HIGH-SENSITIVITY W-BAND MMIC RADIOMETER MODULES

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ABSTRACT

Multichip monolithic-integrated circuit modules that provide low-noise amplification, bandpass filtering, square-law detection, and DC amplification of a broadband millimeter-wave signal are described. The module is compact (4.50 cm^3) and lightweight (37 g), has low power consumption (80 - 130 mW), and is well-suited for use in focal-plane arrays to provide passive imaging of millimeter-wave thermal radiation. The theoretical gain requirement, radiometer construction, and measured results are reported.

INTRODUCTION

Radiometers are broadband receivers used to measure millimeter-wave radiation emitted by all bodies in the universe. Some of the applications of radiometers are for radio astronomy, contraband detection, space-borne earth-resource monitoring, and all-weather terrain imaging systems.

In the past, most radiometers have utilized a superheterodyne receiver with local-oscillator and IF amplifiers. However, tuned-radio-frequency (TRF) receivers are simpler and facilitate wide bandwidth, which increases sensitivity. The TRF technique has been suggested as particularly suitable for microwave monolithic-integrated circuits (MMICs) in focal plane arrays.[1] Of particular importance for focal plane array applications is the fact that the radiometer can occupy an area that is less than a 2λ square. This is the area occupied by an efficient feed for an F/D=1 lens or reflector (keeping F/D low reduces the size of the antenna system while a large F/D is needed to reduce off-axis distortion of the focal plane ; F/D=1 is a reasonable compromise).

Previous direct detection W-Band TRF radiometers, with lower sensitivity, have been reported by Dow, et al.,[2] and Lo, et al.[3]

RF GAIN AND DETECTOR NOISE REQUIREMENTS

The radiometer must have sufficient RF gain so that the noise on the DC output is due to the RF front-end noise as described by noise figure, rather than the noise arising in the detector and following DC amplifier. The noise spectral density in units of Volts/root-Hertz due to the front-end noise and referred to the output of a square-law detector is given by:

$$V_{AC} = V_{DC} \sqrt{\frac{2}{B_{RF}}} \qquad (1),$$

$$V_{DC} = \beta \, G_{RF} \, k \, (T_N + T_A) \, B_{RF} \qquad (2)$$

where V_{DC} is the detector DC output voltage, β is the detector voltage sensitivity in units of Volts/Watt, G_{RF} is the RF power gain, k= 1.38 x 10^{-23} Watts/Hertz, T_N = (F-1) 290K is the receiver noise temperature in terms of noise figure F, T_A is the measured antenna temperature in degrees Kelvin, and B_{RF} is the RF bandwidth. In terms of these quantities, the rms uncertainty ΔT of a temperature measurement with 1 Hz post-detection bandwidth is given by :

$$\frac{\Delta T}{(T_N + T_A)} = \frac{V_{AC}}{V_{DC}} = \sqrt{\frac{2}{B_{RF}}} \qquad (3)$$

The detector and following DC amplifier noise can be described by a parasitic voltage noise, V_N, which includes thermal and 1/f noise in the detector diode, as well as the DC amplifier input noise. If we assume that V_N is uncorrelated with other noise sources, and limit the decrease in radiometer sensitivity resulting from V_N to 4%, then the gain must be sufficient such that $V_N = V_{AC} / 5$ or :

$$G_{RF} = \frac{5 V_N}{\beta \, k \, (T_N + T_A) \sqrt{2 \, B_{RF}}} \qquad (4)$$

The noise voltage V_N is a function of video frequency, and the relevant video frequency is the frequency at which the comparison of the measured T_A to a reference temperature is made. For the radiometers that we have constructed, typical values of each of these quantities are $V_N = 14.1\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ @ 10 Hz, $\beta = 125$ mV/mW @ 100 GHz, $T_N + T_A = 1000\mathrm{K}$, $B_{RF} = 7$ GHz, and thus $G_{RF} = 3.45 \times 10^5$ (or ≈ 55.4 dB) is necessary to achieve the 4% limit in radiometer sensitivity degradation.

MODULE COMPONENTS AND CONSTRUCTION

A MMIC W-Band direct detection radiometer contains four basic building blocks: W-Band low noise amplifiers (LNAs), a bandpass filter to define bandwidth, a detector diode for RF to DC conversion, and a DC amplifier to increase the output voltage. A block diagram of the module is shown in Figure 1.

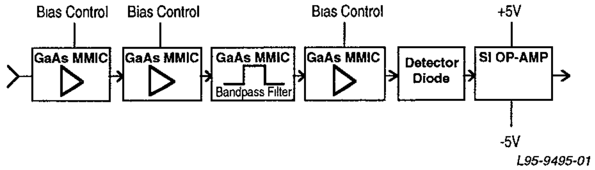

Figure 1. W-Band Radiometer Block Diagram.

W-BAND LOW NOISE AMPLIFIERS

The four-stage MMIC LNAs utilize 0.1-μm gate length by 50-μm gate periphery AlGaAs/InGaAs pHEMTs and are described in a previous paper by Tu, et al.[4] Typical chips have peak gains of > 23 dB @ 99 GHz and noise figures of < 4.5 dB @ 92 GHz.

BANDPASS FILTER

Undesired gain at frequencies where the amplifier has a high noise figure or at frequencies below the cut-off of the input waveguide can increase the effective noise figure of the radiometer. A MMIC three-pole, coupled-line, microstrip bandpass filter on 100-μm-thick GaAs was fabricated to eliminate these unwanted effects. Reasons for this choice of filter topology can be found in Herman, et al.[5] The filter was designed utilizing PARFIL CAD software, and reasonable agreement between theoretical and measured results were obtained. The bandpass filter has a center frequency of 99 GHz with an effective bandwidth of 12 GHz. The insertion loss is no greater than 2.5 dB at 99 GHz. A plot of the measured S_{11} and S_{21} magnitudes versus frequency is shown in Figure 2.

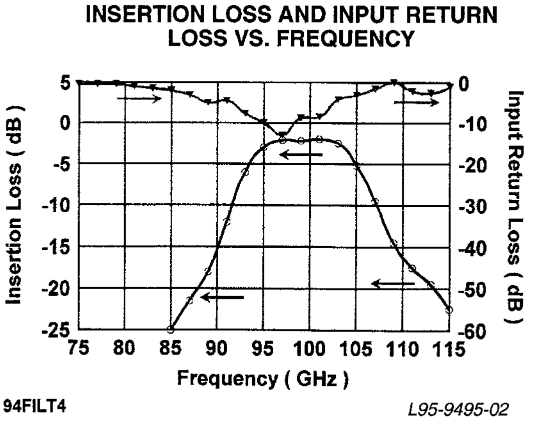

Figure 2. Insertion Loss and Input Return Loss vs. Frequency for MMIC Filter.

DETECTOR DIODE

From equation 5, it can be seen that the reduction of the ratio of V_N/β will decrease the gain requirement. We first fabricated and tested both biased HEMT diode and biased Schottky diode GaAs detector MMICs. These circuits had high measured sensitivities (β) at 100 GHz, but also high parasitic noise voltages (V_N), particularly at low video frequencies. The best result for the biased Schottky diode MMIC was a V_N/β ratio equal to 0.34 nW at 10 Hz, and 0.04 nW at 1 kHz, where V_N includes a small contribution of noise in the operational amplifier.

Further tests led to the use of a zero-bias silicon Schottky diode,[6] which had lower sensitivity but an improved V_N/β ratio of 0.11 nW at 10 Hz, and 0.08 nW at 1 kHz. It should be noted that from thermodynamic arguments, any zero-biased detector can have no noise other than the thermal noise arising from the video resistance, since there is no source of energy with low RF input power. A plot of sensitivity versus frequency for this diode is shown in Figure 3, and indicates that diode capacitance is limiting the high frequency sensitivity.

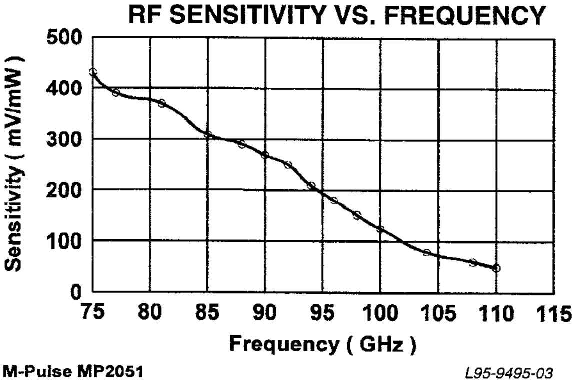

Figure 3. Sensitivity vs. Frequency for Impulse MP2051 Schottky Diode.

DC AMPLIFIER

A DC amplifier is required to amplify the detector output, which is on the order of 10 mV. The gain of the amplifier was chosen to be 180, which gives an approximate output voltage of +1 V with an input 300K antenna temperature. The operational amplifier must be chosen carefully, since the input noise can severely increase the V_N/β ratio. The operational amplifier that we selected was the AD743, which had a very low current noise (40 fA /√ Hz @ 10 Hz) and a reasonably low voltage noise (5.5 nV /√ Hz @ 10 Hz). In addition, the input bias current is very small (30 pA typical at ± 5 V), and does not appreciably bias the detector diode, or cause a DC offset.

CARRIER FABRICATION AND MODULE HOUSING

All of the RF and DC circuitry is packaged compactly onto a carrier with a total surface area of only 1.75 cm^2. The gates are biased using small multi-pad chip resistors that act as simple voltage divider networks from the drain supply voltage. A photograph of the carrier is shown in Figure 4. The carrier can then be mounted as one of many into a multi-channel array, or in a single radiometric housing as is shown in Figure 5. This module provides a WR-10 waveguide to coplanar-waveguide (CPW) transition for the MMICs as well as supplies additional filtering for the three DC inputs (+1.5V to +2.5V for the LNAs, ± 5V for the OP-AMP) and improved RF interference protection for the radiometric output signal.

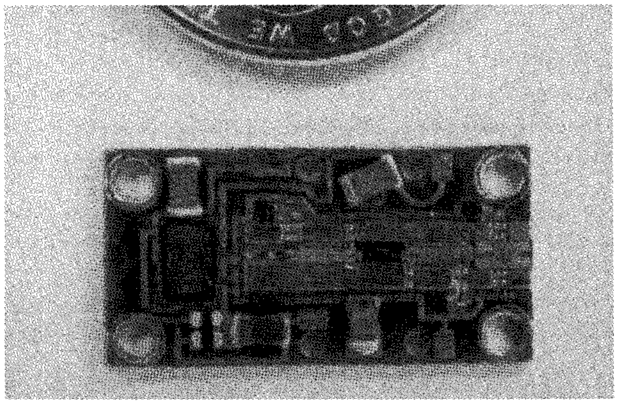

Figure 4. Photograph of W-Band Radiometric Carrier.

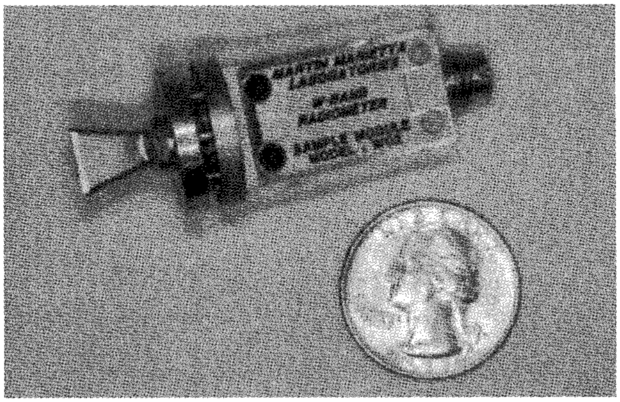

Figure 5. Photograph of W-Band Radiometric Module with WR-10 Horn Attached.

RESULTS

Before connecting the diode detector and following DC amplifier to the MMICs, the overall RF gain response was measured to ensure that the desired gain and correct bandwidth had been realized. This was accomplished utilizing GGB Industries W-Band wafer probes connected to a scalar analyzer, which was calibrated using a Cascade ISS calibration substrate for through-transmission lines. A plot of the gain frequency response is given in Figure 6 for one of our modules. The average gain for this radiometer is 56 dB with an effective bandwidth of 7 GHz centered at 100 GHz.

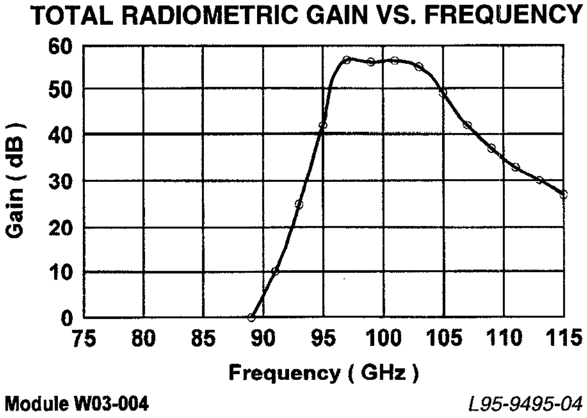

Figure 6. Overall Radiometric RF Gain for 3 LNAs and MMIC Filter.

After the carrier was installed into the radiometric housing, a WR-10 horn was mounted on the module. The RF noise figure and the video frequency noise spectra were measured to determine the rms minimum resolvable temperature uncertainty, ΔT_{meas}, for the unit. The noise figure was measured by the hot-cold load technique using 77K and 295K absorber placed in the horn beam. The best noise figure of 5.5 dB was obtained at a LNA bias of 1.85 V.

The low frequency noise spectrum was measured from 10 Hz to 1 kHz using the Hewlett Packard 3561A Dynamic Signal Analyzer. The analyzer input signal was AC coupled to remove the DC component, and a comparison was made between the conditions of LNA DC supply on and off to evaluate the contribution of V_N (LNAs off) to the total noise output. A plot of these two cases is presented in Figure 7.

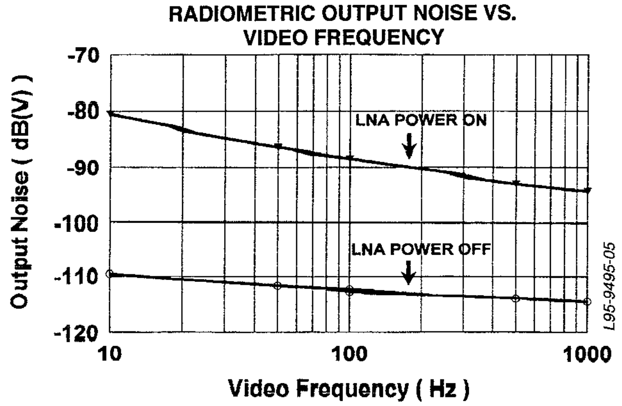

Figure 7. Low Frequency Noise (E_{AC}) of the Radiometric Output Signal.

Figure 7 shows that the noise voltage due to the detector and DC amplifier is a factor of 4 to 15 times lower than the noise due to the LNAs. The figure also shows that the radiometer output noise and ΔT_{meas} increase as video frequency decreases; values for ΔT_{meas} as well as the ratio of $\Delta T_{meas} / \Delta T_{theor}$ as a function of video frequency and for 1 Hz video bandwidth are given in Table I. We believe the increase in the ΔT_{meas} at low video frequency is due to the 1/f gain fluctuations in the transistors as has been reported by Jarosik, et al.[7] This is an important effect that can be overcome by chopping (Dicke switching) at a rate > 1 kHz at the radiometer input, or perhaps by future improvements in the transistors.

Table I

Frequency (Hz)	**ΔT_{meas} (°K)**	**$\Delta T_{meas} / \Delta T_{theor}$**
10	0.110	5.65
50	0.055	2.84
100	0.045	2.29
500	0.028	1.42
1000	0.021	1.09

ACKNOWLEDGMENTS

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