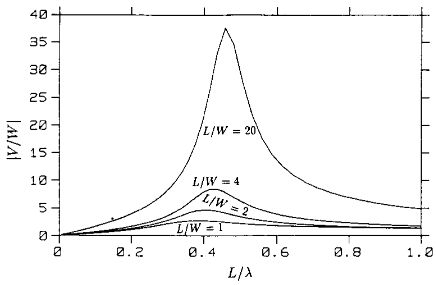

Fig. 3. Plots of the magnitude of V/W versus L/λ for various ratios of aperture length L to width W. The incident electric field is $-\hat{y}$.

where Y_{ij}^{wg} is given by [5, eq. (4)]. The A's and Y's in [5, eq. (4)] are evaluated in [5].

For the dominant TE_{10} waveguide mode normalized so that the root mean square value of its electric field over the waveguide cross section would be unity if there were no reflection from the aperture,

$$\mathbf{H}_t^{imp} = \hat{x}2\sqrt{2}\,Y_{10}^{TE} \sin \frac{\pi(x - x_1)}{a} \quad (22)$$

where Y_{10}^{TE} is the characteristic admittance of the TE_{10} mode. Substitution of (2) and (22) into (8) leads to

$$I^{imp} = \frac{4\sqrt{2}\,Y_{10}^{TE} a^2 L}{\pi(a^2 - L^2)} \sin\left(\pi\left(\frac{L - 2x_1}{2a}\right)\right) \cos\frac{\pi L}{2a}. \quad (23)$$

If $L = a$, then (23) should be replaced by

$$I^{imp} = \sqrt{2}\,Y_{10}^{TE} L \cos\frac{\pi x_1}{a}. \quad (24)$$

With Y^{hs}, Y^{wg}, and I^{imp} given by (15), (21), and (24), we used (20) to calculate

$$\begin{aligned} V/W &= 3.60\angle -52^\circ, \quad a = L = \lambda, \quad \frac{a}{b} = 2, \\ W &= b/5, \quad (x_1, y_1) = \left(0, -\frac{2b}{5}\right) \\ V/W &= 1.54\angle -11.89^\circ, \quad a = L = 0.6\lambda, \quad \frac{a}{b} = 2.25, \\ W &= b, \quad (x_1, y_1) = (0,0) \\ V/W &= 1.50\angle -13.09^\circ, \quad a = L = 0.8\lambda, \quad \frac{a}{b} = 2.25, \\ W &= b, \quad (x_1, y_1) = (0,0) \\ V/W &= 1.26\angle -1.06^\circ, \quad a = L = 0.6\lambda, \quad \frac{a}{b} = 1, \\ W &= b, \quad (x_1, y_1) = (0,0) \\ V/W &= 1.50\angle -13.09^\circ, \quad a = L = 0.8\lambda, \quad \frac{a}{b} = 1, \\ W &= b, \quad (x_1, y_1) = (0,0). \end{aligned} \quad (25)$$

The above V agree well with those in [5, figs. 2a, 3a, 3b, 5a, and 5b]. Reference [5] is available from J. R. Mautz.

VI. Conclusion

The equivalent magnetic current in a rectangular aperture not more than one wavelength long in a conducting plane between two half-spaces or between a rectangular waveguide and a half-space can be accurately approximated by $V\mathbf{M}_0$ where V is a complex constant and $\mathbf{M}_0$ is the sinusoidal vector expansion function (2). Equation (5) determines V. According to (5), V depends only on the aperture admittances Y^- and Y^+ and I^{imp}. Computation of Y^-, Y^+, and I^{imp} is not difficult because Y^- depends only on the characteristics of the region on the $z < 0$ side of the aperture, Y^+ depends only on the characteristics of the region on the $z > 0$ side of the aperture, and I^{imp} depends only on the short-circuit magnetic field that excites the aperture.

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Thin-Film Power-Density Meter for Millimeter Wavelengths

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Abstract—**A quasi-optical power-density meter for millimeter and submillimeter wavelengths has been developed. The device is a 2-cm square thin-film bismuth bolometer deposited on a mylar membrane. The resistance respositivity is 150Ω/W and the time constant is one minute. The meter is calibrated at DC. The bolometer is much thinner than a wavelength and thus can be modeled as a lumped resistance in a transmission-line equivalent circuit. The absorption coefficient is 0.5 for 189 Ω/square film. As an application, the power-density meter has been used to measure absolute power densities for millimeter-wave antenna efficiency measurements. We have measured absolute power densities of 0.5 mW/cm² to an estimated accuracy of 5%.**

I. Introduction

In measuring millimeter-wave antenna efficiencies, knowing the absolute power density at the receiving antenna is essential. Relative power-density measurements at millimeter and submillimeter wavelengths are readily performed using commercial detectors. These

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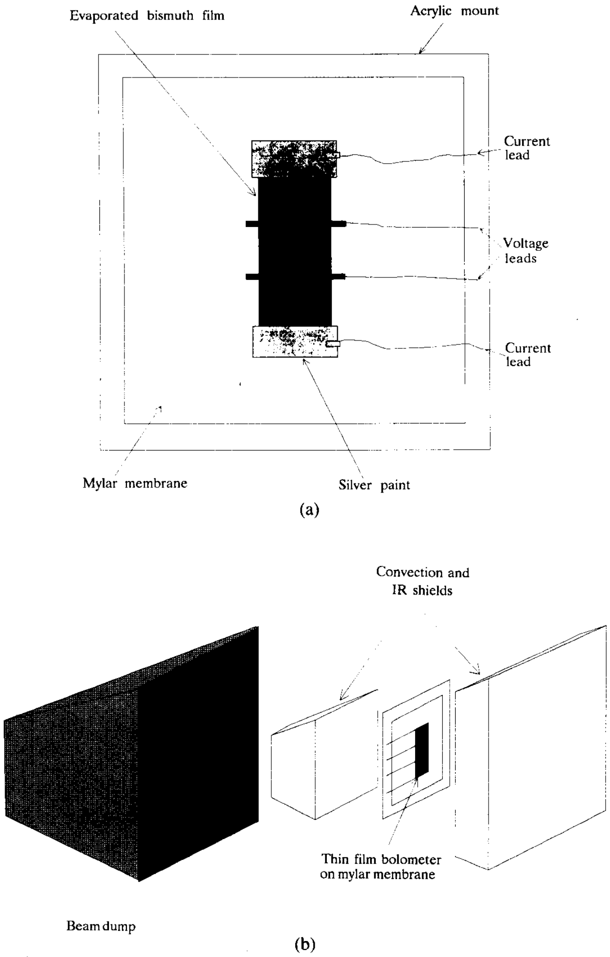

Fig. 1. (a) Thin-film bolometer on a membrane. (b) Power-density meter with bolometer embedded in styrofoam.

consist of two principal types: quasi-optical power meters in which the radiation is incident on an absorbing element in free space [1], and waveguide power meters in which the radiation is coupled by a horn to fundamental-mode waveguide and absorbed by an element in the guide. However, absolute power-density measurements are more difficult. With the quasi-optical power meters the uncertainty comes about from not knowing accurately the absorption coefficient of the detector element. This problem also exists in the waveguide power meters. Other problems with waveguide power-meter measurements are the repeatability of connections, calibration of directional couplers, and the uncertainty in standard-gains horns.

Recently, there has been interest in millimeter-wave power-density meters whose absorption coefficient is accurately known and whose response can be calibrated at low frequencies. In one approach, developed by Derek Martin, radiation is absorbed in a metallic thin film suspended in a gas cell, and a microphone detects the resulting pressure change [2]. An accuracy of 10% is quoted. Another approach consists of a thin-film bolometer on a silicon-oxynitride membrane whose responsivity is calibrated with an amplitude-modulated ac current. The resistance change resulting from the incident chopped millimeter-wave signal is measured with a lock-in amplifier [3].

Our meter is a simple design consisting of an evaporated bismuth film on a mylar membrane (Fig. 1(a)). There are no vacuum windows and the device is easy to fabricate. Calibration is performed with dc measurements only. This means that no chopping factors or frequency roll-off corrections are required. The device is polarization independent and the reception patterns are smooth, with no spikes at normal incidence. A primary application for this device is absolute power calibration for antenna efficiency measurements.

II. Description and Fabrication

A bolometer is a thermal detector whose resistance change is proportional to its thermal impedance. The resistance responsivity in Ω / W is given by

$$\mathscr{R}_{\Omega} = a\alpha R_e R_t \tag{1}$$

where a is the millimeter-wave absorptance, α is the temperature coefficient of the bolometer material, R_e is the electrical resistance, and R_t is the thermal resistance. We have constructed our bolometer on a 5-μm mylar membrane in order to increase the thermal resistance of the device. The bolometer is surrounded by 5-cm styrofoam blocks to reduce convection heat loss to the air and to block infrared radiation. The bolometer has a time constant of 1 min, which appears to be determined by thermal diffusion through the styrofoam. The attenuation at 93 GHz in the styrofoam was measured to be less than 0.01 dB/cm so that its effect on our measurements is negligible. By placing the structure in an absorbing beam dump, reflections and other unwanted signals are minimized (Fig. 1(b)).

The bismuth film was evaporated through a metal mask onto the mylar until the dc sheet resistance was 189 Ω. The thickness was about 500 Å. This sheet resistance gives the maximum absorptance by a thin film, 0.5, and is insensitive to small changes in the resistance and the angle of incidence. In addition, the absorptance is independent of polarization and frequency. We have chosen bismuth as the bolometer material because of its high temperature coefficient, measured to be 0.0026 K^{-1}. The geometry of the device allows for a four-point measurement which eliminates the effect of resistance in the contacts because the biasing leads are separate from the voltage sensing leads. The bolometer is square and much thinner than the skin depth in bismuth at millimeter and submillimeter wavelengths (5 μm at 93 GHz), so the RF sheet resistance is the same as the dc resistance.

III. Calibration and Measurement

The power density is determined from the resistance change due to millimeter-wave power. Fig. 2 shows a typical measurement sequence. All voltage and current measurements are made with a Hewlett-Packard $6\frac{1}{2}$-digit multimeter. We need to wait at least 5 min before making a resistance measurement to allow for the long time constant of the bolometer. We multiply the resistance change by the responsivity to get the power density. The meter is calibrated by a similar measurement sequence with a known amount of dc power, and then making a correction for the absorptivity to get the millimeter-wave responsivity. There is a resistance drift, which is typically 0.1 Ω/hour. We correct for the drift by taking the average of two readings at different times.

IV. Systematic Checks

To obtain accurate absolute power measurements from the meter, edge effects and the effects of the biasing contacts and the voltage sensing leads should be negligible. To check for these effects, several bolometers of different sizes were constructed. The measurements from the different bolometers agreed to within ±2%. The results are shown in Table I. The bolometer response was also measured as a function of incident angle (Fig. 3). We can use the transmission-line model to calculate the received power as a function of the angle of incidence $P(\theta)$. When the sheet resistance is half the free-space impedance, the pattern is independent of the

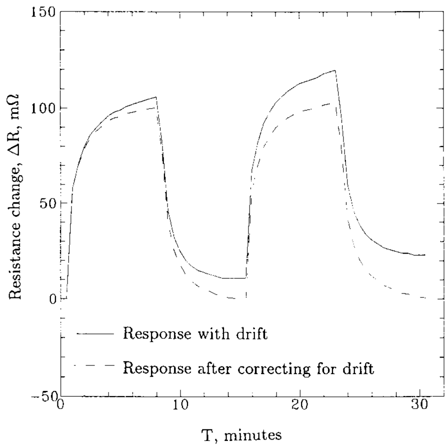

Fig. 2. Response to blocked and incident millimeter-wave power.

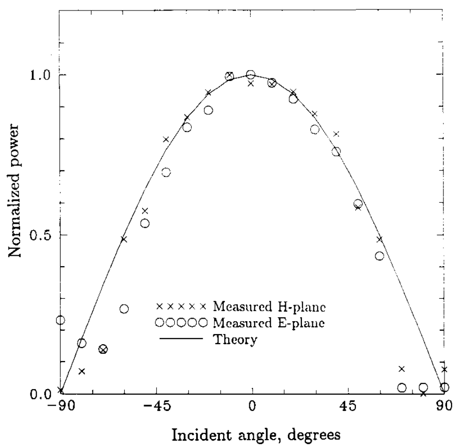

Fig. 3. Measured response to vertically polarized radiation in the *E*-plane and *H*-plane as a function of incident angle at 93 GHz. The received power at angles greater than 60° is reduced by blockage from the mount.

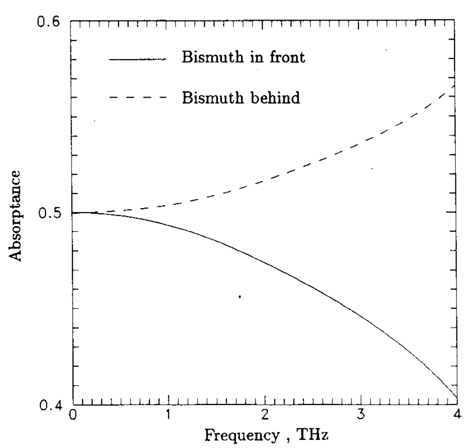

Fig. 4. Calculated absorptance of the power-density meter at higher frequencies.

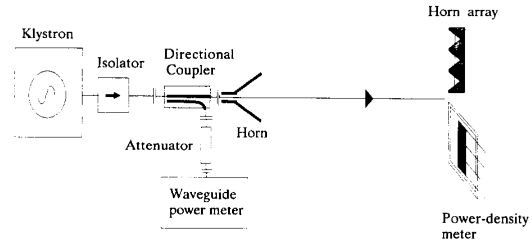

Fig. 5. Aperture efficiency measurement of horn antenna arrays at 93 GHz.

TABLE I
POWER DENSITIES MEASURED WITH DIFFERENT BOLOMETERS AT 93 GHz; SAMPLE STANDARD DEVIATION IS 1.2%

Width (cm)	Length (cm)	Power density (μW/cm^2)
2.0	2.0	575
2.0	1.5	565
2.0	1.0	564
1.5	2.0	582
1.0	2.0	569

polarization and given by

$$P(\theta) = \frac{2\cos^2\theta}{(1+\cos\theta)^2} \tag{2}$$

where θ is the incident angle. The measurements agreed well with the theory. There are no spikes near normal incidence [4].

At higher frequencies, the finite thickness of the mylar membrane will affect the absorptance of the film, and this must be corrected. The calculated correction factors are shown in Fig. 4. For mylar, the refractive index is taken from [5]. The correction is 5% at 2 THz. Alternatively, the thickness of the membrane could be reduced to avoid using the correction [3]. In addition, the absorptance of the styrofoam may affect the measurement and this would need to be checked.

V. APPLICATION: ANTENNA EFFICIENCY MEASUREMENT AT 93 GHz

The power-density meter was developed to make accurate aperture efficiency measurements on horns at 93 GHz. These antennas are fabricated on a silicon wafer with integrated microbolometers [6]. The aperture efficiency is the ratio of the power received by the microbolometer in the horn to the power incident on the aperture. The horns are placed in the far field of a source (Fig. 5) and the change in resistance of the microbolometer is measured. The power-density meter is placed at the same location and its change in resistance is measured. The aperture efficiency η of a horn is given by a simple formula

$$\eta = \frac{A_m \mathcal{R}_m \Delta R_a}{A_a \mathcal{R}_a \Delta R_m} \tag{3}$$

where A is the area, $\mathcal{R}$ is the resistance responsivity, ΔR is the resistance change, and the subscripts m and a denote the power-density meter and the antenna respectively.

Alternatively, the power-density measurement can be related to the reading on the waveguide power meter in Fig. 5. This makes it unnecessary to calibrate the directional coupler, attenuator, and horn individually.

VI. Conclusion

By using a metal film bolometer, we made accurate absolute power measurements at 93 GHz. The calibration procedure is simple and accurate to within 5%, and the actual measurement involves knowing only a few fundamental parameters. This device is useful for measuring millimeter-wave antenna aperture efficiencies.

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