A Wide-Band Monolithic Quasi-Optical Power Meter for Millimeter- and Submillimeter-Wave Applications

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***Abstract*—A novel monolithic power meter has been developed for submillimeter-wave applications (100 GHz to 10 THz). The detector is a large-area bismuth bolometer integrated on a 1.2-μm-thick dielectric membrane. This approach results in a wide-band, 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 90, 140, and 240 GHz show that the bolometer is polarization independent and could be modeled by a simple transmission-line model. Absolute power measurements at 90, 140, and 240 GHz show a ±5% accuracy and agree well with a calibrated Anritsu power meter at 90 GHz. Potential application areas are power calibration, antenna coupling efficiency measurements, and absolute power measurements from solid-state devices and far-infrared lasers at submillimeter wavelengths. Absolute output power measurements on a 220–280 GHz tripler using the quasi-optical power meter are presented as an application example.**

I. Introduction

POWER measurements at millimeter-wave frequencies are conventionally done using waveguide power meters. These employ a thermistor or a diode suspended in a waveguide. Examples of these are the Anritsu, Hughes, and HP power meters [1]. They are calibrated at the factory, limited to a waveguide band, and become very expensive for frequencies above 100 GHz. They also become increasingly inaccurate above 200 GHz (±2 dB) and are simply not available for frequencies above 300 GHz. Neikirk and Rutledge [2] developed a bismuth microbolometer for millimeter-wave and far-infrared detection. The microbolometer is very small compared with the wavelength and requires 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 de-embed the antenna gain and mismatch from the measurements. 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 ±2 dB. 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.

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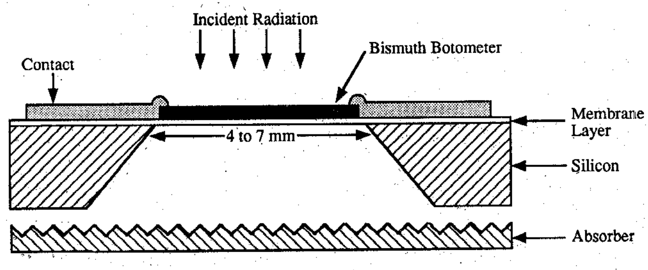

Fig. 1. A monolithic wide-band quasi-optical power meter.

II. Quasi-Optical Membrane Power Meter

We have developed a high-responsivity quasi-optical power meter well suited 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 a thermal detector with a slow time constant (around 200–500 ms) and responds only to the average absorbed power. Therefore, it can be calibrated using a low-frequency (0.5–5 MHz) network. The bolometer is larger than a wavelength, and this allows the use of a transmission-line (TL) equivalent circuit to determine the fraction of incident power absorbed by the bolometer. It is modeled by a resistive sheet with an RF impedance equal to its dc resistance [5]. The bolometer is integrated on a 1.2-μm-thick dielectric 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.
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 wide-band submillimeter-wave detector.

The membrane technology is also used to integrate high-efficiency antennas at millimeter frequencies [6], [7]. The low-frequency cutoff is given by the size of the bolometer, that is, when diffraction becomes severe and the TL and thermal equivalence models break down. The experimental results indicate that this happens when the bolometer is approximately 1.5λ long. The high-frequency cutoff is given by the electronic properties of thin-film bismuth which occur in the infrared and UV range [5]. Also, the transmission-line model indicates that a 1.2 μm membrane with a dielectric constant of 4.5 introduces a 2% error at 3 THz. However, one could easily integrate the bolometers on 3000 Å membranes, thereby pushing the 2% error frequency to 10 THz.

III. Fabrication

A three-layer $SiO_2/Si_3N_4/SiO_2$ structure with respective thicknesses of 5000, 3000, and 4000 Å is deposited on both sides of a ⟨111⟩ silicon wafer. This combination yields a 1.2-μm-thick dielectric layer in tension. The layer must be in tension to yield flat and rigid self-supporting membranes. These are fabricated in two steps. First, an opening in the silicon nitride layers is defined on the back of the wafer, and the silicon is etched until a transparent 5×5 mm^2 membrane appears. In this case, the shape of the surrounding silicon cavity is not important, and any isotropic or nonisotropic silicon etchant can be used [8]. Next, the bolometer and contacts are defined on the top side of the wafer. Bismuth is chosen as the detector material for its high resistivity and high temperature coefficient of resistance [2]. The surface resistance of the detector film should be around 100–200 Ω, and this is achieved with a 400–700 Å evaporated bismuth layer. The contacts are evaporated silver 500–1000 Å thick. One can also use NiCr or Au as bolometer materials, but the evaporated layers are only 30–50 Å thick and do not yield repeatable performance [9]. The bismuth bolometer is compatible with standard IC fabrication techniques, and it is possible to integrate it with the bias and detection electronics to result in a fully integrated circuit power meter.

IV. Low-Frequency Calibration

Thermal modeling on a mass-flow sensor–transducer with a similar geometry indicates that the temperature is nearly constant on the bolometer surface and falls off rapidly to room temperature at the membrane–silicon interface [10]. Thermal modeling can also predict the absolute responsivity of the bolometer. However, accurate electrical and thermal data for thin-film bismuth are not available, and do vary with the thickness and deposition techniques. The absolute responsivity is not needed for millimeter-wave measurements, since the millimeter-wave power is calibrated using a low-frequency network. For millimeter-wave applications, a wave incident normally on the bolometer produces a current distribution which is similar to that of the LF applied current. This produces the same temperature distribution across the bolometer. The millimeter-wave diffraction effects are not severe for dimensions comparable to a wavelength because the bolometer is a lossy resistive surface and, in contrast to metallic surfaces, does not exhibit current peaks along its edges [11]. Quantitative diffraction calculations have not yet been done to determine the minimum dimensions of the bolometer. However, millimeter-wave measurements indicate that 1.5λ square bolometers yield readings accurate to within $\pm 5\%$.

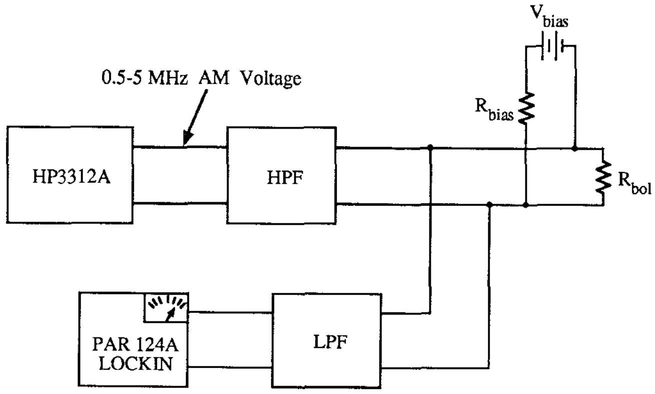

Fig. 2. The low-frequency (0.5 to 5 MHz) calibration network.

The low-frequency calibration rests on the fact that the bolometer has a slow thermal response and will detect only the average applied power. The bolometer absorbs power, heats up, and changes its resistance. There are two ways to calibrate the bolometer at low frequencies: a purely dc method or an amplitude-modulated ac current. The dc method is simple to use and has been investigated by Rutledge [12]. It consists in applying an incremental dc power to the bolometer, and measuring the change in resistance using a four-wire measurement technique and a six-digital multimeter. This technique is accurate for resistance changes of 0.05 Ω or higher, which translates into a minimum detectable absorbed power of about 0.5 mW. The AM technique consists in applying an amplitude modulated 0.5–5 MHz signal to the bolometer (Fig. 2). The bolometer is too slow to respond to the ac modulated signal, and sees it as square wave applied power at the AM modulation frequency. This is exactly the same way it functions in the millimeter- and submillimeter-wave regions for incident radiation chopped at the same modulation frequency. The input and output AM signals are filtered using passive *LC* filters, and the square wave bolometer response is detected using a lock-in amplifier. The frequency response is found by varying the modulation frequency from 1 Hz to 1 kHz.

The frequency response can also be found using a millimeter-wave system (Fig. 3). In this case, a 140 GHz source is AM modulated and the bolometer response is measured. The output signal drops as $1/f$ in the LF and 140 GHz measurements, indicating a single pole thermal response (Fig. 4). The output is also a linear function of the applied LF and RF power and of the bias voltage. The AM technique is more complicated and requires expensive equipment, but eliminates dc drift problems associated with convection and infrared radiation and

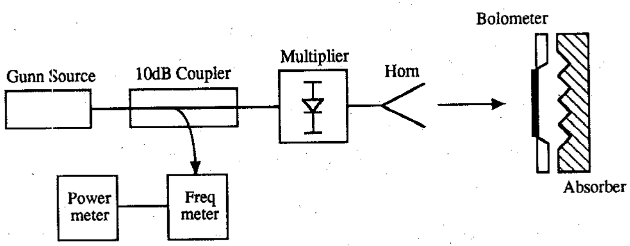

Fig. 3. The millimeter-wave quasi-optical measurement setup.

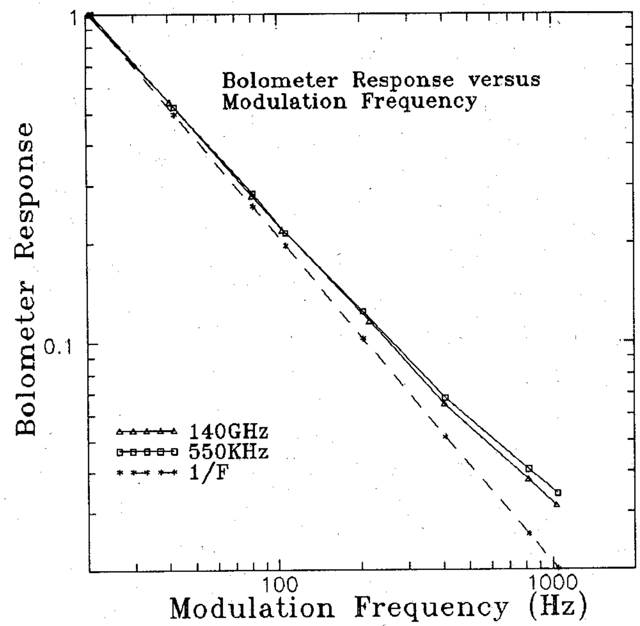

Fig. 4. The bolometer response versus modulation frequency. The output drops as $1/f$, indicating a single-pole thermal response.

allows the measurement of very low level voltages. Using this technique, a 100 nW absorbed power can be easily detected with a 3 s integration time, and this agrees well with the measured NEP of approximatively 50 nW/$\sqrt{\text{Hz}}$ for a 100 Ω bolometer at a 10 mA bias current and an AM modulation frequency of 300 Hz.

V. Millimeter-Wave Measurements

The bolometer quasi-optical response was measured at 90, 140, and 240 GHz on 7×7 mm^2 and 4×4 mm^2 bolometers. The bolometer was sandwiched between thick (1 in.) Styrofoam layers to eliminate the very low frequency drift caused by air convection and infrared radiation. Also, an absorber was used behind the bolometer to minimize reflections. We found that a badly designed or misaligned absorber can affect the measurement by as much as ±25%. The Styrofoam layers had a minimal effect on the measurements because the low-frequency drifts were eliminated by the lock-in amplifier. The bolometer is polarization independent for normal incidence (Fig. 5). The transmission-line model is used to calculate the bolometer response as a function of angle of incidence [13]. For a bolometer with a normalized sheet resistance r with respect to the free-space impedance of

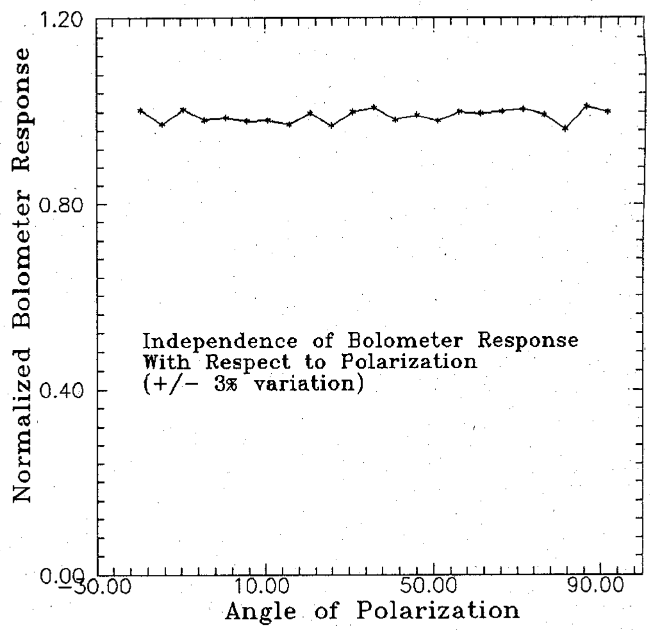

Fig. 5. The bolometer response at 140 GHz for normal incidence and varying polarization.

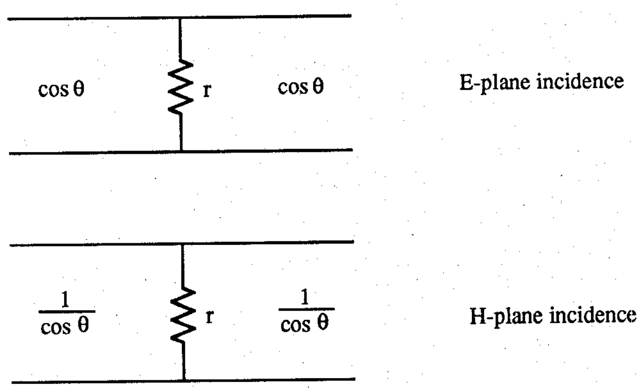

Fig. 6. The transmission-line equivalent circuit for E- and H-plane incidence.

377 Ω, the load impedance is given by (Fig. 6)

$$z_{\text{load}} = \frac{r\cos\theta}{r+\cos\theta} \qquad \text{for } E\text{-plane incidence} \tag{1}$$

$$z_{\text{load}} = \frac{r}{r\cos\theta+1} \qquad \text{for } H\text{-plane incidence.} \tag{2}$$

The power absorbed by the bolometer is therefore

$$P_{\text{abs}} = \cos\theta(1-\rho^2)\frac{z_{\text{load}}}{r} \tag{3}$$

where $\cos\theta$ accounts for the reduction in the effective area of the bolometer, and ρ is the reflection coefficient of the load. The absorption peaks at 50% for a sheet resistance of 189 Ω (half of the free-space impedance). For this case, the pattern is independent of the polarization and is given by

$$P_{\text{abs}} = \frac{2\cos^2\theta}{(1+\cos\theta)^2}. \tag{4}$$

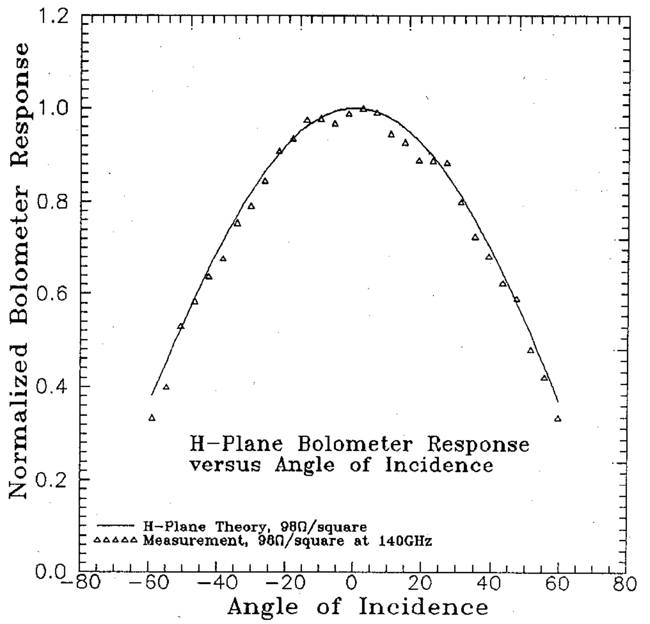

Fig. 7. *H*-plane pattern at 140 GHz for a 7×7 mm² bolometer with a sheet resistance of 98 Ω.

The 140 GHz *H*-plane scan for a 7×7 mm² bolometer with a surface resistance of 98 Ω is presented in Fig. 7. The theoretical and experimental results differ for incidence angles greater than 70° owing to the small size of the bolometer. At these angles, the projected length is less than 1.5λ, and the TL model breaks down. The transmission-line equivalent circuit is also checked by measuring the bolometer response at 140 and 240 GHz with a sliding ground plane behind the silicon substrate (Fig. 8). The theoretical power absorbed by the bolometer is given by $(1 - S_{11}^2)$, where S_{11} is calculated using the TL equivalent circuit. A small loss was assumed in the TL model to account for the plane-wave diffraction between the bolometer and the ground plane. The measured minima occur at a half-wavelength period, and the measured frequency using the mirror data agrees exactly with the waveguide frequency meter.

Absolute power measurements were done on four independent 7×7 mm² bolometers at 90, 140, and 240 GHz. The millimeter-wave plane wave was generated by waveguide Gunn diode sources feeding doublers or triplers, when necessary, and a standard gain horn. The millimeter-wave sources were amplitude modulated at 100 Hz. The bolometers were placed well into the far field of the transmitting horn. The power measurements were done by the method of substitution; that is, first the bolometer output resulting from the millimeter-wave radiation was recorded. The millimeter-wave signal was then removed, and a low-frequency amplitude-modulated signal was applied until the same output voltage is achieved. It is not necessary to de-embed the filters or the lock-in amplifier responses, since the millimeter-wave power absorbed is determined from the amplitude of the modulated ac current across the bolometer. The absolute plane wave power density is then calculated from the surface area of the bolometer and the TL equivalent model. The results,

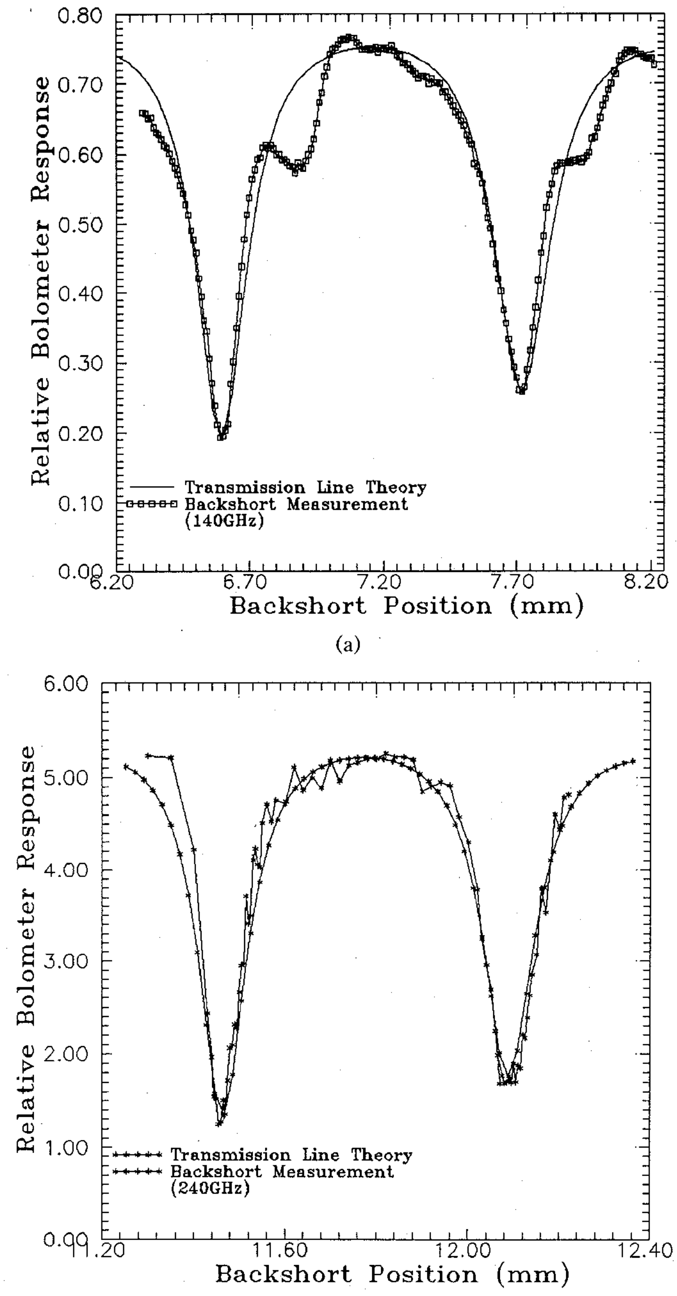

Fig. 8. Relative absorbed power versus mirror position for a 4×4 mm² bolometer at (a) 140 GHz and (b) 240 GHz. The resonance at 140 GHz is due to interactions between the cavity and the mirror.

summarized in Table I, indicate that an accuracy of ±5% is achievable over a wide frequency range. This accuracy includes the alignment of bolometers to the incident plane wave, the placement of the back absorber, the voltage readings on the lock-in amplifier and across the bolometers, and connector repeatability.

The results were also compared with a calibrated waveguide power meter at 90 GHz. In this case, a standard gain horn and an Anritsu power meter were placed at the same position as the bolometer. The receiving horn gain was independently calibrated to ±2% using standard-gain horn tables [14], two-dimensional pattern measurements for directivity calculations, and the Friis transmission for-

TABLE I
ABSOLUTE MEASURED POWER DENSITY OF AN INCIDENT PLANE WAVE USING FOUR INDEPENDENT BOLOMETERS AT 90, 140, AND 240 GHz

Power Density, $\mu W/cm^2$ (7×7 mm Bolometers)				
Bolometer R(Ω) Bias(V)	90 GHz	Anritsu 90 GHz	140 GHz	240 GHz
98 Ω 0.772 V	14.5	15.3	25.3	10.6
98 Ω 0.774 V	14.7	15.3	23.2	10.4
98 Ω 0.776 V	15.5	15.3	24.1	10.6
102 Ω 0.792 V	15.3	15.3	24.5	10.6

The results at 90 GHz agree well with the Anritsu power meter measurement.

TABLE II
MEASURED OUTPUT POWER OF A MILLITECH MUT-03 TRIPLER

Tripler Output	Bolometer 1 98 Ω 0.772 V	Bolometer 2 102 Ω 0.792 V
222 GHz	0.70 mW	0.76 mW
240 GHz	1.7 mW	1.9 mW
249 GHz	1.5 mW	1.5 mW
270 GHz	2.0 mW	2.2 mW
279 GHz	1.5 mW	1.7 mW

The bolometers presented here are those with the largest measurement discrepancy over the 220–280 GHz region.

mula using two identical horns [15]. The power density was then calculated from the calibrated antenna gain and the Anritsu power meter reading.

VI. ABSOLUTE OUTPUT POWER OF A MILLIMETER-WAVE TRIPLER

An important application area is the measurement of the absolute output power of triplers above 180 GHz. This provides an experimental verification of nonlinear analysis programs, Schottky diode parameters, and the effects of the parasitic capacitance and series resistance on the performance of the device. The output power of a 220–280 GHz tripler (Millitech, MUT-03) was measured using a calibrated standard-gain horn (WR-03) and a quasi-optical power meter placed in the far field of the tripler–horn combination. In each case, the bias, the input power at the fundamental frequency, and the input and output tuning screws were optimized for maximum output power. Table II shows the results of two specific bolometers which yielded the widest discrepancy across 220–280 GHz. The output power readings are still within $\pm5\%$ over the entire frequency band. Other application areas of the power meter include efficiency measurements of doublers and triplers at submillimeter-wave frequencies, antenna-gain and coupling-efficiency measurements, and the determination of the total output power from terahertz solid-state sources and far-infrared lasers.

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