Design of a 350 GHz Circular Waveguide Superconductor-Insulator-Superconductor Mixer for Array Applications

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***Abstract*—We present the design of a superconductor-insulator-superconductor (SIS) mixer fed with a 2-probe antenna mounted in a circular waveguide, hence avoiding the need for a rectangular waveguide that is often difficult to machine at high millimetre and sub-millimetre frequencies. The mixer is designed to operate from 275–375 GHz, covering a similar frequency range to the HARP-B receiver of the James Clerk Maxwell Telescope. Each antenna probe is connected to a separate but identical mixer circuit comprising three SIS junctions connected in series to reduce the parasitic capacitance, and the relevant tuning circuits and RF chokes. The down-converted IF power at the output of each mixer branch is expected to be combined using either a microwave Wilkinson power combiner or a 180° hybrid, to recover the full signal strength. In this paper, we present in the detail the electromagnetic simulations of each RF component making up the mixer chip, as well as the performance of the entire 2-probe mixer including the RF and IF performance predicted using SuperMix, a software package developed based on Tucker's theory of quantum mixing. Finally, we show how such circular waveguide SIS mixers can be easily populated onto a simple split-block to form a 16-pixel array.**

***Index Terms*—Superconductor-Insulator-Superconductor (SIS), Heterodyne Mixers, Focal Plane Array, Circular Waveguide, Probe Antenna**

I. INTRODUCTION

SINCE the establishment of the National Astronomical Research Institute of Thailand (NARIT), astronomical research and developments in Thailand have expanded rapidly in recent years, including the building of the 2.4 m Thai National Telescope (TNT) and the Thai National Radio Observatory (TNRO) which oversee the operation of the 40 m Thai National Radio Telescope (TNRT) and the 13 m VLBI2010 Global Observing System (VGOS) telescope. NARIT also plays an important role as the regional centre for South East Asian (SEA) countries e.g., hosting the SEA Astronomy Network, the SEA Regional Office of Astronomy for Development and International Training Centre for Astronomy under the auspices of UNESCO, and the International Astronomical Union (IAU) regional office in SEA, which focuses on developing strategic plan to improve the overall education and capital development in SEA via involvement in promoting Science, Technology, Engineering and Mathematics (STEM) subjects in universities & research, children in primary and secondary schools and public outreach.

Although NARIT has been building the infrastructures for instrumentation at radio and optical wavelengths, including the establishment of mechanical/electronic workshops and laboratories for instrument construction, their involvement in millimetre (mm) astronomical receivers is still at the nascent stage. Through the collaboration with the UK, in particular via the support of the UK STFC-NARIT Newton Fund, NARIT aims to accelerate research in astronomy and extend its technological capabilities and infrastructures into the mm wavelengths, one of the modern sciences which utilises the most cutting-edge technologies such as cryogenic engineering, quantum superconducting devices etc. In particular, Thailand has also recently joined the East Asia Observatory (EAO) which operates the James Clerk Maxwell Telescope (JCMT) at Hawai'i, the largest single-dish sub-mm telescope in the world. One of the strategic plans of EAO for the upcoming decade is to upgrade JCMT's existing mm-wave focal plane array (FPA), HARP-B [1], a 16-pixel superconductor-insulator-superconductor (SIS) mixer array operating near 350 GHz. Both EAO and NARIT have already expressed strong interest in collaborating to build such an array receiver.

However, the development of large pixel count FPA at high frequency is challenging, as the dimension of various components comprising the FPA become increasingly smaller and difficult to fabricate to the required accuracy without state-of-the-art machines. For example, fabrication of a high aspect ratio rectangular waveguide [2], [3] to couple the energy from the telescope to the SIS mixer at mm and sub-mm frequency range often requires an investment of an expensive 5- or 6-axis milling machine with high accuracy. Therefore, in this paper, we describe our effort to simplify the construction of the FPA via novel innovation and design of the SIS receiver using planar superconducting circuit technology to ease the build of such FPA. Furthermore, the performance of large format FPA is often boosted with the use of membrane technologies such as silicon-on-insulator technology [4], [5], [6], to ease the mounting, alignment and shaping of mixer chip. Unfortunately,

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such technologies are not commonly shared and are only available from a few laboratories worldwide. Therefore, we explore the use of conventional substrate technology to form our mixer chip without compromising the performance of our array. Finally, we also utilise the now widely used smooth-walled horn technology to form the FPA, further simplifying the design of the FPA.

II. Mixer Chip Design

In this section, we describe the design of our SIS mixers which utilise a 2-probe antenna housed within a circular waveguide connected directly to the smooth-walled horn. We utilise the commonly-used quartz substrate technology to form our mixer chips and ensure that we can achieve optimal coupling from the incoming signal to the tunnel junctions without the need for ultra-thin membrane technology. We also utilise three moderately large junctions connected in series to broaden the RF and IF bandwidth of our SIS receiver, and make sure that our mixer design can be easily populated throughout an easily machined mixer array block to form the FPA.

A. 2-Probe Antenna

Most of the SIS mixer chip deployed to dates are housed within a rectangular waveguide, utilising for example a radial probe [7], [8], a unilateral/antipodal finline [9], [10], [11] or a bowtie probe [12], [13] as the waveguide to planar circuit transition. The approach has been highly successful, and such type of mixers has been deployed to numerous millimetre (mm) and sub-mm telescope such as Atacama Large Millimetre/sub-millimetre Array (ALMA), JCMT and Sub-Millimetre Array (SMA). However, this technique often requires a separate rectangular to circular waveguide transition mounted at the back of a feed horn that has a circular waveguide output. This waveguide transition is difficult to machine due to its small size, and the requirement to split the transition piece to fabricate the rectangular section. The situation is even more challenging at high frequencies. Hence, to ease the design of the mixer block, especially for large array applications at short wavelength, we opt to demonstrate a mixer design that can be mounted directly in a circular waveguide, hence removing the requirement for the rectangular waveguide section, to ease operation at sub-mm and supra-terahertz range in the near future.

In our case, we use a 2-probe antenna as our circular waveguide to microstrip transition. The design is similar to a 4-probe orthomode transducer (OMT) [14], [15] that allows the detection of both polarisation states simultaneously with a set of four probe antenna. However, this approach requires a delicate and complicated setup on-chip as the outputs of each opposing probe set need to be combined using additional components with minimal cross-talk [16], [17]. To simplify the mixer chip design, we utilise only one set of opposing probes with two identical SIS mixer branches connected directly to the output of each probe, and we combine the down-converted IF power using a commercially available power combiner such as the Wilkinson combiner or a 180° hybrid. It is worthwhile noting that this approach can also be easily extended to the dual-polarisation operational mode, by simply utilising another IF power combiner to recover the signal strength of the second opposing probe set for the orthogonal polarised state, without the need for an RF crossover. In this paper, we focus on the single polarisation design to demonstrate the feasibility of this new approach.

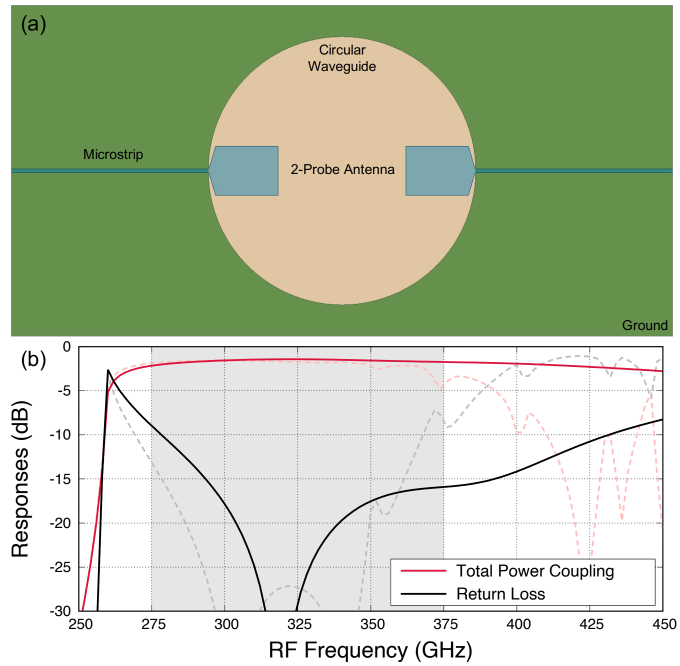

Fig. 1. (a) Image illustrating the layout of the 2-probe antenna mounted across a circular waveguide. The image shown is not-to-scale to show clarity. (b) The total power coupling from the circular waveguide to both the microstrip output ports and the return loss performance was simulated using HFSS. The solid red and black curves indicate the performance of the 2-probe antenna, whereas the dashed pink and grey lines show the inferior performance of the antenna if one of the probes is removed.

Fig. 1 depicts the simple layout of our 2-probe antenna. The set of niobium (Nb) probes is supported on top of a 40 µm thick quartz substrate. For operation near 350 GHz, we set the diameter of the circular waveguide to 0.7 mm with a cutoff frequency of 260 GHz. The antenna chip is mounted along a small opening milled across the circular waveguide with a height of 90 µm, and the antenna is placed approximately 200 µm above the termination of the circular waveguide forming the backshort, without any waveguide choke external to the circular waveguide. The width of the microstrip is set to match the output impedance of the probe. The dimension of the probe, the backshort and the width of the microstrip are then optimised using Ansys® High Frequency Structure Simulator (HFSS) for optimal power coupling and bandwidth performance.

The simulated performance is shown in Fig. 1(b), demonstrating the broadband nature of the antenna, covering a bandwidth from approximately 275–450 GHz. The insertion loss from the circular waveguide to the probe set is about 2 dB, caused mainly by the quartz substrate which is still considerably thick in this case, and more crucially the power leakage through the substrate and the 50 µm gap above the chip required to avoid the planar circuit being shorted by the mixer block. It would be technically very challenging to further thin the quartz beyond 40 µm to reduce substrate loss and minimise power leakage through a narrower slot, but it is possible to improve the total power coupling further by using a thinner membrane such as the use of several µm thick silicon-on-insulator or silicon nitride substrate [18]. However, as mentioned earlier, such membrane technologies are not widely available; hence with conventional low dielectric constant quartz substrate, we believe the presented results are the optimal performance achievable with this technology.

In principle, this approach of utilising direct circular waveguide to planar circuit coupler can be simplified by using only one probe antenna [19] instead of two. In this case, we can eliminate the need for an additional mixer circuit, and more crucially the need for an IF power combiner. Nevertheless, as shown in Fig. 1(b), the performance of a single-probe antenna in a circular waveguide is inherently narrower and tent to excite unwanted modes within the circular waveguide. For example, we can observe from the electromagnetic model that the several notches near 350 GHz, 375 GHz, and above, which are caused by the imbalanced coupling from the other side of the circular waveguide without a probe. Also, without the symmetric arrangement, the bandwidth performance is now only about half of that of the 2-probe antenna design. Therefore, we chose to use the 2-probe antenna for our SIS receiver design to maximise the performance across a much wider band.

B. Mixer Chip Design

Fig. 2(a) shows the configuration of our mixer chip. Apart from the use of the 2-probe antenna, the main feature of our mixer design is that we utilise multiple tunnel junctions connected in series, following the approach presented by [20] and [21], to reduce the total junction capacitance and to improve the RF and IF bandwidth performance. In our case, we use three 1.2 μm^2 tunnel junctions with a normal resistance of 20 $\Omega/\mu m^2$ and a specific capacitance of 80 $fF/\mu m^2$. The junction arrays are embedded in a microstrip transmission line, formed using a 350 nm top and 200 nm ground Nb film sandwiching a 490 nm thick silicon monoxide (SiO) dielectric layer, to provide convenient access to the required characteristic impedance range. The dielectric is fabricated by stacking a 250 nm SiO on top of a another 240 nm SiO layer, where the upper layer was removed near the junction array to make sure the top Nb is in electrical contact with the first tunnel junction. The series link with the subsequent junctions is provided by using a small coplanar waveguide section, in conjunction with another short microstrip line, as illustrated in Fig. 2(b).

For tuning out the residual parasitic capacitance which would otherwise short the junctions, we utilise a commonly used end-loaded tuner circuit approach [22]. The low impedance stub is shown as the wider microstrip section between the junction array and the probe antenna in Fig. 2(c), and the width and length of the narrower microstrip section connecting the stub and the junction array is adjusted to

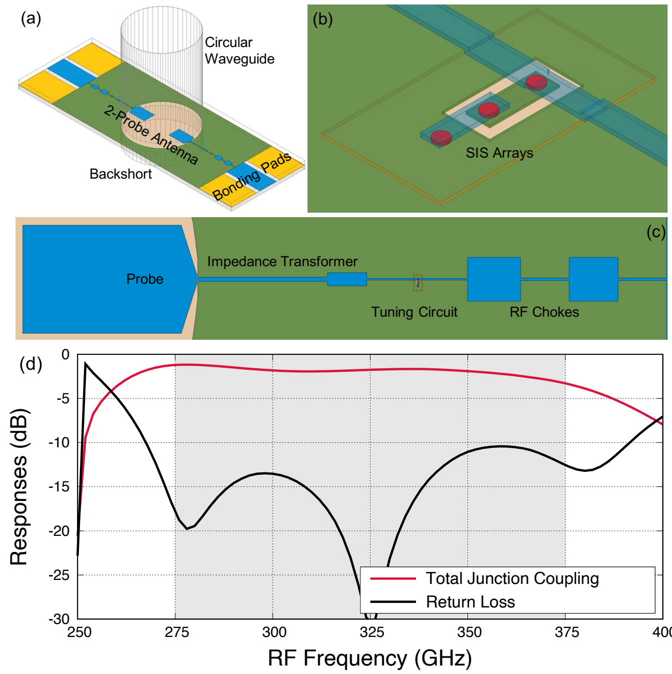

Fig. 2. (a) The layout of the mixer chip mounted across a circular input waveguide with backshort. (b) Zoom-in image of the junction array and (c) the complete mixer circuit connected to one of the probes. (d) HFSS predicted total power coupling from the input waveguide to both the junction array, as well as the return loss performance of the entire setup including the 2-probe antenna.

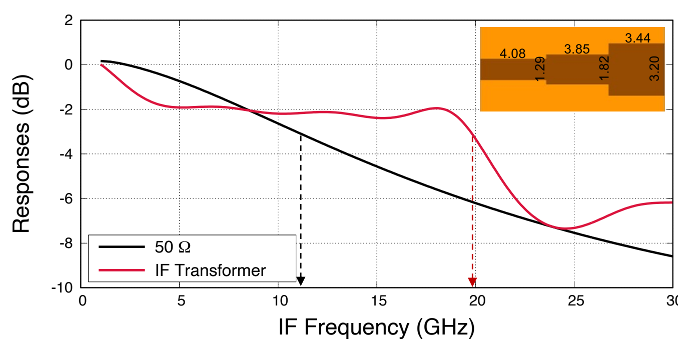

Fig. 3. The power coupling of each set of junctions to the relative IF output port where the black curve shows the performance when the IF is connected directly to a 50 Ω load, while the red curve shows a much broader –3 dB coupling with the use of a 3-sections IF transformer to match the impedance of the tunnel junctions and the 50 Ω load. The inlet shows the 3-sections IF transformer board designed using 20 mil. Roger Duroid 4350b PCB with 17 µm copper on each side forming a microstrip structure. The dimensions shown are in mm.

present an inductive load to the junction array. An impedance transformer section is concatenated before the tuner circuit to bridge the impedance mismatch between the output of the probe antenna and the junction array, and a 5-section high-low impedance RF choke is deployed after the tuner circuit to prevent RF power leakage into the IF chain. The entire planar mixer circuit is then optimised using HFSS, without altering the setup of the antenna and the waveguide. The same mixer circuit is deployed to both the probe antenna forming a symmetric configuration.

Fig. 2(d) shows the predicted performance of our mixer. As can be seen, we successfully achieve closed to –3 dB total power coupling from the input circular waveguide to both the junction arrays from 265–375 GHz, slightly wider than the designated operating range. Similar return loss performance is observed over the same frequency range, if we define the bandwidth using the –10 dB cutoff points. Note that the simulated performance includes the effect of the probe antenna which inherently impose a –2 dB insertion loss already across the designated band, which could be further improved if membrane technologies are accessible.

Fig. 3 shows the HFSS predicted IF coupling range of our mixer chip for one of the IF ports, which is identical to the opposite IF port. Using the –3 dB point as the indicator for the operational IF bandwidth, we can see that if we connected these IF ports directly to a 50 Ω environment, inherently we expect an IF bandwidth of approximately 11 GHz. This is considerably wide due to the low total junction capacitance of the 3-junction array. Following the approach we previously presented in [23] to further broaden the IF bandwidth, we opt to install two IF transformers after the mixer chip IF ports to better match the output impedance of the mixer circuit and the subsequent 50 Ω microwave power combiner. Here, we design a simple 3-section transformer using commercially available Roger Duroid® 4350b printed circuit board (PCB). As can be seen from Fig. 3, with such IF impedance transformers, we manage to almost double the IF bandwidth from 11 to 20 GHz, with a very flat and consistent coupling from 4–18 GHz.

C. Heterodyne Performance

Once the mixer chip and the IF transformer designs were finalised using the electromagnetic modelling package to optimise the power coupling between the input circular waveguide to the tunnel junction arrays, as well as from the array to the IF ports in the microwave regime, we checked the heterodyne mixing performance of the SIS receiver using SuperMix [24]. The S-parameter matrixes of the mixer chip and the IF transformers simulated from HFSS were exported to SuperMix to form the full receiver circuit [25]. For this exercise, we make use of an ideal Wilkinson power combiner with the two input ports connected to the respective IF output ports of the mixer chip via the IF transformers to recover the full down-converted signal strength. As shown in Fig. 4, we successfully cover the entire 275–375 GHz range with a noise temperature of less than 30 K and a better than –2.5 dB double sideband (DSB) conversion gain, across the entire bandwidth. Similarly, with the installation of the IF transformer boards, we managed to achieve close to 20 GHz operational bandwidth, if we take the –3 dB point of the DSB gain curve as reference.

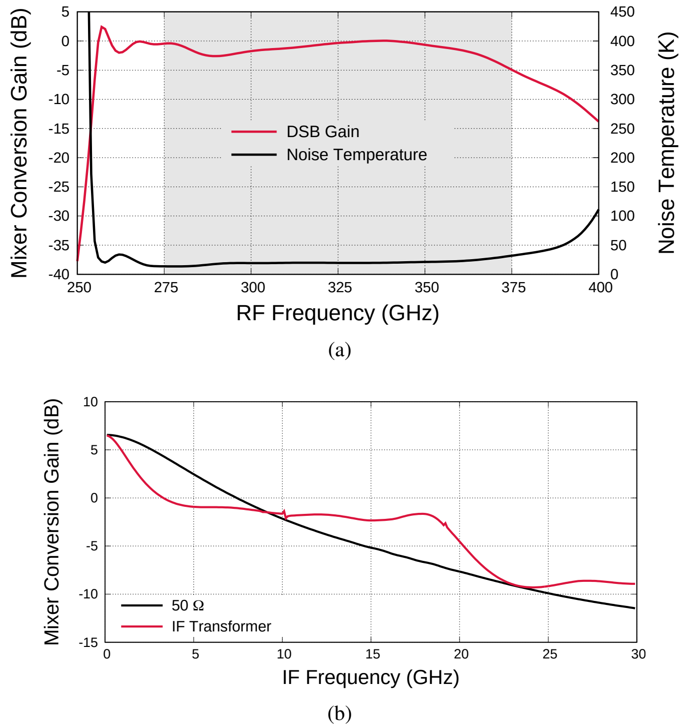

Fig. 4. (a) SuperMix predicted RF noise temperature and DSB conversion gain of the entire SIS receiver, and (b) the IF DSB gain-bandwidth performance.

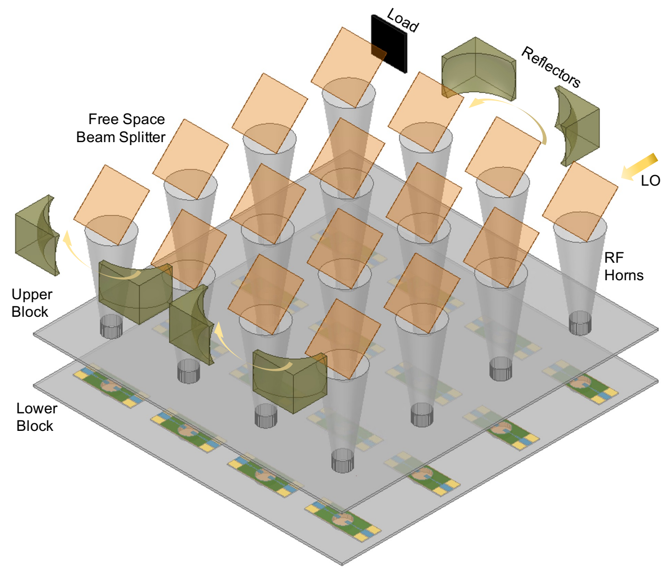

Fig. 5. Illustration of a 4×4 array that can be constructed to house the circular waveguide fed SIS mixer chips, showing the simplicity of the array block. The image shown is not-to-scale to show clarity.

III. Mixer Array Block Design

The above-described mixer chip is ready to be extended into an array by populating the individual chips into an array block as shown in Fig. 5. The array block can now be constructed with standard split block technology without much complication. The upper block consist of an array of feed horns which can be directly drilled using a shaped machining tool [26]. In Fig. 6, we show the design of the accompanied 350 GHz 3-section smooth-walled horn that was scaled directly from the design presented in [27], and its corresponding beam patterns at the centre and near the edges of the frequency band. As can be seen, the far field radiation patterns are clean with sidelobes level well below –25 dB. The E- and H-field of the main beam are also identical throughout, except at the lowest frequency point where they start to diverge below the –10 dB level. The design of this smooth-walled horn can be further optimised, if need be, to the specification of the telescope

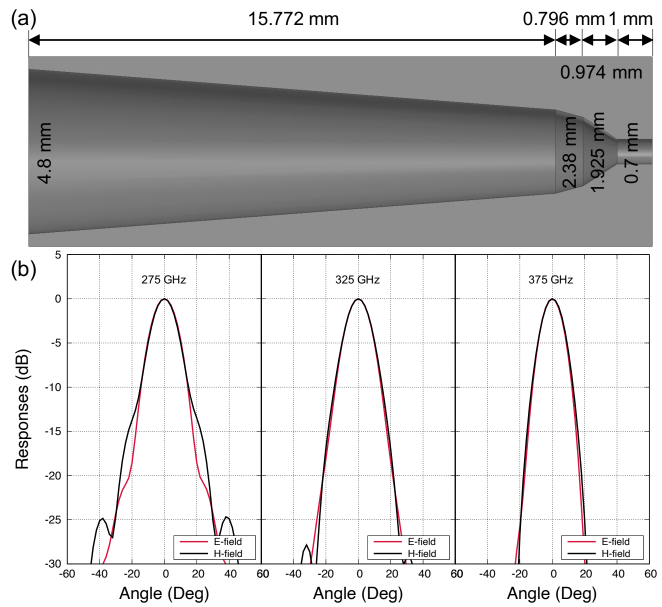

Fig. 6. (a) The design of a 3-section smooth-walled horn for operation from 275–375 GHz, with the dimension given in lengths and diameters of each section, including the output circular waveguide. (b) The HFSS simulated far-field beam patterns of the smooth-walled horn at 275, 325 and 375 GHz.

optics.

The bottom part of the array block would consist of pockets for mounting the SIS mixer chips, as well as the IF transformer PCBs with the corresponding SMA connectors, similar to the design provided in [17]. The mixer chip will be aligned directly underneath the circular waveguide output of the feed horns and wire bonded to the IF board. The outputs of the IF transformer sets will then be guided through the back of the array block via the SMA connectors, which subsequently combine the two down-converted IF signals with a power combiner before feeding to the low noise amplifiers and posterior IF chain for performing characterisation and measurements. The magnetic coil required could be installed adjacent to the feed horn following the design shown in [17] as well. Finally, the LO injection can be provided quasi-optically using the traditional dielectric beam splitter array with corresponding mirror sets to re-focus and meander the LO beam.

IV. Conclusion

We have presented the design of an SIS mixer chip that can be fed directly with a circular waveguide with the use of a 2-probe antenna, eliminating the need for a rectangular waveguide that is more difficult to fabricate than the circular waveguide. Two identical mixer circuits designed to cover the frequency range from 275–375 GHz are concatenated directly to the output of the 2-probe antenna, where the down-converted IF signal from each mixer chain is power combined using a microwave power combiner. Rigorous *em* simulations show that our mixer design can covers the required RF range with good noise temperature performance. With the array of three series-connected tunnel junctions in conjunction with the 3-section IF transformers, we manage to provide an IF coverage close to 20 GHz. In the final section, we show how such a circular waveguide SIS mixer chip can simplify the design of the mixer block array, which can now be fabricated using a standard split block technology without much complication, paving the way for the construction of even larger array in the future, in particular near the supra-THz frequency regime.

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