A 585 GHz Annular-Slot Antenna Coupled Two-Dimensional (Two-D) Focal-Plane Array Utilizing Twin-HEB Devices

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***Abstract*—We report on the design and fabrication of 585 GHz focal-plane arrays utilizing annular-slot antennas and twin-HEB devices. Design details and simulation results are presented. DC characteristics of the twin-HEB devices, including R-T and I-V curves, have been tested. In addition, initial RF measurement results of the focal-plane array (FPA) mixers are presented.**

I. Introduction And Background

In recent years, focal-plane arrays (FPA's) for the terahertz (THz) frequency region have received much interest due to their applications in astronomy, biological spectroscopy and security. We have designed and fabricated prototype two-D (2 × 2) FPA's for operation at 585 GHz on silicon wafers that are based on the reverse-microscope concept described by Rutledge et al in 1982 [1]. In this design, annular slot antennas (ASA's) are used for the elementary mixer coupling structures due to their compact and symmetric geometry. ADS Momentum simulations have been performed to characterize the self- and mutual- impedances of the ASA's in the array. In addition, the antenna off-axis radiation patterns have been calculated using the ray-tracing techniques [2].

Superconducting hot-electron bolometers (HEB's) have been widely utilized in terahertz mixers and receivers, particularly above 700 GHz (the gap frequency for Nb) [3]-[6]. To optimize mixer performance, the HEB device impedance should be matched to the annular slot antenna input impedance (~100 Ω). In addition, the spacing between adjacent antennas in the array should not exceed one wavelength to achieve diffraction-limited imaging. This makes it difficult to accommodate distributed impedance matching networks between the mixing elements and the annular slot antennas. Tuning the device impedance by fabricating longer HEB microbridges, however, risks exceeding the diffusion cooling length for the device, resulting in a narrow IF bandwidth. Although a HEB microbridge array was proposed in Prober's pioneering work in 1993 [3], little research has been focused on these devices. This paper reports twin-HEB devices integrated directly onto the feed of annular slot antennas for impedance matching while maintaining broad IF bandwidth. DC characteristics of this device including R-T and I-V have been measured. Initial RF measurement results of the mixer array are also presented in this paper.

II. Array Design and Fabrication

To achieve a diffraction-limited imaging with a HEB mixer array at submillimeter frequencies, the "reverse-microscope" optical configuration proposed by Rutledge

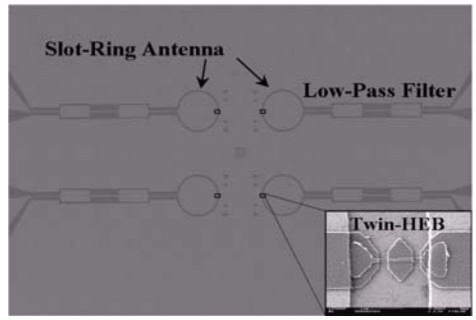

Fig 1. SEM picture of the two-D FPA utilizing twin-HEB devices.

et al. [1] is utilized. In this configuration, the ASA array substrate is attached to the back side of the imaging lens and an objective lens is placed in front of the imaging lens. The imaging signal is focused through both lenses onto the mixer array. The imaging is reconstructed from the IF output signal of each element in the array. By utilizing the same material (silicon) for both the array substrate and the imaging lens in this configuration, the trapped surface-wave is eliminated and the cross-talk between adjacent imaging elements is reduced, allowing a high imaging resolution to be achieved [1].

Fig. 1 shows a prototype two-D array (2 × 2) containing four ASA's. For operation at 585 GHz, each ASA has a radius *a,* of 36 μm and a slot width, 2*w,* of 2.6 μm. The antenna spacings in the x and y directions are *d*. The ADS *Momentum* simulation results of this two-D ASA array with element spacing of 0.8 λ_d are shown in Fig. 2. The coupling between two adjacent antennas is less than -28 dB over the frequency range of 200 GHz to 700 GHz, and the input impedance is (100+j0) Ω at 585 GHz, which is quite close to the single antenna driving point impedance, demonstrating that the cross-talk between the adjacent antenna elements is small. The absolute values of the real- and imaginary-part of the mutual impedances shown in Fig. 2 (b) are less than 6 Ω over the entire frequency range. The total mutual impedance at 585 GHz is estimated to be (-2 – j5) Ω, which is much smaller than the antenna input impedance. According to Shannon's theory, the element spacing for a FPA populated with heterodyne detectors should be less than one wavelength in the imaging

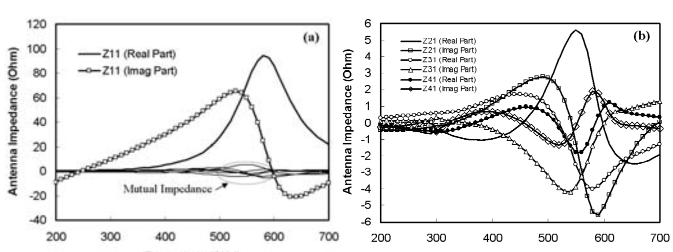

Fig 2. ADS simulation of antenna impedances for a two-D ASA array.

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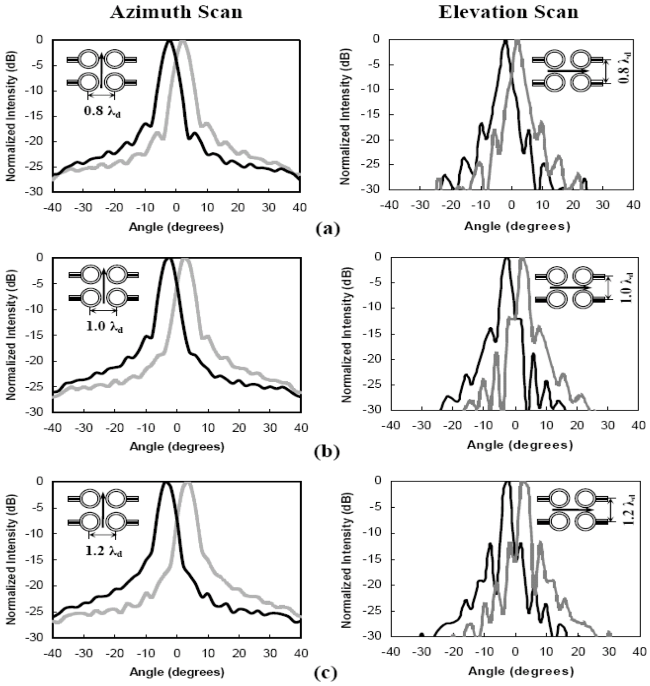

Fig 3. Annular slot antenna off-axis radiation patterns on silicon lens.

medium. However, at a distance less than 0.8 λ_d, the mutual impedance for the ASA array described above increases dramatically, and thus a minimum element spacing of 0.8 λ_d is maintained for this research.

For a prototype demonstration, two-D HEB mixer arrays (2×2) with element spacing of 0.8 λ_d, 1.0 λ_d and 1.1 λ_d have been designed and the antenna off-axis radiation patterns on an extended (*L*) hemispherical silicon lens (*R* =4.5mm, *L*=1.6mm) have been calculated using the ray-tracing techniques [2]. As shown in Fig. 3, the antenna pattern in the azimuth scan arrays has a 3-dB beam width of $\theta_{3\text{-dB}} \sim 4°$ with side-lobe levels less than -10 dB. The beam spacings between adjacent antennas are $\Delta\theta$~4.0°, 5.0°, and 5.7° with crossover power level of -3.9 dB, -6.0 dB, and -7.0 dB for $d = 0.8\ \lambda_d$, 1.0 λ_d, and 1.1 λ_d, respectively. The pattern in the elevation scan has a 3-dB beam width of $\theta_{3\text{-dB}}$~3.5° with side-lobe levels less than -10 dB. The beam spacings are $\Delta\theta \sim 4.0°$, 5.0°, and 6.0° with crossover power level of -7.0 dB, -11.0 dB, and -12.5 dB for $d = 0.8\ \lambda_d$, 1.0 λ_d, and 1.1 λ_d.

As discussed previously, there is limited room in the two-D array for accommodating peripheral circuits especially impedance transformers. Tuning the device impedance to match the 100 Ω antenna impedance by fabricating longer HEB microbridges, however, risks exceeding the diffusion cooling length for the device, resulting in a narrow IF bandwidth. Thus the twin-HEB devices (Fig. 1) are employed to realize this two-by-two mixer imaging array.

The fabrication process starts with sputtering of a Nb/Au (10*nm*/10*nm*) bi-layer onto a Si wafer, followed by a standard lift-off process to define the base layer. The twin-HEB bridges (two bridges) are defined using a two-step e-beam lithography process. RIE etches are then performed to remove the unwanted metal layer, which leaves the Nb bridges between the gold cooling pads (see inset of Fig. 1).

III. Measurement Results

Prototype twin-HEB devices were fabricated and dip-stick testing results are shown in Fig. 4. The R-T curve measured with current of 10 μA in (a) shows that the superconducting transition occurs at $T_c \sim 6.1$ K with a broad transition width of $\Delta T_c \sim 0.9$ K. Three sharp transitions can be seen at 6.4 K, 6.2 K, corresponding to the two HEB microbridges, and 5.5 K introduced by the niobium underneath the Au contact pads due to the proximity effect. I-V curves are measured at bath temperatures of 4.2 K and 5.0 K. Two superconducting transitions can be clearly seen on both curves. At T = 4.2 K, the first transition occurs at a critical current of $I_{c1} \sim 50\ \mu$A, and the second occurs at $I_{c1} \sim 120\ \mu$A. As the bath temperature increases to 5.0 K, the critical currents decrease to 30 μA and 80 μA as anticipated. The above results demonstrate that although geometric variations between the two HEB bridges are manifest in their I-V characteristics, these devices have promise as mixer elements in FPA's.

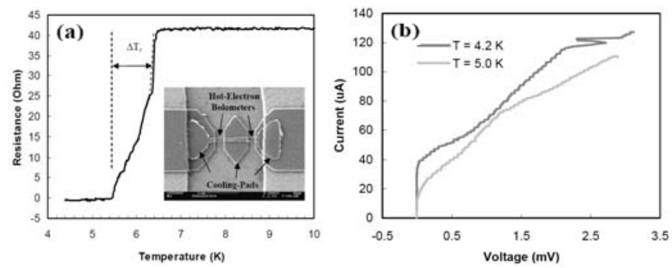

Fig 4. DC measurement results for the twin-HEB devices.

Measurements have been also performed on a one-dimensional ASA array with conventional single-bridge HEB devices based on the "reverse-microscope" configuration. An angular resolution of ~5.04° has been demonstrated at 585 GHz with the design of 1.0 λ_d element spacing, which agrees well with theory prediction. Y-factor measurements show that DSB mixer noise temperatures of 1675 K and 3517 K, with mixer conversion gains of -14.73 dB and -17.74 dB, respectively, have been obtained for two adjacent elements in a mixer FPA, which is comparable to other results reported in the literature [7].

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