# Development of a 585 GHz One-Dimensional Diffusion-Cooled Niobium HEB Mixer Imaging Array Based on the "Reverse-Microscope" Concept

L. Liu, Q. Xiao, H. Xu, A. W. Lichtenberger, and R. M. Weikle, II

*Abstract*—**We have designed and fabricated prototype 585 GHz one-dimensional (1-D) slot-ring antenna (SRA) coupled d-HEB imaging mixer arrays (four pixels) based on the "reverse-microscope" concept. Due to the small element spacing, the mutual coupling between adjacent SRA's in the mixer array can not be ignored. ADS momentum simulation has been performed to study the self- and mutual- impedances of the SRA array with various element spacings. The element SRA off-axis radiation patterns (with silicon lens) have been calculated using ray-tracing techniques and the imaging angular resolution has been predicted. Fabrication and measurement systems are discussed.**

***Index Terms*—Diffusion-cooled, hot-electron bolometer, imaging array, reverse-microscope.**

## I. Introduction

HIGHLY-sensitive receivers employing superconducting diffusion-cooled hot-electron bolometers (d-HEB) have been intensively studied and applied for millimeter-wave and far-infrared (FIR) imaging and remote sensing in recent years [1-2]. However, for many applications, only one pixel of object information from the receiver is not sufficient. To map the distribution of radiation intensity, for instance, many pixels of imaging information are required. Although mechanical scanning can be applied to a single element mixer to fulfill this requirement, this approach can present problems due to the longer observing time. Imaging mixer arrays are needed for these applications since they can greatly reduce the observing and processing time by recording imaging information in parallel.

In 1982, Rutledge *et al* proposed a high-resolution imaging antenna array diagram with a "reverse-microscope" optical configuration [3]. On the bases of this concept, a UC-Davis group is currently working on a 90 GHz Schottky diode mixer array using bow-tie antennas [4]. Bow-tie antennas are difficult to use, however, for high resolution imaging applications in the THz region as they are not sufficiently compact for single imaging element design. JPL proposed a 1.6 THz one dimensional array using diagonal horns feeding waveguide receivers [5]. However, two-dimensional arrays based on this scheme are difficult to realize. More recently, another approach called the "fly's-eye concept" has been proposed [6]. A 3-element HEB focal plane array based on this concept has been reported demonstrating promising performance [7]. In this approach, each mixer element uses a separate imaging lens, which may cause some difficulties for design, fabrication and assembling.

This paper describes a prototype 585 GHz one-dimensional slot-ring antenna (SRA) coupled d-HEB mixer arrays (four pixels) that has been designed and fabricated based on the "reverse-microscope" concept. Due to the small element spacing, the mutual coupling between adjacent SRA's in the mixer array can not be ignored. ADS momentum simulations have been performed to study the self- and mutual-impedances of the SRA array for various element spacings. The off-axis radiation patterns have been calculated using ray-tracing techniques, and the imaging angular resolution has been predicted. Fabrication results and the measurement setup are presented and discussed.

## II. Array Design And Simulation

### A. *"Reverse Microscope" Configuration*

Fig. 1 shows a diagram of the proposed d-HEB imaging mixer array mounted on an extended hemispherical silicon lens. Each of the imaging elements employs a receiving antenna structure as the coupling component in which a

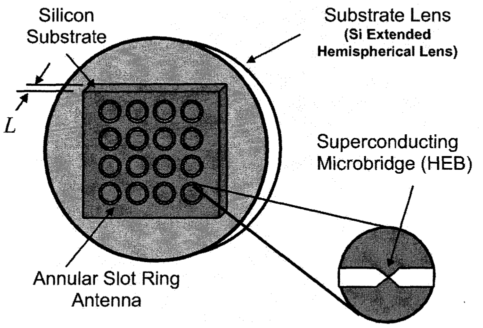

**Fig. 1**: Schematic of a d-HEB imaging mixer array mounted on an expanded silicon hemispherical lens (expansion length *L*).

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superconducting d-HEB micro-bridge is integrated. An input image signal is focused through an objective lens (not shown in fig.1), the substrate lens and the substrate onto the mixer array. Images are obtained by measuring the IF output signal from 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 can be eliminated and hence a high imaging resolution can be achieved [3].

### *B. Mixer Array Element Design and Mutual Coupling*

Single element receivers and mixers employing HEB's have been proposed and studied by a variety of research groups including the Jet Propulsion Laboratory (JPL) in Pasadena, CA [2], and the Delft University of Technology in the Netherlands [1]. The RF circuit design and antenna structures utilized in these receivers, however, have not always been suitable for imaging mixer array applications. The slot-ring antenna provides a compact structure, making it an attractive candidate for the proposed mixer imaging arrays. 585 GHz d-HEB mixer element coupled with SRA's have been studied previously [8] and shown in Fig. 2 is the schematic of a one-dimensional array containing four SRA's. For operation at 585 GHz, each SRA has a radius *a,* of 36 *μm* and a slot width, *w,* of 2.6 *μm*. High-resistivity silicon is chosen as the substrate due to its high dielectric constant ($\varepsilon_r = 11.7$), which results in a high directivity and efficiency for the receiving antenna. The hemispherical silicon lens (see fig. 1) has a radius $R = 4.5$ *mm*. The radiation patterns of a single element SRA mounted on the silicon lens have been calculated in [8] using ray-tracing technique [9] and an extension length $L = 1.6$ *mm* (see Fig. 1) is selected for the highest antenna directivity while maintaining an acceptable Gaussian coupling efficiency.

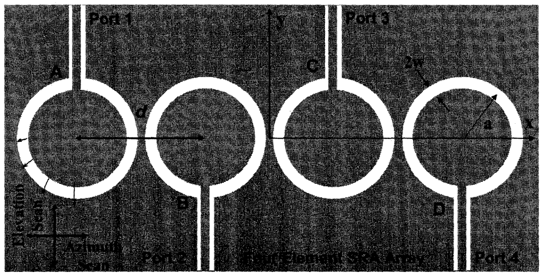

**Fig. 2:** Schematic of a one-dimensional SRA array with element spacing of *d*. Each SRA has a radius *a,* of 36 *μm* and a slot width, *w,* of 2.6 *μm*.

Due to the small element spacing required ($\sim\lambda_d$, where $\lambda_d$ is the wave-length in the silicon substrate) for diffraction-limited imaging, the mutual coupling between adjacent SRA's in the mixer array can not be ignored. ADS momentum simulations have been performed to study the self- and mutual- impedance of the four-element SRA array with various element spacings. As shown in Fig. 2 ($d=0.8\ \lambda_d$), the element-A's (or D) the self-impedance is $Z_{0A}$~75+j0 Ω, and the mutual-impedance $Z_{mA}$ ($Z_{mA}=Z_{21}+Z_{31}+Z_{41}$) is estimated to be approximately 1.6+j0.8 Ω at 585 GHz. For element B (or C), the self- and mutual-impedance are $Z_{0B}$~75+j0 Ω, and $Z_{mB}$~4.2+j0.8 Ω ($Z_{mB}=Z_{12}+Z_{32}+Z_{42}$), respectively. Compared to self-impedances, the mutual-impedances are much smaller. This has a relatively minor effect at such an element spacing of 0.8 $\lambda_d$. An EMF-based analysis has also been developed to study the SRA self- and mutual- coupling analytically. Results will be presented elsewhere [10].

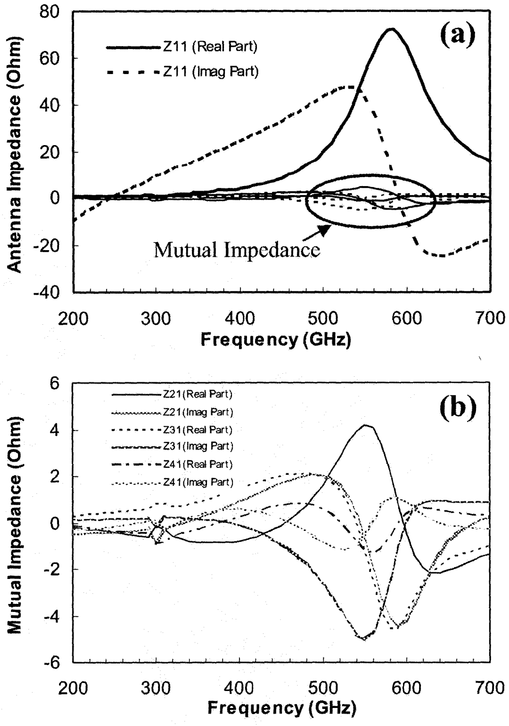

**Fig. 3:** ADS momentum simulated (a) self- and (b) mutual-impedances of element A in the 1-D SRA array.

### *C. Off-axis Radiation Patterns and Angular Resolution*

The element SRA off-axis radiation patterns for various spacings in the array have been calculated again using ray-tracing technique. As shown in Fig. 4, the element SRA pattern has a 3-dB beam width of $\theta_{3\text{-dB}} \sim 3°$ with side-lobe levels less than -10 dB. The beam spacings between adjacent SRA's are $\Delta\theta \sim 4.0°$, 5.0°, and 5.7° with crossover power level around -7.2 dB, -11.0 dB, and -12.5 dB for $d = 0.8\ \lambda_d$, 1.0 $\lambda_d$, and 1.1 $\lambda_d$, respectively. According to the imaging theories, the angular imaging resolution is determined by the beam pattern spacing and limited by 3-dB beam width. The relationship between the angular imaging resolution and SRA element spacing is calculated and shown in fig. 5. With decreasing element spacing, the imaging resolution increases nearly linearly. However, the imaging contrast may become worse. Thus, a trade-off between imaging resolution and contrast must be made by selecting appropriate element spacing in the one-dimensional mixer array.

## III. ARRAY FABRICATION

The d-HEB mixer imaging array fabrication used in our research work is based on a process developed by the University of Virginia's Superconducting Devices and Materials Research Group [11]. The process begins 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 consisting of the SRA array, low-pass filters (LPF's) and tuning circuits.

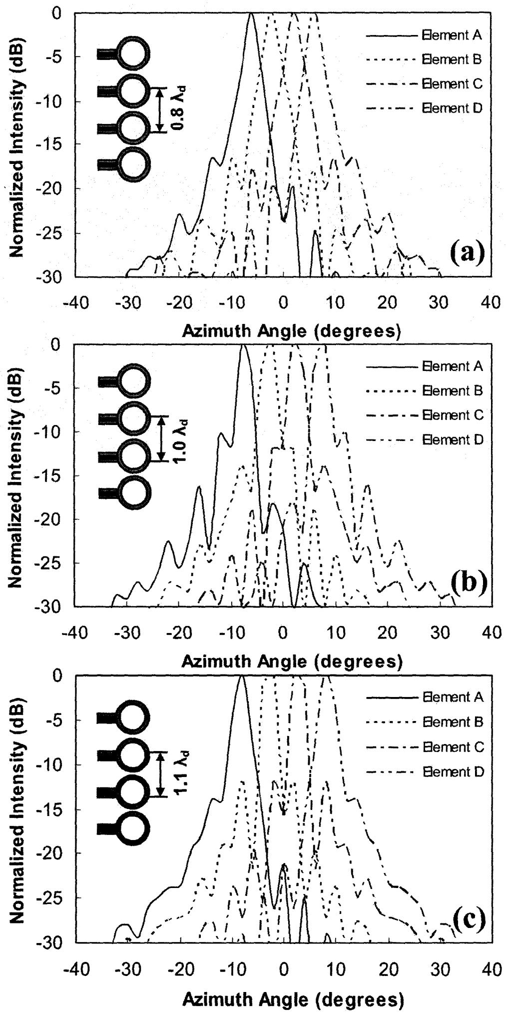

**Fig. 4:** Off-axis element radiation patterns for 1-D SRA array calculated using ray-tracing technique.

After the base layer is defined, the mixing elements – the HEB bridges – are then fabricated using a two-step electron-beam lithography (EBL) process. In the first EBL step, a bilayer PMMA (950/495) is spun on the base layer as the resist structure. The d-HEB cooling pad patterns are then directly written by an electron-beam controlled by the Nano-Pattern Generation System (NPGS). The trilayer Nb/Au/Nb (10 *nm*/50 *nm*/10 *nm*) cooling pads are hence generated and the Nb microbridge lengths are defined after a lift-off process. During the second EBL step, the HEB bridges are first patterned by the NPGS with single layer PMMA (950). A Au/Nb (20 *nm*/20 *nm*) bilayer is deposited, and after lift-off, bridges are left spanning the cooling pads.

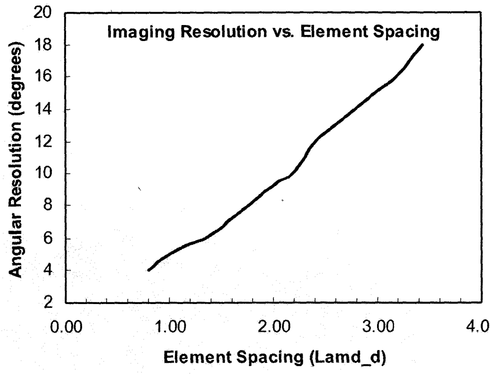

**Fig. 5:** Relationship between the angular imaging resolution and element spacing predicted using ray-tracing technique.

Reactive-ion etches (RIE) are then performed to remove the unwanted metal layers. First, an argon RIE is used to remove the Au capping layer. An $SF_6$-based RIE is then used to etch the exposed Nb layer on top of the HEB bridges, followed by another Ar RIE to remove the other layer of Au on top of the bridge, which leaves Nb bridges between the gold cooling pads. The length of the HEB-bridge is chosen to be approximately 200 *nm*, a value significantly less then the inelastic electron-phonon length, resulting in a diffusion-cooled HEB device. The bridge width can be modified to produce the desired device resistance for circuit matching since the sheet resistance for 10 *nm* thick Nb film is known to be 30-35 Ω/square in the normal state [11].

From the ADS momentum simulation described in section II (B), the elementary SRA in the array has a self-impedance around 75 Ω. A d-HEB with such a resistance requires more than two squares of Nb thin film, hence the resulting device length may risk exceeding the diffusion cooling length. In addition, the resolution of the NPGS employed at the University of Virginia is approximately 100 *nm*. Decreasing the Nb bridge width will result in fabrication difficulties. Moreover, an HEB with substantial bridge width is required to reduce the susceptibility of electrostatic discharge during the measurement process. A short HEB is preferred for a receiver system to exhibit broad IF bandwidth and fast response. Thus, two impedance-matching schemes are proposed and studied to optimize power coupling from the SRA's to the mixer element. One scheme employs simple quarter-wavelength impedance transformers while the alternative approach utilizes two d-HEB's fabricated in series at the feed point of the SRA's, as shown in Fig. 6 the SEM pictures for the fabricated 1-D d-HEB mixer imaging arrays.

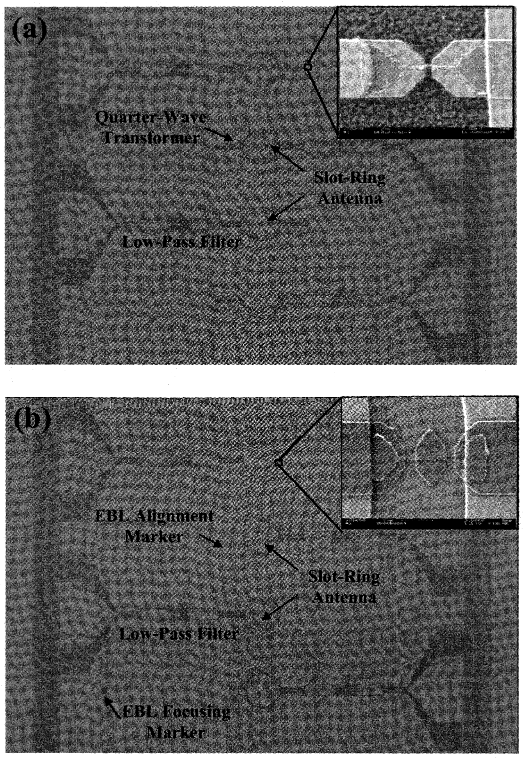

**Fig. 6:** SEM pictures of fabricated 1-D d-HEB mixer imaging arrays: (a) scheme-I mixer array with impedance transformers; (b) scheme-II mixer array with two HEB's in series.

## IV. MEASUREMENT SETUP

A quasi-optical mixer array block has been designed as shown in Fig. 7. An IF output supporting chip containing four CPW transmission-lines (50 Ω) has been fabricated on a high-resitivity Si wafer with thickness of 1.1 *mm*. The HEB array chip will be mounted using cryogenic epoxy. This output supporting circuit also serves as the extension length for the SRA array and yields a total extension length of 1.6 *mm*. Another transmission-line circuit fabricated on a Duroid substrate with four SMA connectors is utilized to output the IF signal to bias-T's. The quasi-optical mixer block was been fabricated and installed into an HD-3(8) dewar system for cryogenic tests and RF measurements. This dewar can be cooled to 4.2 K with a hold time of around 30 hours. For prototype demonstration, a commercial SP4T coaxial switch will be employed to select one IF signal from the four outputs. The selected IF signal is output to an isolator and low noise amplifier (LNA) before being fed to the external IF chain. An RF measurement system has been set up to characterize the performance of the mixer array, including the conversion gain, coupling efficiency and noise temperature. In this system, a VDI (Virginia Diodes, Inc.) 576 – 640 GHz FEM (Frequency Extension Module) is employed to provide LO power. A hot/cold load is utilized to provide blackbody radiation for a system Y-factor measurement. Both the LO and RF are coupled into the cryogenic dewar through a set of lenses and mirrors. Imaging experiments will be performed with this system to evaluate its performance at 585 GHz

## V. CONCLUSION

A 585 GHz one-dimensional slot-ring antenna (SRA) coupled d-HEB imaging mixer arrays (four pixels) based on the "reverse-microscope" concept has been designed and fabricated. ADS momentum simulations have been performed to study the self- and mutual- impedances of the SRA array with various element spacings. The element SRA off-axis radiation patterns (with silicon lens) have been calculated using ray-tracing techniques and the imaging angular resolution has been predicted. Fabrication and measurement systems are discussed.

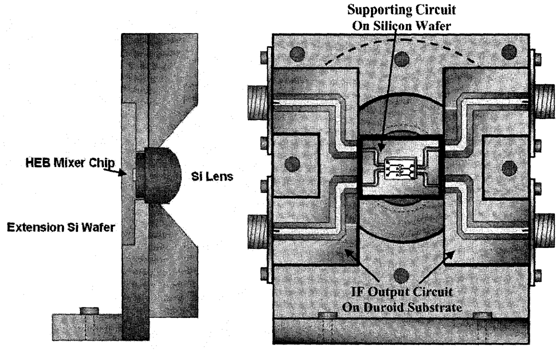

**Fig. 7:** Schematic drawing of the designed 1-D d-HEB mixer imaging array quasi-optical block.

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