

A Wideband Monolithic Submillimeter-Wave Quasi-Optical Power Meter

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ABSTRACT- A novel monolithic power meter has been developed for submillimeter-wave applications (100GHz to 10THz). The detector is a 4x4 mm Bismuth bolometer integrated on a 1.2 μm thick dielectric membrane. This approach results in a wideband high-responsivity detector. The power meter is simple to fabricate, inexpensive, and can be easily calibrated using a low-frequency network. Quasi-optical measurements at 185GHz show that the bolometer is polarization independent, acts as a lambertian surface, and could be modelled by a simple transmission line model. The measured low-frequency responsivity for a 70 Ω bolometer, at a bias of 1V, and a video modulation of 300Hz, is around 1V/W. The NEP of the detector is around 3nWHz^{-1/2}. Potential application areas are antenna coupling efficiency measurements and absolute power measurements at submillimeter wavelengths.

INTRODUCTION

Power measurements at millimeter-wave frequencies is conventionally done using waveguide power meters. These employ a thermistor or a diode suspended in a waveguide [1]. They are calibrated at the factory, limited to a waveguide band, and become very expensive for frequencies above 100GHz. They also become inaccurate near 200GHz (+/-1dB), and are simply not available for frequencies above 300GHz. Neikirk and Rutledge [2] developed a Bismuth microbolometer for millimeter-wave and far-infrared detection. The microbolometer is very small compared to wavelength, and needs a millimeter-wave antenna to gather the incident energy. Although this detector is easily calibrated, it is not suited for absolute power measurements because one must deimbed the antenna gain and mismatch from the measurements. Indeed, this topic is an active area of antenna research by itself. Other submillimeter wave power meters include the calibrated water calorimeter [3] and the new Keiting

(acoustic based) power meter [4]. However, all these units are expensive and accurate to within +/-2dB. In fact, there is a lack of simple and accurate power meters at submillimeter-wave frequencies, and our detector is specifically intended to fill this need.

QUASI-OPTICAL POWER METER

We have developed a high-responsivity quasi-optical power meter optimized for measurements at submillimeter wavelengths (Fig.1). In contrast to a waveguide power meter which measures the total incident power, this device is "quasi-optical", and measures the power density of an incident plane wave. The bolometer is larger than a wavelength, and this allows the use of a transmission-line (T.L) equivalent circuit to determine the fraction of the incident power absorbed by the bolometer. The bolometer can be modeled by a resistive sheet with an RF impedance equal to its DC resistance [5]. The bolometer is integrated on a 1- μm thick dielectric

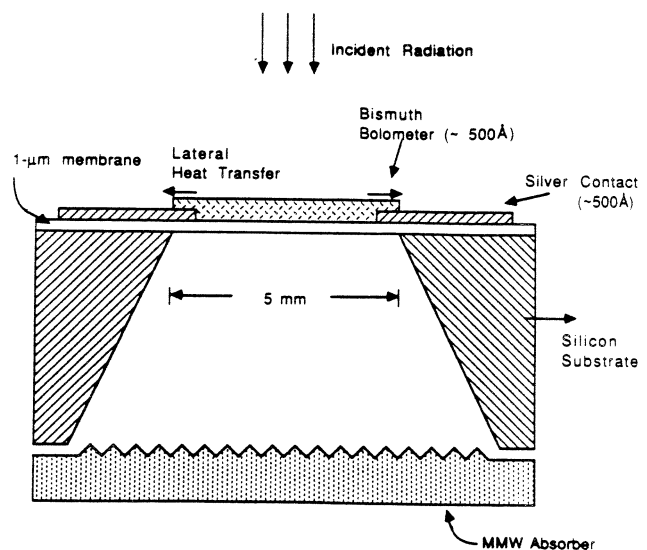


Figure 1: Quasi-optical membrane power-meter

membrane. The use of a membrane offers two important advantages: 1) It results in a low thermal conductance path between the bismuth bolometer and the supporting silicon wafer thereby yielding a high-responsivity detector, and 2) it is much thinner than a wavelength so that the bolometer is effectively suspended in free space. This yields a frequency independent transmission-line model, and results in a wideband submillimeter-wave detector. The low-frequency cutoff is given by the size of the bolometer; that is, when diffraction becomes severe and the TL model breaks down. The high frequency cutoff is given by the electronic properties of thin film bismuth, and this occurs in the far-infrared range [5]. A 4x4 mm bolometer should cover the frequency range from 100GHz to 10THz. Finally, the bolometer is a thermal detector with a slow time constant (around 100msec), and responds only to the average absorbed power. Therefore, it can be easily calibrated using a low-frequency (10MHz) network, and an absolute power-density measurement can be made at submillimeter frequencies.

FABRICATION

A 3-layer SiO₂/Si₃N₄/SiO₂ structure with respective thicknesses of 5000Å/3000Å/4000Å is deposited on both sides of a <100> silicon wafer. The first layer is grown using wet oxidation at 1100°C, and the top two layers are deposited in a high temperature chemical-vapor-deposition furnace at 700°C. The silicon-dioxide layers are in compression while the silicon-nitride layer is in tension. This combination yields a 1.2 μm thick dielectric layer in tension with a tensile stress of 2x10⁷ dynes/cm² [6]. The layer must be in tension to yield flat and rigid self-supporting membranes. These are fabricated in two steps. First, an opening is defined on the back of the wafer, then the silicon is etched until a transparent 5x5 mm membrane is exposed. The etching process is anisotropic and forms a pyramidal cavity bounded by the <111> crystal planes [7]. Next, the bolometer and contacts are defined on the top side of the wafer. The contacts are evaporated silver 500Å thick, and the bolometer is evaporated bismuth 500-700Å thick with a DC resistance of 70-100Ω. The process is monolithic and compatible with standard IC fabrication techniques.

LOW-FREQUENCY MEASUREMENTS

The frequency response and responsivity of the bolometer is measured using a low-frequency network. An amplitude modulated 10MHz signal is

applied to the bolometer. The frequency response is found by varying the modulation frequency from 50Hz to 10KHz, and measuring the bolometer response using a lock-in amplifier. The frequency response can also be found using the millimeter-wave system shown in Fig. 3. In this case, a 90.7GHz Gunn source is modulated from 80Hz to 2KHz, and the bolometer response is measured. The output signal drops as 1/f in the LF and 90.7GHz measurements (Fig. 2). In order to calibrate the bolometer at low-frequencies, the 10MHz power absorbed must be accurately measured. This is done by monitoring the instantaneous voltage across the bolometer. Several 4x4 mm bolometers with resistances between 70Ω and 95Ω were measured, and absolute responsivities between 0.6V/W and 2.0V/W were obtained, at a bias of 1V, and a modulation frequency of 300Hz. The output was also a linear function of the applied RF power at 90.7GHz, and of the bias voltage. All of the above experimental data indicate that the bolometer is behaving as a standard high-responsivity thermal detector. Finally, the noise of several 4x4 mm bolometers was measured from 20Hz till 100KHz. The noise spectrum exhibits a 1/f rolloff till 300Hz, and is limited by the Johnson noise for higher frequencies. The NEP is around 3nWHz^{-1/2} at a bias of 1V, and a video modulation of 300Hz.

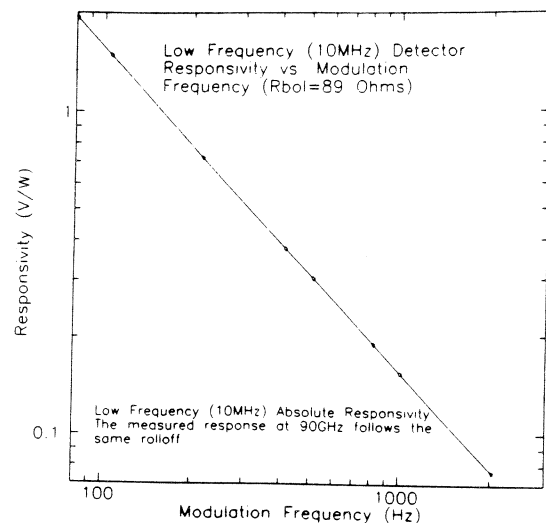


Figure 2: Measured low-frequency responsivity vs. modulation frequency. The 90GHz response has an identical rolloff.

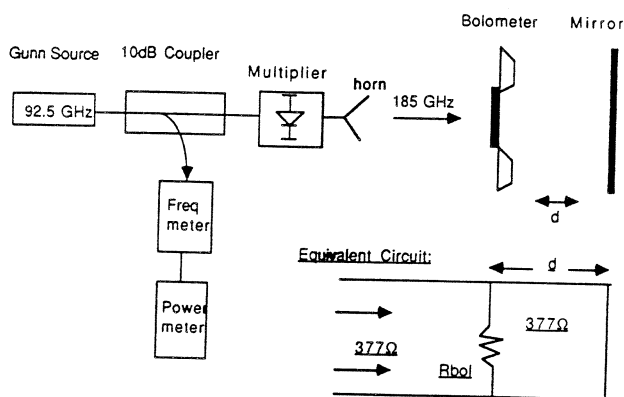


Figure 3: Millimeter-wave setup with back shorting mirror and TL equivalent circuit

SUBMILLIMETER-WAVE MEASUREMENTS

The bolometer response vs. incidence angle was measured at 185GHz. The vertical and horizontal patterns are identical, follow a cosine-law, and are independent of the polarization of the incident signal (Fig. 4). The transmission-line equivalent circuit is checked by measuring the bolometer response at 182GHz with a sliding ground plane behind the silicon substrate. The power absorbed by the bolometer is given by $(1-S_{11})^2$, where S_{11} is calculated using the TL equivalent circuit (Fig. 3) [8]. The preliminary measurements agree with the TL model, although there is a strong standing wave riding on the predicted response (Fig. 5). The measured minima occur at a half-wavelength period, and the measured frequency using the mirror data agree exactly with the waveguide frequency meter. These experiments indicate that the bolometer behaves as a quasi-optical power meter, although still not a calibrated one.

The absolute responsivity can also be found at 140GHz, by measuring the source power with an accurate waveguide power meter, and using a calibrated horn antenna. This gives a plane-wave with an absolute power density incident on the bolometer. The responsivity is then found from the measured voltage. It should be noted that in a

practical setup, the bolometer is calibrated using a LF network, and the LF responsivity is used to measure the millimeter-wave power. However, by measuring the absolute responsivity at 140GHz, one can determine the validity of the LF calibration. We are now in the process of calibrating our millimeter-wave system at 140GHz using an Anritsu power meter.

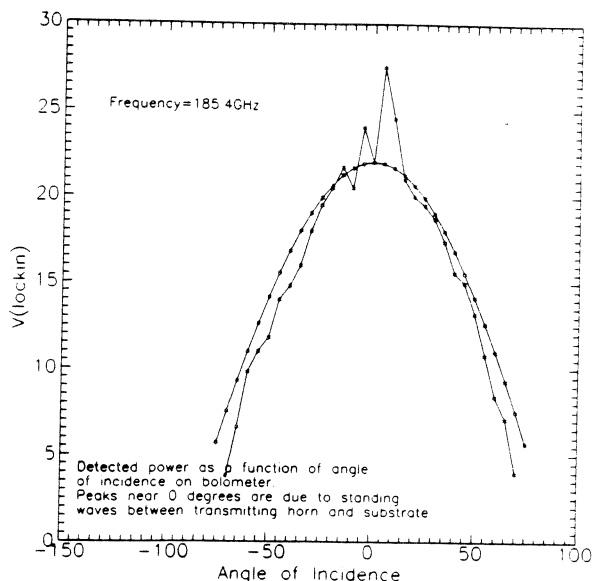


Figure 4: Measured response vs. incidence angle at 185GHz. The peaks are standing waves between the bolometer and the horn transmitter.

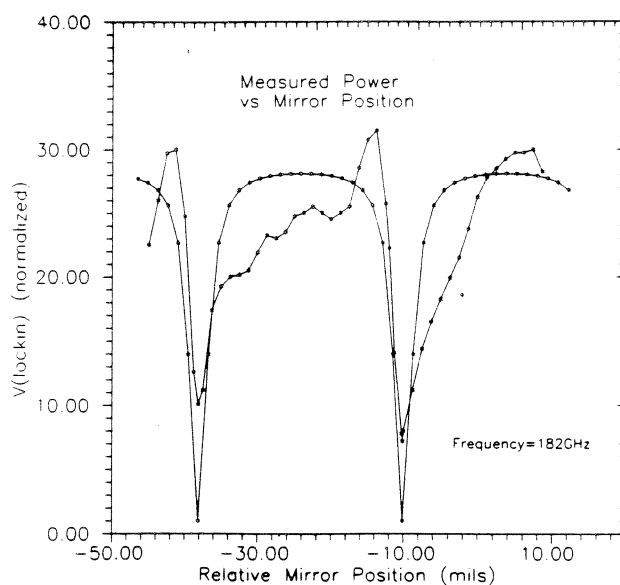


Figure 5: Measured response vs. mirror position at 182GHz. The peaks and dips are due to standing waves in the bolometer-mirror setup.

CONCLUSIONS

A wideband high responsivity quasi-optical power meter has been developed for submillimeter-wave applications. The integration of the detector on a thin 1.2 μ m dielectric membrane results in a novel wideband high responsivity detector. Preliminary experiments indicate that the detection is of thermal nature, and the large-area bolometer behaves as a quasi-optical detector. Current experiments are being done to reduce the standing waves, and to calibrate the system at 140GHz. The bolometer has been routinely used to detect power in the range of 10nW to 40nW at 200GHz. Within our knowledge, this is the least expensive and most sensitive room temperature laboratory power meter. A two-dimensional detector array is also under construction at the University of Michigan.

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