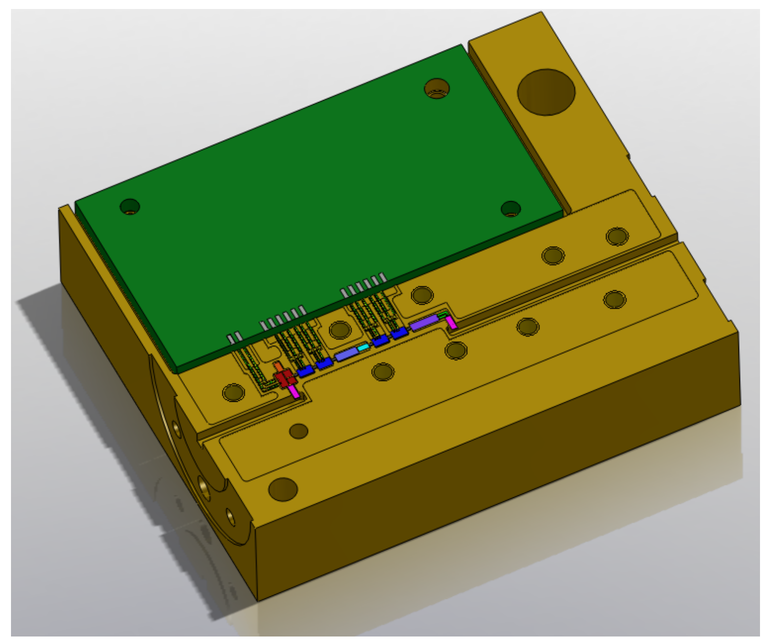


- MMIC LNA was packaged in WR-8 and WR-10 housings for characterization over a broad bandwidth.

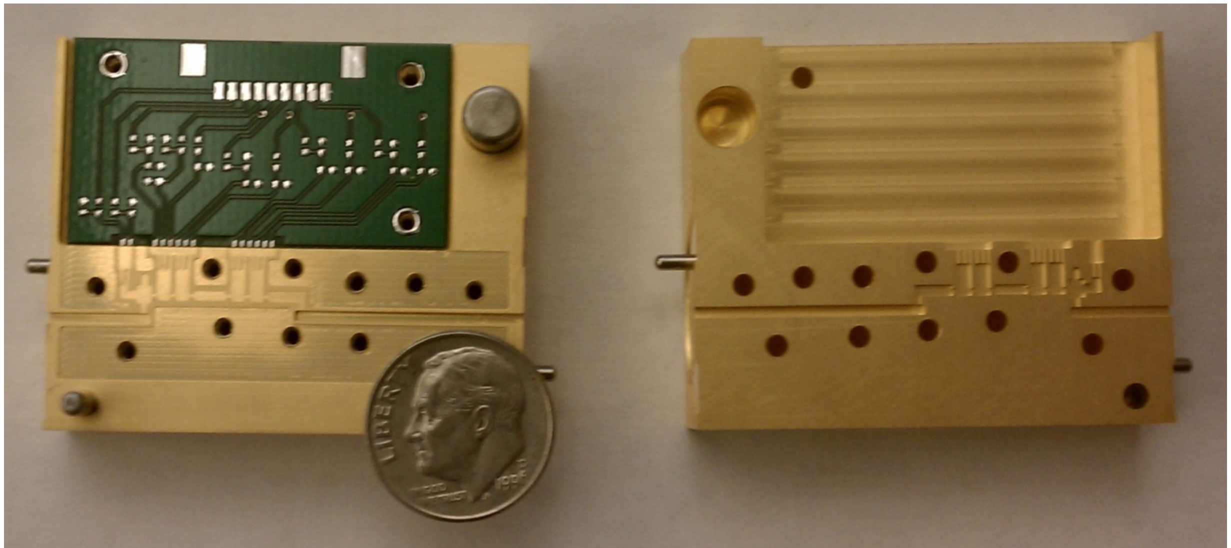
130-GHz Multi-Chip Module

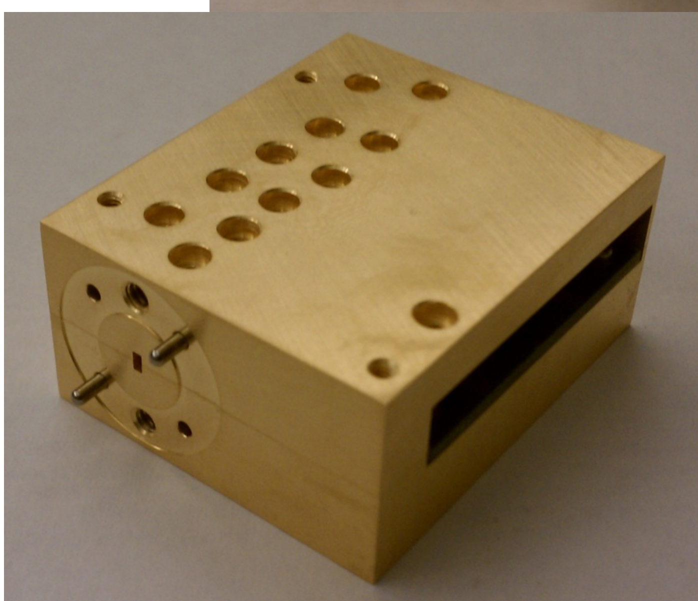


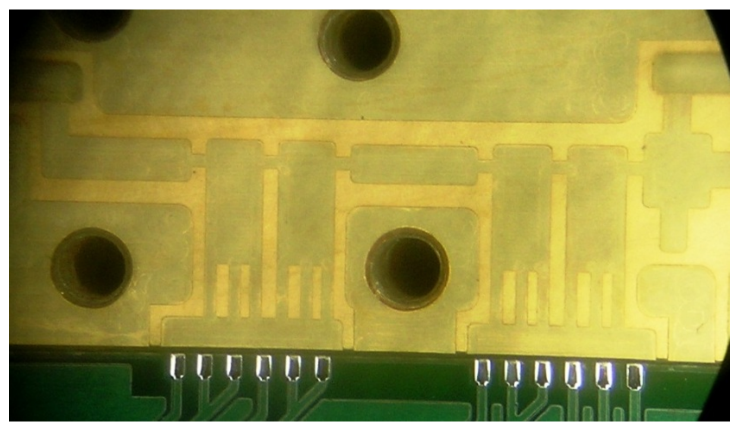




130-GHz Multi-Chip Module







Compact Airborne Microwave Radiometer

- Under a new NASA IIP-10 award, CSU and JPL will develop, demonstrate and fly the Compact Airborne Microwave Radiometer to combine low-frequency wet-delay correction channels (18-34 GHz) with high-frequency mm-wave window (90-170 GHz) and sounding (118 and 183 GHz) channels. It will be capable of deployment on the NASA King Air, Ikhana and Global Hawk.
  - Migrate 34 GHz of the Jason-2's Advanced Microwave Radiometer to 31 GHz to avoid frequency cross-talk with KaRIn radiometer
  - Assess variability of wet-tropospheric path delay on 10-km and smaller spatial scales
  - Demonstrate high-frequency radiometry to improve both coastal and over-land retrievals of wet path delay
  - Provide a calibration and validation instrument to support of the SWOT mission.

Summary

- Conventional altimeters include a nadir-viewing 18-37 GHz microwave radiometer to measure wet-tropospheric path delay. However, they have reduced accuracy within 25-50 km of land.
- The potential addition of higher-frequency microwave channels to SWOT's Jason-2 baseline radiometer is expected improve retrievals in coastal regions and may enable retrievals over land.
- We have developed PIN-diode switches, noise sources and a tri-frequency feed horn for wide-band performance near 92, 130 and 166 GHz.
- To demonstrate these components, we are producing a three-frequency-band, millimeter-wave MMIC-based low-mass, low-power, small-volume radiometer with internal calibration sources integrated with the tri-frequency feed horn.

Thanks to NASA ESTO for their continued support!