Development of a compact sideband-separating SIS mixer for the Africa Millimetre Telescope targeting 211–373 GHz

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ABSTRACT

Millimeter and sub-millimeter wavelength astronomical heterodyne receivers operating in the simplest double-sideband (DSB) mode down-convert both the upper and lower sidebands (USB/LSB) near the local oscillator (LO) frequency to the same intermediate-frequency (IF) band, causing spectral confusion. The down-converted USB and LSB signals can be separated using a sideband-separating (2SB) scheme, which requires passive components such as hybrid couplers, in-phase power splitters, and directional couplers, in addition to a pair of near-identical DSB mixers. Traditionally, these passive components are implemented using waveguide technology, making them bulky and increasingly difficult to fabricate with high precision at higher frequencies.

In this manuscript, we present a compact 2SB receiver concept. By rearranging the pair of DSB mixers and replacing these waveguide-based passive components with superconducting planar-circuit counterparts, we aim to substantially reduce the receiver size while potentially minimizing transmission losses. We demonstrate this approach by presenting the design of a compact 2SB receiver that continuously covers the Atacama Large Mm/sub-mm Array (ALMA) Band 6 and Band 7 frequency ranges, intended as a second-generation instrument for the Africa Millimetre Telescope (AMT).

Keywords: Astronomical receivers, millimeter and sub-millimeter, heterodyne mixers, superconductor-insulator-superconductor, sideband separating, planar superconducting circuit

1. INTRODUCTION

Superconductor-insulator-superconductor (SIS) mixers are one of the leading technologies used in sub-millimeter and millimeter (sub-mm/mm) astronomical receivers. These heterodyne receivers facilitate spectroscopic observations that are crucial for studies of stellar, planetary, and galaxy evolution. The nonlinearity of SIS mixers allows the RF signal from the sky, when combined with a local oscillator (LO) signal, to be down-converted to an intermediate-frequency (IF) signal that can be more readily processed by conventional microwave equipment.

The simplest form of a heterodyne receiver, whether based on SIS mixers, hot-electron bolometers (HEBs), Schottky diodes, or other mixer technologies, operates in the double-sideband (DSB) mode, where the RF signals contained within the upper and lower sidebands (USB/LSB) near the LO frequency are concurrently down-converted to the same IF range, causing spectral confusion. A sideband-separating (2SB) receiver is required to separate these sidebands and thereby widen the observable RF bandwidth. Consequently, most sub-mm/mm telescopes currently employ 2SB receivers for astronomical observations.[1,2]

Conventional 2SB receiver designs require two DSB SIS mixers, an RF 90° quadrature hybrid to split the LO signal between the two mixers, an in-phase power divider to split the RF signal (or vice versa), a pair of directional couplers to inject the LO signal into the mixers, and an IF quadrature hybrid to recombine and separate the down-converted USB and LSB signals. These passive components (except the IF hybrid) have traditionally been realized using waveguide technology, which adds bulk and transmission loss to the receiver.

We aim to depart from conventional 2SB designs by developing a new receiver architecture with a more compact footprint through the replacement of most waveguide components with superconducting planar circuits.

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The proposed compact 2SB receiver architecture, ideally with improved performance, is highly relevant to upcoming experiments, new observatories, and planned upgrades to existing facilities. Examples include the ALMA Wideband Sensitivity Upgrade (WSU), which aims to broaden the RF and IF bandwidths of the Atacama Large Millimeter/submillimeter Array (ALMA) receivers,[2] and the Africa Millimetre Telescope (AMT)[3] in Namibia, the latest addition to the Event Horizon Telescope (EHT) network.

In this manuscript, we focus on a compact 2SB receiver design for the AMT, targeting the ALMA-defined Band 6 (211–275 GHz) and Band 7 (275–373 GHz) frequency ranges simultaneously, such that the same receiver architecture can be used to perform concurrent observations required for AMT operations. In the following sections, we present the overall receiver architecture comprising modular superconducting planar-circuit chips before describing the design of each module in detail.

All circuit components are implemented using a planar microstrip structure comprising a 250 nm niobium (Nb) ground plane and a 400 nm Nb wiring layer separated by a 450 nm silicon monoxide (SiO) dielectric layer, supported on a 10 µm-thick silicon-on-insulator (SOI) substrate, as listed in Table. 1. An 800 nm-thick gold beam lead is subsequently deposited on each fabricated chip to provide electrical connections. The fabrication topology is based on our existing SOI process developed for single-ended DSB mixer chips.[4,5] The same topology is used for all modular circuit chips, allowing them to be fabricated simultaneously on a single wafer. All RF components presented here were designed and optimized using Ansys® High Frequency Structure Simulator (HFSS). In this paper, we focus primarily on the RF components and do not include the design of the IF quadrature hybrid.

Table 1. SOI microstrip topology specifications.

Layer	**Material**	**Thickness (µm)**
Beam leads	Au	0.80
Wiring	Nb	0.40
Dielectric	SiO	0.20+0.25
Ground	Nb	0.25
Substrate	Si	10

2. PROPOSED LAYOUT OF THE COMPACT 2SB RECEIVER

Fig. 1 shows the layout of our proposed compact 2SB SIS receiver, comprising several modular superconducting chips, namely an RF quadrature hybrid chip and two DSB mixer chips, interconnected via two modular microstrip chips. Gold beam leads are deposited on the chips to provide the electrical interconnections. Similar to a conventional 2SB receiver, the LO and radio-frequency (RF) signals are injected into the receiver through two separate ports. In our design, the RF signal is guided through a circular waveguide connected directly to the output of a feed horn, while the LO signal is injected through the input port of a waveguide-coupled planar RF quadrature hybrid chip, anticipated to be connected through a circular-to-rectangular waveguide transition to the output of a second feed horn.

Along the LO path, the injected LO signal is equally split in amplitude with a 90° phase difference between the two output ports i.e., the through and coupled ports of the quadrature hybrid. The isolated port is terminated with a matched load. While the input and isolated ports are coupled from the waveguide environment using probe antennas, the two output ports terminate in bonding pads attached to gold beam leads. These beam leads provide the electrical connections to the interconnecting microstrip chips, which subsequently deliver the split LO power to the two DSB mixer chips. This approach avoids the additional bulk associated with waveguides for routing the LO signal from the hybrid to the mixer chips. From a mechanical perspective, it also avoids the challenges of machining multiple closely spaced antenna-coupled waveguides.

The interconnecting microstrip chips are fabricated on standard 100 µm-thick silicon substrates rather than SOI membranes (see Sec. 3), since the interconnecting beam leads must be mechanically tapped or bonded to secure the electrical connections. The thicker silicon substrate provides the mechanical strength required for this

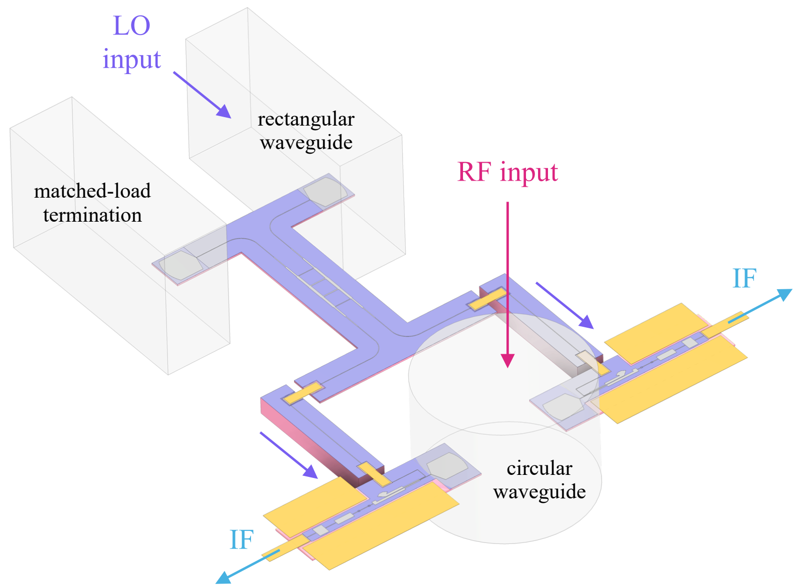


Figure 1. A conceptual RF-circuit layout of the modular-chips-based compact 2SB receiver excluding the IF quadrature hybrid. The purple arrows indicate the LO path, while the red arrows represent the RF path with the IF path shown as light blue. For clarity, some of the required gold beam leads on the SOI chips e.g., the grounding beam leads around the chips, are omitted.

process. Consequently, beam leads are deposited only on the hybrid chip, while the interconnecting microstrip chips terminate with bonding pads.

Similarly, beam leads are provided on the DSB mixer chips to be bonded to the corresponding bonding pads on the interconnecting microstrip chips. On-chip microstrip lines then guide the LO power toward the front of each mixer chip, immediately after the probe antenna, where it is combined with the equally divided RF signal through an on-chip directional coupler (see Sec. 6.2).

The incoming RF signal is coupled to the pair of DSB mixer chips through a top-down circular waveguide. The two probe-antenna mixer chips are arranged such that each receives -3 dB of the RF power with a 180° phase difference (see Sec. 5). This arrangement effectively replaces the need for an additional in-phase power splitter. As described earlier, the split RF signal is combined with the split LO signal through the directional coupler before passing through the mixer tuning circuits (see Sec. 6) and subsequently the RF choke. The down-converted IF signal is then routed off-chip through the gold beam leads at the ends of the mixer chips.

To further broaden the IF bandwidth, we are currently exploring a planar superconducting IF matching circuit based on the same silicon-substrate technology, rather than the conventional printed-circuit-board approach.[6,7] This approach further reduces the receiver size. Although the IF matching circuit could be integrated directly onto the DSB mixer chips, as is commonly practiced,[8] we have adopted a modular approach because of the size and irregular geometry of the mixer chips. To recombine the split IF signals and recover the USB and LSB outputs, we plan to employ commercially available or community-developed IF quadrature hybrids.[9,10]

3. 90° LO QUADRATURE HYBRID DESIGN

For a 2SB configuration, an LO (or RF) signal entering the receiver must be split into two paths with equal amplitude and a 90° phase difference, while the RF (or LO) signal is injected in phase (or 180° out of phase) before being recombined in a pair of DSB mixer chips. The former i.e., a quadrature hybrid, is traditionally realized using waveguide technology.[11–13] In our approach, we aim to replace the waveguide hybrid with a modular planar superconducting circuit chip to substantially reduce the size of the receiver.

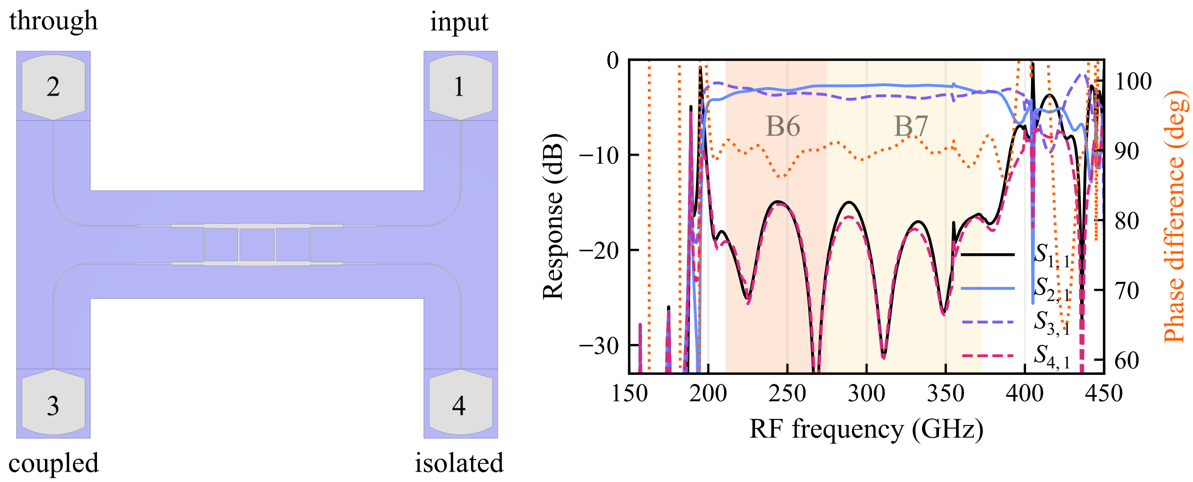


Figure 2. *Left:* The design for the 90° quadrature hybrid for the LO path, constructing using planar superconducting microstrip technology. The triple-box branchline coupler in the center functions as the hybrid, with impedance transformers to minimize the return loss between the hybrid and the four probe antennas used as waveguide-to-planar-circuit transitions. The ports are labeled for convenient cross-referencing with the simulated S-parameters. *Right:* The HFSS simulated S-parameters for the LO hybrid, plotting the response at each labeled port in dB over RF frequency in GHz. The input signal (1) has a nearly –3 dB division across the two outputs ports 2 and 3, with the expected 90° phase difference shown as a dashed line.

Fig. 2 shows the proposed LO quadrature hybrid. The quadrature hybrid itself is a microstrip branch-line coupler located at the center of the chip, as shown on the left side of the figure. We employ a three-section configuration, with the dimensions of each section optimized in HFSS to achieve a –3 dB power split across the full ALMA Band 6 and Band 7 frequency range. Four probe antennas are coupled to the ports of the hybrid, serving as broadband waveguide-to-planar-circuit transitions. The two probe antennas connected to the output ports will be replaced with beam-lead connections at a later stage for connection to the interconnecting microstrip chips.

The right-hand plot in Fig. 2 presents the simulated performance of the LO quadrature hybrid. The LO signal enters Port 1 and is split evenly between Ports 2 and 3, while Port 4 is terminated with a matched load to isolate it from the input port. As shown, the coupling to both output ports remains close to –3 dB across the designated 211–373 GHz frequency range. The return loss remains below –15 dB over the same range, while Port 4 remains well isolated with comparable performance.

In this simulation, all probe antennas extend into rectangular waveguides (0.385 µm × 0.77 µm) and are suspended at the E-plane of the waveguide with a backshort length of 0.26 µm. This layout is achievable using membrane technologies such as the SOI process employed here, which allows arbitrary-shaped superconducting circuit chips to be fabricated. The SOI chip-release process requires only the chip outline to be defined lithographically across the wafer, followed by removal of the handle silicon and buried oxide layers, rather than relying on the more restrictive mechanical dicing process typically used for thicker substrates. Consequently, the SOI process enables H-shaped chip geometries such as that shown in Fig. 2.

Furthermore, the SOI membrane minimizes RF leakage through the trench surrounding the chip and enables the use of beam-lead technology, eliminating the need for fragile wire-bond connections while reducing the parasitic inductance associated with bond wires.[14] Note that the effects of the beam leads are not included in the simulations shown in Fig. 2.

4. INTERCONNECTING MICROSTRIP CHIPS DESIGN

With a traditional waveguide-based 2SB receiver, waveguide channels are naturally used to connect the various components in the system, e.g., the architecture of the existing ALMA Band 9 2SB receiver.[15] In an effort to

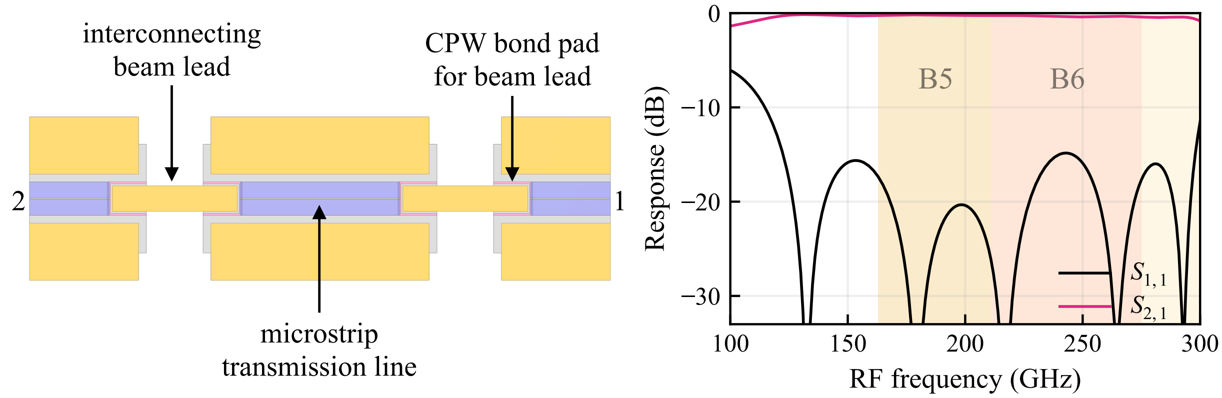


Figure 3. *Left:* The preliminary model for investigating the performance of the high-frequency interconnecting microstrip chips. Three separate SOI chips are RF-connected with bridging gold beam leads. *Right:* The HFSS simulation results for the interconnecting chips model shown in (a). The return loss is less than –15 dB across 125–300 GHz.

further reduce the footprint of our receiver, we have devised a more compact alternative by using a superconducting microstrip interconnecting chip instead of waveguides to route the LO signal from the quadrature hybrid chip to the DSB mixer chips.

As most of the receiver components are SOI-based, we designed these interconnecting microstrip chips with bond pads to which gold beam leads can be bonded, thereby acting as electrical bridges between the chips. Our prototype design is the center chip shown on the left-hand side of Fig. 3. As a first modeling attempt, both the interconnecting chip and the adjacent components are implemented on SOI. The two adjacent components each incorporate beam leads that extend to the interconnecting microstrip chip. Although the main transmission line is implemented as a microstrip, it transitions to a coplanar waveguide (CPW) structure at each end to provide the bond pads required for beam-lead bonding. The dimensions of both the beam leads and the bond pads are optimized to maximize RF signal coupling.

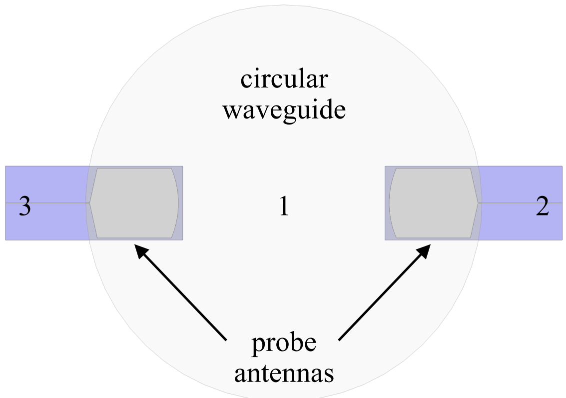
There may be mechanical challenges associated with bonding beam leads onto SOI chips however, due to the risk of damaging the membrane. Therefore, in the next design iteration, the interconnecting microstrip chips will be modelled with thicker silicon substrates. The thicker substrate will better tolerate the bonding force applied to the gold beam leads from the adjacent chips.

This initial modeling iteration of the interconnecting chip was originally intended for use across ALMA Bands 5 and 6 (159–275 GHz) for a different project, hence the different frequency range shown on the right-hand side of Fig. 3. Nevertheless, the simulated performance demonstrates a return loss better than −15 dB and insertion loss close to 0 dB across 125–300 GHz, spanning more than two ALMA bands. Work is ongoing to adapt the design for operation across Bands 6 and 7.

5. 180° RF-SPLITTING CIRCULAR WAVEGUIDE

Similar to the LO signal, the RF signal must also be equally distributed to both DSB mixers, but with a 90° phase difference relative to the LO path before being injected into the mixers. This can be achieved using either an in-phase power splitter or its 180° counterpart. Instead of designing a separate passive component to split the incoming RF signal, we utilize the circular waveguide itself as the power divider, following Ref. 16.

With two probe antennas suspended back-to-back across a circular waveguide (see the left side of Fig. 4), the incoming RF signal naturally splits equally between the two antennas with a 180° phase difference. The waveguide radius is 0.47 mm to support operation across the target ALMA Band 6 and Band 7 frequency range.



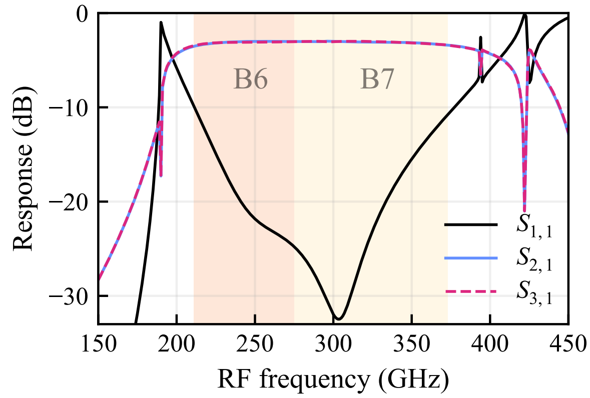
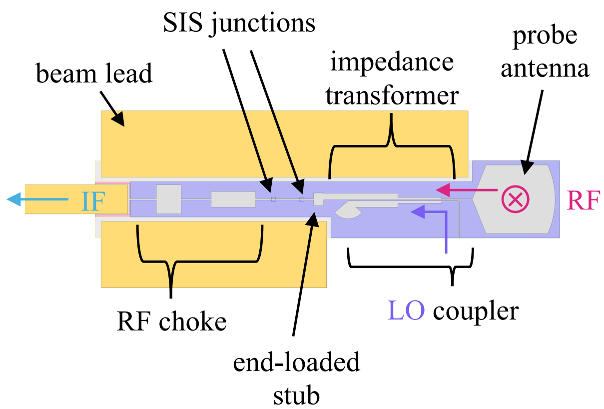


Figure 4. *Left:* The design for the RF signal-carrying circular waveguide utilized as a 180° power divider across two probe antennas. Each antenna is suspended across the E-plane of the waveguide with an 0.3 µm height backshort. The port numbers referenced in the S-parameters are labeled on the layout accordingly. *Right:* The HFSS simulated return loss and coupling performance. The coupling to both antennas are identical and close to the –3 dB level across the entire band 6+7 range.

Within the HFSS model, we optimized the waveguide backshort, probe-antenna dimensions, and antenna position inside the waveguide to maximize the RF coupling.

As shown on the right side of Fig. 4, the RF coupling to both mixer chips is nearly identical. The circular waveguide provides a return loss better than –10 dB across the operational bandwidth, demonstrating that the additional RF power-splitting component can be eliminated simply by appropriately arranging the pair of DSB mixer chips.

6. 211–373 GHZ DSB MIXER CHIP DESIGN



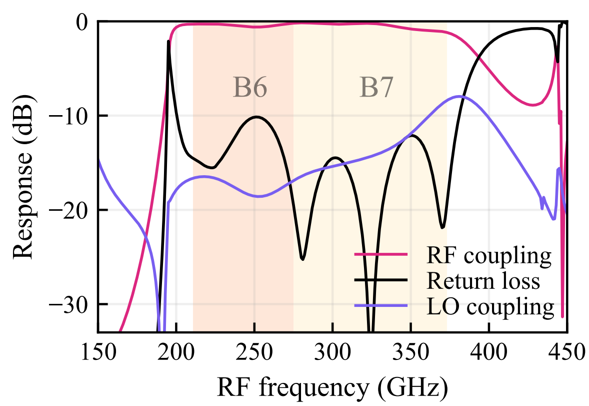


Figure 5. *Left:* The model of the DSB SIS mixer chip. *Right:* The HFSS estimated performance of the mixer, including the RF coupling to the mixers, the LO coupling to the mixers, and the return loss.

In this section, we present the design of the DSB SIS mixer chip. The two mixer chips are identical in design, except that they are mirror images of each other, as shown in Fig. 1. The left-hand illustration in Fig. 5 shows the major circuit components of the mixer chip. In the following, we first discuss the RF signal path before describing the LO coupling mechanism.

6.1 RF-Signal Circuits

For each mixer chip, a probe antenna (as described in Sec. 5) couples the RF signal from the circular waveguide to the on-chip circuit. A two-step Chebyshev impedance transformer is used to bridge the impedance mismatch between the probe antenna and the SIS junction tuning circuit.

To achieve the broad RF bandwidth, we employ twin SIS junctions connected in parallel as the primary tuning mechanism.[17] The junctions are 1 μm^2 in size and are fabricated from a Nb/AlOx-Al/Nb trilayer with a critical current density of J_C = 8–10 kA/cm^2, a normal resistance of $R_N = 20\ \Omega \cdot \mu m^2$, and a capacitance of $C_J = 80$ fF/μm^2. To further broaden the RF bandwidth, an end-loaded stub is added immediately after the impedance transformer and before the twin-junction tuner. In addition, the microstrip length between the twin junctions and the first low-impedance stub of the RF choke is adjusted to form the end-loaded tuning structure.[8] The high-low impedance RF choke acts as a low-pass filter, allowing only the down-converted IF signal to propagate. This RF signal path is largely identical to that of the single-ended DSB mixer chip presented previously, and further details can be found in Refs. 4 and 5.

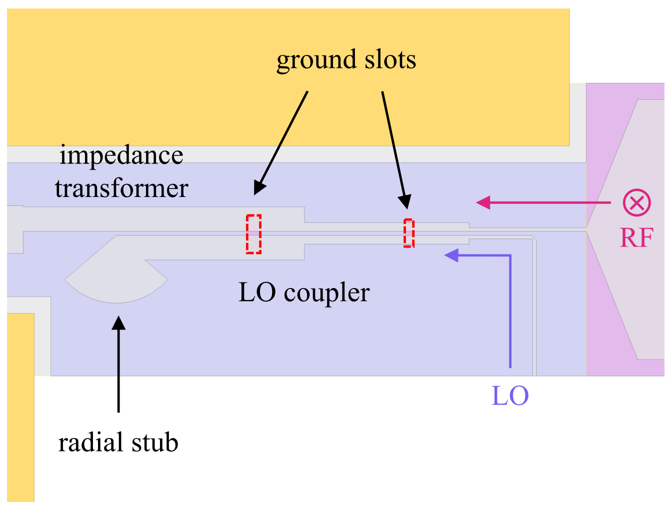


Figure 6. A closeup of the LO coupler on the mixer chip. The bottom wiring is the LO coupler, and the top wiring is the impedance transformer on the main RF circuit. The rectangular cutouts in the ground layer are outlined with dashed lines.

6.2 LO Coupling Circuit

To inject the required LO signal into the SIS junctions, a directional coupler is generally employed. Similar to the approach adopted throughout this work, we implement the coupler using planar superconducting circuit technology instead of waveguide technology.

We have designed an asymmetrical three-section directional coupler to inject the LO signal from the front of the mixer chip, with a coupling coefficient between −10 to −20 dB. The coupler is aligned with the impedance transformer, with each section matching the dimensions of the corresponding section of the transformer. Consequently, the three coupler sections run parallel to the transmission line from the probe antenna and the two sections of the Chebyshev transformer, with identical widths. The inward-facing edges of the coupler and transmission line are equally spaced across all three sections. The middle section extends over the full length of the first Chebyshev section, while the lengths of the two outer sections are adjusted to optimize the coupling. A radial stub at the end of the coupler terminates the remaining through LO signal.

The coupler alone is not sufficient enough to achieve coupling greater than −20 dB. To further enhance the coupling, two rectangular slots are cut out from the ground plane beneath the coupler and impedance-transformer section, forcing the electromagnetic fields of the two microstrip lines to overlap and thereby increasing the coupling.[18] The rectangular slots are centered between the two lines, with their longer dimensions oriented perpendicular to the transmission lines. The size and position of the slots were optimized to achieve a minimum coupling of −16 dB across the target frequency range.

The HFSS simulation results are shown on the right-hand side of Fig. 5. The return loss remains below −10 dB across the Band 6 and Band 7 frequency range, while the RF transmission remains close to 0 dB throughout. The LO coupling is approximately −16 dB at the lower end of the band and gradually increases to just above −10 dB at the upper end. Since the output power of the LO source can be readily adjusted, a perfectly uniform coupling level across the operating bandwidth is not required. In fact, the increased coupling at higher frequencies is advantageous, as the available LO source power typically decreases with increasing frequency.

7. CONCLUSIONS

We have proposed a compact architecture for a 2SB SIS receiver covering 211–373 GHz for the AMT, with an overall footprint of only a few square millimeters. Most conventional passive waveguide components have been replaced with modular SOI-based superconducting planar-circuit chips, thereby significantly reducing the receiver footprint.

The flexibility in chip geometry afforded by SOI technology, together with the versatility of the interconnecting microstrip chips, provides substantial freedom to accommodate future mechanical design considerations. For example, the interconnecting chips can readily be extended to create a larger separation between the LO quadrature hybrid and the circular waveguide, if required.

Importantly, all of the proposed components can be readily scaled to other frequency ranges. By preserving the same circuit layout while adjusting the physical dimensions, comparable performance can be achieved across different frequency bands. For example, the LO quadrature hybrid has also been designed for operation across ALMA Bands 5 and 6 during the development of this work, while the DSB SIS mixer chip has likewise been scaled to Bands 5 and 6.[4] Consequently, the proposed architecture has broad applicability to a range of future scientific instruments. We also anticipate that the transition toward SOI planar-circuit receiver architectures will facilitate the development of future large-format focal-plane arrays for sub-mm/mm astronomical observatories.

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