Aperture Efficiency of Chemically Etched Horns at 93 GHz

Yong Guo *, Karen Lee, Philip Stimson
Kent A. Potter, David B. Rutledge

Division of Engineering and Applied Science
California Institute of Technology
Pasadena, CA 91125

Abstract — **The aperture efficiency of monolithic two-dimensional horn imaging arrays has been optimized at 93 GHz. The imaging arrays consist of several silicon wafers into which arrays of pyramidal horns are etched chemically. Dipole antennas and detectors are suspended on thin silicon oxynitride membranes on one of the central silicon wafers about half way down the horns. The devices are 7×7 arrays with a 1λ opening and a 71° flare angle. Antenna impedances have been measured on a low frequency model. A variety of millimeter-wave dipole antennas and bolometers have been designed and tested. A large area bismuth thin film power meter is used to obtain accurate absolute power. The measured aperture efficiency improved from 44% to 72%. The highest system coupling efficiency with a lens was 36%, including lens absorption and reflection losses.**

INTRODUCTION

The goal of this project is to develop an efficient, high speed, monolithic imaging array working at frequencies up to hundreds of gigahertz. The horn antenna imaging array is composed of four stacked silicon wafers. Since silicon has an anisotropic crystal structure, it can be etched in the [100] crystal direction to form a pyramidal cavity bounded by (111) crystal planes using an anisotropic etchant (ethylenediamine pyrocatechol solution). The patterns on each wafer are defined so as to form horns with smooth walls when the wafers are stacked and glued together (Fig. 1). To produce the membrane, a silicon-oxynitride layer is deposited on the second wafer by plasma-enchanced CVD. When the wafer is etched through, it leaves the free-standing membrane. Dipole antennas and detectors are fabricated on these 5-μm thick suspended membranes. The opening in the front wafer defines the aperture size. The thickness of the two front wafers determines the position of the antenna inside horn. The last two wafers form a reflecting cavity [1,2].

This paper describes optimization of the aperture efficiency of the horn arrays. For an imaging array in the focal plane, array elements need to be as large as the spot size of the imaging optics to get good coupling efficiencies. This limits the area available for supporting electronics. Our two dimensional horn arrays provide both efficient reception and sufficient room for electronic connections. The pyramidal horns couple the incoming signal very efficiently to the dipole probe antennas inside the horns,

90CH2776-3/0000-1425 $1.00 ©1990 IEEE

while there is plenty of space on the membrane wafer between the individual horns for electronic circuitry, which can be produced at the same time as the antennas and detectors. The membrane is so thin compared to the wavelength that the antenna effectively radiates in free space inside the horn, and dielectric absorption losses are eliminated. Applications of these arrays include remote sensing, astrophysical mapping, atmospheric sensing of pollutants, plasma diagnostics, and military targeting.

Low Frequency Modeling

To find the antenna impedance at 93 GHz, measurements on a low frequency scale model at 7.3 GHz were performed. The model is an aluminium 3×3 horn array with a 70° flare angle. Dipole antennas and coplanar-strip transmission lines made of copper foil were suspended inside of the horns 0.37λ away from the horn apex, which is the position of the antennas inside the 93 GHz horn arrays. The antennas are fed by coaxial lines. The antenna impedances measured on a network analyzer were $54\Omega + j95\Omega$, $50\Omega - j0.1\Omega$, $160\Omega - j79\Omega$ and $220\Omega - j116\Omega$ respectively when dipole antenna half lengths were 0.24λ, 0.2λ, 0.15λ and 0.10λ. For the half antenna length of 0.24λ, the calculated mismatch loss from 50 Ω is 2.2 dB. The loss is given by $4R_aR_b/ \mid Z_a + R_b \mid^2$, where R_a is the antenna radiation resistance, R_b is the bolometer resistance (138 Ω), and Z_a is the antenna impedance ($54\Omega+j95\Omega$). Because the bolometer is purely resistive, it is essential to eliminate the reactive part of the antenna impedance to minimize the mismatch loss between the antenna and detector. The design value of the dipole antenna half length should therefore be around 0.20λ.

Design and Fabrication

In order to find the optimal antenna length at 93 GHz, several different dipole antennas, which cover the range of the half dipole length from 0.16λ to 0.25λ, were investigated. A four-wire measurement method is used to eliminate series resistance effects. The signal leads from an RF isolation filter. The coplanar strips of the filter are designed to have an characteristic impedance of 4 Ω when sandwiched between the two silicon wafers 0.25λ away from the center of the dipole. The quarter-wavelength section of the coplanar strips transforms the 4-Ω impedance into a very large impedance at the dipole, so the low impedance bolometer will absorb all the received power. A double-layer photoresist technique is used to obtain a photoresist bridge between the two legs of the dipole. In this process, silver is evaporated normal to the substrate to form the dipole antennas. The 3μm $\times$ 3μm detectors are made underneath the bridge by evaporating bismuth at an angle from both sides. The patterns of the antennas and the detectors are defined at the same time, and they are self-aligned. Because the two layers of metal are made in vacuum without exposing them to the air, these bolometers have low $1/f$ noise, and a high responsivity, typically 40 V/W. The resistive loss of the side-walls on the membrane wafer was calculated to be 0.7 dB. This is due to the conduction currents induced in the silicon walls of the horn by the incoming power. This problem was solved by coating the side-walls with gold, using a tilted substrate evaporation technique.

A large area bismuth thin film power meter 2cm × 2cm in size, was fabricated by evaporating bismuth onto a thin membrane of Mylar until a resistance of 189 Ω was reached. The thickness of bismuth is much thinner than a wavelength at 93 GHz; as a result the surface impedance is the same as the DC resistance. Half of the incoming power is absorbed.

EFFICIENCY MEASUREMENTS

We define the aperture efficiency of an individual element of an array as the ratio of the power received in the detector to the power incident on the aperture of that horn when the device is illuminated by a plane wave. The measurements are carried out using an all DC technique requiring no modulation, frequency response or conversion factors. The signal source at 93 GHz is a klystron with a output power of 170 mW. Both the bismuth power meter and horn bolometer are calibrated by measuring their DC responsivity from their DC resistance–power curve. The change in the resistance is a linear function of the power dissipated, $R = R_o + \mathcal{R}P$. To measure the efficiency, the imaging array is placed about 60 cm from the klystron and the change in the resistance caused by the incident millimeter-wave power is measured. The array is then removed, the power meter placed in the same position and another resistance change measured. The aperture efficiency η_a of a single element is given by:

$$\eta_a = \frac{A_m \mathcal{R}_m \Delta R_a}{A_a \mathcal{R}_a \Delta R_m}$$

where A is the area and ΔR is the resistance change caused by incident millimeter-wave power. The subscript m represents the power meter and the a represents the horn antennas. The measurement results are given in Fig. 2. The bolometer resistances vary from 50 Ω to 100 Ω. The aperture efficiency attains its maximum value 72% when the half dipole length is 0.185λ, the bolometer resistance is 90 Ω and $\mathcal{R}_a$ is 20 Ω/mW.

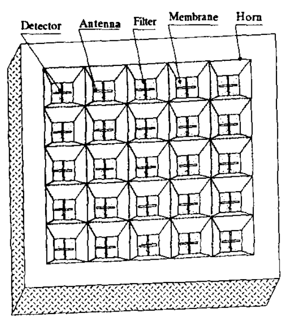

Fig. 1. A horn imaging array

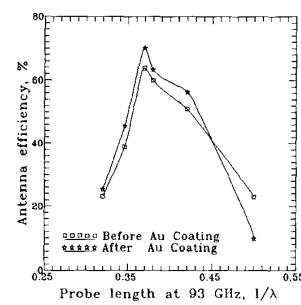

Fig. 2. Efficiency vs. dipole length

Intrinsic Pattern Loss	$-0.2\,\mathrm{dB}$
Mismatch Loss	$-0.4\,\mathrm{dB}$
Cross-Polarization Loss	$-0.2\,\mathrm{dB}$
Horn-to-Horn Coupling Loss	$-0.1\,\mathrm{dB}$
Total Calculated Loss	$-0.9\,\mathrm{dB}$
Total Measured Loss	$-1.4\,\mathrm{dB}$

Table 1. Aperture efficiency losses

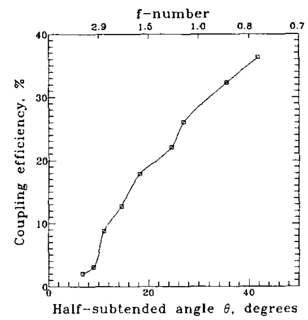

Fig. 3. Coupling efficiency vs. f-number

Table 1 gives the power loss mechanisms in the horn arrays. The total calculated loss is 0.9 dB, close to the measured 1.4 dB. For dipole antennas with a half length of 0.25λ, the efficiency is worse when the side-walls of the membrane wafer are coated with gold. Possibly this occurs because the end the dipole is very close to gold wall.

The system coupling efficiency with a lens has also been measured. This is the ratio of the power received by a single horn placed at the focal point to the total power incident on the primary lens. Fig. 3 shows a plot of coupling efficiency versus f-number. The highest system coupling efficiency with a lens is 36%, when the f-number is 0.7. We estimate that the loss from reflection and absorption in the lens is 15%, indicating that it should be possible to achieve a system efficiency of 51% with reflecting optics.

ACKNOWLEDGEMENTS

This research was supported by the Department of Defense Terahertz Technology Program, contract F19628-87-K-0051, Jet Propulsion Laboratory and Aerojet ElectroSystems Co.

REFERENCES

[1] G. M. Rebeiz, D. P. Kasilingam, Y. Guo, P. A. Stimson, D. B. Rutledge, "Monolithic Millimeter-Wave Two-Dimensional Horn Imaging Arrays", to be published in IEEE Transactions on Antennas and Propagation, January, 1989.

[2] G. M. Rebeiz, Y. Guo, D. B. Rutledge and D. P. Kasilingam, "Two-Dimensional Horn Imaging Arrays", *12'th Annual IEEE Int. Conf. on IRMM Waves*, Lake Buena Vista, Florida, Dec 14-18, 1987.