An End-Fire SIS Mixer with Near Quantum-Limited Performance

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***Abstract*—In this letter, we report the near quantum-limited performance of an end-fire millimeter-wavelength superconductor-insulator-superconductor (SIS) mixer. An important feature of this mixer is its use of a unilateral finline as the input antenna, which allows for a wide RF bandwidth, a simple waveguide structure with easy alignment and for the mixer chip to be aligned along the optical axis. Each of these factors is beneficial in the construction of large-format focal plane arrays. We tested the new finline mixer from 210 to 260 GHz and the best recorded noise temperature was approximately twice the quantum limit, which is comparable to conventional radial probe mixers. This suggests that end-fire SIS mixers can be used in large format arrays, comprising of 100s or even 1000s of SIS mixing elements, while retaining state-of-the-art quantum mixing performance.**

I. Introduction

OBSERVING millimeter-wavelength spectral lines is crucial for studying the physical and chemical properties of the interstellar medium. However, wide-field surveys of the Milky Way and nearby galaxies are time consuming using large single dish telescopes and even more so using interferometers, which have inherently small fields of view. To increase the mapping speed, it would be beneficial improve the sensitivity of the receivers, but the sensitivity of modern superconductor-insulator-superconductor (SIS) mixers is already very close to the quantum limit [1]–[3]. The next step is then to increase the number of pixels observing simultaneously within each telescope, which has to be accomplished without compromising the near quantum-limited performance of the SIS mixers. Another important consideration is that for the next generation of large-format focal plane arrays (>100 pixels), telescope optics will likely be re-imaged to allow for smaller feed horns and closer pixel spacing. The maximum pixel density will then be limited by the size of the SIS devices (in the direction perpendicular to the optical axis), the magnetic coils and the IF components that are placed immediately adjacent to the SIS devices.

Currently, most SIS devices use radial probes to couple the RF signals from the waveguides to the planar circuits, which requires the SIS device to be mounted perpendicular to the optical axis. To increase the pixel density in arrays, a new receiver architecture is needed where the SIS mixers and the IF components are completely aligned with the feed horn's optical axis and fit within the footprint of a small feed horn. One possibility is to use finline tapers for the input antennas [4], [5]; however, these finline-based SIS mixers have so far exhibited higher noise temperatures than radial probe designs. In order to use finline mixers in focal plane arrays, it is important to ensure that this type of end-fire SIS mixer can achieve the same quantum-limited performance.

In this letter, we present the design and measured performance of an end-fire SIS mixer operating at 230 GHz. The RF and local-oscillator (LO) signals are fed into this mixer using a unilateral finline antenna aligned along the optical axis of the receiver, which allows for a small footprint perpendicular to the optical axis. The SIS device is housed within the waveguide located at the back of the feed horn without any complicated waveguide structures, such as back-shorts or E-plane tuners. The only mechanical components required are the feed horn and a straight waveguide to house the mixer chip. The fabrication of these components is straightforward and relatively insensitive to alignment errors, meaning that these devices are much easier to mount within the waveguide.

II. Design and Fabrication

The layout of the 230 GHz SIS mixer is shown in Fig. 1. It utilizes a 1.5 μm^2 Nb/AlO$_x$/Nb tunnel junction with a normal resistance of $R = 14~\Omega$, a capacitance of $C = 120$ fF and an ωRC-product of $\sim$2.4 (where $\omega = 2\pi\cdot$230-GHz). The profile of the unilateral finline was designed using the Optimum Taper Method (OTM) to provide low insertion loss across a broad RF bandwidth while minimizing the overall length of the finline [6], [7]. A matching notch was added before the finline to help match the impedance of the empty waveguide to that of the substrate loaded waveguide. We used two radial stubs approximately $\lambda_g/4$ in radius, where λ_g is the guided wavelength, to couple the output of the finline taper to the microstrip line [8]. The mixer's tuning circuit consists of a 3-step quarter-wavelength transformer to match the impedance of the slotline-to-microstrip transition to the junction and two inductive strips before and after the junction to provide broadband tuning [4], [5]. Lastly, RF chokes were placed after the SIS junction to prevent the RF signals from leaking into the IF circuitry.

The exact dimensions of the planar components were optimized using full-wave electromagnetic simulation software (Ansys® HFSS). These simulations included the complex

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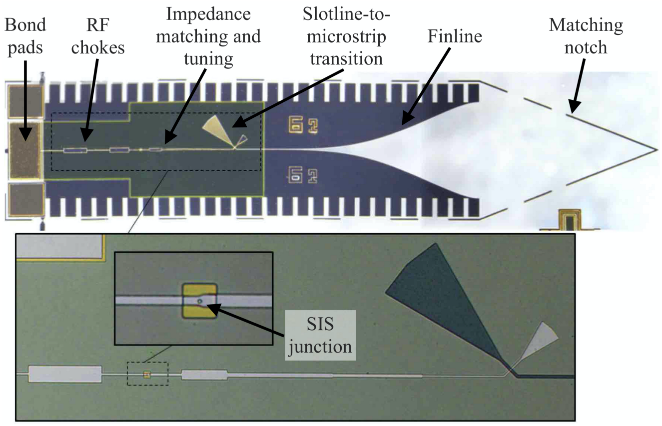

Fig. 1. A microscope image of the 230 GHz SIS device. The entire device is shown at the top of the figure and two magnified images are shown below. The SIS junction itself is visible in the bottom image. There is a square window around the SIS junction where the dielectric is reduced to half the normal thickness, which helps to improve the electrical contact with the SIS junction.

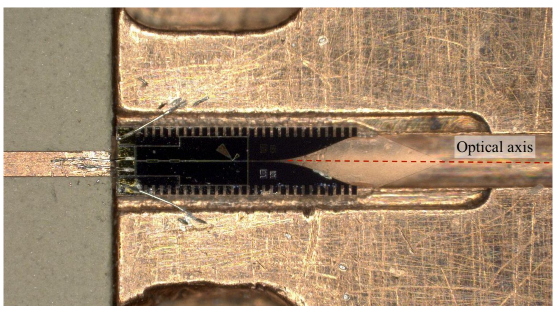

Fig. 2. An image of the SIS mixer mounted in the mixer block. The RF and LO signals arrive together through the waveguide on the right and the down-converted IF signal is carried off the device through the bond wires on the left. The optical axis is also shown, which passes through the center of the feed horn.

surface impedances of the superconducting layers, which were calculated using Mattis-Bardeen theory [9]. The IF output of the mixer chip was matched to the 50 Ω input impedance of the low noise amplifier (LNA) through a multi-stage IF transformer that was optimized to have the best performance between 2 and 12 GHz [10]. Finally, the heterodyne performance of the mixer design was verified using CalTech's superconducting mixer design package, SuperMix [11], and our own open-source SIS simulation software, QMix [12], [13]. The optimized mixer chip was fabricated in the Paris Observatory's clean room facility.

One of the SIS mixers mounted in a waveguide is shown in Fig. 2. As we can see, the SIS device has a very small footprint perpendicular to the optical axis. The performance of this device is also relatively insensitive to alignment errors. Unlike radial probe designs, which have to be positioned very carefully across the waveguide, the mixer in Fig. 2 can move left or right without any significant loss in coupling. This is helpful in the construction of large arrays because it is simple to mount the devices and easy to visually inspect their alignment.

III. Experimental Results

The heterodyne performance of the mixer was measured using the standard Y-factor technique by comparing the down-converted output power when the mixer is illuminated by hot (295 K) and cold (77 K) black-body radiation. The signals from the black-body loads were focused into the mixer through a parabolic reflector, while the local oscillator (LO) power was coupled into the signal path via a 12-μm-thick Mylar beam splitter. The mixer assembly, including the mixer block and first-stage IF amplifier, was cooled to cryogenic temperatures using a liquid helium cryostat ($\sim$4 K). The down-converted IF signal was first amplified by a 3–21 GHz cryogenic LNA (Low Noise Factory AB, Gothenburg, Sweden) and then filtered using a 4–5 GHz or a 4–6 GHz bandpass filter.

The noise temperature of the SIS mixer was measured from 210 to 260 GHz, which is the bandwidth of the LO source. As shown in Fig. 3, the lowest measured noise temperature was $T_{\rm N} = 33$ K at $\sim$230 GHz. This same measurement had a conversion gain of $G_{\rm c} = -2.0$ dB. Our design opted for a slightly lower conversion gain with a capacitive embedding impedance to ensure stable operation, while retaining optimal noise performance. The experimental noise temperatures in Fig. 3 are uncorrected, meaning that they include the noise contributions from the RF and IF components. The performance of these components cascades with the performance of the SIS mixer by:

$$T_{\rm N} = T_{\rm RF} + \frac{T_{\rm SIS}}{G_{\rm RF}} + \frac{T_{\rm IF}}{G_{\rm RF}\,G_{\rm SIS}} \qquad (1)$$

where $T_{\rm N}$ is the overall system noise temperature, $T_{\rm RF}$ and $G_{\rm RF}$ are the noise temperature and gain of the RF components, $T_{\rm SIS}$ and $G_{\rm SIS}$ are the noise temperature and gain of the SIS mixer, and $T_{\rm IF}$ is the noise temperature of the IF components. Using standard analysis techniques [14]–[16], we calculate values of $T_{\rm RF} = 9.2$ K, $G_{\rm RF} = -0.81$ dB, $G_{\rm SIS} = -1.19$ dB and $T_{\rm IF} = 7.0$ K. The isolated noise temperature of the SIS mixer is then $T_{\rm SIS} = 11$ K, which is two times the quantum noise limit of a double sideband mixer ($T_{\rm Q}^{\rm DSB} = hf/2k = 5.5$ K at 230 GHz). From this analysis, it is clear that the performance of this mixer is comparable to conventional radial probe SIS mixers, which is impressive as the new mixer design does not require any mechanical tuning, is very easy to handle and operate, and it is aligned with the optical axis, which provides the mixer with a very small footprint perpendicular to the axis.

As seen in Fig. 3, we were also able to reproduce the measured results using the SuperMix simulation software. (Note that the simulated noise temperature from SuperMix did not originally include the RF or IF noise contributions, so we added these contributions using Eqn. 1. $T_{\rm RF}$ and $G_{\rm RF}$ are frequency dependent, but here we have assumed constant values for the purpose of simplicity.) The simulated RF bandwidth of this device is very wide and would be able to cover band-5 and band-6 of the Atacama Large Millimeter/submillimeter Array (ALMA) with some minor modifications to the planar circuit to improve the high-frequency response.

The IF performance of the mixer was also measured using a spectrum analyzer and the results are shown in Fig. 4. In

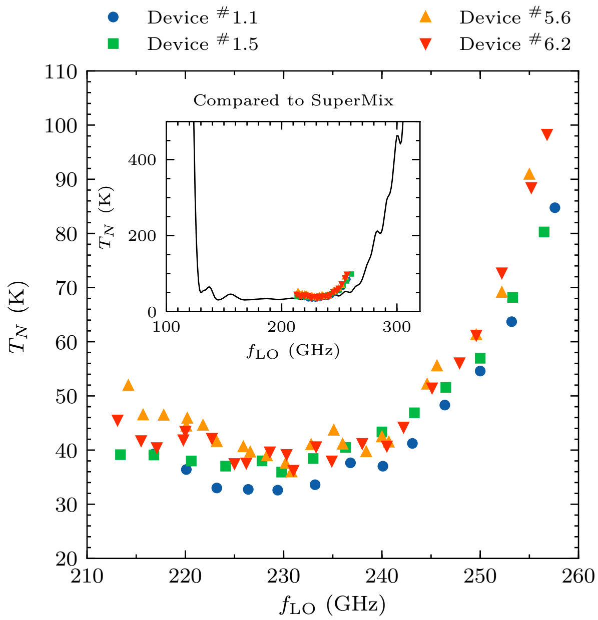

Fig. 3. The measured noise temperature from 4 different SIS devices. These results have not been corrected, e.g., to remove the effect of the beam splitter or any other optical components. All of these values were measured using a 4–6 GHz bandpass filter, except for device #1.1, which used a 4–5 GHz bandpass filter. As shown in the insert, the simulated results from SuperMix estimate a wide RF bandwidth, but we were limited in the experimental system by the bandwidth of the LO source (210–260 GHz).

general, the experimental results closely match the simulated results from SuperMix, apart from the sharp increase in T_{N} in the experimental values around 9.5 GHz. In order to understand the disparity, we measured all of the IF components using a vector network analyzer (VNA) at cryogenic temperatures and found that this peak in T_{N} coincides with a resonance found in the bias tee at cryogenic temperatures [16]. This bias tee was only designed for operation at room temperature. We believe that the electrical properties of the internal inductor change as the bias tee is cooled, leading to poor transmission around 9.5 GHz. By using a bias tee designed for cryogenic temperatures, this resonance could be removed, which would allow this SIS device to operate up to $\sim$12 GHz.

IV. Conclusion

We have presented a new SIS mixer fed by a unilateral finline antenna that is suitable for large-scale focal plane arrays. We measured a minimum noise temperature of 33 K (uncorrected) and a wide IF operating bandwidth of approximately 12 GHz. The isolated noise temperature of the SIS mixer is $\sim$11 K, which is approximately twice the quantum limit for double sideband mixers. The experimental performance also closely matches the simulated results, suggesting that the model of the experimental system is accurate. Overall, this work demonstrates that superconducting finline mixers can indeed achieve state-of-the-art performance while keeping the RF components completely aligned with the optical axis, which is important for minimizing the pixel spacing in large-scale arrays.

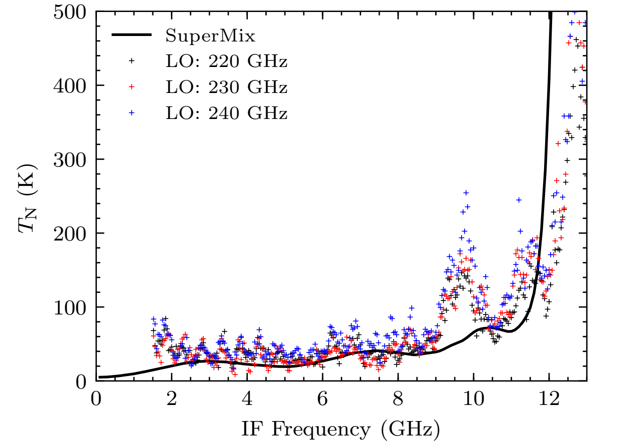

Fig. 4. The IF response at different LO frequencies. The experimental values were measured using a spectrum analyzer and the standard Y-factor technique. For the simulated results, we added the RF and IF noise contributions using Eqn. 1 since they were not included by SuperMix. In the experimental system, we used a 3–21 GHz LNA. The IF matching circuit was optimized to operate from 2–12 GHz, which is why T_{N} rises sharply outside this range.

References

[1] V. Belitsky, M. Bylund, V. Desmaris, A. Ermakov, S.-E. Ferm, M. Fredrixon, S. Krause, I. Lapkin, D. Meledin, A. Pavolotsky, H. Rashid, S. Shafiee, M. Strandberg, E. Sundin, P. Y. Aghdam, R. Hesper, J. Barkhof, M. E. Bekema, J. Adema, R. de Haan, A. Koops, W. Boland, P. Yagoubov, G. Marconi, G. Siringo, E. Humphreys, G. H. Tan, R. Laing, L. Testi, T. Mroczkowski, W. Wild, K. S. Saini, and E. Bryerton, "ALMA Band 5 receiver cartridge," *Astron. Astrophys.*, vol. 611, no. A98, p. 20, Mar. 2018.

[2] A. M. Baryshev, R. Hesper, F. P. Mena, T. M. Klapwijk, T. A. van Kempen, M. R. Hogerheijde, B. D. Jackson, J. Adema, G. J. Gerlofsma, M. E. Bekema, J. Barkhof, L. H. R. de Haan-Stijkel, M. van den Bemt, A. Koops, K. Keizer, C. Pieters, J. Koops van het Jagt, H. H. A. Schaeffer, T. Zijlstra, M. Kroug, C. F. J. Lodewijk, K. Wielinga, W. Boland, M. W. M. de Graauw, E. F. van Dishoeck, H. Jager, and W. Wild, "The ALMA Band 9 receiver," *Astron. Astrophys.*, vol. 577, no. A129, p. 12, May 2015.

[3] A. R. Kerr, S.-K. Pan, S. M. X. Claude, P. Dindo, A. W. Lichtenberger, J. E. Effland, and E. F. Lauria, "Development of the ALMA Band-3 and Band-6 Sideband-Separating SIS Mixers," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 2, pp. 201–212, Mar. 2014.

[4] B.-K. Tan, G. Yassin, and P. Grimes, "Ultra-Wide Intermediate Bandwidth for High-Frequency SIS Mixers," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 2, pp. 165–170, Mar. 2014.

[5] Y. Zhou, G. Yassin, P. Grimes, J. Leech, K. Jacobs, and C. Groppi, "Performance of a 230 GHz Finline SIS Mixer with a Wide IF Bandwidth," in *Proc. 23rd Int. Symp. Space THz Tech. (ISSTT)*, Tokyo, Japan, Apr. 2012, pp. 111–116.

[6] C. North, G. Yassin, and P. Grimes, "Rigorous analysis of finline tapers for high performance millimetre and submillimetre detectors," in *Proc. 17th Int. Symp. Space THz Tech. (ISSTT)*, Paris, France, May 2006, pp. 284–287.

[7] G. Yassin, S. Withington, M. Buffey, K. Jacobs, and S. Wulff, "A 350-GHz SIS antipodal finline mixer," *IEEE Trans. Microw. Theory Techn.*, vol. 48, no. 4, pp. 662–669, Apr. 2000.

[8] G. Yassin, P. Grimes, O. King, and C. North, "Waveguide-to-planar circuit transition for millimetre-wave detectors," *Electron. Lett.*, vol. 44, no. 14, p. 866, Jul. 2008.

[9] D. C. Mattis and J. Bardeen, "Theory of the Anomalous Skin Effect in Normal and Superconducting Metals," *Physical Review*, vol. 111, no. 2, pp. 412–417, Jul. 1958.

[10] B.-K. Tan, G. Yassin, and P. Grimes, "A Simple Method to Widen the IF Bandwidth of a High Frequency SIS Mixer," in *Proc. 24th Int. Symp. Space THz Tech. (ISSTT)*, Groningen, Netherlands, Apr. 2013.

[11] J. Ward, F. Rice, and G. Chattopadhyay, "SuperMix : A Flexible Software Library for High-Frequency Circuit Simulation, Including SIS

Mixers and Superconducting Elements," in *Proc. 10th Int. Symp. Space THz Tech. (ISSTT)*, Charlottesville, VA, Mar. 1999, pp. 269–281.
[12] J. Garrett and G. Yassin, "QMix: A Python package for simulating the quasiparticle tunneling currents in SIS junctions," *J. Open Source Softw.*, vol. 4, no. 35, p. 1231, Mar. 2019.
[13] J. D. Garrett, B. K. Tan, F. Boussaha, C. Chaumont, and G. Yassin, "Simulating the Behavior of a 230-GHz SIS Mixer Using Multitone Spectral Domain Analysis," *IEEE Trans. THz Sci. Technol.*, vol. 9, no. 6, pp. 540–548, Nov. 2019.
[14] C.-Y. E. Tong, A. Hedden, and R. Blundell, "An Empirical Probe to the Operation of SIS Receivers – Revisiting the Technique of Intersecting Lines," in *Proc. 19th Int. Symp. Space THz Tech. (ISSTT)*, Groningen, Netherlands, 2008, pp. 314–318.
[15] D. Woody, R. Miller, and M. Wengler, "85–115-GHz Receivers for Radio Astronomy," *IEEE Trans. Microw. Theory Tech.*, vol. 33, no. 2, pp. 90–95, Feb. 1985.
[16] J. D. Garrett, "A 230 GHz Focal Plane Array Using a Wide IF Bandwidth SIS Receiver," DPhil dissertation, Department of Physics (Astrophysics), University of Oxford, 2018.