Design and Implementation of a Miniaturized Water Vapor Profiling Radiometer

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***Abstract*—At present, the vast majority of ground-based and airborne microwave remote sensing instrumentation is produced using waveguide-based or connectorized discrete microwave components, which are high in cost and large in volume. Recent maturation of Monolithic Microwave and Millimeter-wave Integrated Circuit (MMIC) technologies developed for the wireless communications and defense industries is expected to enable development of a new generation of radiometers. This paper describes the design of a prototype Miniaturized Water Vapor Profiler for the 3-D measurement of tropospheric water vapor using a four-sensor network, including the fabrication and initial performance evaluation of its RF and IF sections.**

I. INTRODUCTION

MICROWAVE system designers now face an exciting set of challenges due to the maturation of new technologies and advantageous system topologies. Recent developments in Monolithic Microwave and Millimeter-wave Integrated Circuit (MMIC) technology have enabled a new vision and design philosophy of wireless communication systems, millimeter-wave radars and passive sensors.

Monolithic integration results in very attractive designs, particularly for radiometers, enabling the development of new sensors with well over an order of magnitude reduction in volume, mass, and cost. In addition, it improves thermal stability, power consumption, system noise temperature and fabrication costs, particularly for large quantities. These advantages enable the efficient implementation of networks of microwave radiometers or the fabrication of a large number of these receivers for continuous imaging of the atmosphere from space using synthetic aperture radiometry.

However, the MMIC approach also has some technological hurdles to overcome. The complexity of MMIC design and fabrication requires long design iteration times. Large quantities of MMICs must be fabricated in order to reduce the per-unit cost of production. After the devices are fabricated, specialized laboratory equipment such as microwave probes, probe stations, and wire bonders are needed for circuit assembly and measurement. In addition, the utilization of MMIC technology in the deployment of microwave and millimeter-wave radiometers demands system designers with expertise in both radiometry and MMIC design. That means that the resources of current laboratories developing microwave and millimeter sensors for earth observation will require not only additional equipment but also personnel with multidisciplinary backgrounds.

At the University of Massachusetts Amherst (UMass) we are in the process of fabricating four miniaturized water vapor profiling radiometers at K-band using MMIC technology. A collaboration has been established between the Microwave Remote Sensing Laboratory (MIRSL) and the Laboratory for Millimeter Wave Devices and Applications (LAMMDA), both at UMass, to develop highly reliable and easily reproducible miniaturized water vapor profilers for the purpose of measuring the 3-D distribution of tropospheric water vapor.

II. PROJECT DESCRIPTION

Microwave radiometers have a demonstrated ability to monitor atmospheric water vapor density in a spatial volume under nearly all weather conditions. In contrast, radiosondes, which provide *in situ* profiles of atmospheric variables, are limited in temporal and spatial coverage and require significant labor to launch. Microwave radiometers are often used to calibrate and validate other methods of sensing tropospheric water vapor, such as radiosondes [1] and networks of GPS receivers that measure water vapor phase delay and employ tomography to retrieve water vapor fields [2]. The development of new techniques for measurement of 3-D water vapor and liquid water in the atmosphere is a key area of research in the atmospheric sciences [3]. Improved temporal and spatial sampling of the 3-D temperature, water vapor and wind fields and assimilation of these measurements into numerical weather prediction models are critical to weather forecasting. They provide a possible avenue for the improvement in near-term weather forecasting and an increase in lead times and spatial accuracy of severe weather warnings.

The availability and affordability of miniaturized microwave radiometers in reasonable quantities is expected to

This work was sponsored by the National Science Foundation through Award No. ATM-0239722.

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provide very significant improvement in the measurement of 3-D water vapor fields. These sensors could be deployed in networks to function in a coordinated fashion to obtain high-resolution observations over a significant geographical area. This would not be feasible with conventional waveguide based radiometers due to limitations in cost and availability.

Commercially available MMICs have reduced mass production costs and increased reliability of microwave electronics due to the recent maturation of technologies developed for the wireless communications and defense industries. Currently, commercial MMIC circuits are available that span the frequency range of operation from DC to 100 GHz [4]. That makes practicable the deployment of miniaturized microwave and millimeter-wave radiometers for both water vapor and temperature profiling, as well as for other remote sensing applications. This work is focused on the design and fabrication of a prototype miniaturized water vapor profiler measuring near the water vapor resonance at 22.235 GHz.

III. Results

It was recently demonstrated using eigenvalue analysis that four frequencies near the K-band water vapor resonance provide sufficient information for water vapor profiling up to 10 km height [5]. Other studies have yielded similar results using a variety of optimization techniques [6]. Based on this result, a Miniaturized Water Vapor profiling Radiometer (MWVR) was designed with four K-band channels (22.18, 22.73, 23.31 and 24.55 GHz) chosen at nearly optimal frequencies for a four-frequency system. Fig. 1 shows a block diagram of the MWVR prototype.

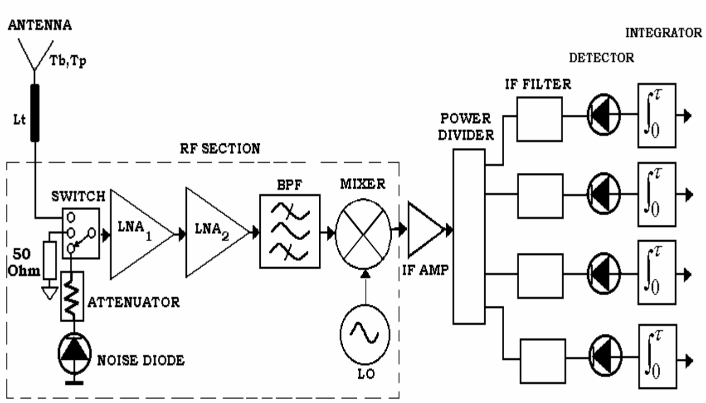


Fig. 1. Block diagram of the miniaturized water vapor profiling radiometer.

The MWVR employs a superheterodyne architecture to achieve selectivity of less than 1% in bandwidth. To achieve two-point calibration when reliable external sources may not be readily available, both hot and cold internal calibration references are implemented using a noise diode and a microwave chip termination, respectively.

For the fabrication of switching radiometers, ferrite switches are commonly used and preferred over other switch technologies due to their high reliability and low loss. Significant investment has been made in the miniaturization of ferrite switches [7]. However, they are still large compared to pin diode switches, which are compatible with MMIC designs. The RF switch in the MWVR is implemented using a pin diode switch with greater than 30 dB isolation and reasonable insertion loss.

Since the low noise amplifier is one of the most important elements determining the noise figure of the system, its selection was based on the commercially available amplifier that had the lowest noise figure. K-band amplifiers are commonly available for a wide range of applications, from military to commercial communication systems, with noise figures of 2.0 dB and relatively high gain.

Fig. 2 shows the current layout of the MMIC circuits in the RF section. Since the input port of the RF section is high frequency, it was decided to use a rectangular waveguide port that is rugged, low-loss and compatible with the 4 X 8 waveguide-based array antenna chosen for this design.

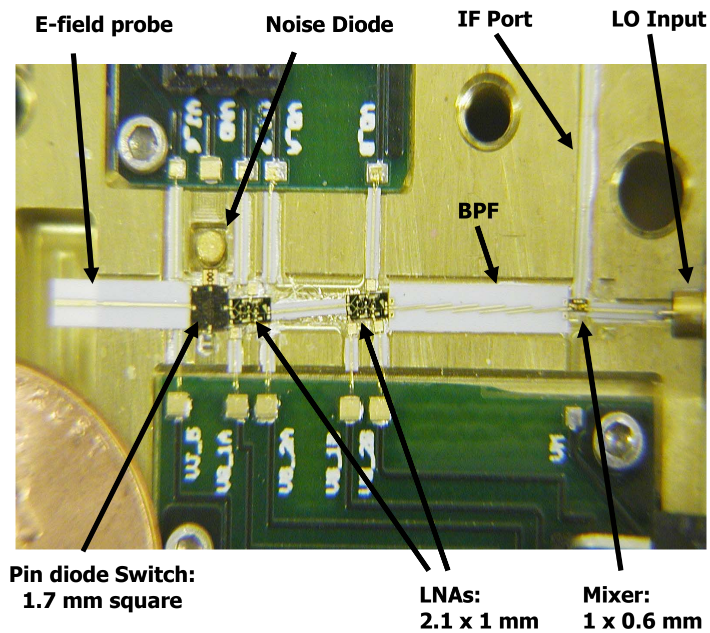


Fig. 2. RF section of MWVR.

A longitudinal E-field probe was designed and fabricated to interface the input port to the MMIC chips. This particular probe is preferable over others due to its high performance, compactness, ease of design, reliability and compatibility with MMICs [8]. Commercial pin diode switches, LNAs, mixers and noise diodes were utilized for the implementation of the RF section. These components were tested and measured individually before mounting as part of the RF section. A six-section coupled line band pass filter was designed and fabricated to provide the required frequency selectivity of the RF section. Measured results of the band pass filter showed insertion loss not greater than 1.0 dB from 20 to 25 GHz.

A specially designed gold plated housing was constructed to integrate the RF section in a single package. As shown in Fig. 2, the RF section is driven using an external local oscillator.

Gain and noise figure measurements of the RF section were performed to validate its functionality. Fig. 3 presents the gain performance measured at the IF port for different drain currents. IF frequencies f_1=2.88 GHz, f_2=3.43 GHz, f_3=4.01 GHz and f_4=5.25 GHz correspond to the four nearly optimal frequencies in the vicinity of the K-band water vapor resonance.

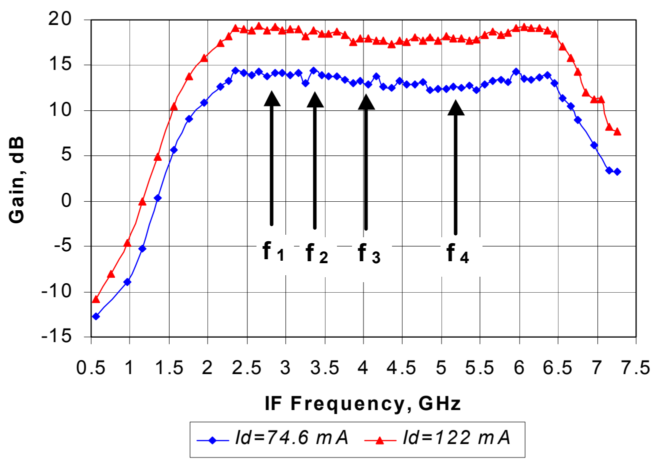


Fig. 3. Gain performance measured at IF port.

Fig. 4 presents the equivalent noise temperature of the radiometer, which was measured using the Y-factor method. As the Y-factor requires, a microwave absorber was measured at two different temperatures, 293 K (ambient temperature) and 77 K (liquid nitrogen). The LNAs were biased to provide the lowest noise temperature.

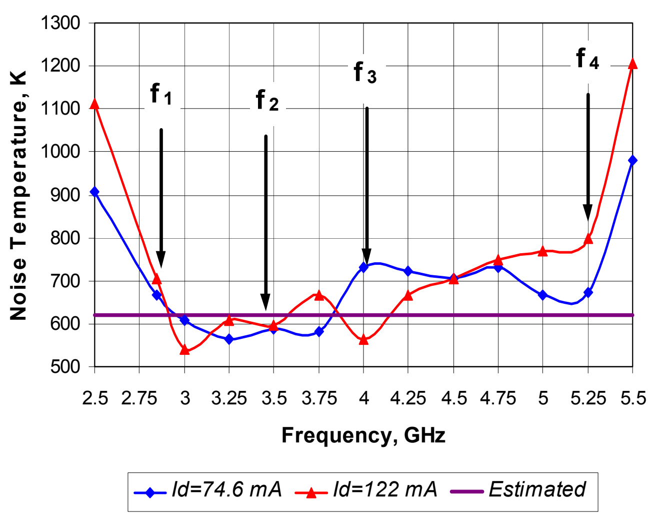


Fig. 4 Measured equivalent noise temperature of MWVR.

The measured results showed that a good tradeoff between gain and equivalent noise temperature occurs when the LNAs are driven with a drain current of 122 mA. Under this bias condition, the radiometer has a noise temperature between 550 K and 800 K over the range from the lowest to the highest frequency of interest. Below 2.75 GHz and above 5.25 GHz the noise performance of the radiometer rapidly degrades due to the limited antenna bandwidth. In Fig. 4, the calculated value of equivalent noise temperature is shown as a horizontal line for the case when the LNAs are driven at 122 mA and using measurements and manufacturers' specifications of individual components. For this particular bias condition, there is very good agreement between measured and calculated noise temperature.

MMIC technology was also used to reduce the size of the IF section. Two gold plated housings were designed and constructed in order to integrate the IF amplifiers into two packages, each measuring 1.2 cm x 2.5 cm x 0.55 cm.

Since the MWVR has the capability to support four K-band channels over 60% IF bandwidth, a broadband power divider was designed using a two-section coupled microstrip power divider [9], as shown in Fig. 5. The power divider was fabricated on a high permittivity substrate using thin film resistors in order to minimize its size.

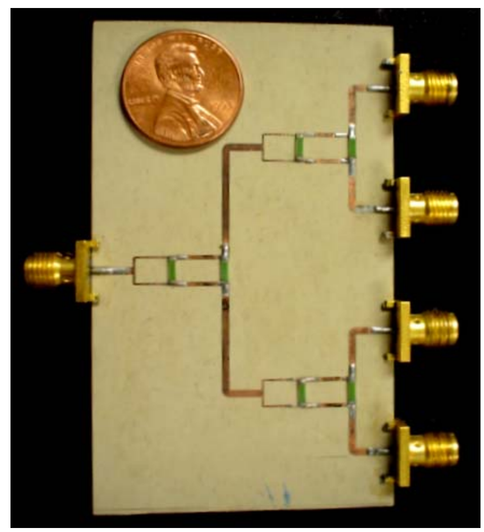
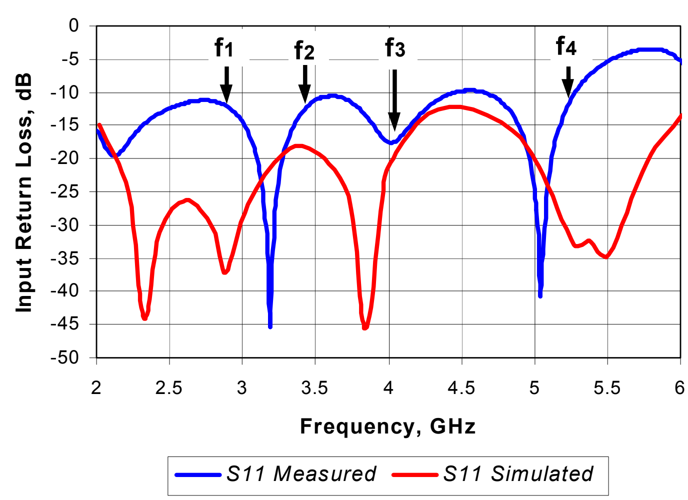
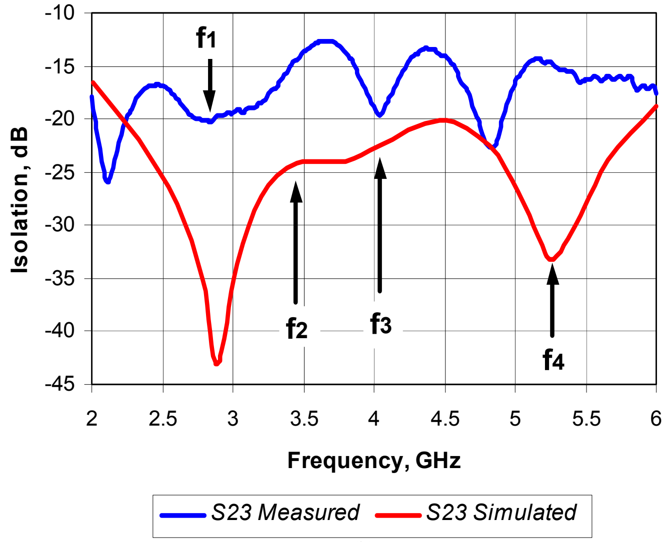


Fig. 5. Two-section coupled microstrip power divider

Fig. 6 shows a comparison of measured and simulated input return loss (a) and isolation (b) of the two-section microstrip power divider. The two-section power divider has low loss, good input matching, and high isolation between adjacent output channels over a wide bandwidth.



(a)



(b)

Fig. 6. Measured and simulated response of (a) input return loss and (b) isolation between two adjacent output ports of the two-section coupled microstrip power divider.

The sensitivity of MWVR was calculated based on the measured equivalent noise temperature of the radiometer. Fig. 7 presents the calculated radiometric resolution of the four K-band channels of MWVR. The sensitivity of each of the four channels of MWVR is less than 0.1 K for integration times greater than 1 second.

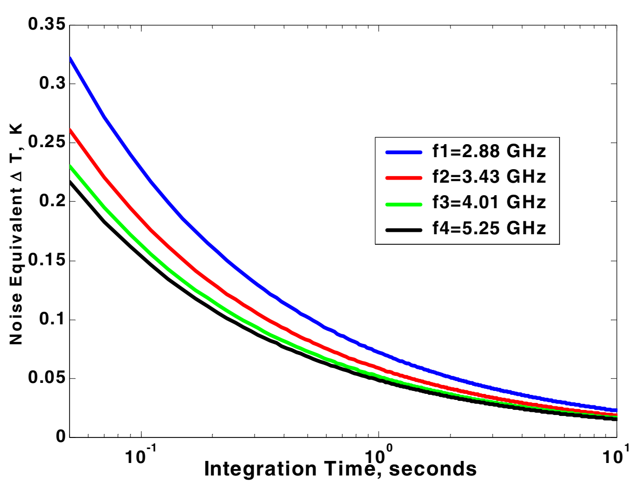


Fig. 7. Sensitivity of MWVR

Table I summarizes the most important parameters of the RF section of MWVR that have been analyzed or observed to date.

IV. Summary

A Miniaturized Water Vapor profiling Radiometer (MWVR) is being designed and fabricated at UMass, based on commercially available MMIC technology for the wireless communications and defense industries. The MWVR is designed for water vapor profiling using four frequencies near the 22.235 GHz resonance. MMIC-based radiometers tend to be more light-weight and less bulky for deployment, more easily mass produced and more reliable. Operation of the recently completed RF section, occupying less than 50 cm^3, has been demonstrated through gain and noise figure measurements. There has been extensive progress toward the miniaturization of the IF section, which is undergoing testing along with the digital subsystems.

TABLE I
Capabilities of MWVR

PARAMETERS	UNITS	SPECIFICATIONS
K-band channels	GHz	22.18, 22.73, 23.31 and 24.55
IF Frequency Range (Upper Side Band)	GHz	2.5 to 6.65
Gain Flatness	dB	+/- 1.2
LO Frequency	GHz	19.3
LO to IF Isolation	dB	36.9
Radiometer equivalent noise temperature	K	550-800
DC Power Consumption of RF and IF section	Watts	< 2.5
Size of RF section	cm^3	41.58
Mass of RF section	Kg	0.26
Waveguide Input		WR-34

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