A Terahertz Focal Plane Array Using HEB Superconducting Mixers and MMIC IF Amplifiers

Abstract—We present a focal plane array (FPA) designed for operation at terahertz frequencies. The FPA is based on NbN phonon-cooled HEB mixers directly coupled to wide-band MMIC IF amplifiers. The array incorporates all the required DC-bias and IF circuitry in a compact split-block design. We present new experimental results describing the optical coupling efficiency to the array, as well as receiver noise temperature measurements. The measurements were performed at 1.6 THz, showing good agreement with theoretical predictions. This is the first low-noise heterodyne focal plane array to be reported for any frequency above 1 THz.

Index Terms—HEB heterodyne detectors, focal plane arrays, terahertz receivers, MMIC low-noise amplifiers.

I. INTRODUCTION
SUPERCONDUCTING hot electron bolometer (HEB) mixers have steadily evolved in performance over the course of the last decade. They have become the most sensitive heterodyne detectors for frequencies above one terahertz. A parallel advancement has taken place in the development of ultra low-noise cryogenic IF amplifiers with low DC-power consumption. In particular, low noise amplifiers (LNAs) based on InP high electron mobility transistors (HEMTs) have demonstrated remarkable performance [1]. The conjunction of these two technologies has brought forth single-pixel instruments with near quantum limited noise performance, which are an excellent option for high resolution spectroscopic imaging in the terahertz range. The mapping speed of these single-pixel receivers can be substantially improved with the integration of the HEB mixers and IF amplifiers into multi-pixel focal plane arrays (FPAs) [2]. The low LO power consumption and low-noise performance of HEB mixers makes them well suited for such integration, specially with the availability of cryogenic monolithic microwave integrated-circuit (MMIC) IF amplifiers.

This letter describes a three-element HEB focal plane array designed according to the fly’s-eye concept. Multi-pixel receivers for lower frequencies with a similar fly’s eye configuration have been described in [3] and [4]. The terahertz FPA we describe is designed for a much higher frequency of operation and incorporates MMIC low-noise IF amplifiers in close proximity with the HEB devices. The IF amplifiers do not require cryogenic isolators for input matching. This feature reduces the size of the array significantly. We have accommodated all the required DC-bias and IF circuitry in the same housing. Standard field-replaceable SMA connectors are used for the IF ports. The FPA prototype was designed to operate at 1.6 THz but can in principle operate at any terahertz frequency by changing the center frequency of the coupling antenna.

II. DESIGN DESCRIPTION
The basic configuration for the single pixel HEB array is shown in Fig. 1. We use a quasi-optical coupling scheme consisting of a silicon elliptical lens and a monolithic terahertz antenna. This configuration has been analyzed in [5]. The active elements are phonon-cooled HEB devices fabricated from thin NbN film on silicon substrates. We have previously developed a fabrication process for this type of devices integrated with either twin-slot or slot-ring antennas. The device chip size is 6 mm x 6 mm x 350 µm. We chose the spacing between adjacent pixels in the array to be 8.5 mm in order to avoid any interaction between radiating elements. The smallest beam spacing, though, will be limited by diffraction effects [6].

The MMIC LNAs utilized in our prototype were originally intended for use on the Allen Telescope Array [7]. These amplifiers have three stages of InP transistors with 0.1 µm gate length. The chips have a gain close to 30 dB over the bandwidth required for this application (1-10 GHz). The total noise temperature of the chip is lower than 8 K throughout the band. The optimum noise performance is achieved at 20 mW of DC-power dissipation and stays nearly constant down to 5 mW. This characteristic permits minimizing the
power dissipation of the FPA without influencing the total receiver noise temperature by more than a few percent. Power dissipation is increasingly important with increasing number of elements in the array. The amplifiers are biased separately with a common drain and a common gate voltage for each chip for best noise performance. Each MMIC is enclosed in a narrow cavity in the mixer block designed to have a cut-off frequency of 75 GHz, which is well above the highest frequency of operation of the MMIC. Eccosorb® microwave absorber is used to cover the microstrip connections to the MMICs. This step is done in order to avoid the excitation of undesired waveguide modes inside the block. These modes can favor positive feedback effects that would otherwise affect the unconditional stability of the amplifier.

The impedance presented by the HEB at the IF frequency can be adjusted in actual operation so that it becomes close to 50 ohms over the bandwidth of interest. This is done by applying the proper combination of LO power and DC voltage [8]. In order to achieve a broadband coupling between the HEB and the MMIC we use a multi-section matching transformer fabricated on microstrip line. The matching transformer eliminates the need for a cryogenic isolator. The successful integration of an HEB in close proximity with an MMIC for the first time is therefore a significant accomplishment.

The matching network described above includes a series DC-blocking chip capacitor and a shunt RF-blocking spiral inductor that form a broadband bias-tee for each mixer. Additional chip capacitors are incorporated on a separate circuit board to provide protection against electromagnetic interference. A set of surface mount chip resistors are used on the same board to monitor the voltage and current signals of the device, as well as for biasing of the MMIC chips.

The split-block housing is shown in Fig. 2. The HEB devices and MMIC amplifiers are located on the same plane. Most of the DC-bias circuitry is contained in the back half of the module, which also holds a miniature multi-pin connector that provides the final interface to the liquid helium dewar wiring.

III. Measurements and Analysis

In order to evaluate the performance of the array, we have measured the noise temperature and the optical coupling efficiency. The devices under test were designated A, B, and C, respectively, C being the center element. Twin-slot antennas were used with elements A and C whereas a slot-ring antenna was used with element B. We have measured all three detectors (pixels) separately. However, since only two coaxial ports are available in our cryostat, it was not possible to measure more than two pixels simultaneously. The FPA was mounted in the cryostat such that the two elements under test (A and C) were along the z-axis.

All measurements were performed using a CO$_2$ laser pumped far-infrared (FIR) gas laser system as the local oscillator (LO) source. The FIR laser runs on a 1.63 THz line using a difluoromethane (CH$_2$F$_2$) gas. The FIR laser produces a stable continuous wave (CW) radiation with a typical power of about 30 mW. This amount of power was found to be sufficient to pump all elements simultaneously by defocussing the laser beam until it covered the three detectors. The LO signal was injected through the dewar window onto the elliptical lenses using a six micron thick mylar beam splitter. This diplexer reflects about 1% of the LO power into the devices and lets most of the signal power reach the detectors.

The noise temperature of elements A and C was measured using the standard Y-factor method. This technique involves introducing a hot/cold blackbody source into the signal beam path and recording the change in the IF output power. The DC-bias and LO power were adjusted to achieve the optimum operating points along the I-V curves of the HEB devices. The measured double-sideband pixel noise temperature for devices A and C was 1,200 K and 3,000 K, respectively. An IF frequency of 1 GHz was used. The measured noise performance as a function of IF frequency is shown in Fig. 3. In general, the useful bandwidth of an HEB receiver is determined by the noise bandwidth, defined as the frequency at which the noise temperature doubles with respect to the low frequency value. The measured noise bandwidth for the detector with the lowest noise temperature was 3.5 GHz (NB$_A$) and close to 4.25 GHz (NB$_C$) for the less sensitive device. The variation in the noise performance between pixels is consistent with our expectations, based on the different IV characteristics of each device. We attribute these differences to inhomogeneity in original film properties, deviations inherent to the fabrication process, and aging effects. According to its IV characteristics, device B is expected to have a noise temperature of about 2,000 K at the lower IF frequencies.
The estimation of the optical coupling efficiency was performed using sideband generation techniques. The signal beam was obtained by mixing a tunable microwave signal with a fixed laser source in order to produce tunable sidebands. This technique has been demonstrated to be efficient in producing tunable CW radiation in the far infrared range with a fair amount of power [9]. An Off-Axis Parabolic (OAP) reflector was used as the last optical component in the sideband beam path. This mirror was used to keep the signal beam focused in the aperture plane of the two silicon lenses in the FPA, inside the cryostat. The OAP was mounted on a special translator such that its position could be changed vertically. The output signals from the two detectors under test were continuously recorded on spectrum analyzers. For convenience, we used an IF frequency of 2 GHz. Fig. 4 shows the IF output power for each pixel as a function of linear displacement of the input sideband beam along the z-axis. The powers are normalized to their respective peaks and plotted on a linear scale. The IF power shows two maxima corresponding to pixel A and pixel C.

We performed numerical modelling of the beams in order to validate the experimental results. We assumed Gaussian illumination for both the input sideband and the response of the individual detectors. For simplicity, the Gaussian beam waists were assumed to be identical. This approximation holds provided that the sideband is optimally focused on the elliptical lenses for the elements under analysis. The Gaussian beam parameter, w, was then adjusted to fit the experimental data (solid curve in Fig. 4). The best fitting value for w was thus obtained to be about 1.5 mm, in close agreement with previous calculations for the particular lens/antenna configuration. The predicted “Gaussicity” for the quasi-optical response was close to 94%. According to the calculations, the separation between the two detected peaks was 8.5 mm, in agreement with the physical separation between lenses. Moreover, these calculations enabled us to estimate the smallest possible spacing between contiguous pixels for focal plane arrays of this kind. This value was found to be 4.25 mm, which is close to the diameter of the elliptical lens.

IV. CONCLUSION

A compact three-element focal plane array using NbN phonon-cooled HEBs and wide-band MMIC IF amplifiers has been demonstrated at 1.6 THz. The integrated quasi-optical pixels can in principle operate at higher terahertz frequencies. Near quantum-limited noise performances ($15 \times h\nu/k$) have been measured for individual array elements. Noise bandwidths greater than 4 GHz can be achieved using this technology. The optical coupling of contiguous elements in the FPA has been carefully measured and the experimental results are in close agreement with the theoretical estimations. The results presented in this letter are very promising for the development of large FPAs with potentially hundreds of pixels. Very large HEB FPAs are needed for systems for radio astronomy, remote sensing, and medical diagnostics.

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REFERENCES