Aperture Efficiency of Integrated-Circuit Horn Antennas

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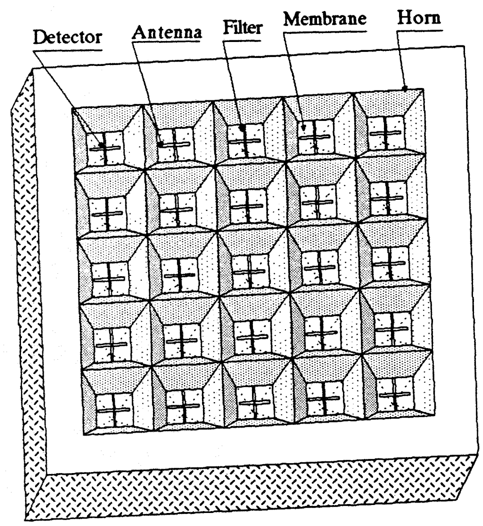
Abstract—**We have improved the aperture efficiency of silicon integrated-circuit horn antennas by optimizing the length of the dipole probes and by coating the entire horn walls with gold. To make these measurements, we developed a new thin-film power-density meter for measuring power density with accuracies better than 5%. The measured aperture efficiency improved from 44% to 72% at 93 GHz. This is sufficient for use in many applications which now use machined waveguide horns.**

INTRODUCTION

Rebeiz *et al.* [1] developed an integrated-circuit horn array based on anisotropic etching of silicon (Figure 1a). The etch forms pyramidal cavities bounded by (111) crystal planes. Gold is evaporated on these walls to make them highly conducting. The power received by the horns is picked up by dipole probes suspended on 1-μm silicon-oxynitride membranes inside the horns. The power is detected by bismuth microbolometers. Horns were demonstrated at 242 GHz and at 93 GHz, and the technology appears to be quite suitable for scaling to the terahertz frequency range. These horns have several potential advantages for use in millimeter and submillimeter arrays. The array is fully two-dimensional, and the horns are made simultaneously by integrated-circuit processing techniques. It should be possible to integrate superconducting tunnel junction devices with the horns. An isotropic etching technology is also available in gallium arsenide, which suggests that it should be possible to make horns that would include monolithic Schottky diodes. The membranes appear fragile, but we have been able to mount beam lead diodes on them, and they have passed standard industrial temperature and vibration tests. However, the measured aperture efficiency was low; Rebeiz *et al.* reported a value of 44% at 93 GHz for a array with a period of 1 λ. This efficiency is not good enough for most applications.

Rebeiz' measured and calculated losses are summarized in Figure 1b. The two major loss components are mismatch loss (2.2 dB) and horn-sidewall loss (0.7 dB). The mismatch loss was estimated from 7-GHz modeling experiments that indicated that



(a)

Loss component	loss, dB
Intrinsic pattern loss	0.2
Mismatch loss	2.2
Cross-polarization loss	0.2
Horn-to-horn coupling loss	0.1
Horn sidewall loss	0.7
Total calculated loss	3.4
Measured loss	3.6

(b)

Figure 1. Integrated-circuit horn array made by anisotropic etching of silicon (a), and the summary of measured and calculated losses (b) reported by Rebeiz *et al* [1].

the antenna impedance is 54 + j95 Ω, compared with the bolometer resistance, 138 Ω. The horn-sidewall loss arose from fact that the entire horn was not coated with gold; part was bare silicon with a resistivity of 0.5 Ωcm. The horn arrays are made as a stack of 4 wafers. One of these wafers includes the membranes; this wafer was not coated with gold because the membranes would also have been covered over during the evaporation. The goal of this work was to eliminate these two sources of loss.

Another difficulty with the previous measurements was measuring the aperture efficiency. A 10% accuracy was claimed, but this is not adequate for testing antennas with higher efficiencies. Although the measurement is fundamentally only the ratio of received power to incident power density, there were many factors that complicated the measurement and affected the accuracy. The power density was calculated from the reading of a waveguide power meter connected by a calibrated directional coupler, together with the calculated gain of a standard gain horn. The received power was measured for a chopped signal, and this required an accurate knowledge of the effective value of the modulation waveform and the frequency roll-off of the bismuth microbolometer. To simplify the measurements and improve the accuracy, we developed a new thin-film power-density meter and used only four-wire DC electrical measurements in the calibration and measurement.

Horn fabrication

A range of horns with dipole probes varying in length from 0.32 λ to 0.50 λ were constructed. In addition, the horn walls on the membrane wafer were coated with gold by evaporating at an extreme angle so that the walls of the horns formed a shadow over the membrane. The bolometers were fabricated by a photoresist bridge technique [2]. They had resistances in the range 50 to 100 Ω, with typical resistance responsivities of 20,000 Ω/W.

Power-Density Meter

Recently there has been renewed interest in developing quasi-optical power meters. Professor Derek Martin has recently developed an approach where the power is absorbed in a metallic thin film suspended in a closed gas cell [3]. The accuracy is reported to be 10%. Professor Gabriel Rebeiz is pursuing a design on a silicon-oxynitride film [4]. Our power meter (Figure 2) consists of an evaporated bismuth film with a sheet resistance of 189 Ω on a 50-μm thick mylar sheet. A film with this sheet resistance absorbs half the incident power and transmits half. The device is surrounded by a 5-cm thick layer of styrofoam to reduce the convection heat loss and to block infrared radiation. The transmitted power is absorbed by a pyramidal beam dump lined with absorber. The power-density meter works as a bolometer. It absorbs power, heats up, and we measure the change in resistance by a 4-wire measurement. The bolometer has an active area of 4 cm^2, and the typical resistance responsivity to RF radiation is 20 $\Omega/(\mathrm{W/cm}^2)$. We have carefully considered and tested for different sources of error: resistance drift, edge effects, time constants, varying angle of incidence, and absorption in the styrofoam, and feel that the measurements are accurate to better than 5% for incident power densities greater than 100 $\mu\mathrm{W/cm}^2$.

Measurements

Both the power-density meter and the horn microbolometers were calibrated by a plot of the resistance R versus DC power P. This plot is of the form

$$R = R_0 + \mathcal{R}P$$

where $\mathcal{R}$ is the resistance responsivity in Ω/W. The resistance responsivity is calculated from the slope of the plot. There is one additional correction factor for the proportion of power that is absorbed by the power-density meter.

In the measurements, the signal source was a 93-GHz klystron with an output power of 170 mW feeding a horn 60 cm from the array. The resistance changes in the horn microbolometers were measured, and then the horn array was replaced by the power-density meter. The aperture efficiency η can then be written as a simple formula

$$\eta = \frac{A_m \mathcal{R}_m \Delta R_h}{A_h \mathcal{R}_h \Delta R_m}$$

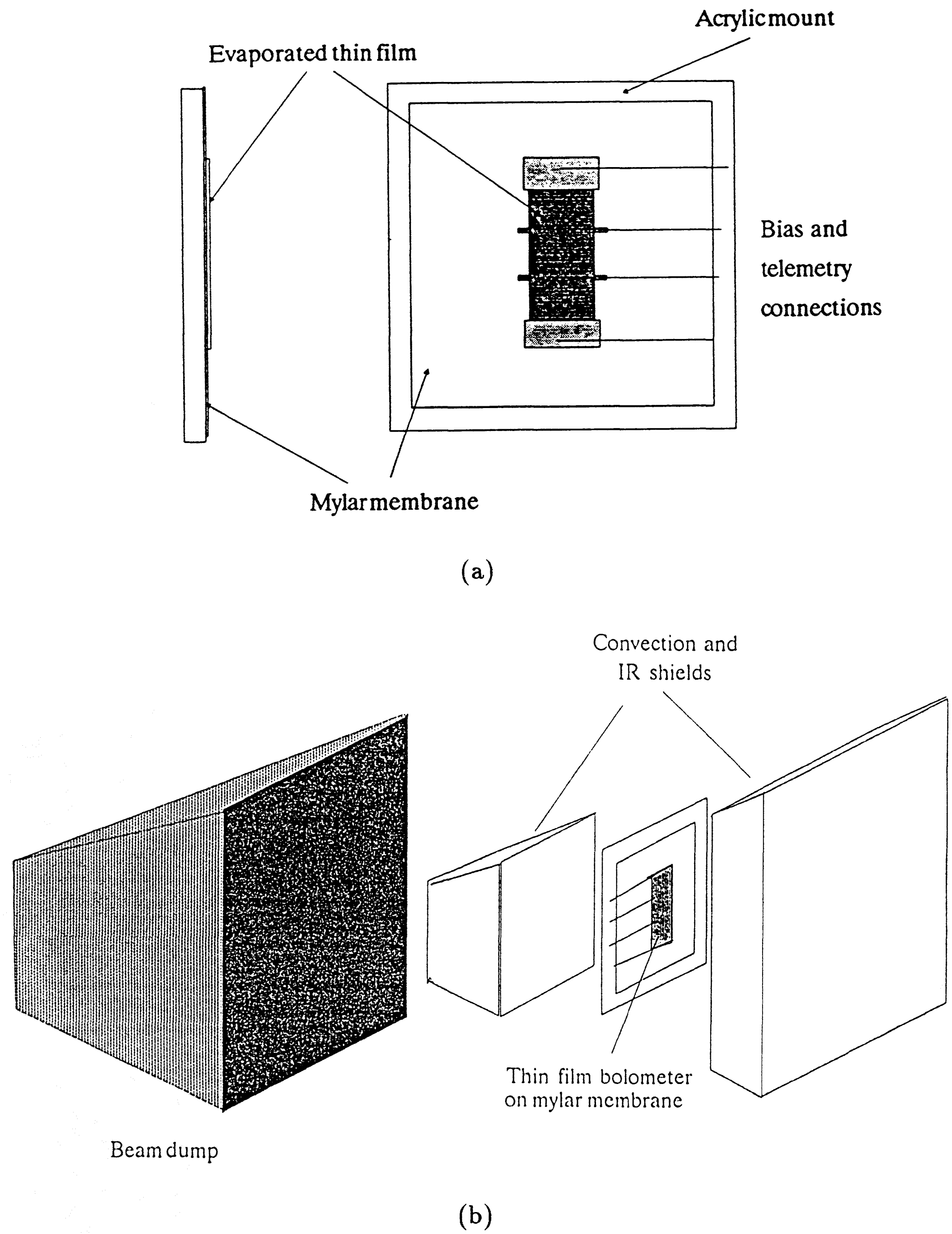
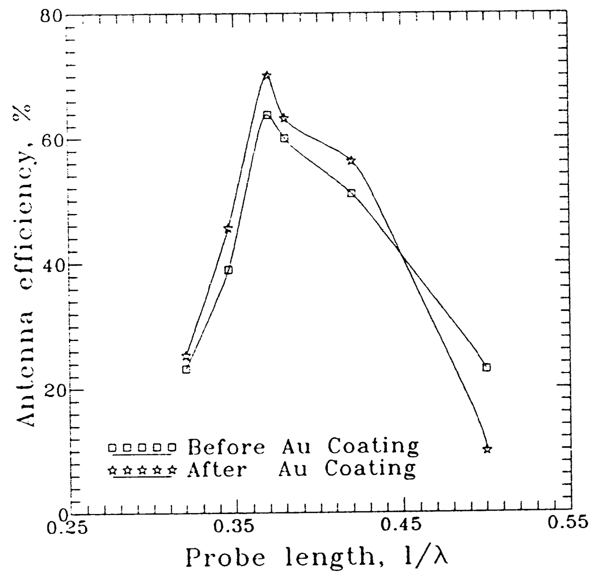


Figure 2. Thin-film power-density meter (a), and assembly (b).

where A_m is the area of the power-density meter, $\mathcal{R}_m$ is the corrected resistance responsivity of the meter, ΔR_h is the resistance change of the horn microbolometer, A_h is area of the horn, $\mathcal{R}_h$ is the responsivity of the horn microbolometer, and ΔR_m is the resistance change of the power-density meter.

Figure 3a shows the measured efficiencies for different antenna lengths. Measurements were made first for membrane wafers without gold coating. After the membrane wafers were coated with gold, the efficiencies were measured again. The efficiency reaches its



(a)

Loss component	loss, dB
Intrinsic pattern loss	0.2
Mismatch loss	0.4
Cross-polarization loss	0.2
Horn-to-horn coupling loss	0.1
Total calculated loss	0.9
Measured loss	1.4

(b)

Figure 3. Measured aperture efficiencies at 93 GHz versus antenna length (a). The efficiencies were measured before and after coating the membrane wafer with evaporated gold. Summary of measured and calculated losses (b).

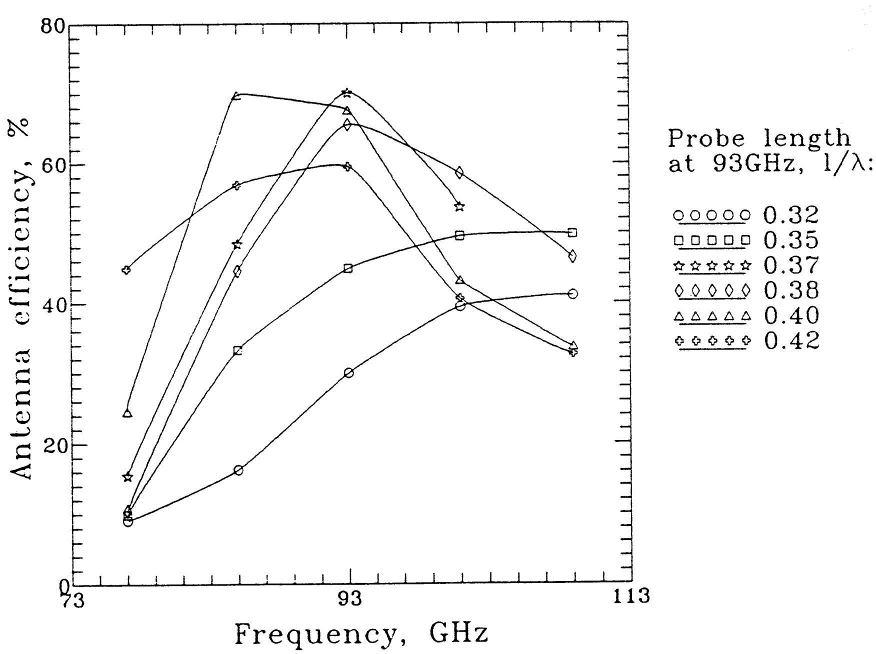


Figure 4. Aperture efficiency versus frequency for different dipole probe lengths.

maximum value, 72%, for a length of 0.37 λ. For all but the longest probe, gold coating the walls of the membrane wafer improves the efficiency. The typical improvement is 6%. Figure 3b shows the estimated loss breakdown. The total calculated loss is 0.9 dB, compared with the measured value, 1.4 dB. There is still some mismatch loss (0.4 dB), because the bolometer resistance in the measurements was 90 Ω, compared with the resonant antenna resistance of 50 Ω that was measured on the microwave model. We also made a plot of efficiency for the frequency range from 77 GHz to 109 GHz for antennas of various lengths, and this is shown in Figure 4. Probes with lengths in the range from 0.37 to 0.40 λ gave efficiencies better than 60%. The 3-dB bandwidths are of the order of 10 GHz.

Finally, we made measurements of the system coupling efficiency with a lens (Figure 5). This system coupling efficiency is the ratio of the detected power to the power incident on the lens. In the measurement, various stops were used to change the half angle subtended by a 100-mm diameter lens with an f-number of 0.75. The highest system coupling efficiency with a lens is 36% for an f-number of 0.75. We estimate that the loss from reflection and absorption in the lens is 28%, so that it should be possible to achieve a coupling efficiency of 50% in a f-0.75 system with reflecting optics, compared with 24% reported by Rebeiz *et al.* [2].

Conclusion

We have improved the aperture efficiency of silicon integrated-circuit horn antennas by optimizing the length of the dipole probes and by coating the entire horn walls

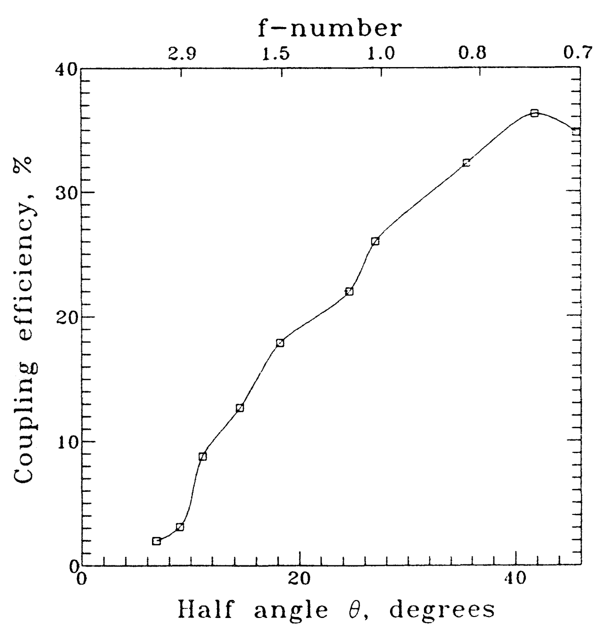


Figure 5. System coupling efficiency with a lens. The horizontal axis is the half angle subtended by the lens, which is varyied by changing stops in front of the lens.

with gold. To make these measurements, we developed a new thin-film bolometer power-density meter for measuring power density with accuracies better than 5%. The measured aperture efficiency improved from 44% to 72% at 93 GHz. These horns are now efficient enough to be considered for use in remote sensing, plasma diagnostics, and radio astronomy.

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[2] D. P. Neikirk, W. W. Lam, and D. B. Rutledge, "Far-infrared microbolometer detectors," *International Journal of Infrared and Millimeter Waves 5*, 1984, pp. 245–278. The bridge technique described in this paper uses a CF_4 plasma to make a buffer layer for the bridge. We are currently using a thin layer of aluminum as the buffer layer.

[3] Professor Martin's power meter is now commercially available from Thomas Keating Ltd., Billinghurst, West Sussex, England.

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