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Wide-Band Measurements of Antenna-Coupled Microbolometers for THz Imaging

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Abstract

We present results of room-temperature characterization of lithographically manufactured antenna-coupled NbN microbolometers. The bolometers are assembled together with a hyper-hemispherical Si lens to couple the incident radiation to the bolometer from the back-side of the substrate. The bolometers are designed to operate at 300～1,000 GHz and they are characterized at 321～782 GHz. Radiation patterns are measured at 321 GHz, 400 GHz, 654 GHz, and at 782 GHz. The frequency dependency of the beamwidth is studied with several azimuthal beam profile measurements at 321～500 GHz.

Key words : Bolometer, Equiangular Spiral Antenna, Radiation Pattern, Substrate Lens, THz-Imaging.

Ⅰ. Introduction

During past decade, personnel screening for contraband has been a major research effort in the scientific community. Traditional pat-down security inspections at airports have found rivalry from portal and stand-off imaging, typically realized with x-ray- or millimeter-wave-based technologies.

Current screening systems suffer from some drawbacks: even with low emitted power, x-ray imagers raise issues among public and are always limited to portal operation only. Millimeter-wave-imagers are used in portal and stand-off imaging. Both active and passive technologies are used. Current imagers provide up to few meter stand-off distance with moderate few-centimeter cross-range resolution.

Increasing the stand-off distance and the cross-range resolution of a fixed-sized imager lays down two requirements: the sensitivity must be improved and the operating frequency increased. Sensitivity is a major issue also when pushing towards video-rate imaging.

The above-mentioned issues are being addressed at VTT Technical Research Centre of Finland, at Aalto University, School of Science and Technology, Espoo, Finland, and NIST National Institute of Standards and Technology, Boulder CO, USA. A passive video-rate THz-camera is developed [1]～[3]. The camera is based on a focal-plane-array(FPA) of antenna-coupled hotspot microbolometers. The camera has 8-meter stand-off range and 2×4-m^2 field of view with 1-cm cross-range resolution. The superconductive operation of the bolometers results in 1 K radiometric resolution at 6 Hz frame rate. The bolometers are optimized for a nominal operating frequency from 300 GHz to 1,000 GHz. The passive detection in the camera is based on wide-band total power from the black-body radiation of the target.

In this paper, we present room-temperature measurements to characterize the bolometers used in the THz-camera. The paper continues the earlier work presented in [4] and [5]. The bolometers are characterized with resistivity and radiation pattern measurements.

Ⅱ. Antenna-Coupled Microbolometer

The construction and superconductive operation of a similar bolometer is described in earlier publications, e.g., in [6]. In short, the detectors are lithographically manufactured on a silicon substrate and they now consist of 60-μm NbN, air-bridges attached to the terminals of equiangular spiral antennas with 600-μm diameter. The substrate is cut to form chips of eight detectors with 3-mm pitch and they are backed with 2-mm silicon lenses to form a hyper-hemispherical geometry. The substrate and lenses are assembled together in a metallic module coupled to the cold-finger in the cryostat.

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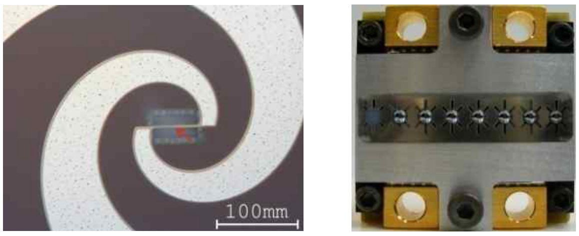
The hyper-hemispherical lens prevents substrate modes from occurring and increases the directivity. The radiation pattern of such a lens-detector ensemble is expected to be close to a Gaussian beam, as shown with experimental studies in [4] and [7].

When cooled and biased from a constant voltage supply, the antenna and the NbN bridge are in superconductive state except for a hot spot in the center of the NbN bridge due to the heating power of the bias current. In operation, the incident THz-radiation adds in to the total heating power, which is maintained roughly constant through electro-thermal feedback and the bias current passing through the bridge is modulated approximately in linear fashion by the incident power. The noise equivalent power(NEP) of the detectors, referred to the input of the bridge, is about 7 fW/Hz^{½}. The baseband variation of the bias current is due to variation of the resistance of the bolometer, which is measured by the read-out electronics. Fig. 1 shows a) a microscopic image of the detector with NbN airbridges and b) the assembly of the module of 8 bolometers.

At room temperature, the bolometer is used very differently from its nominal operation in its bias point at cryogenic temperature of about 8 K. The bolometer acts like a resistor with a negative temperature coefficient. The bolometer is DC current biased, and the incident THz power adds in to the bias heating varying its resistance, which is then measured with the read-out electronics. The room-temperature resistance of the NbN bolometers can be characterized by linear relation,

$$R = \beta P + R_0, \qquad (1)$$

where $P = P_{bias} + P_{THz}$ is the total power dissipated in the bolometer. β is typically -0.05 Ω/μW. R_0 is the zero-bias resistance and it is typically 460 Ω. Fig. 2 shows resistance vs. power-curves of typical bolometers in one module. The zero-bias resistance is subtracted from the curves for emphasizing the change in the resistance. Unlike in nominal operation of bolometers at 8 K, they have substantially degraded sensitivity at room temperature.



(a) (b)

Fig. 1. a) A micrograph of the bolometer. b) A module of eight bolometers. Bolometer #1 has no lens installed. Vertical polarization is defined to be perpendicular to the row of bolometers in the module and in plane of the paper.

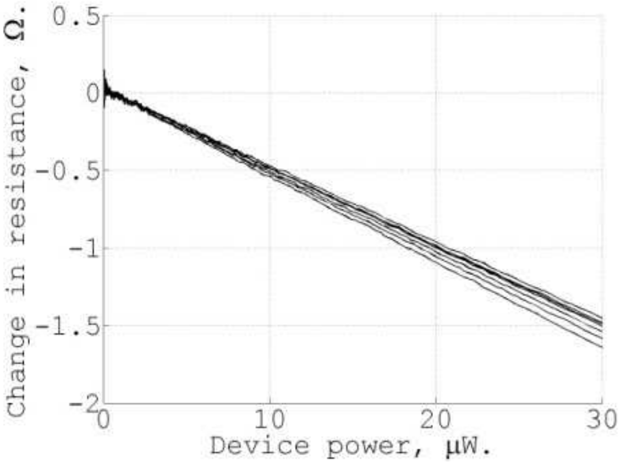


Fig. 2. Change of the resistance as a function of the dissipated power for bolometers in one module. The zero-bias resistance of the bolometer is 460 Ω. First order coefficient of the resistance is typically -0.05 Ω/μW.

Ⅲ. Measurement Setup

The antenna-coupled microbolometers are characterized at frequencies from 320 GHz to 782 GHz. 2D radiation patterns are measured at selected frequencies and frequency-dependent performance is studied. Fig. 3 shows a diagram of the measurement setup. Most importantly, the setup consists of a backward-wave oscillator(BWO), lock-in detection system, on-fly power meter, and an isolated voltage source.

BWOs are used as sources in the bolometer characterization due to the high output power they provide (from a few mW to tens of mW). Typically the output power decreases as the frequency increases. However,

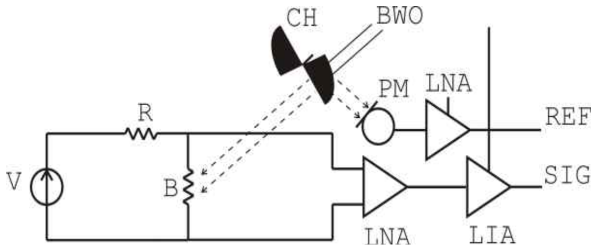
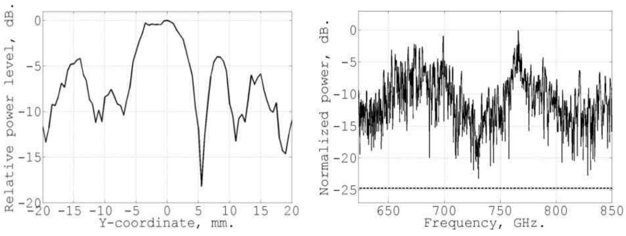
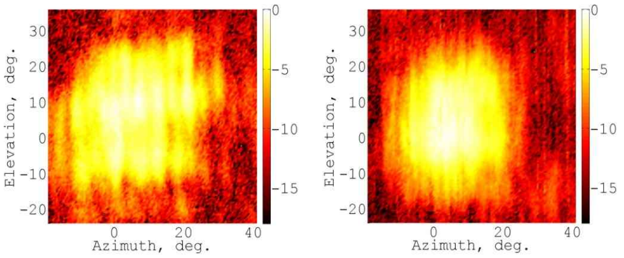


Fig. 3. A diagram of the setup. V=isolated voltage source, R=series resistor, B=bolometer, CH=chopper, LNA =low noise amplifier, LIA=lock-in amplifier, BWO =backward-wave oscillator, PM=power meter, REF =signal relative to the output power of the BWO, and SIG=response from the bolometer.

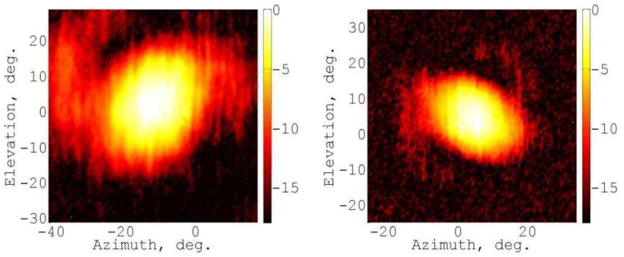


(a) (b)

Fig. 4. a) Incident power across the measurement range at 654 GHz. b) Incident power on the bolometer in the measurement range across frequency of 623~850 GHz(solid line), and noise floor of the power detector (dashed line).



(a) 321 GHz (b) 400 GHz



(c) 654 GHz (d) 782 GHz

Fig. 5. Radiation pattern of bolometer #4. The angular range and resolution is 60 degrees and 0.5 degrees both in azimuth and elevation.

over-moded waveguide output in BWO results in rapidly varying source beam, as a function of both spatial and frequency domains [8]. This reduces power coupling to the bolometer in free-space radiation pattern measurement. Fig. 4 illustrates the variation of the illumination a) when a power detector is scanned across the measurement range and b) when the frequency of the BWO is swept across the operating band of 623~850 GHz.

The detected signal, easily buried in noise, is read with a differential preamplifier and lock-in amplifier. An isolated voltage source is used to further reduce noise, especially AC line leakage. Lock-in detection needs a mechanical chopper to modulate the signal from the BWO source. Chopping frequency of 20 Hz is used in all measurements presented. The chopping frequency is limited due to the time constant of the on-fly power meter.

The on-fly power meter is the photo-acoustic power sensor from Thomas Keating Ltd. It is used for correction in case of power drift during several hours lasting scans. The chopper blade made of aluminum is used to subsequently couple the power from the BWO to the bolometer by transmission through the open path and to the power meter by reflection from the chopper blade surface. When compared to, e.g., thin-film-based beam splitters, power divider realized this way is less limited in bandwidth and does not reduce incident power density at the bolometer.

A stepped elevation-over-azimuth scanner is used for measuring the radiation patterns of the bolometers. The source-bolometer distance in the setup is 20 cm.

Ⅳ. Measurement Results

A bolometer near to the centre of the bolometer module, bolometer #4, was selected for characterization. Radiation patterns measured at 321 GHz, 400 GHz, 654 GHz, and 782 GHz under vertical polarization are shown in Figs. 5 from a) to d). The frequencies are selected according to local maxima in BWO output power as well as to cover a wide range of frequency points. In the following, beamwidth is defined with solid angle of a segment of a sphere:

$$\Omega_{-3dB} = \pi\left(\frac{\phi_{-3dB}}{2}\right)^2, \tag{2}$$

where φ_{-3dB} is the angular extent of the segment, i.e., the FWHM beamwidth. The solid angle Ω_{-3dB} is found by

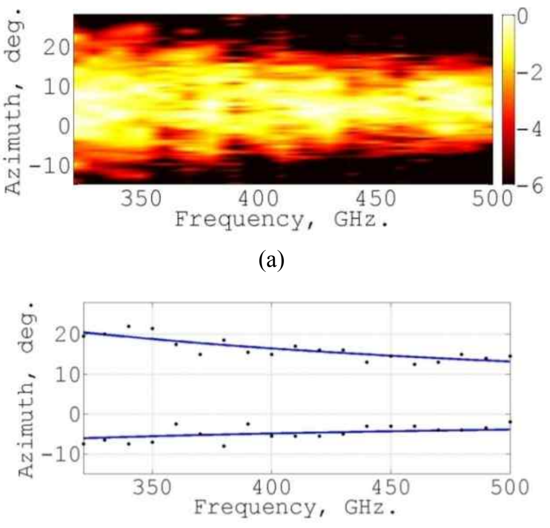
$$\Omega_{-3dB} = \triangle\Omega n_{-3dB}, \tag{3}$$

where $\triangle\Omega$ is the solid angular resolution of the measurement and n_{-3dB} is the number of measurement points with normalized level more than −3 dB.

In Fig. 5 a), the 321-GHz radiation pattern has a beamwidth of 25.3 degrees. However, without symmetry and with a rippled beam profile, the radiation pattern shows no similarity to a Gaussian beam. Maximum SNR of the measurement is about 13 dB.

In Fig. 5 b), the 400-GHz beamwidth is 20.9 degrees and the beam profile has a global maximum with symmetrical tapering around it. Maximum SNR of the measurement is about 15 dB.

In Fig. 5 c), the 654-GHz beamwidth is 17.5 degrees. In addition to a symmetrical main beam, a side lobe structure with a spiral-like pattern is present. The pattern follows the actual equiangular shape of the antenna coupled to the bolometer. Maximum SNR of the measurement is about 25 dB.



(a)

(b)

Fig. 6. a) Azimuth cut of radiation pattern of bolometer #4 at 321～500 GHz, b) Beamwidth at discrete frequencies(dots) and least squares fit(solid line).

In Fig. 5 d), the 782-GHz beamwidth is 12.2 degrees. Similarly to the case of 654-GHz pattern, there is a distinct main lobe and additional side lobe structure repeating the spiral shape of the lithographic antenna. Patterns in Figs. 5 c) and d) have mirrored shape due to design for different handed circular polarization. Maximum SNR of the measurement is 17 dB.

A waterfall plot of azimuthal cuts of the radiation pattern at 321～500 GHz in 19 equal-spaced frequency points is shown in Fig. 6 a). The color depth of the figure is limited to only −6 dB to emphasize the −3 dB beamwidth. As expected, the trend of the beamwidth is inversely proportional to the frequency. Also, the main beam is not centered on origin, rather than around 5 degrees azimuth angle. The offset most likely is due to misalignment of the bolometer and the substrate lens. With current hyper-hemispherical design and dielectric, such a beam tilt results from misalignment of about 40 μm, as noted also in [9].

Fig. 6 b) shows the measured −3 dB points in the azimuthal cuts at 321～500 GHz. Also, a function inversely proportional to frequency is fitted to the measured points with the least squares method. A relation similar to earlier work in [1] was found:

$$\phi_{-3dB}=\frac{8.5^{\circ}\,THz}{f}. \tag{4}$$

Ⅴ. Conclusions

We have presented characterization of antenna-coupled NbN microbolometers in the focus of a hyper-hemispherical silicon substrate lens. Radiation patterns are measured at 321 GHz, 400 GHz, 654 GHz, and 782 GHz at vertical polarization. The beam profile becomes more symmetrical as the frequency increases. At the same, beamwidth narrows from 25.3 degrees to 12.2 degrees. The SNR in the measurements increases at higher frequencies inspite of the higher power available from the BWOs at lower frequencies. This might be indication of better responsitivity of the bolometers towards the high-end of the frequency range. Currently, work is underway in order to obtain power-calibrated measurements to accurately determine the responsitivity as a function of frequency. Also, azimuth cuts of the radiation patterns are measured at 321～500 GHz at closely spaced frequencies. These measurements fitted with least squares method show 8.5-degrees-per-THz relation for the beamwidth of such a detector.

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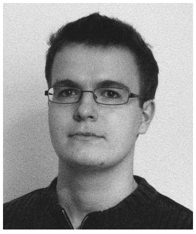

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