Integrated Microbolometer Antenna Characterization from 95–650 GHz

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Abstract—Electrical responsivity and radiation patterns are presented for a Nb microbolometer coupled to an ultrawideband spiral antenna at 300 K. A hyper-hemispherical substrate lens focuses incident radiation through the substrate onto the antenna. The Nb bridge is suspended in air between the feed points of the equiangular spiral antenna with a nominal bandwidth of 0.2–1.8 THz. Pattern measurements are performed at 95 GHz, 235 GHz, and 650 GHz. Polarization at 95 GHz is also explored.

Index Terms—Bolometers, Niobium, lens antennas, submillimeter wave antennas, submillimeter wave detectors, submillimeter wave measurements.

I. INTRODUCTION

Ultrawideband operation is important for submillimeter-wave applications: in passive imaging, broad bandwidth maximizes the incident blackbody signal power from the scene; in either passive or active spectroscopy and imaging, target discrimination and recognition are greatly improved. Ultrawideband antennas, however, present significant challenges in terms of coupling power efficiently into the detector, particularly in arrays. In this paper, we explore an approach consisting of a planar spiral antenna coupled through an integrated hyper-hemispherical substrate lens (Fig. 1). While hemispherical substrate lens-coupled antennas were initially developed by Rutledge [1], substrate lens-coupled spiral antennas were first investigated by Büttgenbach [2]–[3] in connection with SIS heterodyne receivers, and later extended and generalized [4].

The integrated detector-antenna discussed in this paper is being investigated for application in a scanned, linear focal plane array (FPA), configured in a so-called “fly’s eye” geometry, (i.e., separate substrate lenses for each pixel). The system design involves a tradeoff between overall array size, number of pixels, and operating wavelength band. System considerations demand more tightly-packed configurations than the standard design prescription [2] allows for a particular low-frequency bandwidth limit. The goal of the work reported here is to better understand the low-frequency limits of the lens-coupled spiral antenna.

The important dimensional ratios in the tradeoff between standard design of a broadband self-complementary spiral antenna array and more compact systems are the lens radius, the extension length (h+t in Fig. 1), the outer diameter of the spiral antenna, and the low-frequency edge of the design bandwidth. When either the lens radius or the antenna diameter is too small, low-frequency performance is degraded. The present antennas have been designed for 2 mm diameter lenses, which the linear FPA will utilize. Specifically, the ratio of antenna radius to lens radius, 0.19, (Fig. 1) is similar to the value of 0.24 used in the original lens-coupled spiral experiments [1]. The measurements reported here, however, are on single devices coupled to 4 mm diameter lenses. Therefore in this case, the degradation of performance below the design band should reflect limitations due to the antenna size only.

II. BOLOMETRIC DETECTOR CHARACTERIZATION

The antenna-coupled microbolometer discussed in this work is an air bridge made of Nb, suspended between the feed points of an Al equiangular spiral antenna with a nominal bandwidth of 0.2–1.8 THz. The bridge is 24 μm × 1 μm × 20 μm. The Nb and Al layers are deposited on a high-resistivity (ρ = 6000 Ωcm) Si wafer to facilitate antenna pattern testing at 300 K; fabrication of the devices is described elsewhere [5]–[6].

Room-temperature characterization of the bridge is performed using a current biasing scheme. Fig. 2 (top) is
a plot of the measured I-V curve of the antenna-coupled microbolometer. The I-V curve is fit to $V = I(R_o + \beta IV)$, where $R_o$ is the zero-bias resistance of the microbolometer and $\beta$ is the normalized responsivity of the detector in units of [V/W/mA]. The data range used in the fit to this equation is highlighted in Fig. 2, and $\beta$ and $R_o$ are found using a least-squares fit, producing $\beta = 265$ V/W/mA, and $R_o = 505$ Ω. These values are typical of the fabrication process described in [5]-[6], which involves a XeF$_2$ Si etch beneath the Nb bridge to suspend it in free space.

Fig. 2 (bottom) shows the I-V curve plotted in terms of resistance and power, and the extracted parameters $R_o$ and $\beta$ plotted in slope-intercept form to verify the fit accuracy. The apparent large zero-bias resistance is not a property of the Nb bridge itself, but is due to a resistance in series with the Nb bridge, specifically, the Nb-Al interface. Therefore, the extracted value of $\beta$ is correct for low bias currents, as the series Nb-Al resistance is independent and thermally isolated from the Nb bolometric sensing element. This is confirmed by illuminating the detector with a constant irradiance and varying the bias current; the measured response is linear as expected.

III. SUBSTRATE, HEMISPHERICAL LENS, & MOUNTING

The Si wafer is diced into 5 mm square chips; multiple detectors per chip are available but only one is suitable for antenna pattern measurements with a substrate lens centered on the chip. Shown in Fig. 1 is a diagram of the chip, substrate lens, and antenna, depicting the important geometry and associated dimensions. The spiral antenna is 380 μm in diameter, and located at the center of the chip, directly below the apex of the lens. The bolometer axis is collinear with the bias traces extending from the arms of the antenna. It is assumed that the DC bias traces will affect the low-frequency antenna response, producing a modified loaded dipole pattern.

The parameter focused on in prior work [3] is the dimensionless extension length of the lens, which we parameterize by the quantity $n(h + t)/R$. For an aplanatic design, this is unity. For the optimum efficiency “elliptical” design described in [3], this is larger, typically 1.3–1.6 depending on design frequency. Our configuration corresponds to $n(h + t)/R = 1.41$. A metallic mount in the form of a slotted ring captures the substrate lens at its outer diameter, similar to the configuration described in [3]. The ring geometrically vignettes the incident radiation at an angle of 48° from broadside. The mounted configuration can be seen in Fig. 3.

IV. ANTENNA PATTERN MEASUREMENTS

Antenna pattern measurements of the lens-antenna-coupled microbolometer are completed at 650 GHz, 238 GHz, and 95 GHz. Complete 2D pattern measurements are taken at each frequency, and a selection of 2D patterns and cuts are shown.

Fig. 2. (top) I-V data, the highlighted range fit to $V = I(R_o + \beta IV)$. (bottom) I-V data shown in resistance-vs-power ($V/I$ vs. $VI$) form with the extracted parameters $R_o$ and $\beta$ plotted asymptotically.

Fig. 3. Photograph of the assembly utilized for antenna measurements. The Si substrate lens can be seen in the middle of the Al flexure mount; the 5 mm chip is hidden beneath the lens.

A. Experimental procedure at 650 GHz

A backward-wave oscillator (BWO) is used as the 650 GHz source. Mechanically chopped at approximately 170 Hz and linearly polarized (LP), 2D patterns are measured in both orientations of the detector (co- and cross-polarized) for the fixed LP incident field. Bolometer bias current is set to 170 μA. As the irradiance at the plane of the detector is low (order of 1 μW/mm$^2$) due to low BWO transmit power, the dynamic range of the measurement is not greater than 20 dB, even though the measured noise level throughout the experiment remained within a factor of two from the known noise level of the preamp utilized (1.6 nV/√Hz). A co-polarized 2D pattern at 650 GHz is shown in Fig. 4. The beam is nearly circular, with -3 dB beamwidths in orthogonal cuts differing by 0.2°. The scan limits in both azimuth and elevation are ±20°.
B. Experimental procedure at 238 GHz

A Gunn oscillator [7] is followed by a commercial frequency doubler to produce a 238 GHz source. The beam is mechanically chopped at 80 Hz and the electric field is linearly polarized; the bolometer is rotated by 90° to measure both linear polarization senses. The irradiance at the plane of the detector from the LP transmit horn is on the order of 40 μW/mm². The bolometer bias current is set at 550 μA, and the dynamic range of the measurement is increased to 25 dB due to the greater source power. Fig. 5 contains a 2D pattern measured in this configuration. The -3 dB beamwidths are increased by a factor of ~2.6, which is close to the frequency ratio between 650 GHz and 238 GHz, ~2.7. The scan limits in both azimuth and elevation are ±55°.

C. Experimental procedure at 95 GHz

An HP 83624B synthesized sweeper is used to drive a 83558A mm-wave source module for W-band measurements. The source is amplitude-modulated at 1.1 kHz, and the bolometer bias current is set to 200 μA. For these measurements, the bolometer axis is fixed in the elevation scan direction, and the incident electric field polarization is co-, cross-, and circularly-polarized in both senses.

D. Discussion of pattern measurements

The one-dimensional cuts shown in Fig. 6 demonstrate decreasing beamwidth with increasing frequency. As expected, the -3 dB beamwidths decrease nearly monotonically as a function of frequency, narrowing from (mean of all polarizations) 25° at 95 GHz to 7° approaching the center of the design bandwidth of the spiral antenna, 650 GHz. In-band radiation at angles > 48° off broadside, as well as low-frequency radiation, is blocked by the lens mount. In these cases, the measured radiation pattern is no longer a function of only the antenna, but of the entire fixture. It should be noted that 95 GHz is well below the designed system operating frequency. Cross-polarized radiation at or near the low edge of the operating band will not encounter any significant radiating structures of the antenna or DC traces. On the other hand, copolarized radiation below the nominal antenna bandwidth will encounter the DC bias traces, which tend to act as a loaded dipole.

A summary of the co- and cross-polarized 2D pattern data from 95 GHz to 650 GHz is provided in Table I. We show the -3 dB and -10 dB beamwidths for both E- and H-plane cuts. Denoted with (3) are two results at 95 GHz in which an anomalous reflection affected a portion of
the measured data for positive elevation scan angles (seen in Fig. 6). Adjusting for the reflection, the E-plane co-polarized 10 dB beamwidth is reduced to 64.2°; the H-plane cross-polarized 10 dB beamwidth becomes 75.8°.

E. Gaussianity

The overall coupling of an antenna to a Gaussian beam can be expressed as

$$G = \frac{\int S E_M E_G^2 dS}{\sqrt{\int S (E_M)^2 dS \int S (E_G)^2 dS}}$$ (1)

where $E_M$ is the measured radiation pattern (RP) and $E_G$ is the fundamental mode Gaussian beam [8]. For simplification, we assume that the radiating aperture is square and the beam has constant phase, reducing (1) to

$$G = \frac{\int S |E_M(x,y)||E_G(x,y)| dS}{\sqrt{\int S (E_M(x,y))^2 dS \int S (E_G(x,y))^2 dS}}$$ (2)

for $G \in (0,1)$. A two dimensional Gaussian fit $E_G(x,y)$ is estimated based on the measured radiation pattern. The optimal fit was found by minimizing the sum of square errors between a theoretical Gaussian beam and the measured data. The mean Gaussicity of the two detector orientations at 238 GHz is $G = 82.8\%$, and at 650 GHz, $G = 86.0\%$.

V. DISCUSSION

It has been shown that the spiral antenna-coupled microbolometer has ultrabroadband operation with good response and Gaussianity within the operating band. Key characterizing parameters have been summarized distinguishing in-band operation from edge-of-band performance. Expectations regarding the low-frequency antenna performance proved correct — at 95 GHz, the antenna is elliptically polarized, demonstrated by the 3 dB difference in opposite CP responses in Fig. 7. Elliptical polarization suggests a transition from the in-band circularly-polarized spiral antenna pattern toward a linearly-polarized loaded dipole.

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### REFERENCES


