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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***Abstract* — Current satellite ocean altimeters include nadir-viewing, co-located 18-37 GHz multi-channel microwave radiometers to measure wet-tropospheric path delay. Due to the area 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. Higher-frequency radiometers with internal calibration are under development to assess their ability to meet the needs of the Surface Water and Ocean Topography (SWOT) mission recommended by the National Research Council's Earth Science Decadal Survey and planned for launch in 2020. The addition of these high-frequency radiometers to current Jason-class radiometers is expected to improve retrievals of wet-tropospheric delay in coastal areas and to increase the potential for over-land retrievals.**

Critical microwave component and receiver technologies are under development to reduce the risk, cost, volume, mass, and development time for high-frequency microwave radiometers. This project focuses on the design and fabrication of (1) low-power, low-mass and small-volume direct-detection millimeter-wave radiometers with integrated calibration sources operating from 90 to 170 GHz that fit within the overall SWOT mission constraints, and (2) a multi-frequency feed horn covering the same frequency range. The three key component technologies under development to achieve these objectives are a PIN-diode switch for internal calibration that can be integrated into the receiver front end, a high-Excess Noise Ratio (ENR) noise source and a single, tri-frequency feed horn. These new components are being integrated into a MMIC-based low-mass, low-power, small-volume technology-demonstration radiometer with channels centered at 92, 130 and 166 GHz.

***Index Terms* — Atmospheric measurements, humidity measurement, microwave radiometry, monolithic microwave and millimeter-wave integrated circuits (MMICs), multichip modules (MCMs), remote sensing.**

I. Introduction

Conventional satellite altimeters, including TOPEX/Poseidon, Jason-1, and Jason-2/Ocean Surface Topography Mission (OSTM), include nadir-viewing, co-located 18-37 GHz microwave radiometers to measure wet-tropospheric path delay over the oceans. However, due to their relatively large instantaneous fields of view for practical antenna apertures, they have reduced accuracy within approximately 40 km of the coasts [1]. In addition, they do not provide wet path delay estimates over land. In 2007, the National Research Council's Earth Science Decadal Survey recommended a Tier-2 mission entitled Surface Water and Ocean Topography (SWOT). In June 2010, SWOT was selected as one of two missions for acceleration from Tier 2 and is now planned for launch in 2020 [2]. The primary objective of SWOT is to characterize ocean mesoscale and submesoscale processes (on a 10-km scale and larger) in the global oceans, for the first time, and to measure the global water storage in inland surface water bodies, including rivers, lakes, reservoirs, and wetlands.

An important new science objective of SWOT is to transition satellite radar altimetry into the coastal zone, indicating the need for a novel microwave radiometer to provide fine-scale spatial resolution wet-tropospheric path delay corrections near land. In addition, the SWOT radar interferometer will for the first time broaden the altimeter field of view and improve spatial resolution to make coastal and inland surface water measurements, so the variability of atmospheric water vapor across the swath will affect altimeter accuracy. A viable approach to meet these needs is the addition of high-frequency microwave window channels at 90-170 GHz to the baseline low-frequency channels at 18-37 GHz. For a maximum antenna aperture size, the high-frequency microwave radiometer channels have inherently

finer spatial resolution. In addition, the high-frequency microwave channels in the atmospheric transmission windows are sensitive to the water-vapor continuum and therefore can be used to improve the retrieval of wet-tropospheric path delay in coastal regions. Over the open ocean, low-frequency brightness temperatures (T_Bs) are expected to yield path-delay retrieval performance similar to that of current space-based altimeters, better than 1 cm RMS [1]. As the radiometer approaches land, the low-frequency T_Bs will be contaminated by the coastline, and the high-frequency T_Bs will be used to extrapolate the path delay toward the coast from the last uncontaminated ocean pixel.

As part of a related mission-concept study, a radiative transfer simulator, coupled with a high-spatial resolution Weather Research and Forecasting (WRF) model, has been implemented to assess retrieval performance and determine instrument requirements. Results of this study indicated that the addition of three high-frequency radiometer channels centered at 92, 130 and 166 GHz could yield path delay retrievals with an RMS error of less than 1 cm to within 3 km from the coast, in the acceptable range of errors for SWOT. In addition, the performance of a 183-GHz sounding radiometer for over-land retrievals was assessed using a Bayesian retrieval algorithm over land and over ocean. NOAA's National Center for Environmental Prediction (NCEP) model fields were used to generate simulated global 183 GHz T_Bs, and errors were binned as a function of path delay (PD). RMS errors over land ranged from 1.5 to 3.0 cm, and over ocean or large water bodies varied from 0.5 cm at low PDs to 2.0 cm at high PDs. Therefore, channels near the 183-GHz water vapor absorption line are expected to yield useful retrievals over land.

II. High-Frequency Radiometer Technology Development

Development of a new high-frequency radiometer measurement technique for SWOT requires technology developments in both: (1) a low-power, low-mass and small-volume direct-detection millimeter-wave radiometer with integrated calibration sources covering frequencies from 90 to 170 GHz that fits within the overall SWOT mission constraints, and (2) a multi-frequency feed horn covering the same frequency range. This requires essentially a frequency scaling of the design of the Advanced Microwave Radiometer (AMR) flying on the OSTM/Jason-2 altimetry mission that was launched in 2008. The MMIC-based AMR receiver, with integrated radiometer channels at 18.7, 23.8 and 34.0 GHz, was optimized for low mass, volume and power, consuming less than half of the power of the heritage Jason-1 microwave radiometer launched in 2001 and much less than half of the volume and mass. Three key component technologies are needed to scale the design of the AMR to the 90 to 170 GHz frequency range. The first is a PIN-diode switch that can be integrated into the receiver front end. The second is a calibration noise source with sufficient excess noise ratio (ENR) up to 170 GHz. Finally, a linearly-polarized multi-frequency feed horn is needed to cover the high-frequency radiometer channels at 92, 130, and 166 GHz.

The new components developed under this program will be integrated into a MMIC-based, low-mass, low-power, small-volume radiometer with channels centered at 92, 130 and 166 GHz. This radiometer will serve as a laboratory technology demonstrator and provide realistic mass, power and volume estimates to feed into the SWOT mission concept study. A block diagram of the overall radiometer is shown in Figure 1.

III. Tri-Frequency Feed 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 feed horn antenna needs to accept electromagnetic energy in all three radiometer frequency bands and triplex to WR-10, WR-8 and WR-5 waveguide outputs for the radiometers centered at 92, 130 and 166 GHz, respectively.

The tri-frequency horn was custom designed and produced at JPL in a split-block architecture (shown in Figures 2 and 3), containing a corrugated horn with WR-10, WR-8 and WR-5 waveguide ports, as well as an electroform combiner supplied by Custom Microwave, Inc., in Longmont, CO. Ring-loaded slots were required for the feed horn corrugations, and the stringent mechanical requirements necessitated machining each feed horn ring separately and fitting them stably into the split block, as shown in Figure 3. The key design specification for the feed horn is 10-GHz bandwidth in each of the three bands with 15-dB return loss or better. This specification has been met in the WR-10, WR-8 and WR-5 waveguide bands with bandwidths of 11, 18 and 26 GHz, as shown in Figures 4, 5 and 6, respectively. Finally, the measured H-plane and E-plane antenna patterns of the tri-frequency horn at 92, 130 and 166 GHz are shown in Figures 7, 8 and 9, respectively. These figures show that the antenna is designed for nearly-matched 3-dB beamwidths at all three frequencies.

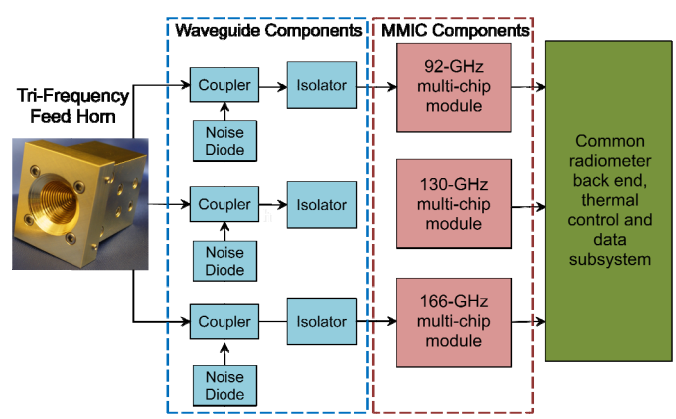

Figure 1. Block diagram of high-frequency microwave radiometer for technology demonstration in preparation for the SWOT mission.

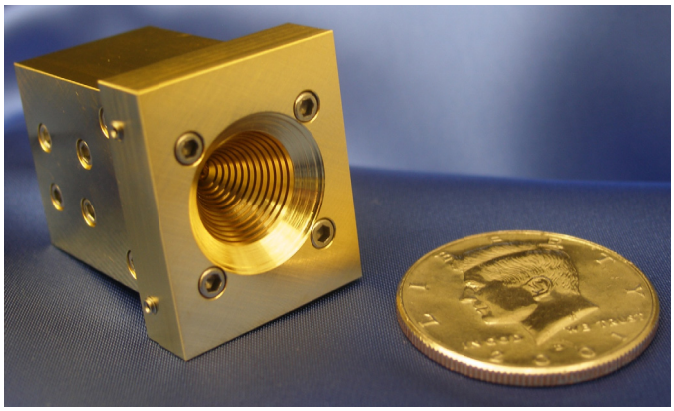

Figure 2. Tri-frequency feed horn and integrated triplexer, with three waveguide outputs: WR-10, WR-8 and WR-5 for radiometers centered at 92, 130 and 166 GHz, respectively.

IV. PIN-Diode Switches and Noise Sources for Internal Calibration

Microwave radiometers for wet-tropospheric path delay corrections in radar altimetry satellite missions are nadir-viewing, so they do not regularly view cosmic background radiation or blackbody sources for radiometric calibration, as conically or cross-track scanning satellite radiometers do. Consequently, internal calibration sources are essential for radiometric calibration. For this purpose, switching sources with known equivalent temperature into the receiver using a PIN-diode switch is currently the most efficient method to meet the requirements of low insertion loss, high return loss, high isolation and high stability. As part of this work, single-pole, double throw (SPDT) switches have been designed at JPL and manufactured using Northrop Grumman Space Technology's (NGST) 75-µm thick InP process [3]. For the 92-GHz radiometer, two different versions of 80-105 GHz switches were developed, symmetric and asymmetric. Both

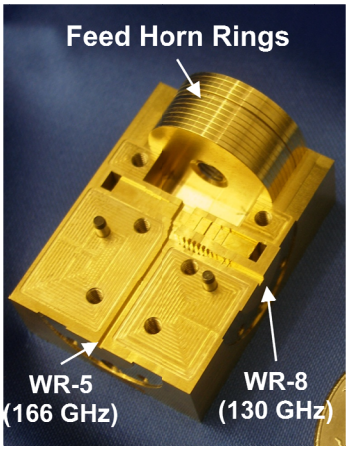

Figure 3. Bottom half of tri-frequency feed horn and triplexer, showing feed horn rings and two of the three waveguide outputs.

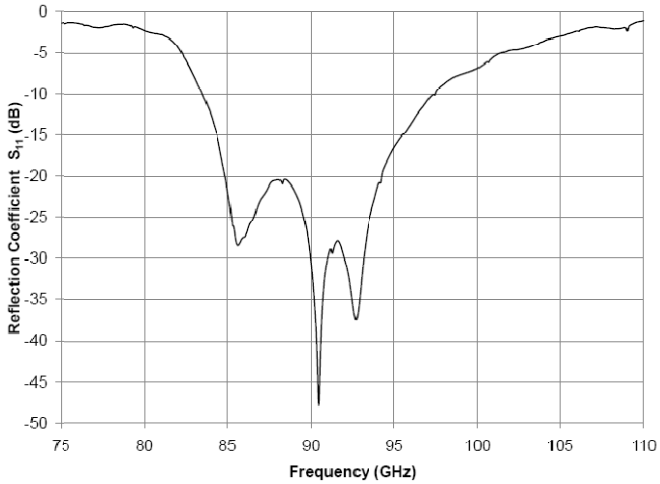

Figure 4. Measured return loss of tri-frequency horn at WR-10 port.

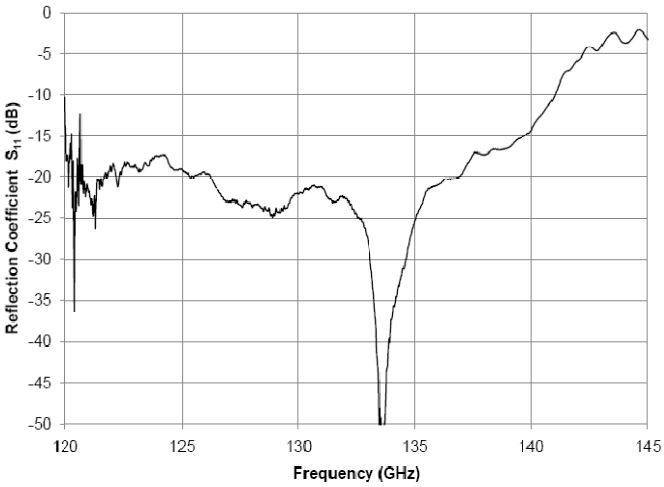

Figure 5. Measured return loss of tri-frequency horn at WR-8 port.

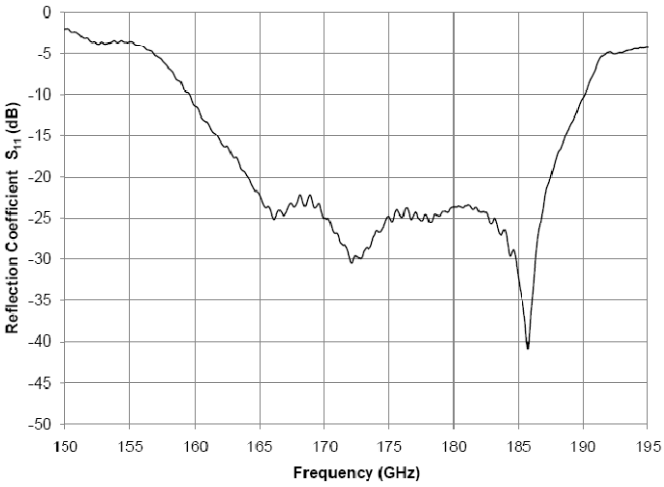

Figure 6. Measured return loss of tri-frequency horn at WR-5 port.

were measured to have <2 dB insertion loss, >15 dB return loss (>18 dB for the asymmetric design), and >15 dB isolation. However, post-fabrication on-chip tuning of the asymmetric design improved the isolation to >18 dB across the entire frequency range and to >20 dB from 85-103 GHz, easily achieving the required isolation at 92 GHz. For the 130-GHz radiometer, 90-135 GHz SPDT switches were fabricated and measured to have <2 dB insertion loss, >15 dB return loss, and 8-12 dB isolation. However, it has been shown that the isolation of this switch design can most likely be significantly improved via the tuning method used in the 80-105 GHz design. The 160-185 GHz has been fabricated, but not yet measured. Simulation results predict this switch will have <2 dB insertion loss, >20 dB return loss, and >20 dB isolation. Afterward, the switches will be integrated into the MMIC-based multi-chip modules (see Section VI).

Two well-characterized noise-equivalent temperature references are needed for internal calibration. The "warm" reference is typically accomplished by Dicke switching the receiver from viewing the external scene to viewing a matched load. The noise-equivalent temperature is then equal to the physical temperature of the load, which is easily measured. The "hot" reference is usually achieved by coupling the output of a stable noise source into the receiver. This requires a noise source of sufficient power (expressed in excess noise ratio, ENR), that is stable over a sufficiently long time period.

To achieve the "hot" reference, commercial noise diodes are available in bare die or in beam-lead packages to facilitate a variety of packaging approaches. The ENR of commercially-available diodes was measured by mounting them on existing substrates and integrating them into available waveguide-to-microstrip chassis in both the WR-10 and WR-8 waveguide bands. The required power output level of noise sources in current high-frequency microwave radiometer architectures is at least 10-dB ENR to enable coupling thru a 10-dB coupler to the radiometer. The output of a coupler, assumed for zeroth-order analysis to be lossless, with the noise diode on would be 0-dB ENR, equivalent to 580 K, or twice the power of a matched load at the reference room temperature, T_0, or 290 K. Tests in available chassis showed that a beam-lead noise source can produce at least 13-dB and 8-dB ENR in the 92-GHz and 130-GHz radiometer bands, respectively. Since the waveguide chassis were not optimized for this purpose, we expect that 10-dB ENR in the 130-GHz radiometer band can be easily achieved.

V. Millimeter-Wave Components

Passive millimeter-wave components were custom designed in microstrip on alumina substrates at Colorado State University for the frequency bands of all three radiometers. These include RF bandpass filters, matched loads, attenuators, and matching interconnects to insert between cascaded MMICs. In addition, probes were designed to couple energy from the waveguide-based antenna input onto MMIC-compatible microstrip transmission lines [4].

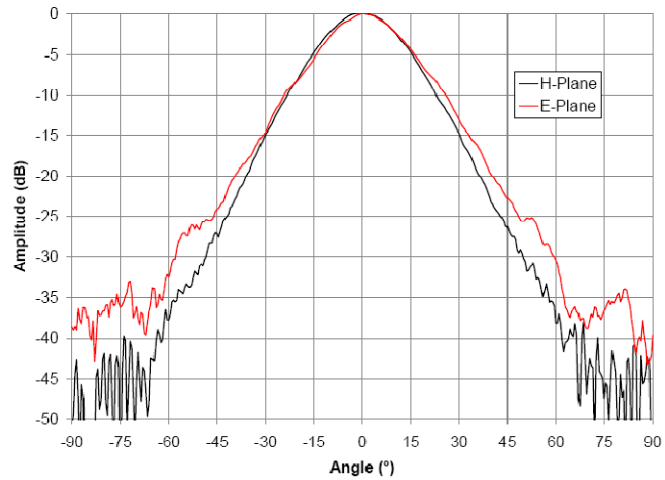

Figure 7. Measured antenna pattern of tri-frequency horn at 92 GHz.

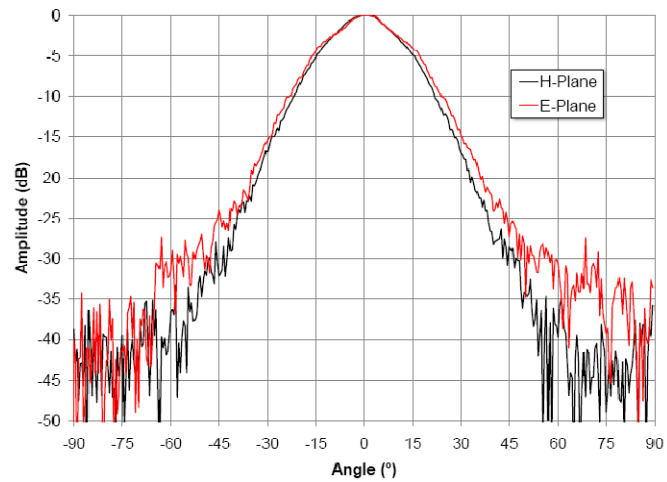

Figure 8. Measured antenna pattern of tri-frequency horn at 130 GHz.

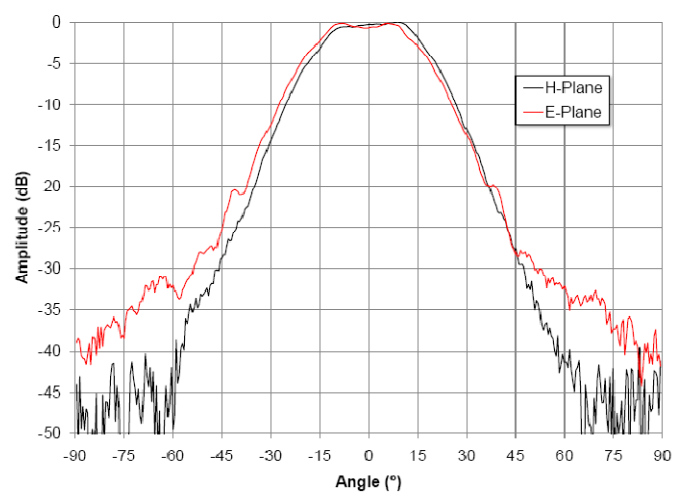

Figure 9. Measured antenna pattern of tri-frequency horn at 166 GHz.

The components for the 92-GHz radiometer have been tested using a WR-10 probe station connected to a vector network analyzer. As shown in Figure 10, the measured frequency response of the bandpass filter compared well with Ansoft HFSS simulation results for open-air conditions. The same was true for return loss (not shown), and for the 50-Ω matched loads. Performance simulations for the 130-GHz and 166-GHz components using Ansoft HFSS show that the radiometer design specifications will be met or exceeded over the design bandwidths of 5 GHz.

In order to minimize both receiver noise temperature and power consumption, direct-detection architecture was chosen over the more-common mixer-based superheterodyne architecture. Recent measurements at room temperature with new InP high-electron mobility transistor (HEMT) LNAs, developed collaboratively by JPL and Northrup Grumman, demonstrated a noise temperature of 300 K at 160 GHz, more than a factor of two below the previous state of the art [5],[6]. This reduces the receiver noise temperature below that of recent mixer-based receivers [7]. These new InP HEMT LNAs will be used in the 130 and 166-GHz radiometers. In the 92-GHz radiometer band, a commercially-available MMIC LNA from HRL Laboratories, LLC, was found to meet performance specifications.

Since the isolator and directional coupler are not available in MMIC-compatible form factors in the 90 to 170-GHz frequency band, commercially-available waveguide-based alternatives are implemented in this technology demonstration, as shown in the block diagram in Figure 1. All front-end components after the isolator are mounted in custom-designed MMIC-based, low-mass, small-volume multi-chip modules (MCM), an extension of prior successful design experience at both Colorado State University and JPL [4],[8]-[9].

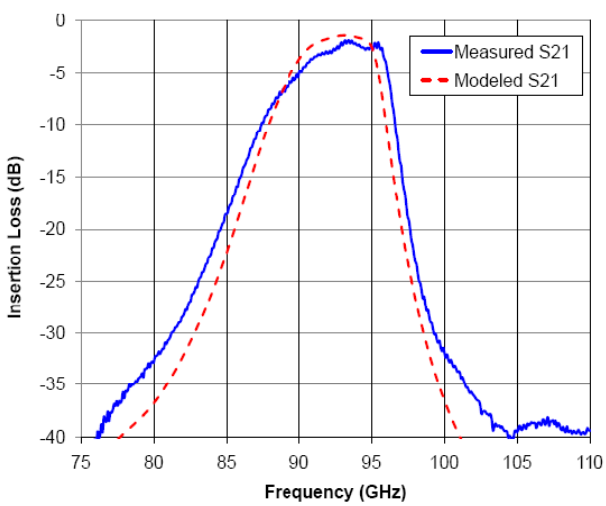

Figure 10. Comparison of measured and modeled bandpass filter frequency response for 92-GHz radiometer.

VI. MMIC-BASED MULTI-CHIP MODULES

The MMIC-based multi-chip module for the 92-GHz radiometer has been fabricated and populated with components, as shown in Figure 11. On-going tests of the complete radiometer indicate that the noise temperature of the radiometer will be less than 1500 K, including all front-end waveguide components, yielding a radiometric resolution (NEΔT) of better than 0.2 K for 0.1 sec integration time.

All commercially-available components for the 130-GHz and 166-GHz radiometers have been acquired. The passive millimeter-wave components have been fabricated in microstrip architecture, and the multi-chip module split-block housings are being machined. The next steps include testing of passive components in the 130- and 166-GHz bands, assembly and testing of the 130- and 166-GHz radiometers, as well as demonstration of all three radiometers with the tri-frequency horn.

VII. CONCLUSION

Critical microwave component and receiver technologies are under development to reduce the risk, cost, volume, mass, and development time for a high-frequency microwave radiometer needed to enable wet-tropospheric correction in the coastal zone on the NRC Decadal Survey-recommended Surface Water and Ocean Topography (SWOT) Mission. This work focuses on the development of a low-power, low-mass and small-volume direct-detection millimeter-wave radiometer with integrated calibration sources centered at 92, 130 and 166 GHz, as well as a single, tri-frequency feed horn covering the same frequency range. The three key component technologies under development to achieve these objectives are PIN-diode switches for calibration that can be integrated into the receiver front end, high-Excess Noise Ratio (ENR) noise sources and a single, tri-frequency feed horn.

PIN-diode switches have been fabricated for all three radiometer frequencies, and the switches meet the design objectives at 92 and 130 GHz. Testing at 166 GHz is ongoing. Commercially-available noise diodes have been shown to provide 13-dB and 8-dB ENR in WR-10 and WR-8 waveguide-to microstrip chassis, respectively, and can be tuned to meet the 10-dB ENR system requirement. The tri-frequency feed horn has been measured and meets all specifications. Finally, the 92-GHz radiometer has been assembled and tested. The components for the 130-GHz and 166-GHz radiometers have been acquired. The next steps in this technology development are the testing of passive components in the 130- and 166-GHz bands, as well as assembly and testing of the 130- and 166-GHz radiometers. Finally, the performance of all three radiometers will be demonstrated with the tri-frequency horn and triplexer.

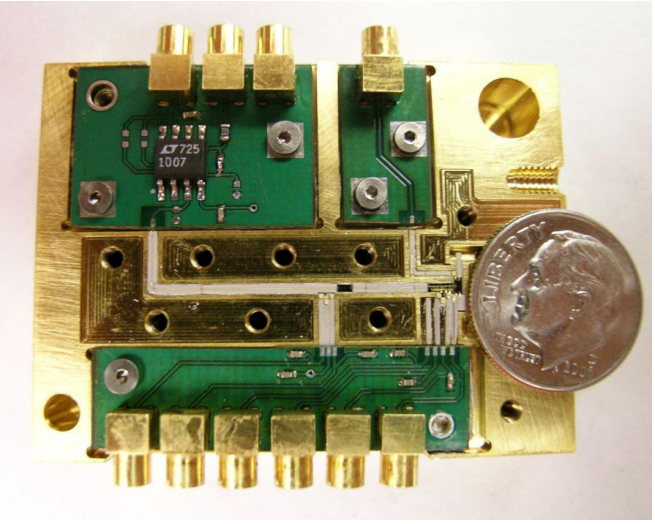

Figure 11. Multi-chip module for 92-GHz radiometer with integrated MMICs and microstrip-based components.

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