LARGE AREA BOLOMETERS FOR MILLIMETER-WAVE POWER CALIBRATION

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Abstract- An accurate monolithic power meter has been de-
veloped for millimeter-wave applications. The detector is a
large-area Bismuth bolometer, integrated on a fused-Quartz
substrate. It simply measures the temperature change caused
by the absorption of millimeter-wave radiation. The power
meter is simple to fabricate, inexpensive, and can be easily
calibrated using a low-frequency network. The measured re-
sponsivity for a 50Ω bolometer, with an area of 1x1cm, at a
bias of 1V. and a video modulation of 100Hz, is 1mV/W. The
noise spectrum exhibits a 1/f rolloff till 1KHz, and is limited
by the Johnson noise for higher frequencies. The NEP of the
detector is $3\mu W Hz^{-1/2}$ at a video modulation of 1KHz. It is possi-
ble to decrease the current NEP by fabricating bolometers
with higher responsivities. Possible application areas are ab-
solute power calibration and localized power density mea-
surements at millimeter and submillimeter wavelengths.

INTRODUCTION

Power measurements at millimeter-wave frequencies is con-
ventionally done using waveguide power meters. These em-
ploy a thermistor or a diode suspended in a waveguide, and be-
come very expensive at millimeter-wave frequencies. Also,
they are inaccurate for frequencies around 200GHz, and sim-
ply not available for frequencies higher than 300GHz. Neikirk
and Rutledge [1] developed a Bismuth microbolometer for mil-
limeter-wave and far-infrared detection. The microbolometer
is very small compared to wavelength, and needs a millimeter-

wave antenna to gather the incident energy. This detector is
not suited for absolute power measurements, because one must
deimbed the antenna gain and mismatch from the results.
Bloch and Gaddy [2] integrated a 0.75mm square Bismuth
bolometer for infrared-radiation detection. The measured re-
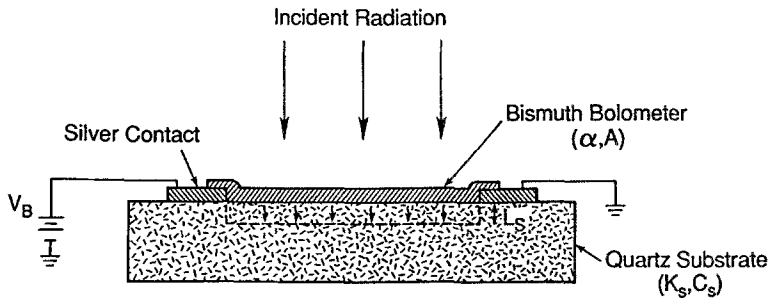sponsivities were low because the bolometer was optimized for
high-speed operation.

Figure 1. A monolithic large-area Bismuth bolometer.

We have developed a large-area bolometer optimized for abso-
lute millimeter-wave power measurements (Fig.1). The
bolometer is much thinner than a wavelength, and therefore
presents a millimeter-wave surface impedance equal to its DC
resistance per unit square. This fact, in conjunction with the
bolometer large size compared to a wavelength, allows the use
of a transmission line equivalent circuit to determine accu-
rately the mismatch between a bolometer and an incident
plane wave (Fig. 2). The mismatch gives the fraction of the
incident power absorbed by the bolometer. If the bolometer
responsivity is known using, for example, a LF calibration
network, an accurate power-density measurement is then
made at millimeter wavelengths. Since the bolometer is a
thermal detector, it works well throughout the millimeter and
submillimeter-wave regions. One only needs to change the
transmission-line model to account for the frequency change.

THERMAL MODEL

The bolometer is a heat sensitive device, and will respond to
the average power of an amplitude modulated signal. The
bolometer heats up and cools down at the modulation fre-
quency. This generates a heat wave that propagates a distance
L_S (thermal diffusion length) into the substrate. The bolome-
ter dimensions are much larger than L_S, and a one dimen-
sional heat flow model is assumed in the analysis. Neglecting

the thermal conductance of air and the silver contacts, L_S is given by [3]

$$L_S = \sqrt{K_S/(2\pi f C_S)}$$

where K_S and C_S are the thermal conductivity and capacity of the substrate, respectively, and f is the modulation frequency. The thermal diffusion length is very short in a fused-Quartz substrate, being less than $100\mu m$ for a modulation frequency of 10Hz. This means that, for all practical purposes, the heat wave never reaches the back of the substrate. The bolometer responsivity is the given by [3]

$$Resp = \alpha \, V_b \, L_S \, / \, (AK_S)$$

where α is the temperature coefficient of resistivity of Bismuth, A is the area of the bolometer, and V_b is the bias voltage. For a fused-Quartz substrate with $K_S=1.6\,Wm^{-1}K^{-1}$ and $C_S=2.36 \times 10^6 Jm^{-3}K^{-1}$, and with $\alpha=0.003K^{-1}$ for a 1000Å Bismuth layer, the theoretical responsivity for a bolometer with the same specifications given above, is equal to 0.65mV/W.
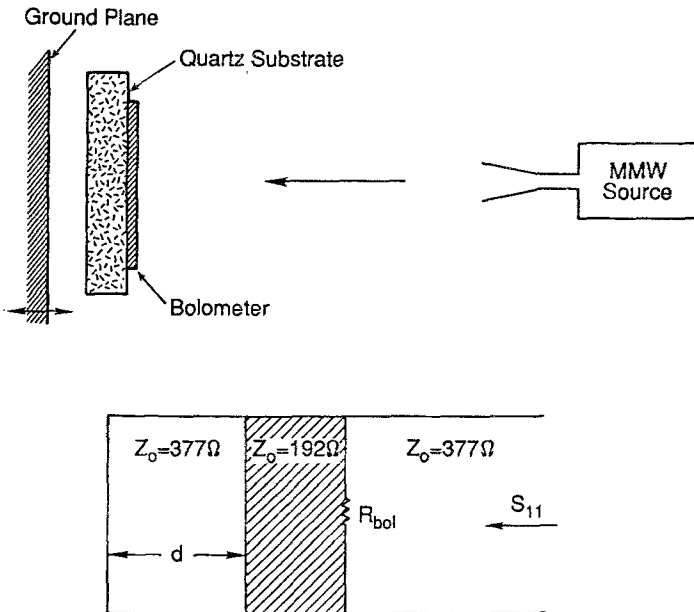

Figure 2. Millimeter-wave measurement setup, and the corresponding transmission-line equivalent circuit.

MEASUREMENTS

The large-area bolometers are fabricated on 600µm thick fused-Quartz substrate using standard photolithography and liftoff. The silver contacts are 1000Å thick, and the bolometer is evaporated bismuth 1000Å-1500Å thick. The dc resistances were between 35Ω and 75Ω. The frequency response and responsivity of the bolometer is measured using a low-frequency network. An amplitude modulated 4.3MHz signal is applied to the bolometer. The frequency response is found by varying the modulation frequency from 5Hz 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. 2. In this case, an 80.7GHz Gunn source is modulated from 10Hz to 1KHz, and the bolometer response is measured.   The output signal drops as $f^{-1/2}$ in the LF and 80.7GHz set-ups, which is in agreement with the theoretical model. The output was also a linear function of the applied RF power at 80.7GHz, and of the bias voltage.

The transmission-line equivalent circuit is checked by measuring the bolometer response at 93GHz with a sliding ground plane behind the Quartz 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. 2). The measurements agree well with the TL model, being always within 10% of the predicted results (Fig. 3). The discrepancies arise from standing waves between the bolometer and the source. The peaks in the measured data were higher and sharper, and were tamed by placing absorber around the bolometer.

In order to calibrate the bolometer at low-frequencies, the RF power absorbed must be accurately measured. This is done by monitoring the instantaneous voltage across the bolometer. Several 1x1cm bolometers with resistances between 25Ω and 75Ω were measured, and absolute responsivities between 0.75mV/W and 1.0mV/W were obtained, at a bias of 1V. and a modulation frequency of 100Hz. The discrepancy with the theoretical model arise from uncertainties in the values of α and K_S.

The absolute responsivity can also be found at 93GHz, by measuring the source power with an accurate waveguide power meter, and using a calibrated transmitting horn antenna. This gives a plane-wave with a known 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 93GHz, one can determine the validity of the measured LF calibration. The absolute responsivities measured with a 93GHz system (and an 80.7GHz system) were within 10% of the LF responsivities. We attribute the discrepancies to uncertainties in our waveguide power meter, and to standing waves in the system. However, it is clear that the LF calibration gives accurate power measurements at millimeter and submillimeter wavelengths.
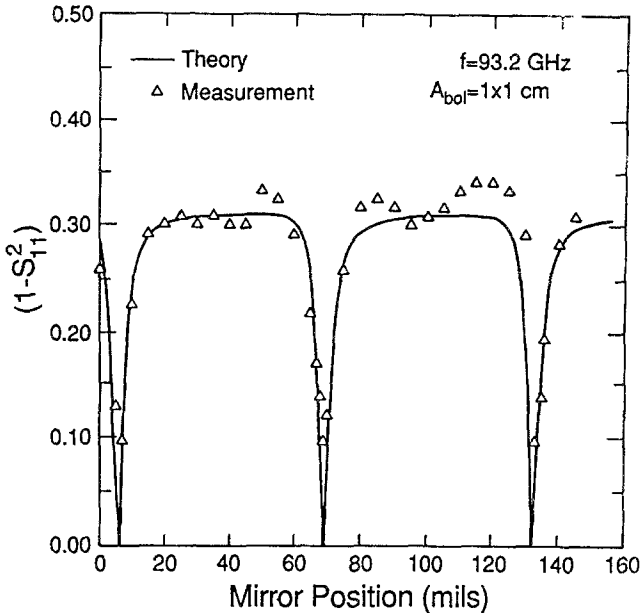

Figure 3. The computed and measured power absorbed by the bolometer vs. mirror position.

Finally, the noise of several 1x1cm bolometers was measured from 20Hz till 100KHz. The bolometer was not placed in a shielded box, but rather in a box with one side open to air. This resulted in some noise pick-up at low frequencies. The noise spectrum exhibits a 1/f rolloff till 1KHz, and is limited by the Johnson noise for higher frequencies (Fig. 4). For a bias voltage greater than 2V., the bolometer heats up and the noise rises. The NEP is $3\mu W Hz^{-1/2}$ at a video modulation of 1KHz.
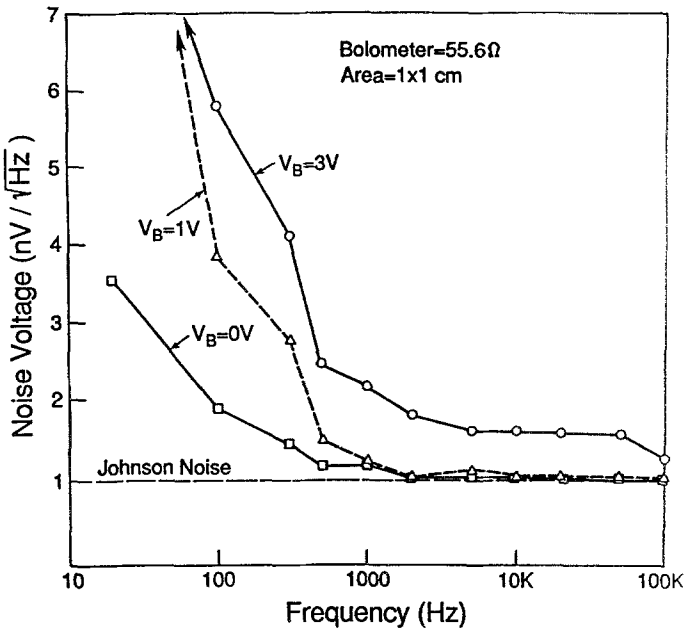
Figure 4. The measured noise-voltage of a large-area bolometer at different bias voltages.

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