Electromagnetic performance comparisons of 0.85 THz integrated bias-tee SIS mixers with twin-junction and end-loaded tuning schemes

Boon-Kok Tan, Kirill Rudakov, Valery Koshelets, Andrey Khudchenko, Andrey Baryshev, et al.

Boon-Kok Tan, Kirill Rudakov, Valery P. Koshelets, Andrey Khudchenko, Andrey M. Baryshev, Ghassan Yassin, "Electromagnetic performance comparisons of 0.85 THz integrated bias-tee SIS mixers with twin-junction and end-loaded tuning schemes," Proc. SPIE 12190, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI, 1219020 (31 August 2022); doi: 10.1117/12.2628733

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

Electromagnetic performance comparisons of 0.85 THz integrated bias-tee SIS mixers with twin-junction and end-loaded tuning schemes

Boon-Kok Tan[a*], Kirill Rudakov[b], Valery P. Koshelets[c], Andrey Khudchenko[d], Andrey M. Baryshev[b], and Ghassan Yassin[a]

[a]Dept. of Physics (Astrophysics), Univ. of Oxford, DWB Keble Road, OX1 3RH, Oxford, U.K.
[b]Kapteyn Astronomical Institute, Groningen, 9747 AD The Netherlands.
[c]Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Science.
[d]Astro Space Center of Lebedev Physical Institute, Russian Academy of Science.

ABSTRACT

We compare the design of two 0.85 THz SIS mixers fed with a radial probe antenna aligned to the E-Plane of the input full-height rectangular waveguide connected to a drilled smooth-walled horn. Both designs employ the same $0.5\,\mu m^2$ hybrid Nb/AlN/NbN tunnel junction technology, sandwiched between a NbTiN ground and aluminium wiring layer fabricated on top of a 40 µm quartz substrate. The two designs is differed by how we tune out the unwanted junction capacitance for broadband performance. The first design uses the commonly-used twin-junction tuning scheme; whilst the second design utilises an end-loaded scheme. We successfully achieve close to $2\times$ the double sideband quantum noise performance for both schemes, but the twin-junction design is less sensitive to fabrication accuracy of planar circuit components utilised. However, the end-loaded design offers a much better IF bandwidth performance, almost twice wider than the twin-junction design. The need for an ultra-wide IF bandwidth mixer is becoming more pressing and important for the future and up-coming upgrades of various millimetre (mm) and sub-mm astronomical instruments, hence we conclude that the end-loaded design is a better solution for the THz heterodyne mixing applications.

Keywords: Superconductor-Insulator-Superconductor (SIS) mixer, Millimetre/Sub-Millimetre Astronomy, Terahertz Technology, Heterodyne Technique, Electromagnetism

1. INTRODUCTION

Astronomical spectroscopic observations near and above 1 THz are important for understanding the life cycle of interstellar medium (ISM) as well as history of galaxy formation in the early Universe.[1,2] However, the performance of supra-THz superconductor-insulator-superconductor (SIS) mixer at such high frequencies is still struggling to match the quantum-limited noise performance of the lower frequency counterpart.[3,4] Nevertheless, in recent years, the tunnel junction and superconducting planar circuit technologies has advanced to a stage where it is now possible to improve the performance of such high frequency SIS mixers. Here, we present two THz SIS mixer designs that can potentially achieve near to quantum-limit noise performance utilising sub-micron niobium/aluminium nitride/niobium nitride (Nb/AlN/NbN) high current density tunnel junction technology. In particular, we investigate the difference in performance for these mixers that were designed using two different junction tuning methodologies. The first utilising a commonly-used twin-junction tuner, while the other an end-loaded tuner with only one tunnel junction. In addition, as the mixer circuit features becoming much smaller at higher frequency, we further compare how the performances of these mixers vary with fabrication errors of various critical circuit dimension, including the offset in the junction(s) position.

*E-mail: boonkok.tan@physics.ox.ac.uk; Conference presentation by Jakob Wenninger.

Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI, edited by Jonas Zmuidzinas, Jian-Rong Gao, Proc. of SPIE Vol. 12190, 1219020 · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2628733

2. THz MIXER ELECTROMAGNETIC DESIGNS & SIMULATIONS

In previous works, we described a THz SIS mixer design fed with a probe antenna aligned along the E-plane of a half-height rectangular waveguide, and showed that these mixers can produce promising noise temperature performance.[5–7] Here, we further improve the mixer design by replacing the triangular probe with a radial probe for broader RF bandwidth performance, as well as opting for a full-height waveguide design to ease the machining process. The layout of the new design is illustrated in Fig. 1, where the radial probe is extending to $\sim 35\%$ of the full waveguide height with a high impedance line connecting the radial probe with the ground pad on the other end of the mixer. This forms the integrated bias-tee design that enable direct IF connection and DC biasing to the chip without additional complicated setup.[8] Two RF chokes are integrated at both ends of the mixer circuit to prevent leakage of RF signal towards the IF path. The entire structure including the waveguide, back-short and the superconducting circuit is then optimised using Ansys High Frequency Structure Simulator (HFSS) to maximise the coupling from the probe antenna to the tunnel junction(s) across the desired bandwidth, which in our case from 0.78–0.95 THz.

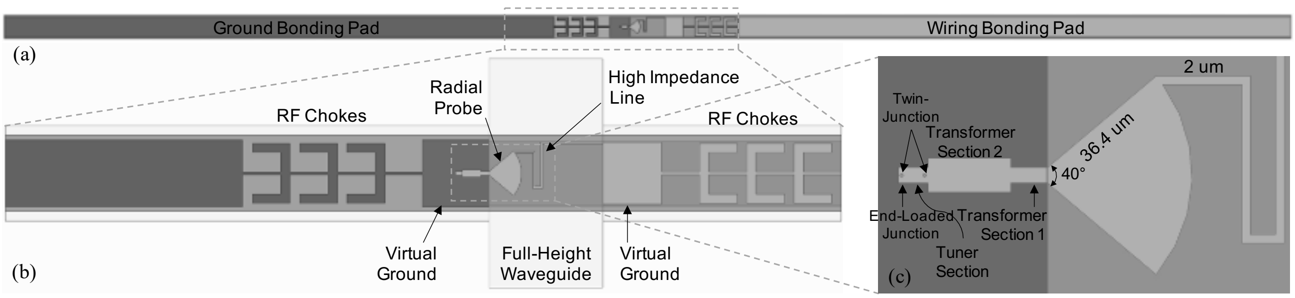

Figure 1. (a) Layout of the THz mixer chip with the superconducting planar circuits fabricated on top of a 1.62 mm long, 80 µm wide, and 40 µm thick quartz substrate. (b) Zoomed-in of the mixer chip showing the radial-probe antenna, tunnel junction tuner circuit, virtual grounds, high impedance line and the RF chokes. (c) Detail of the radial-probe and the twin-junction tuner circuit. In the case of single-junction tuning, the first (right-hand-side) junction is removed.

Our mixer circuits are designed based on the use of high current density (30 kA/cm^2) tunnel junction technology, with a circular area of 0.5 µm^2. The tunnel junction is comprised of hybrid electrodes with a niobium (Nb) bottom and a niobium nitride (NbN) top electrode. Both electrodes are 100 nm thick, sandwiched between a 300 nm niobium titanium nitride (NbTiN) ground and a 500 nm aluminium (Al) wiring layer, with a 250 nm thick silicon dioxide (SiO_2) as the dielectric layer, forming a microstrip line structure on top of a 40 µm thick quartz substrate. The mixer chip is aligned on a backpiece where the normal vector of the probe is pointing towards the direction of the propagation of the incoming waves from the feed horn. The assembly of the feed horn and the back-piece is then integrated into an Atacama Large Millimetre/sub-millimetre Array (ALMA)-styled mixer block,[9] modified for operation between 0.78–0.95 THz.

Table 1. Dimension of TX_1, TX_2 and the tuner section for the optimised twin-junction and end-loaded tuner.

		TX_1	TX_2	Tuner		TX_1	TX_2	Tuner
Width (µm)	Twin	3.6	7.9	3.6	End	3.6	8.7	3.6
Length (µm)	Junction	8.5	19.6	7.1	Loaded	8.0	19.0	7.0

As mentioned earlier, we intent to compare the RF and IF performance of the THz mixer utilising either one or two tunnel junctions, hence we designed our mixer using both tuning method i.e., the popular twin-junction method[10–12] as well as the end-loaded tuning design[13] with only one tunnel junction used. The two mixer designs are largely similar topologically, except the tuner part shown in Fig. 1(c), where the first junction nearer to the probe is removed for end-loaded design. Two short microstrip sections (herein after TX_1 & TX_2) connects the output of the probe antenna to the tuner section that contain the junction(s). The width of the tuner section is initially chosen to be the same as the normal resistance of the junction, and all three sections are then re-optimised for optimal performance, while retaining the dimensions of the remaining mixer components unchanged. The obtained tuning circuit dimensions are listed in Table 1.

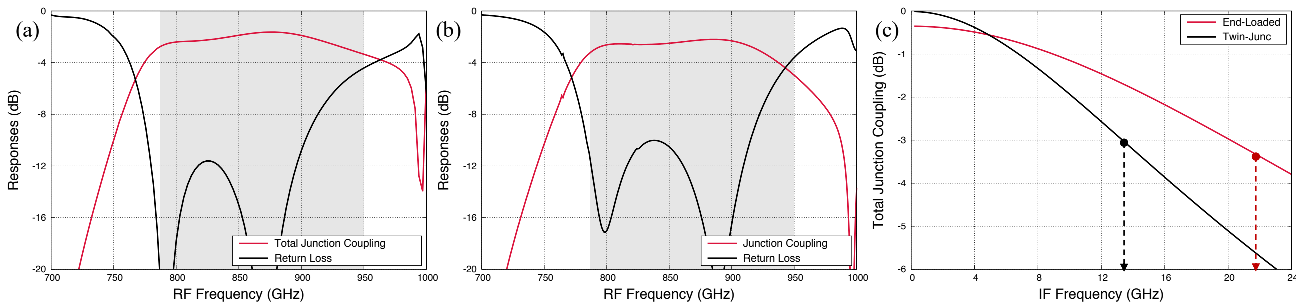

Figure 2. The power coupling to the tunnel junction(s) and the return loss performance of (a) twin-junction tuned and (b) single-junction end-loaded tuned, mixer chips. (c) The IF bandwidth performances of the two mixers.

Fig. 2(a) and (b) shows the total junction coupling and return loss performance for both mixers, clearly shown that we successfully cover the entire ALMA Band-10 range for both designs. The twin-junction design shows a wider and improved junctions coupling compared to the end-loaded design, but not vastly different. However, the IF performance of the end-loaded design is obviously much better than the twin-junction design, as shown in Fig. 2(c). Here, we refer the bandwidth limit using the −3 dB cutoff point, where one noted that end-loaded IF bandwidth can achieve closed to 22 GHz but the twin-junction only to about 13 GHz. This is hardly surprising because the IF capacitance is twice higher with two junctions in parallel, hence limiting the IF bandwidth. For the RF performance however, there's not much difference between the two because even though the RF capacitance is doubled, but the normal resistance is halved, hence the ωRC product remains the same. Given that the RF performance is largely similar between the two, but the end-loaded design have a superior IF performance, we argue that overall the end-loaded design is better.

3. TOLERANCE ANALYSIS

At high frequencies, the circuit dimension of the THz mixers become comparatively smaller e.g., the need for sub-micron tunnel junction, hence the mixer performance could be more prone to fabrication tolerance. In this section, we study how these fabrication error could affect the mixer performance. Here, we focus on the width of the 3 critical sections of the tuner circuit, and the error on the placement of the junction(s) location. Note that in the following, we base our analysis predominantly on the total junction coupling plots even though the return loss curves often shows more dramatic fluctuation. This is because the plots are in exponential scale, hence the changes in the return loss at lower dB level is comparatively less important than the power coupling. Furthermore, the junction coupling is more directly relevant to the gain-noise performance of the mixer, which takes into account other form of losses including the return loss. Nevertheless, the return loss plots are included here for completion.

Fig. 3 shows the results of tolerance analysis for both mixer designs. Overall, the performance of the twin-junction design is less sensitive to fabrication error, but the performance departure from the nominal design for end-loaded mixer is not too significant either. Reassuringly, the effect of junction shifting by ±0.5 µm appears to be moderate as well, although the twin-junction design is more consistent because this tuning method relies mainly on the relative distance between the two junctions, instead of the distance between the junction and the end-load in the single-junction design. Hence, the effect is more pronounced in latter case especially at the higher frequency end. Compared to the junction offset, the error in the width of TX_1 has less impact for both mixers, since this section is employed mainly to provide bridging impedance stages between the output impedance of the antenna and the tuner section. Hence, a small deviation in the characteristic impedance would result in almost identical power coupling behaviour. The tolerance analysis with regards to TX_2 is not included here as the strip is relatively wide, hence a small changes in the width would have only marginal effect on the mixer performance.

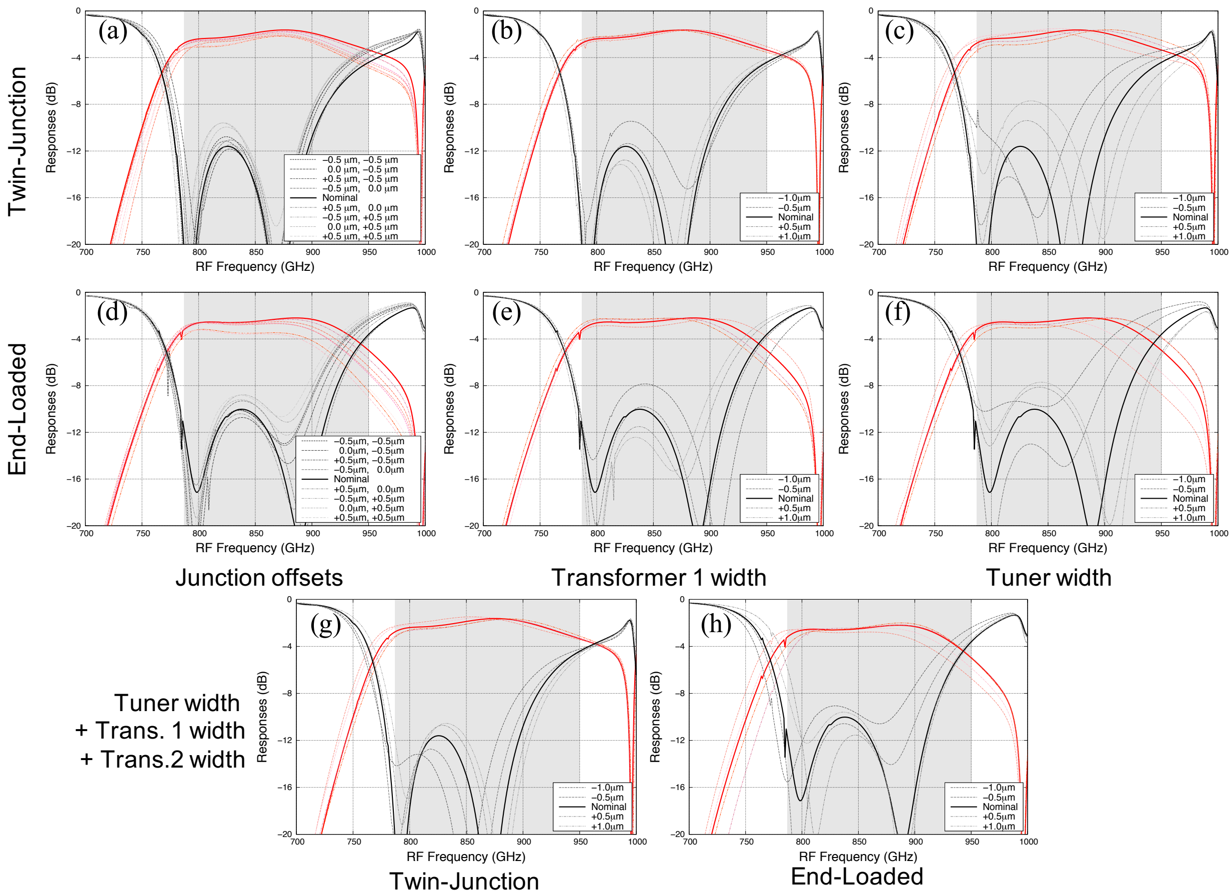

Figure 3. Plots show how the coupling (red) and S_{11} (black) responses altered with fabrication errors. The 1st and 2nd column of the legend in (a) & (d) indicates the offset in the x- (horizontal in Fig. 1(c)) and y-direction respectively.

Among these critical dimensions, it is noted immediately that the major influence comes from the change in the width of the tuner section (w_{tuner}) for both cases. This is because its characteristic impedance is directly related to the junction(s) impedance, hence a small change in the width would impart large impedance mismatch. For both designs, the junction coupling curve tents to displace higher if the tuner strip is wider, and vice versa. However, it appears that the situation is much worse when the tuner strip is narrower, especially for the end-loaded design e.g., reducing the tuner width by 1 µm could effectively reducing the bandwidth (especially the upper limit) by close to 50 GHz.

Assuming the junction(s) is located at its designated position, it is more likely that all the tuning circuit widths being fabricated wider due to over-exposure or vice versa, instead of changes only on part of the circuit. These potential scenarios are simulated in Fig. 3(g) and (h), where the plots clearly show that the twin-junction design perform better than the single-junction design. As expected, the departure from optimal mixer coupling performance is dominated by w_{tuner}, but compared to Fig. 3(b) and (e), one could observe that the variation is smaller here. This is because the changes in the width of TX_1 is behaving in an opposite way compare to the tuner section i.e., narrower TX_1 shift the performance higher, while narrower w_{tuner} results in better performance at lower frequency end, hence compensated the final results. This is reassuring as controlling the fabrication error within a ± 1 µm margin is within the accuracy limit of modern photolithography technique.

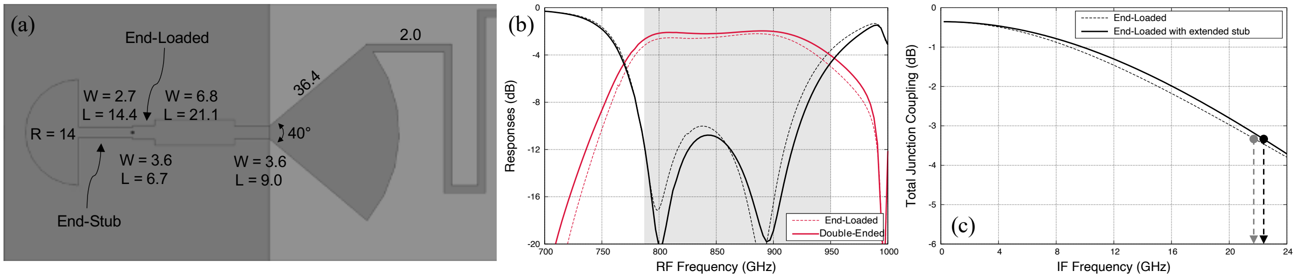

Figure 4. (a) Tuning circuit design with additional end-stub tuner. All quoted widths and lengths are in µm. (b) RF performance comparison between the original end-loaded design with the scheme where both end-loaded and end-stub tuners are incorporated. (c) IF performance comparison similar to (b).

4. PERFORMANCE IMPROVEMENT

From the above analysis, we can see that both the single- and the twin-junction tuned mixers are rather tolerable to fabrication error, and the RF power coupling performance of both designs are largely similar, except for a slightly narrower bandwidth performance from the single-junction mixer, especially at the higher frequency end. Nevertheless, the IF performance of the end-loaded mixer is much superior than the twin-junction design. Therefore, it is clear that the end-loaded mixer is a better option for our application.

The slight inferior RF bandwidth performance of the single-junction design can be further improved while retaining the advantage of the IF band, by concatenated the singly junction with another microstrip section along with an additional radial stub, a scheme termed as end-stub tuner.[13] The layout of this double-ended tuning circuit is shown in Fig. 4(a). This method provides us with an additional parameter space to improve the RF performance by shifting the central tuned frequency of the end-load and the end-stub to slightly different frequencies,[14,15] hence covering wider bandwidth. With this methodology and optimised using the method described earlier, we show the simulated RF and IF performance of the final optimised double-ended mixer design is shown in Fig. 4(b) and (c). As can be seen, we successfully widen the RF performance while keeping the IF performance comparatively wide with higher than 20 GHz performance. We expect the performance deviation due to fabrication tolerance for this design is largely similar to the analyses performed above.

5. CONCLUSION

We have presented two 0.85 THz SIS mixer designs tuned with either end-loaded or twin-junction scheme. We compared the RF and IF performances, as well as tolerance analysis for both designs. We found that the RF power coupling performance of both mixers are largely unaffected by the fabrication error, as long as the deviation is kept below ±1 µm margin. The RF performance of the twin-junction mixer is slightly better than the end-loaded design, but the IF bandwidth improved by close to 70% if we employ the single-junction design with end-loaded tuner. Although the IF performance of the twin-junction design can be further improved by incorporating additional IF impedance matching circuit,[16] this method is not feasible for our current mixer design due to the integrated bias-tee arrangement, and hence the mixer block do not have a provision for additional IF circuitry. Therefore, we conclude that for operation at the THz frequency range, with the mixer design employing a sub-micron high current density tunnel junction, the end-loaded design is preferable for our application. Finally, we further improve the RF performance of the single-junction design by concatenating the end-loaded tuner with another end-stub tuner.

ACKNOWLEDGMENTS

This research was funded in part by the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 (RadioNet) and the UK-STFC Consortium Grant (ST/R000662/1). For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

REFERENCES

[1] Combes, F., des Forets, G. P., et al., [*Molecular hydrogen in space*], Cambridge University Press (2000).

[2] Rigopoulou, D., Laing, R., Withington, S., Magdis, G., Graves, S., Richer, J., and Ellison, B., "Science with ALMA Band 11 (1.0–1.6 THz)," *The Messenger* **153**, 35–37 (2013).

[3] Uzawa, Y., Fujii, Y., Gonzalez, A., Kaneko, K., Kroug, M., Kojima, T., Miyachi, A., Makise, K., Saito, S., Terai, H., et al., "Tuning circuit material for mass-produced terahertz SIS receivers," *IEEE Transactions on Applied Superconductivity* **25**(3), 1–5 (2015).

[4] De Lange, G., Jackson, B., Jochemsen, M., Laauwen, W., De Jong, L., Kroug, M., Zijlstra, T., and Klapwijk, T., "Performance of the flight model HIFI band 3 and 4 mixer units," in [*Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III*], **6275**, 627517, International Society for Optics and Photonics (2006).

[5] Khudchenko, A., Baryshev, A. M., Rudakov, K. I., Dmitriev, P. M., Hesper, R., de Jong, L., and Koshelets, V. P., "High-gap Nb-AlN-NbN SIS junctions for frequency band 790–950 GHz," *IEEE Transactions on Terahertz Science and Technology* **6**(1), 127–132 (2016).

[6] Traini, A., Tan, B.-K., Garrett, J. D., Khudchenko, A., Hesper, R., Baryshev, A. M., Dmitriev, P. N., Koshelets, V. P., and Yassin, G., "The Influence of LO Power Heating of the Tunnel Junction on the Performance of THz SIS Mixers," *IEEE Transactions on Terahertz Science and Technology* **10**(6), 721–730 (2020).

[7] Tan, B.-K., Mahashabde, S., Hector, A., Yassin, G., Khudchenko, A., Hesper, R., Baryshev, A. M., Dmitriev, P., Rudakov, K., and Koshelets, V. P., "Investigation of the performance of an SIS mixer with Nb-AlN-NbN tunnel junctions in the 780–950 GHz frequency band," in [*Proceeding of the 29th International Symposium on Space Terahertz Technology*], National Radio Astronomy Observatory (2018).

[8] Risacher, C., Vassilev, V., Pavolotsky, A., and Belitsky, V., "Waveguide-to-microstrip transition with integrated bias-T," *IEEE Microwave and Wireless Components Letters* **13**(7), 262–264 (2003).

[9] Baryshev, A., Hesper, R., Mena, F., Klapwijk, T., Van Kempen, T., Hogerheijde, M., Jackson, B., Adema, J., Gerlofsma, G., Bekema, M., et al., "The ALMA Band 9 receiver - design, construction, characterization, and first light," *Astronomy & Astrophysics* **577**, A129 (2015).

[10] Belitsky, V. Y. and Tarasov, M., "SIS junction reactance complete compensation," *IEEE transactions on magnetics* **27**(2), 2638–2641 (1991).

[11] Zmuidzinas, J., LeDuc, H. G., Stern, J. A., and Cypher, S. R., "Two-junction tuning circuits for submillimeter SIS mixers," *IEEE transactions on microwave theory and techniques* **42**(4), 698–706 (1994).

[12] Belitsky, V. Y., Jacobsson, S., Filippenko, L., and Kollberg, E., "Broadband twin-junction tuning circuit for submillimeter SIS mixers," *Microwave and Optical Technology Letters* **10**(2), 74–78 (1995).

[13] Kooi, J. W., [*Advanced receivers for submillimeter and far infrared astronomy*], Rijkuniversiteit Groningen (2008).

[14] Tan, B.-K., Yassin, G., Grimes, P., Leech, J., Jacobs, K., and Groppi, C., "A 650 GHz unilateral finline SIS mixer fed by a multiple flare-angle smooth-walled horn," *IEEE Transactions on Terahertz Science and Technology* **2**(1), 40–49 (2011).

[15] Tan, B. K., [*Development of coherent detector technologies for sub-millimetre wave astronomy observations*], Springer (2015).

[16] Tan, B.-K., Yassin, G., and Grimes, P., "A simple method to widen the IF bandwidth of a high frequency SIS mixer," in [*Proceeding of the 24th International Symposium on Space Terahertz Technology*], National Radio Astronomy Observatory (2013).