K-BAND DIRECT DETECT MMIC SI MICROMACHINED RADIOMETER

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ABSTRACT — **This paper describes the design of a K-Band direct detect MMIC radiometer using bulk micromachining techniques to create the conformal package, interconnecting structures and CPW-fed slot-coupled patch antenna array. Parylene encapsulation is used following die-attach and wire bonding. Also, a unique on-board calibration technique using an MHEMT based cold/warm noise source offers an alternative to other forms of calibration of radiometers and radar receivers. Experimental results are given for the 20.7 GHz radiometer printed on high-resistivity silicon.**

I. INTRODUCTION

Benefits of higher millimeter wave frequencies in communication systems include increased RF bandwidth (~3GHz) and increased satellite capacity (4-50Gb/s). However, with these frequencies there is the disadvantage of significant link outages due to rain. This creates an ever-growing need for a solution to mitigate link outages. One proposed solution is a specialized class of ground based radiometers that provide an *a priori* link analysis and preemptive command from the radiometer processor to the communication system to allow for link compensation techniques. This could include switching to another satellite in the constellation, changing data rates, and increasing transmit power or gain of a receiver. This solution becomes especially germane due to the orderly progression in the SATCOM communications frequency bands due to spectrum crowding C- to Ku, Ku- to K and K- to Ka. This evolution will continue into the higher Q and V bands. Some 16 new system services have already been proposed to the FCC for Q and V bands alone.

This paper describes the design of a miniature link assurance radiometer (Figure 1) that measures the atmospheric effects on radio propagation in an earth-space path. A Si micromachined conformal package includes an integral planar antenna, MMIC radiometer with on-board calibration Cold/Warm Noise Source (CNS) using MHEMT devices and MMICs from Raytheon's Advanced Device Center (ADC) [1].

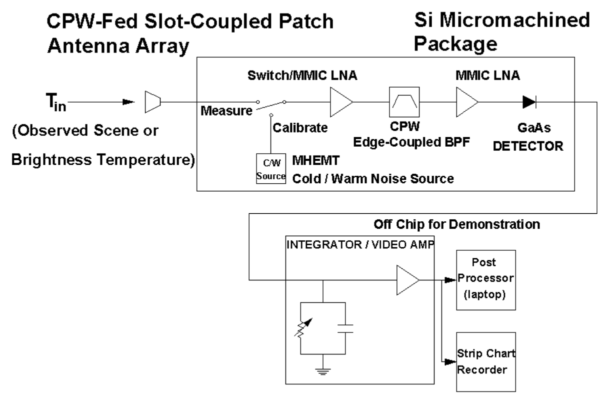

Fig. 1. Block diagram of Si micromachined MMIC radiometer/CPW-Fed Patch Antenna.

A goal of this study is to lead to smaller size and comparable performance to that of waveguide systems. Si micromachining is an enabling technology that provides advantages to allow for extremely accurate three dimensional or planar structures - miniature packages containing antennas, passives, multifunction MMICs and associated analog/digital circuitry are realizable. Many other remote sensing, radar and communications applications will benefit from this miniaturization technology. Examples include aircraft ice detection, radar surveillance detection, weapons guidance, Through the Wall Surveillance (TWS), passive scatterometers, collision avoidance (helicopters and automotive). Therefore, this study should serve as a demonstration test-bed for future millimeter wave systems for engineer/scientists searching for alternate solutions to waveguide realizations.

II. RADIOMETER AND ANTENNA DESIGN

A CPW-fed, slot-coupled patch antenna is used as the radiating element (Figure 2a). The micromachined substrate of the patch provides a lower effective dielectric beneath the antenna and suppresses substrate mode propagation, thus improving the radiation efficiency [3].

X-shaped slots patterned in the patch (Figure 2b) will later be used to reduce the size of the antenna [2].

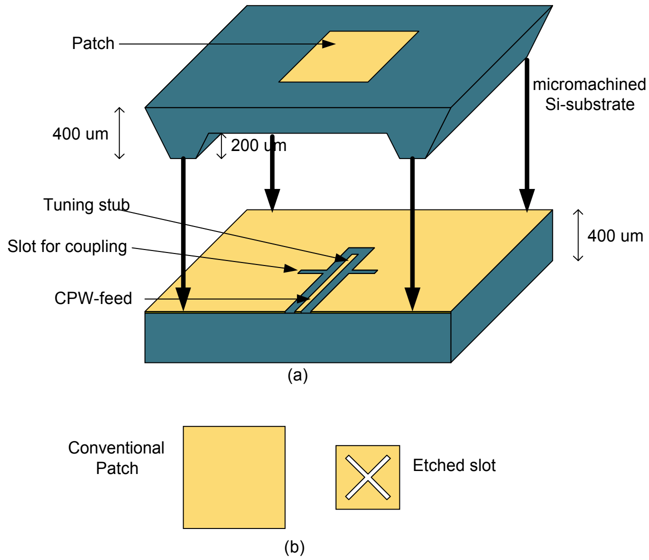

Fig. 2. (a) CPW folded slot-coupled patch antenna, (b) Relative patch area with and without slot.

Electromagnetic energy is coupled to the antenna by slots that are patterned in the CPW ground plane. This coupling is provided with no physical contact between to the antenna thus allowing for independent optimization of the antenna and feed network [4]-[5].

The directivity goal for the array is 14 dBi. In order to meet this specification using the aforementioned patch elements, an array size of 4x4 is under development (Figure 3). This array will provide uni-directional radiation and a directivity near 18 dBi. The element spacing will be approximately $0.5\lambda_o$, resulting in an overall array footprint of approximately 2.2 by 2.2 cm^2.

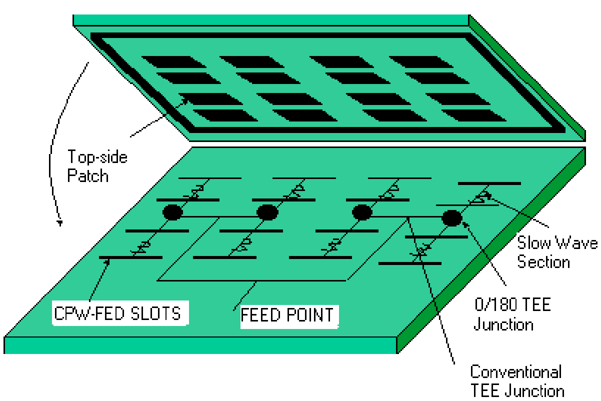

Fig. 3. 4x4 antenna array configuration.

The simulated performance of a single antenna element is shown in Fig. 4. The normalized E and H plane patterns are labeled as ADPTotal at phi =90 and ADPTotal at phi =0 respectively.

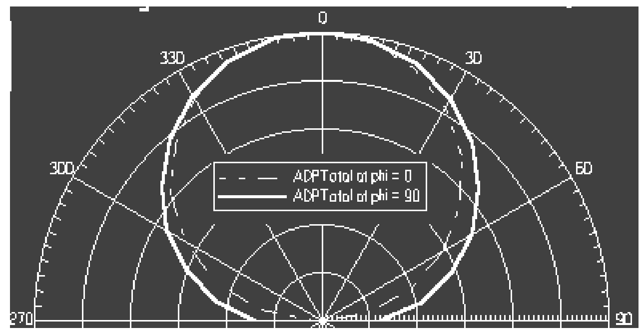

Fig. 4 HFSS simulated far-field E and H plane patterns of a single antenna element at 20.7GHz.

The antenna transitions into a 20GHz Switch/PHEMT LNA MMIC in *measure mode* and switches to the MHEMT CNS for *calibrate mode* (Figure 5).

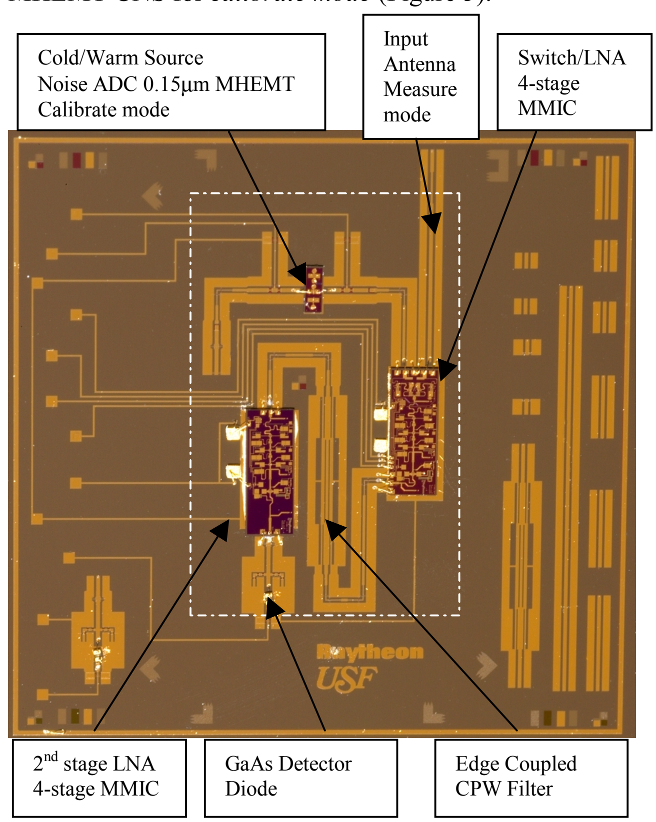

Fig. 5. Fabricated Direct Detect MMIC Si Micromachined Radiometer (dashed lines- area is 16.95mm x 10.0mm).

As shown in Figure 5, the CPW filter is cascaded with an 18-22GHz 4-stage 0.15μm PHEMT MMIC LNA into a GaAs detector diode. At this phase in the study an off chip integrator /video amp is used to feed into a processor resident in a laptop computer.

Following MMIC die-attach and wire bonding, first level (hermetic) packaging is realized using a Parylene encapsulate. Parylene has excellent chemical resistance and is a widely used sealant in the electronics industry. We have also found it to have extremely good high-frequency properties. To demonstrate, the measured response of a 10 GHz, 5-section CPW bandpass filter, with and without a 5-µm Parylene coating, is shown in Figure 6. The filter is 1.7 cm long, and no observable increase in the insertion loss or shift in the center frequency is evident to ~25 GHz. (The filter used in the radiometer is a 3rd order design similar to the one considered here [6].) In order to accommodate the coating, ground equalization of the CPW discontinuities is realized using 'buried' air-bridges (beneath the CPW metal) rather than the conventional structures that are elevated above the lines. This was done to avoid the excess capacitance that would result from filling the air gap between bridge and the CPW metal with Parylene.

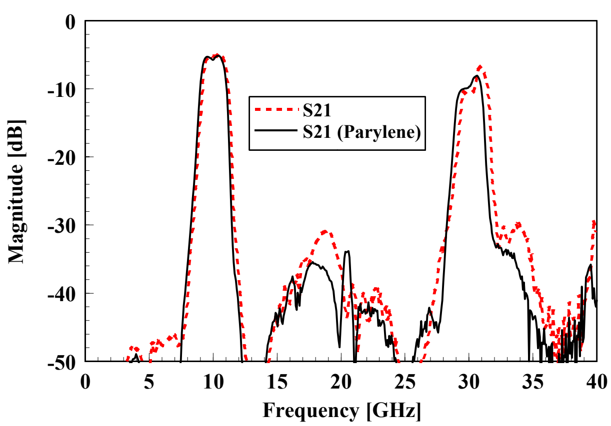

Fig. 6. Transmission response for a 10 GHz, 5th order CPW edge-coupled filter (total length = 1.7 cm) with (solid) and without (dashed) a 5 µm-thick Parylene coating.

The final packaging includes a Si micromachined lid shown in Fig. 7 that supports the patch antenna. The lid also offers a future pathway to multi-layer integration of other circuitry such as the integrator/video amp. The lid was fabricated using TMAH etch with 200µm removed. The <100> plane on top in Fig. 7 exposes the gray or bare Si with the walls of the lid etched back to the <111> plane leaving a slope of 54.7°.

II. RADIOMETER MEASUREMENTS

The radiometer is a simple total power, direct-detection receiver selected to achieve maximum sensitivity with lowest cost. The overall receiver gain (RF and video) was defined based on measuring an antenna brightness temperature of <30 to >300°K. It is planned to calibrate this prototype with the Raytheon Cold/Warm Noise Source (U.S. patent #6,137,440, with other Raytheon/USF patents pending) to correlate this calibration with lab standards and calibration tip curves [7]. The measured RF gain is 56dB and the current equivalent rectangular noise bandwidth was calculated to be 322MHz.

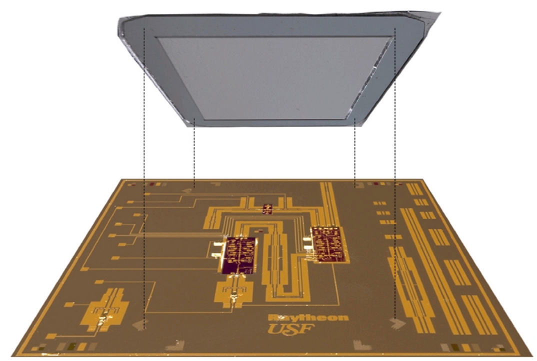

Fig. 7. Shown on top a bulk micromachined Si lid, gray color indicative of bare Si, attaches to the radiometer circuit shown below.

Atmospheric attenuation statistics for tropical clouds and rain that are characteristic of a Florida climate, would ideally require a 3-channel radiometer at 13.4GHz, 20.7 and 31.6 GHz for more accurate link assurance. Ku Band has lower absorption (emission) capable of observing brightness temperature changes in deeper fades thus 13.4 GHz was chosen. It is also a frequency that Raytheon has extensive components developed for remote sensing and this frequency extends the range over which higher emissions can be measured. The 20.7 GHz channel responds well to the broad water vapor line centered at 22.235 GHz and was chosen as the first prototype channel to investigate. In higher liquid water environments and through lower elevation angle measurements, the 20.7 GHz and 31.6 GHz channels will both approach a maximum ambient brightness temperature of approximately 300K.

In its final form, the radiometer design will provide for easy set-up, calibration, unattended operation, and data recording. The antenna with auto-positioning will be slewable in azimuth and elevation for ease in pointing alignment. A mode for occasional "tip- curve" calibration to validate the internal noise source calibration will be used for calibration standard check. Recently a Raytheon CNS using a 0.15µm InP HEMT has completed long and short term stability testing at the National Institute of Standards and Technology (NIST) over the last year. Its stability was measured and compared to other diode based noise sources from 12 to 26.5GHz. Short-term drifts in noise temperature were typically less than the uncertainty of the tests, about 0.03% per day or about 0.05% per year for hot sources. This is the first known comparative stability study of noise sources for short (intermediate) and long term stability drift data from a controlled metrology laboratory. The NIST studies indicate that this InP or MHEMT based one port device looks promising as a candidate to replace more costly methods used in the current art of radiometer calibration [8]-[9].

Calibration accuracy is critical to the performance of most radiometer sensors. The major contributing errors to radiometer system calibration arise from (1) uncertainty in the cold calibration temperature, (2) uncertainty in the warm calibration temperature, (3) performance of the radiometer transfer function including any non-linearity and drift, (4) errors in the ground retrieval algorithm, and (5) uncertainties in knowledge of the antenna characteristics. Each of these major contributors must be addressed separately and their solutions combined to establish the overall system calibration accuracy [10]. A calibration curve for this radiometer is shown in Figure 8.

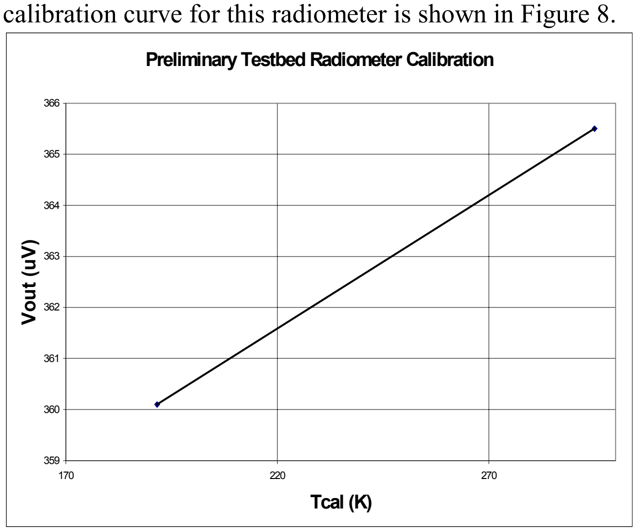

Fig. 8. Preliminary 2 point Calibration Curve of Radiometer

III. Conclusion

A demonstration of a 20.7GHz MMIC radiometer/integral planar antenna with on-board calibration in a Si micromachined conformal package has been described. Further hermeticity testing of the package, measured E and H antenna patterns and sky measurements will appear in final paper submission.

Acknowledgement

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