# Planar Multi-Pixel Heterodyne Array Architecture Suitable for Large Arrays

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**Program: FY21 R&TD Strategic Initiative** **Strategic Focus Area: Long-Wavelength Detectors**

## Objective:

The objective of this effort is to develop submillimeter-wave planar heterodyne array architecture that will lead to hundreds of pixels in a highly compact and efficient instrument package. One of the key objectives is the efficient use of available local oscillator signal allowing to extend the pixel counts of such instruments compared to the state-of-the-art. This will be achieved through highly innovative planar coupling methods and architectures. Planar architecture with photolithographic fabrication will allow precise process control, quality assurance, and repeatable performance. An important enabling technology is silicon microfabrication technique that allows the fabrication of smaller features, higher accuracy, and better surface roughness compared to metal machining. Moreover silicon microfabrication based packaging technology enables a more compact architecture, improved sensitivity, larger pixel-count, and mapping of the field of observation. We are developing a planar architecture for a modular multi-pixel 1.9 THz heterodyne array that will provide an efficient LO and RF signal coupling. In this scheme, the RF is efficiently coupled from one face of the array and the LO signal is quasi-optically distributed amongst the multiple receivers. The LO coupling in this technique is highly efficiently and broadband.

## Approach and Results:

The basic layout of the proposed front-end multi-pixel architecture is shown in Fig. 1. It is composed of a planar HEB mixer array fabricated on thin silicon membrane and integrated on silicon micromachined packaging and two array of lenses couple the RF and LO signal from the front and back respectively. We are using a total quasi-optical approach using a planar antenna architecture and integration is being done in such way that the HEB mixers will not be diced individually and hand assembled, but a full wafer containing all the HEB junctions and coupling structures will be fabricated photolithographically and integrated with the lens arrays. However, in the initial stages, we will show the performance with individual devices. Also, for demonstration purposes, we decided to design and fabricate a 2x2 hot electron bolometer (HEB) based receiver array that will be fabricated using stacked silicon micromachined wafers.

**Antenna and Quasi-Optical Design:** A novel resonant leaky-wave (LW) antenna has been designed for the RF- and LO signal coupling. The antenna is improved with respect to the conventional LW antenna in terms of bandwidth and fabrication difficulty. The difference is the addition of a matching layer between the dielectric lens and resonant air cavity. Thanks to this matching layer, no double-slot iris is necessary to terminate the circular waveguide, easing the fabrication enormously at this high frequency. The matching layer can easily be synthesized by perforating the silicon, using in-house silicon micromachining technology, until a specific porosity is achieved.

The feed is optimized together with an elliptical silicon lens in terms of aperture efficiency. In this way, an aperture efficiency higher than 80% is achieved from 1.4 THz to 2 THz and higher than 70% up to 2.1 THz. The lens diameter is determined by the desired periodicity of about $4F_{\#}\lambda_0$ for a $F_{\#} = 8$ optical system. A compact waveguide transition, suitable for silicon micromachining, is designed that converts the $TE_{11}$ circular waveguide mode to a $TE_{10}$ rectangular mode that is coupled to the HEB mixers. Similarly, an identical array of leaky-wave lens antennas will couple the LO signal to the HEB mixers. This array is mirrored with respect to the RF lens array and will be integrated in the same wafer stack. Fig. 2 shows the quasi-optical design of the leaky-wave antenna for RF and LO signal coupling (a), and the designed feed for the transition for the array (b).

Fig. 3 shows the wafer stacks for the 2x2 HEB array that we have designed and how the different layers stack up with each other. On the tope layer, we have the 2x2 lens antenna array for the RF signal followed by a matching layer and leaky-wave cavity. Then there is a circular waveguide to rectangular waveguide transition to couple to the HEB mixer layer. On the other side we have the similar lens array layer for LO coupling. On the right of Fig. 3 is the geometry of the lens antenna and its simulated performance. The results show good directivity, gain, and aperture efficiency. We are currently fabricating these wafers.

**SiGe Based Low-Noise IF Amplifier Design:** The goal of this part of the work has been to develop low-power cryogenic low-noise amplifiers (LNAs) for a large format array. Even though for this particular task, we are designing a 16-pixel array receiver, we wanted to have a modular design so that the IF LNAs are modular and can work well with large format arrays. The LNAs will be at 4K physical temperature and we aim to have less than 2mW of DC power consumption with a goal of 1 mW DC power consumption per pixel. We are also targeting to have 15 dB gain and somewhere in the range of 5K noise temperature.

We carried out detailed simulations using the physical elements provided by the IHP process design kit, including the Wilkinson power combiner. We did this using Keysight ADS Momentum software, to capture electromagnetic effects out to the unity gain frequency of the design. This required modification of the process stack-up, contained within the design kit, to turn off noise sources that would disappear at cryogenic frequencies. Unfortunately, we were not able to excise all excess noise sources from the simulator and provide a clean estimation of noise across our passband. Noise, gain and match plots are shown in Fig. 4. From the noise plot, te(2) on the left of the figure, it can be seen that the noise has several rapid steps and glitches. These jumps are unphysical, although the region from 2-3 GHz matches in general the behavior using lumped components. We view incomplete knowledge of the noise as low risk as we have previous experimental evidence that the loss mechanism disappears for spiral inductors, metal-insulator-metal (mim) capacitors, chip wiring, and bond pads at cryogenic temperatures. Additionally, the match and noise are smooth functions of frequency and well behaved at the frequencies exhibiting jumps in the noise.

Following a design review, the LNA went into final layout using Cadence design tools (the EM simulations and pre-layout were completed in ADS). The final layout of the LNA is shown in Fig. 4 (right). It has been submitted to IHP for fabrication. Also included on the run is a discrete transistor test structure, so that the HBTs themselves maybe characterized for noise, should this prove important. During the final layout, IHP was contacted several times for review of the layout, to ensure we maximized chances for first pass success. These conversations resulted in changes to our M1 ground plane, as well as interconnects between substrate, active regions, and ground. Professor Bardin's group, at University of Massachusetts Amherst, was also consulted to ensure we had made the appropriate device scaling based on their report of IHP HBT cryogenic noise performance. Following design submission, we will work on the packaging of the LNA for testing at 4K in a 50 Ohm connectorized environment.

**Integrated System:** Finally, Fig. 5 shows the schematic of how the different components will be integrated into the 2x2 receiver array.

## Background:

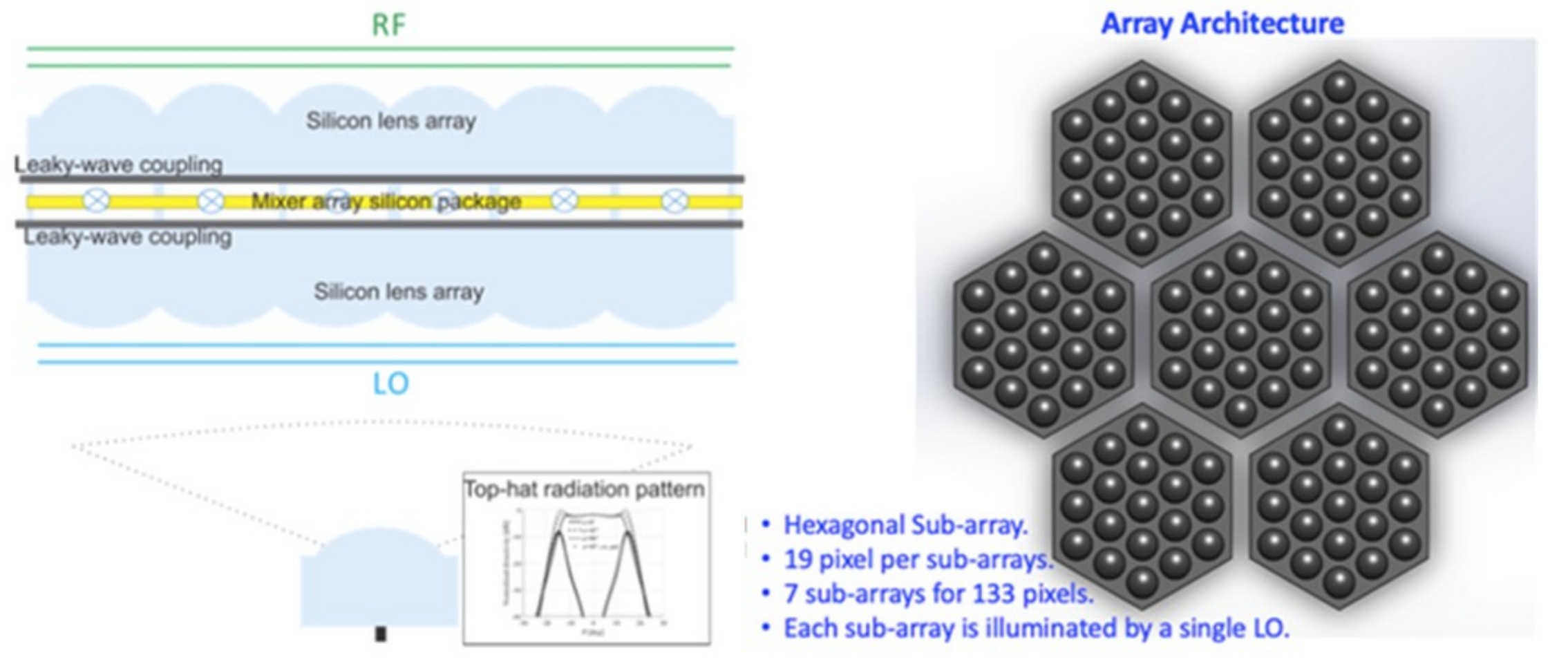
Current state-of-the-art heterodyne receivers at submillimeter wave frequencies are based on the fabrication and assembly of several metal blocks containing the receiver front-end. This technology is constrained by the tolerances and accuracies achieved in the fabrication and assembly processes. This limitation has an impact on the performance in terms of limited number of pixels resulting in poor sensitivity and achievable mapping speed. Moreover, the current method of combining LO and RF signal into the mixer by using a thin Mylar film beam-splitter s very inefficient. This method discards at least 90% of the LO power. For a single-pixel configuration this power loss is still acceptable, as the required LO pump to feed an HEB mixer low. However, current state of the art multi-pixel receivers are still relying on the same principle, using one LO source per mixer pixel, and dismissing 90% of the power in the beam-splitter. In waveguide based LO distribution scheme, available LO power is divided using Y-junction power dividers. At frequencies beyond a couple of hundred gigahertz, the waveguide losses are substantial, leading to a very inefficient LO coupling scheme, limiting the pixel count in an array.

## Significant Benefit to JPL and NASA:

Under this long wavelength initiative, the emphasis is two-fold: on the one hand, there is a drive to mature existing technologies to a stage where they can help bridge gaps in technological needs for instruments that can be proposed for future flight missions on somewhat short time-scale. On the other hand, this initiative is also aiming at taking a long-term view, coming up with new technology solutions for building a new class of instruments to do more or better science. This work addresses the second need. This work will change the way large-format multi-pixel heterodyne instruments are built and deployed for future astrophysics missions.

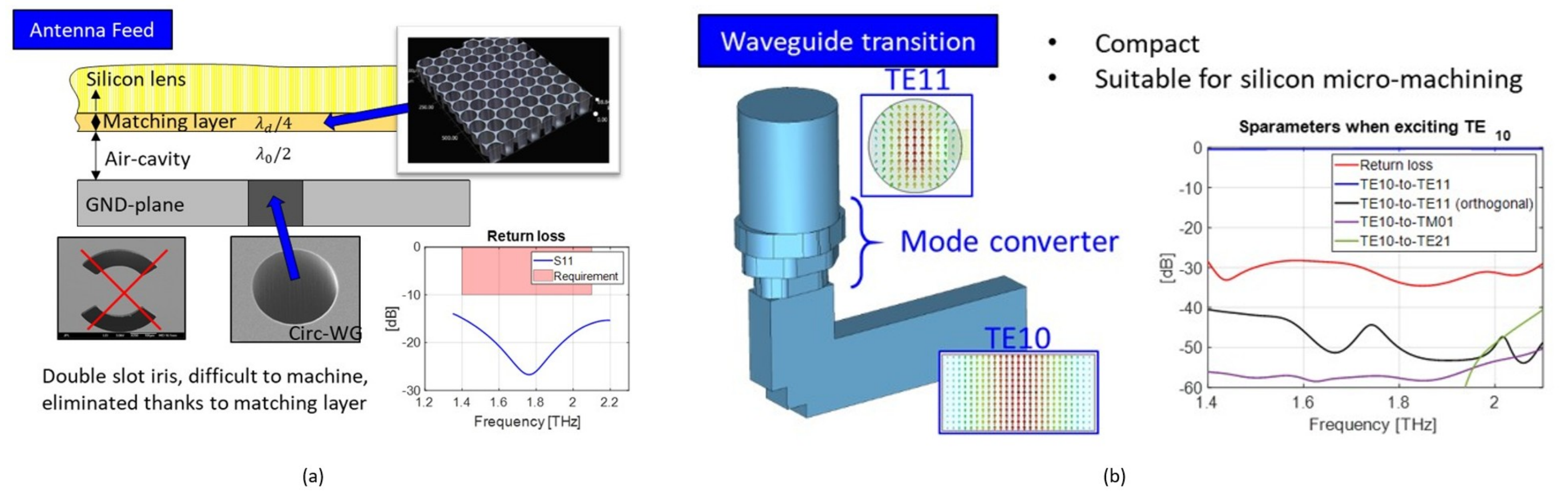
There are multi-layers of innovation in this concept that will allow significant progress of the state-of-the-art. This architecture will be compact and power efficient for multi-pixel arrays. By avoiding use of the conventional beam-splitter and wire grids, where 90% of the power is typically lost in the RF and LO coupling, we can use just a single LO source to feed multiple-HEB mixer chips. This architecture simplifies the fabrication and assembly for multi-pixel arrays. The entire array will be fabricated on a single wafer and thus, avoiding the hand assembly and alignment of multiple devices. Hence reducing the risk of failure by manipulation. This architecture can also provide improved sensitivity. The improved coupling and silicon packaging will decrease the total of RF loss, which translates into an improvement of sensitivity.

Through this work we are showing that a planar multi-pixel array design is possible and a modular design approach will enable instruments with many more pixels than the traditional approaches are being currently used.



- Hexagonal Sub-array.
- 19 pixel per sub-arrays.
- 7 sub-arrays for 133 pixels.
- Each sub-array is illuminated by a single LO.

Fig. 1: Schematic of the basic architecture of the multi-pixel planar terahertz heterodyne receiver array.



Double slot iris, difficult to machine, eliminated thanks to matching layer

- Compact
- Suitable for silicon micro-machining

Fig. 2: Quasi-optical design of the leaky-wave antenna for RF and LO signal coupling (a), and the designed feed for the array and its expected S-parameters.

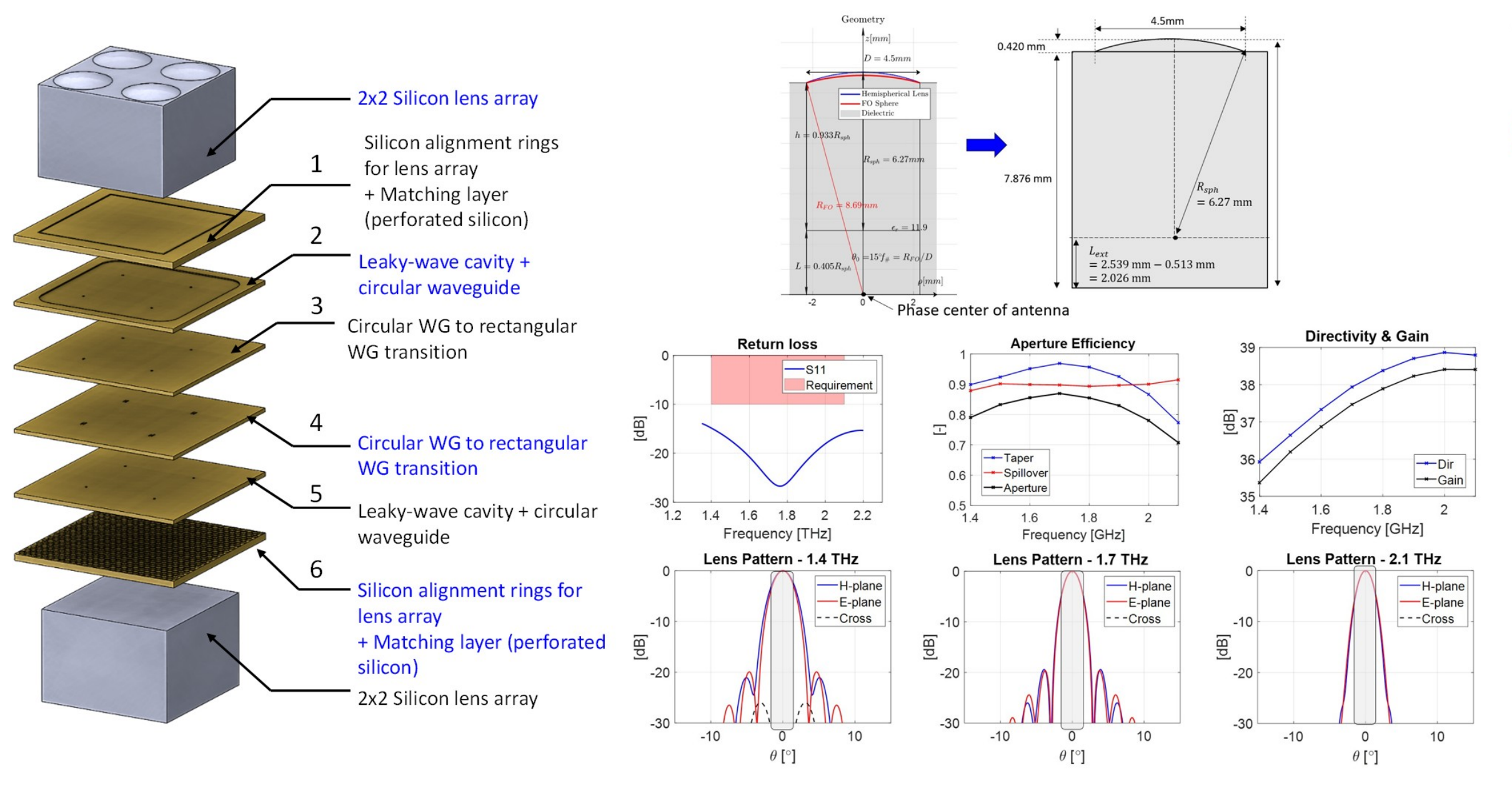


Fig. 3: Wafer stack for the 2x2 HEB receiver array. Details of the antenna structure and expected performance.

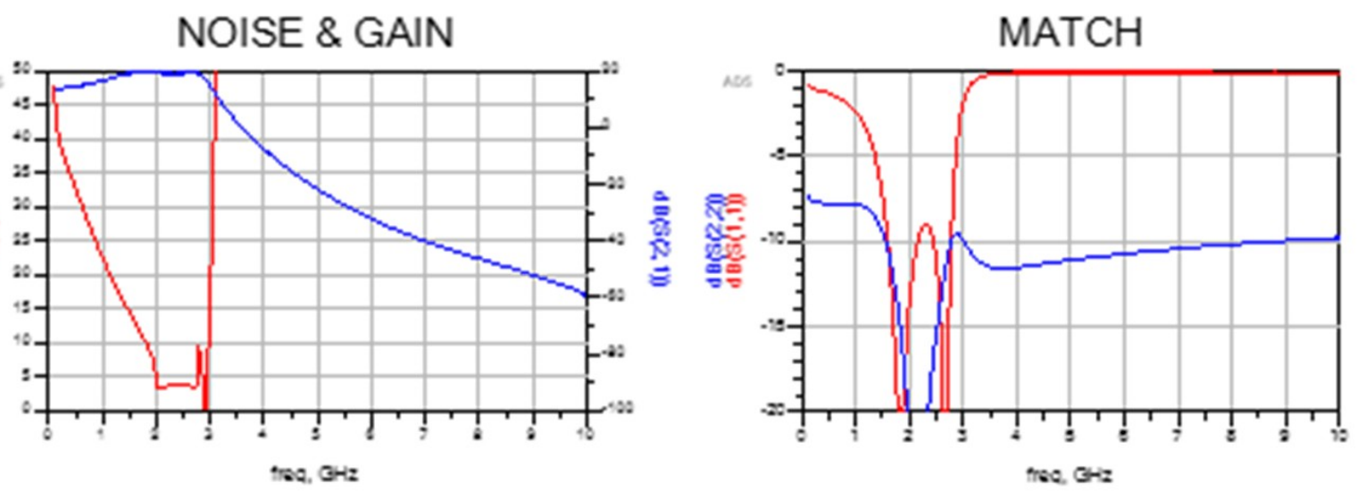
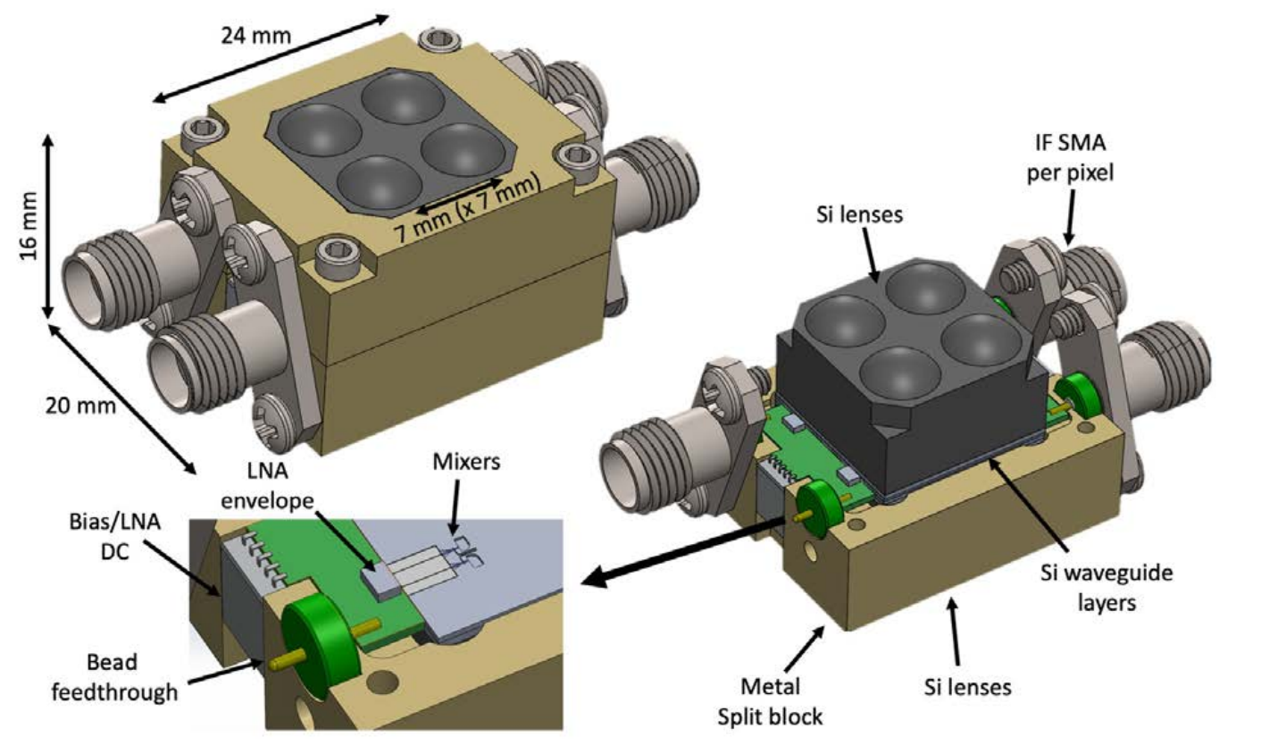


Fig. 4: Noise, gain, and match of the LNAs, incorporating Momentum simulations of passive structures (left). Layout of completed LNA (right). Device dimensions are 1.52 x 1.125 mm.

Fig. 5: Schematic of how the different components will be integrated into the 2x2 receiver array.



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