# Development of NbN Terahertz HEB Mixers Coupled Through Slot–Ring Antennas*

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***ABSTRACT*** - In order to improve the power coupling to phonon-cooled hot electron bolometer (PHEB) devices, we are experimenting with a different type of antenna. The development of focal plane arrays (FPAs) with HEB devices requires a new approach for local oscillator (LO) injection. The goal of the project is to eliminate the need for a beam splitter or diplexer and to couple both the LO beam and the signal beam directly to the antenna. This direct coupling can be done by fixing the polarizations of the LO and signal beams to be orthogonal to each other. The slot-ring antenna has been used successfully at millimeter-wave frequencies, up to 94 GHz, integrated with Schottky barrier diodes. It can be easily coupled to a dielectric lens since it has a roughly symmetric radiation pattern. Slot-ring antennas are well suited for use with terahertz PHEBs.

We have designed, fabricated, and tested the first generation of slot-ring antenna coupled HEB mixers. The slot-ring antenna frequency is centered at 1.6 THz. A coplanar waveguide (CPW) stub filter, which presents an open circuit at the slot-ring, is used. The CPW requires air bridges (well-known in monolithic microwave integrated circuit (MMIC) technology at lower frequencies) in order to ensure that only the main CPW mode can propagate. Although slot-ring antennas have been used successfully at much lower frequencies, they present a challenge at terahertz frequencies. Nevertheless, a preliminary result of noise temperature of 2000 K at 1.6 THz represents the suitability of the slot-ring antenna in future FPAs based on HEB devices.

## I. INTRODUCTION

Hot electron bolometric (HEB) mixer receivers for terahertz frequencies have been under development for the last 10 years. A few instruments based on HEB technology have been deployed primarily for astrophysical application [1]. Heterodyne detection is the most sensitive spectroscopic technique over a broad frequency range. In astronomical applications, observations of spectral lines

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have played a major role in expanding our understanding of the interstellar medium and planetary atmospheres. In order to achieve the required sensitivity for astronomical, remote-sensing, and plasma-diagnostics applications, we need to develop receivers operating at sensitivities near the quantum noise limit, and focal plane arrays (FPAs) with multiple mixer elements. HEB mixers, which use nonlinear heating effects in superconductors near their transition temperature, have become an excellent candidate for applications requiring low noise temperatures at frequencies from 1 THz to 12 THz. In order to develop focal plane arrays with tens or hundreds of HEB devices, a new type of array architecture is needed.

Figure 1 illustrates a conceptual design for an FPA with multiple HEB devices. One of the main barriers for the development of terahertz imagers is the availability of LO sources with sufficient power and high tunability. Despite the low power requirement of a single HEB mixer (on the order of

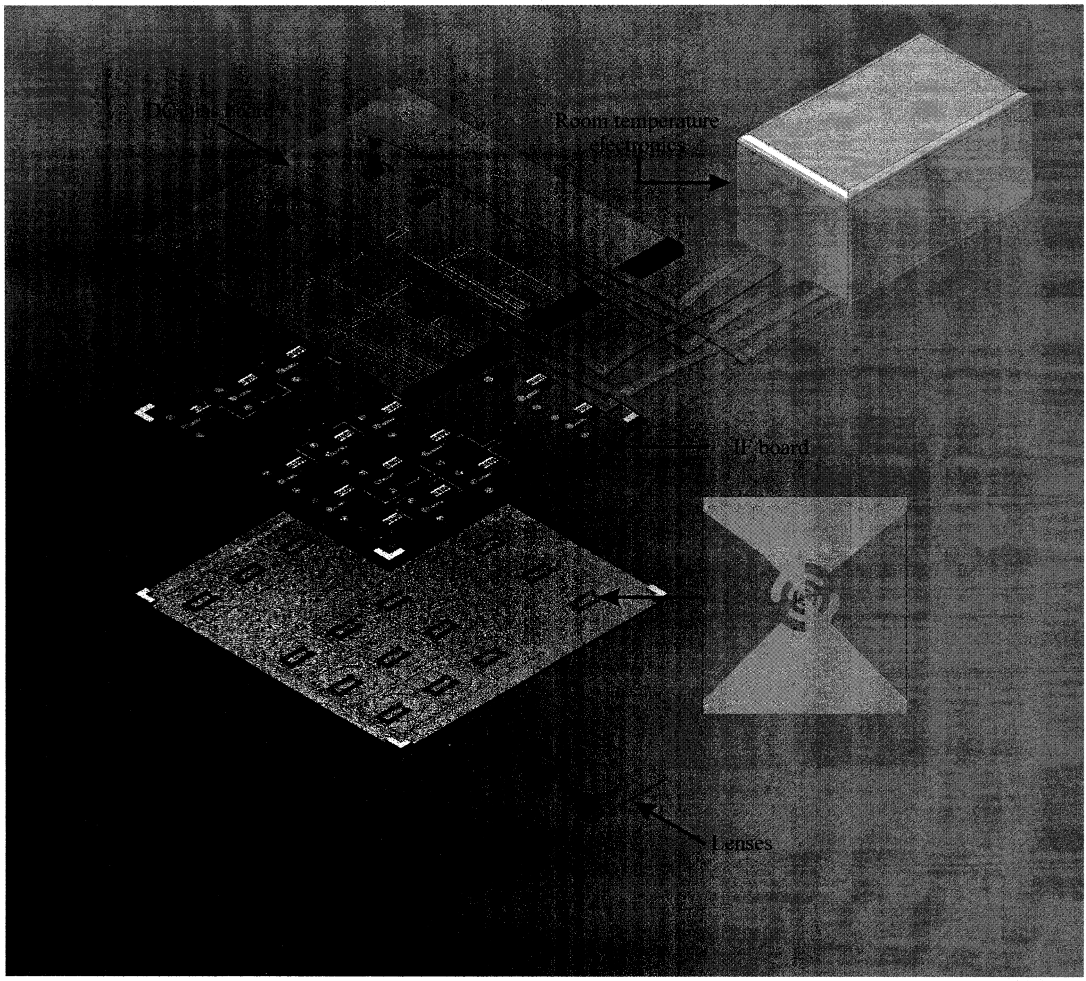

**Figure 1: A proposed configuration for a terahertz heterodyne focal plane array with HEB devices.**

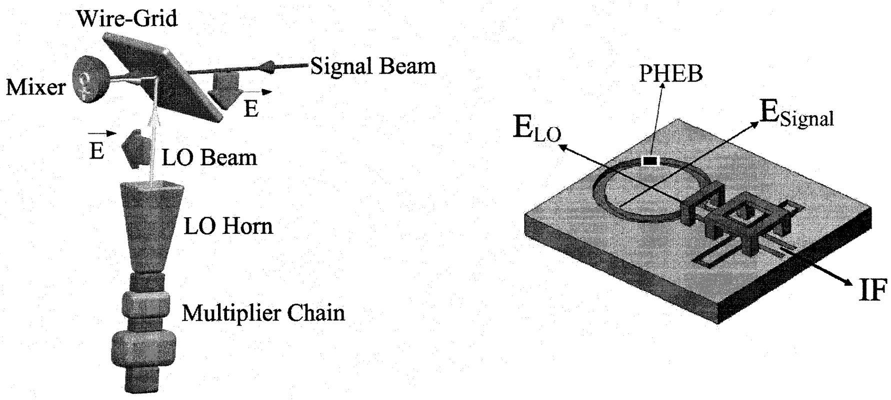

**Figure 2: LO injection scheme using a slot-ring antenna and HEB mixer.**

a few hundreds of nanowatts) only far-infrared (FIR) laser sources have sufficient LO power for an FPA. FIR gas lasers are not tunable and are very costly. The LO power is injected into the HEB device through a diplexer or a beam splitter so only a small portion (1-6%) of the LO power is utilized. Antenna designs used so far with HEB devices dictate that the polarizations of the LO and signal beams are parallel. By introducing slot-ring antennas, the polarizations of the LO and signal beams can be orthogonal to each other, thus allowing us to replace the beam splitter with a simple wire grid for LO injection, as shown in Figure 2. This method of injection was demonstrated to work well for a slot-ring antenna loaded with two Schottky-barrier diodes in the 45 degree positions [2], at 9 GHz and 35 GHz. Since the wire grid has almost no loss, both the signal and the LO will be coupled very efficiently. In the HEB mixer case, only one device can be used since the HEB devices are non-reciprocal. This paper describes the development of slot-ring antennas for HEB mixers at terahertz frequencies.

## II. ANTENNA DESIGN

Slot-ring antennas were developed for use in millimeter wave frequencies with Schottky -barrier diode receivers and other active devices [2,3,4]. This type of antenna is well suited for quasi-optical design configuration where the antenna and mixer are placed on the planar side of a dielectric lens. This configuration yields a symmetric radiation pattern. Most of the energy radiates into the dielectric half-space. Slot-ring antennas can be used with single or dual polarizations. This antenna/lens configuration is compact and of low cost compared to other antenna designs and thus suitable for array configuration. The slot resonance is set by the circumference of the ring where the radius, a, corresponds to one wavelength ($\lambda_g$) in the dielectric half space. A more careful design of a slot-ring antenna calls for the circumference of the ring to be 1.08 $\lambda_g$. The width of the slot, 2w, is set by scaling from lower frequency (10, 35, 94 GHz) designs. A ratio of $w/a=0.025$ results in an antenna resistance of 105 Ω [3]. The intermediate frequency (IF) signal is then extracted through a CPW with two parallel quarter-wavelength open stubs placed a quarter wavelength away from the slot-ring. The purpose of the open stub filter is to introduce an open circuit at the slot-ring port, preventing any leakage of the signal or LO radiations into the IF port. The small dimensions of the open stubs make them preferable to other types of filters, which require a much larger footprint. In order to ensure that only the main CPW mode propagates, air bridges are placed on the filter. The HEB mixer device can be positioned in the orthogonal direction with respect to the CPW port to allow both the signal and LO beams, with the same polarization, to couple into the device. By altering the position of the HEB device to 135 degrees away from the CPW port, as in Figure 2, the polarizations of the signal and LO beams can be modified such that they are orthogonal to each other, as described above. The resulting efficient LO and signal injection represent the main incentive for choosing the slot-ring antenna design. Slot-ring antennas are well suited for use with terahertz PHEBs.

In order to study the coupling of the slot-ring structures at terahertz frequencies, we first designed a slot-ring antenna with a resonance frequency centered at 1.56 THz and a mixer placed at 90 degrees away from the CPW filter. The loading of the device on the slot-ring broadens the response of the antenna and produces a small shift in the resonance frequency. The design produced a slot-ring with a radius of 13.5 μm and a width of 2 μm (w/a=0.074). The width was determined by fabrication restrictions. The w/a ratio is larger than the one analyzed previously, so the design was simulated (see Figure 3) to determine the antenna impedance. At the design frequency of 1.56 THz, the antenna resistance was simulated using HFSS and found to be about 90 Ω. The theory presented in [3] yields about 110 Ω. Both these values are close to what is required to match a typical HEB device (~200 Ω).

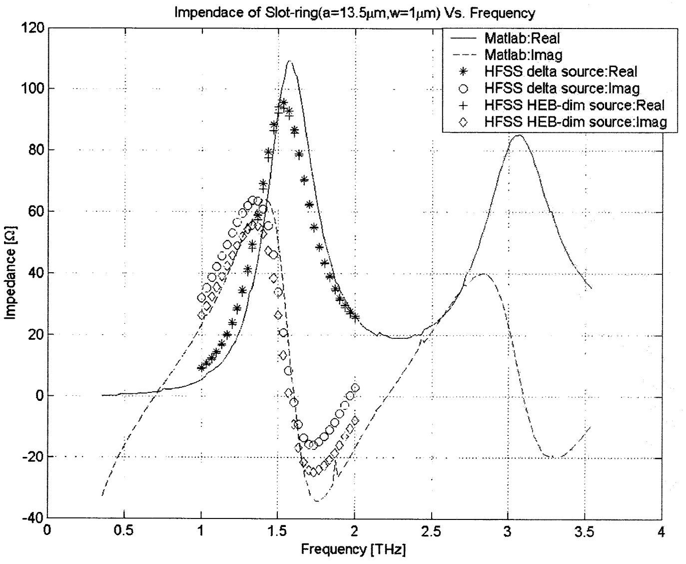

**Figure 3: Slot-ring antenna impedance simulations using both MATLAB and HFSS.**

Future development will study the coupling dependencies of slot-ring antennas with lower w/a ratios centered at terahertz frequencies. Edge effects altered the dimensions of the CPW filter stub compared with the nominal quarter-wavelength value, and our use of the SONNET simulator determined the stub length to be 22 μm at a distance of 19 μm away from the slot-ring. The HEB device is 0.4 μm long and 4 μm wide. The CPW requires air bridges (well-known in MMIC technology at lower frequencies) in order to ensure that only the main CPW mode can propagate. Due to the small dimensions of the structure air bridges were not introduced at this stage. With the HEB mixer device at 90 degrees away from the CPW port, and the LO and signal polarizations in the direction of the device, there is no field at the CPW port and the air bridges can be omitted.

## III. DEVICE FABRICATION

PHEB devices were fabricated on 3.5 nm thick NbN film, which was deposited on silicon substrate by DC magnetron sputtering. The active area of the device was 4 μm wide by 0.4 μm long located in the center of the slot.

Figure 4 illustrates the main steps of the fabrication process. Due to the limitations of standard contact UV lithography, we have developed a process using an advanced stepper lithographic instru-

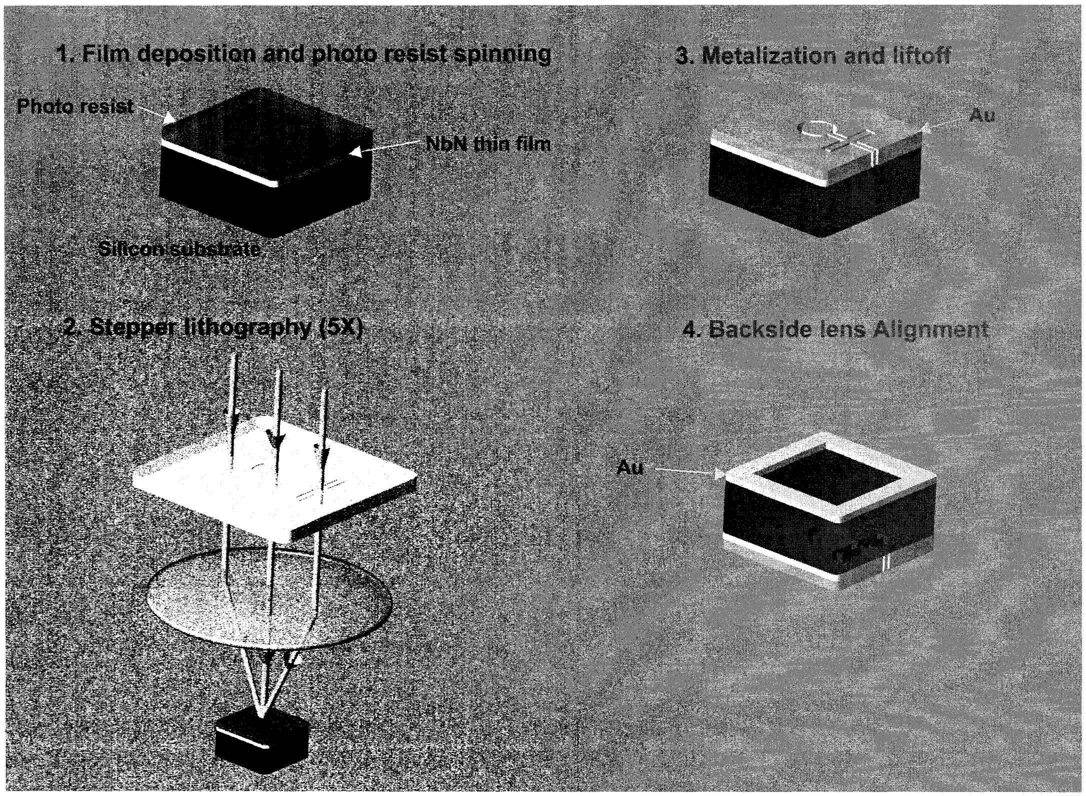

**Figure 4: HEB device fabrication steps.**

ment. This technique utilizes a very short wavelength UV light to reduce diffraction and thus achieve higher resolution. Furthermore, the stepper instrument uses lenses of high numerical aperture to project the exposure light, and consequently achieve a reduction by a factor of five of the image size on the wafer. The stepper lithographic technique is well suited for fabrication of multi-pixel arrays as opposed to electron-beam writing. We have also introduced a bi-level lift-off process that improves the success on this critical submicrometer lift-off step. In addition to the standard photo resist layer, a polymer lift-off resist (LOR) layer was spun first. At a specific pre-bake temperature, the LOR layer yields a 10 nm/sec undercut rate. After the metallization and lift-off steps, a strip of photo resist was patterned on the wafer to protect the device region from the reactive ion etch (RIE) step. Next, the excess NbN film was etched away by RIE.

The last step consists of a backside alignment window for lens positioning. This step was performed by use of a standard contact aligner and an infrared camera. Then, an elliptical silicon lens was affixed to the backside of the substrate with purified bee's wax. A photograph of the slot-ring antenna and PHEB device is shown in Figure 5.

## IV. EXPERIMENTAL SETUP

The lens/substrate assembly was inserted into a mixer block [1], also serves as a bias tee. The mixer block is attached to a copper post, which is thermally anchored at its other end to the liquid helium reservoir of a commercial dewar. A heater controls the temperature of the mixer block. A cooled HEMT MMIC amplifier with a gain of 30 dB is used inside the dewar. This IF amplifier has a pass band from 0.5 GHz to 10 GHz and a noise temperature varying from 5 K to 10 K. The receiver noise temperature was measured with a $CO_2$ laser pumped far-infrared (FIR) gas laser as the LO source. Thin polyester film beam splitters with a thickness of 6 μm acted as a diplexer between the LO and a chopped hot/cold noise source. The LO radiation was focused by an off-axis paraboloid mirror.

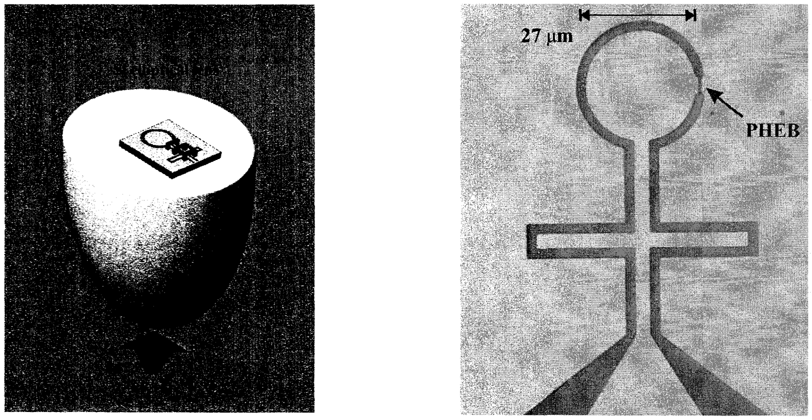

**Figure 5: (left) an illustration of a quasi-optical configuration for the slot-ring antenna design; (right) a photograph of the antenna/ device structure.**

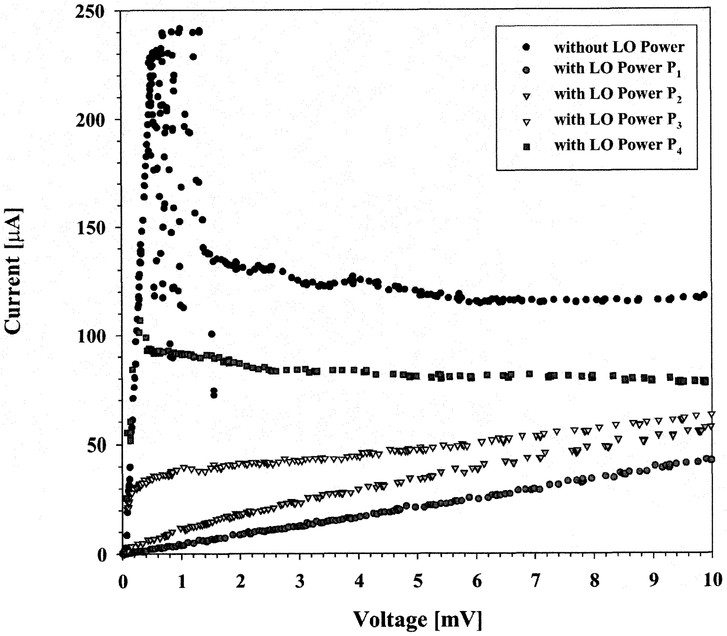

**Figure 6: Measured I-V curves for the HEB device and the slot-ring antenna with no LO power and with decreasing levels of LO power ($P_1$>$P_2$>$P_3$>$P_4$).**

## V. RESULTS AND FUTURE DEVELOPMENT

The room temperature and the 20 K resistance values of one of our first PHEB devices are $R_{300}$=160 Ω and $R_{20}$=270 Ω, respectively. Total coupling efficiency of the structure is 14 dB, partly due to the mismatch between the device resistance (270 Ω) and the antenna resistance (90 Ω). The measured I-V characteristics suggests good HEB performance (see Figure 6). The optimum operating point for the noise temperature measurement is 0.5 mV and 55 µA. The best uncorrected double-sideband noise temperature was 2000 K at 1.63 THz. There was no significant degradation of noise temperature at 1.4 THz confirming the wideband response expected for the slot-ring antenna. This preliminary result demonstrates the feasability of slot-ring antennas in future FPA with many PHEB devices.

The next step in the development of a dual polarization slot-ring antenna at terahertz frequencies is the design for the air-bridge structure. The small dimensions of the antenna makes this task difficult. Our approach is to fabricate the structure illustrated in Figure 7 using the deep reactive ion etching (DRIE) technique on a separate silicon substrate. A window is used on the back side of the slot-ring antenna to ensure 97 % of the power couples to the antenna. Special alignment marks are designed for assembly with the device substrate. This technique is well-suited for future development of multi-pixel arrays.

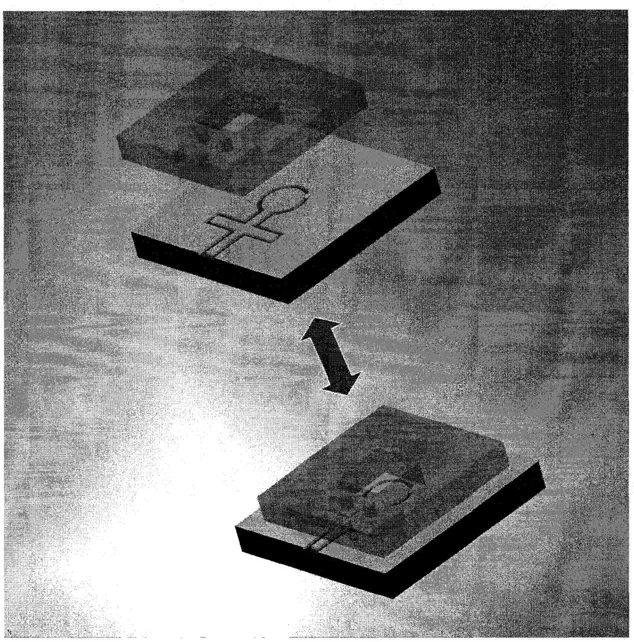

**Figure 7: Concept for an integrated air-bridge/antenna design.**

## ACKNOWLEDGMENTS

This work was supported by NASA through grant NRA-00-01-SARA-012 to NIST and UMass/Amherst, and contract NAS1-01058 to UMass/Amherst.

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