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Design of High Compression Point Josephson Junction Travelling Wave Parametric Amplifiers for Readout of Millimetre and Sub-Millimetre Astronomical Receivers

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ABSTRACT

Supra-THz heterodyne mixers generally have higher conversion loss compared to the millimetre-wave mixers. Hence, the overall receiver noise temperature becomes increasingly dominated by the first-stage semiconductor low noise amplifier (LNA), which still struggles to achieve quantum-limited noise performance. Here, we aim to develop a Josephson junction travelling wave parametric amplifier (JTWPA) that can achieve high gain over broad bandwidth but with better noise performance to replace these Intermediate Frequency (IF) amplifiers. JTWPAs are typically considered not suitable for astronomical receivers due to their low power handling capability. However, the critical current of the Josephson junctions (JJ) can be easily engineered to match the output power of the front-end detectors. Nevertheless, this may results in the requirement of a higher number of JJs as the junction inductance is in reverse relation with the critical current. Therefore, in this paper, we aim to explore the different design parameters required for developing a JTWPA with a dynamic range compatible for readout a Superconductor-Insulator-Superconductor (SIS) mixer, as an example. Here, we present two JTWPA models that are suitable for the objective, one requiring 3,142 Nb/Al-AlO$_x$/Nb junctions with a maximum gain of 23 dB, and the other with a lower gain at 16 dB but requires only 1,317 JJs. We then compare the SIS receiver noise performance utilising these JTWPAs with that of using a conventional high gain High Electron Mobility Transistor (HEMT) amplifier. We show that we can improve the receiver sensitivity significantly by either cascading two 23 dB gain JTWPA or using a combination of a 16 dB gain JTWPA and a HEMT amplifier. We conclude that the former option more suitable for large detector array applications as it completely replaces the high heat dissipation HEMT amplifiers; while the latter option is favourable at this stage for low pixel count application as it is easier to fabricate a lower number of junctions JTWPA.

Keywords: Parametric Amplifier, Travelling Waves, Josephson Junctions, quantum-limited, Millimetre and Sub-Millimetre, Astronomical Receivers, Heterodyne

1. INTRODUCTION

Heterodyne receivers such as superconductor-insulator-superconductor (SIS) and hot electron bolometer (HEB) mixers are important instruments for studying the millimetre (mm) and sub-mm sky as they allow for high spectral resolution analysis of astronomical objects, as well as increasing spatial resolution via interferometric operation. Spectrometric mixers down-convert the astronomical signal in the terahertz (THz) range to an Intermediate Frequency (IF) regime with an output power between −90 dBm and −80 dBm. The IF signal is subsequently readout using a low noise amplifier (LNA) to amplify the weak signal and to minimise the overall receiver noise temperature. Although this approach has been successfully implemented in many mm/sub-mm observatories, the noise performance of the semiconductor-based LNAs used is still 5–10 times the quantum limit. This is particularly detrimental for high frequency mixer operating in the supra-THz regime as the conversion loss of these first-stage detectors could be high, resulting in a significant increase of the noise contribution from the subsequent IF chain. These LNAs also dissipate a huge amount of thermal energy, limiting their use in large array applications. Therefore, it is important to replace these LNAs with a superconducting counterpart that could potentially achieve quantum-limited noise performance with negligible heat dissipation, to further improve the sensitivity of a receiver array.

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Travelling wave parametric amplifiers (TWPAs) are superconducting quantum devices that allow for high gain over broad bandwidth with minimal heat dissipation and add only half a quantum noise.[1,2] For astronomical receivers with relatively high output power, Josephson junction (J-)TWPAs reported in the literature are generally not suitable as they have a much lower compression point around −100 dBm.[3] Kinetic inductance (KI-)TWPAs on the other hand have a higher critical current limit which allow for handling of higher input power around −40 to −60 dBm.[3] However, this translates to the requirement for higher driving 'pump' current, which is undesirable as it may potentially induces higher resistive losses and increases heat dissipation, deteriorating the noise performance of the receiver. Therefore, a better approach would be to engineer a TWPA that have the compression point close to the expected power output from the heterodyne detectors. While it may be difficult to alter the critical current of superconducting thin films, the critical current of Josephson junctions can be easily optimised to provide the required dynamic range, by simply controlling the thickness of the insulating layer.

In our work, we aim to explore new approaches to develop a high dynamic range JTWPA, that could potentially operate at liquid helium bath temperature, for the readout of mm/sub-mm mixers. One crucial challenge here is that increasing the critical current limit of the Josephson junctions implies lower junction inductance and hence the need for increasing the number of junctions to achieve the same high gain. This is undesirable in the point of view of fabrication, as it may decrease yield. Furthermore, it could be a crucial bottleneck as a single junction failure may render the amplifier unusable. Therefore, we further explore and attempt to optimise the various circuit parameters such as the transmission line electromagnetic characteristics and the junction size variations in order to minimised the required number of junctions, while retaining the same gain, bandwidth and compression point performance, as well as complying to the fabrication limits of standard photolithography technique. Although our main objective for developing such TWPA is for readout of heterodyne detectors, a similar approach can also be utilised for other detectors technologies such as microwave kinetic inductance detectors (MKIDs) and transition-edge sensors (TES), as well as non-astronomical applications such as qubit platforms,[4] axion dark matter search experiments[5] and other cryogenic applications that requires quantum-limited sensitivity.

2. THz RECEIVER WITH TWPA AS READOUT LNA

As mentioned earlier, at THz frequencies, the mixer generally have lower conversion gain, hence the noise contribution from the subsequent IF components become non-negligible. In this section, we investigate the effect of replacing a conventional cryogenic HEMT amplifier in a heterodyne receiver chain with a quantum-limited TWPA. Here, we assume an SIS mixer as the front-end detector of the receiver. In Fig. 1 (a) we show the layout of a THz SIS mixer designed to operate in the frequency range of Atacama Large Millimetre/sub-millimetre Array (ALMA) Band 10 window, from 780–950 GHz. The detail design of this mixer can be found in Tan et. al.[6] in the same proceeding. We simulate the performance of this mixer using a combination of 3-D electromagnetic software, Ansys® High Frequency Structure Simulator (HFSS) and SuperMix,[7] a quantum mixing code developed based on the Tucker's theory. The analysis model predicts only the noise and gain characteristic of the mixer chip alone, without taking into account the contribution of the RF and IF components forming the receiver chain. To retrieve the receiver performance as a whole, we make use of the Friss's noise cascaded equation. Referring to Fig. 1 (b), the receiver noise temperature can be calculated as,

$$T_{\rm rec} = \left(\frac{1}{G_{\rm RF}-1}\right) T_{\rm RF} + \frac{T_{\rm mixer}}{G_{\rm RF}} + \frac{T_{\rm LNA}}{G_{\rm RF}G_{\rm Mixer}}, \tag{1}$$

where $T_{\rm RF}$, $T_{\rm Mixer}$ and $T_{\rm LNA}$ are the noise temperature of the RF optics components, the SIS mixer and the LNA respectively; and $G_{\rm RF}$ and $G_{\rm Mixer}$ represents the gain of each element. In this comparison, we assume a negligible RF losses of 3.2 % across the receiver's RF bandwidth to take into account all the optical losses before the SIS mixer. The down-converted IF signal is then readout by either a conventional HEMT amplifier or a TWPA. We assume that both amplifiers can achieve a flat 46 dB gain across the IF frequency range (for the TWPA case, a cascade of two 23 dB gain amplifiers), and we assume that the HEMT amplifier has a noise temperature $T_{\rm LNA}$ =5 K, while the TWPA added only 0.5 K noise, approximately twice the quantum limit at 5 GHz.

Fig. 1 (c) shows the dependence of the receiver noise temperature (in terms of multiple of quantum limit) on the mixer double-sideband (DSB) conversion gain, assuming an SIS mixer chip operating at 865 GHz with

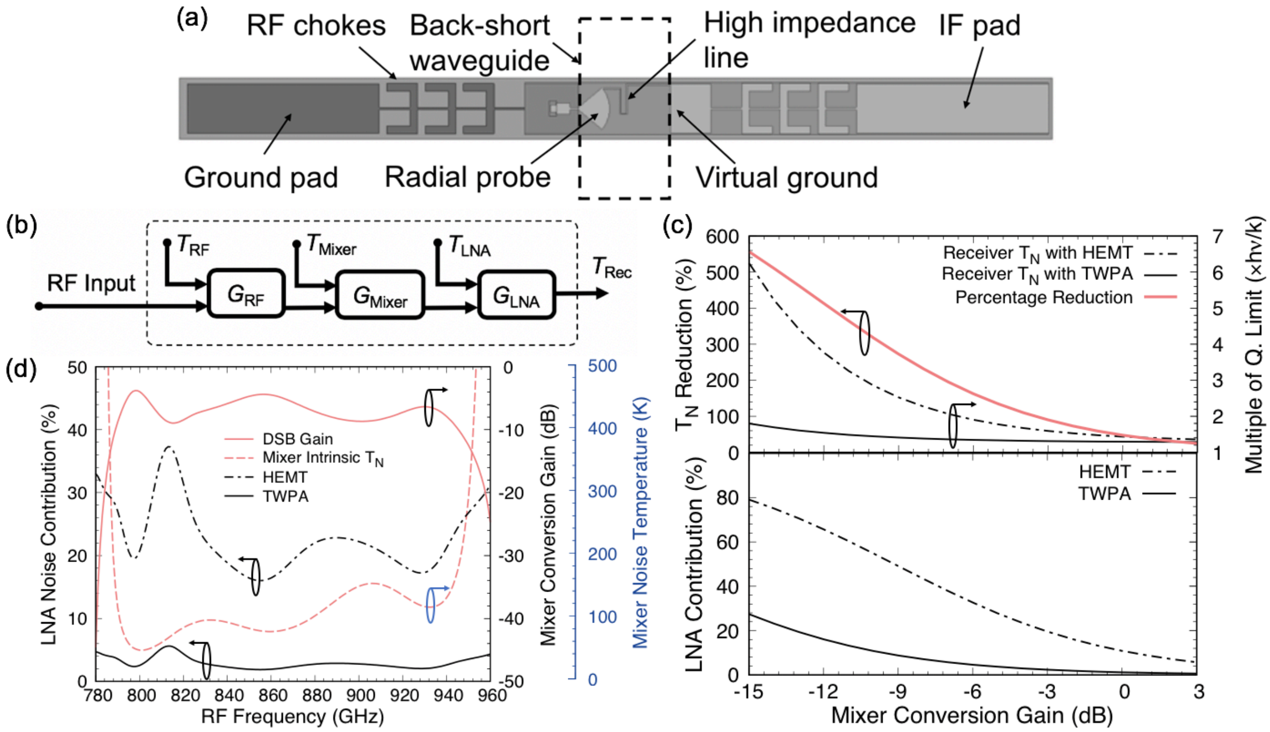

Figure 1. (a) Design of an ALMA Band 10 SIS mixer chip. (b) Diagram showing the main components in an SIS receiver chain that contribute to the overall receiver noise temperature. (c) Improvement of receiver noise temperature in terms of multiple of quantum limits, by replacing the HEMT readout LNA with a cascaded 23 dB TWPA, calculated at 865 GHz. (d) The noise contribution of the HEMT and TWPA to the total receiver noise temperature of the THz SIS receiver.

quantum limit (Q.L.) noise performance, which is equivalent to an intrinsic noise of 41.4 K added by the SIS mixer. It is clear from the figure that with very high conversion gain, the effect of replacing the HEMT with TWPA is noticeable but not significant. However, if the mixer conversion loss is high, we could see a significant improvement in receiver sensitivity e.g., at −10 dB, the receiver noise temperature is reduced from closed to 3× to about 1.45× of the quantum limit. At −15 dB the sensitivity improvement could be more than 5× better. Note that for HEB receivers which generally have inferior conversion gain performance than the SIS receiver, this improvement in receiver noise temperature is even more important. Another way to demonstrating the importance of an ultra-low noise LNA in a receiver chain is by examining the contribution of the LNA's noise compared to the total receiver noise, as shown in the lower panel of Fig. 1 (c). With low mixer conversion gain (say at −15 dB), the noise contribution from the LNA could be reduced from 80% of overall noise to about 25% with the TWPA. With better conversion gain, using a TWPA as readout amplifier could reduce the LNA noise contribution to almost non-existence.

Finally in Fig. 1 (d), we show the expected performance of a realistically simulated ALMA Band 10 SIS receiver (which includes various losses from the substrates and superconducting films above the superconducting gap) we developed earlier. Here, we show the intrinsic DSB conversion gain and the noise temperature of the mixer chip alone, predicted using SuperMix across the operational RF bandwidth. We then apply the same analysis above throughout the entire RF spectrum with the more realistic gain and noise behaviour of the mixer chip instead of assuming a quantum-limited mixer. To make a proper comparison between the use of TWPA or HEMT amplifiers as the readout amplifier, we take the ratio of the noise contributed by these readout amplifiers against the total noise temperature of the receiver. It is clear from the plot that with conventional HEMT amplifier, the noise contribution from the LNA can be as high as >20% of the total receiver noise; where as with a TWPA, this can be kept as low as approximately 3%, a significant improvement to the receiver noise performance across the entire RF bandwidth of the THz mixer.

It is worthwhile noting that although we make use of SIS mixer as our example here, the same can be applied to the HEBs (and other bolometric) receivers, which generally employ the same IF readout chain as the SIS receivers. In this case, the receiver performance improvement could be even more pronounced since the conversion gain of the HEB mixers are generally much lower than the SIS mixers.

3. DESIGNS OF HIGH COMPRESSION POINT JTWPA

In the previous section, we argued for the advantages of replacing HEMT amplifier with a TWPA for the readout of an astronomical receiver. Although the TWPA does hold the prospect of achieving the ultimate quantum-limited noise performance, but in reality it is still a challenging task that requires careful design and fabrication considerations. For instance, superconducting films used for KITWPA have a higher critical current than the Josephson junctions in the JTWPA counterpart, hence requiring higher pump current. It is suspected that the higher pump current consequently heats up the high gap superconducting transmission line due to the residual surface resistance of the film, resulting in slightly inferior noise performance when compared to that of a JTWPA. Here, we attempt to circumvent this problem by engineering the characteristic of a JTWPA such that we can operate it at exactly the IF signal power level required for readout of an astronomical receiver, close to the compression point of the amplifier.

We assume our JTWPA designs are comprised of a series of repeated unit cells forming an artificial transmission line, where the equivalent circuit diagram of the unit cell is shown in Fig. 2 (a). Here, we consider the use of Nb/Al-AlO$_x$/Nb junctions, hence facilitating the operation of the JTWPA at 4 K temperatures. The shunt capacitance (C_s) of the unit cell is given by the intrinsic shunt capacitance of the transmission line, however, it can be altered by means of parallel plate capacitors or capacitive stubs.[8] The substrate under consideration is of a high resistivity silicon or sapphire,[9] to reduce losses in the substrate.

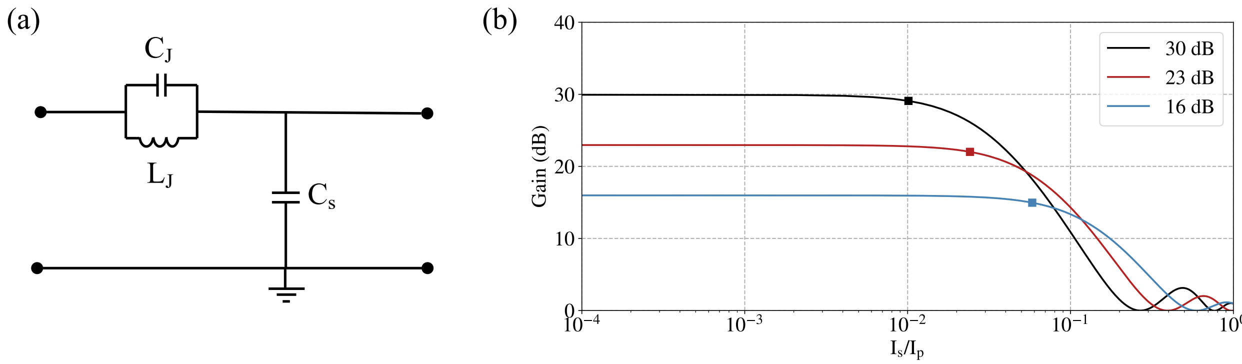

Figure 2. (a) Circuit diagram of the unit cell forming our JTWPAs. (b) Gain as a function of the ratio between the signal current amplitude (I_s) and the pump current amplitude (I_p) for a JTWPA model with the same parameters but different number of junctions to achieve 16, 23 and 30 dB gain. The square markers show the –1 dB compression point.

Our investigation focuses mainly on two critical parameters: the compression point ($P_{-1\mathrm{dB}}$) that dictates the input power the JTWPA can handle, which should be only slightly higher than the output power of the SIS detectors; and the number of junctions (N_{JJ}) forming the JTWPA, which is a major concern with regards to the yield from the fabrication process. In this work, we aim to develop a JTWPA with a compression point in the range of –90 to –80 dBm and a value of N_{JJ} as low as possible to achieve a decent gain. We expect N_{JJ} required to be much lower than 4,500, the maximum number of junctions for a single JTWPA reported in most literatures, in hope to increase the chance of success in fabricating our JTWPAs.

As both of these parameters ($P_{-1\mathrm{dB}}$ and N_{JJ}) are related directly to the critical current (I_C) of the junction, which also determines the device's inductance per length, we start our investigation by first exploring how we can achieve a certain critical current value by altering both the critical current density (J_c) and the area (A_{JJ}) of the junctions. We also include the shunt capacitance (C_s) of the transmission line as a parameter in our analysis, as we have previously shown that modifying the shunt capacitance is an effective strategy to reduce the number of junctions.[10]

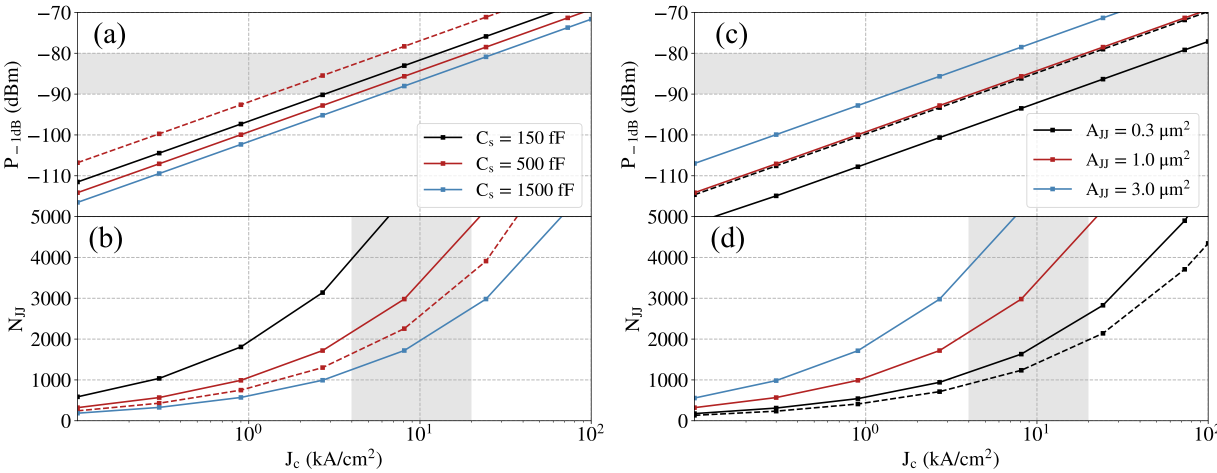

Figure 3. Relation between various critical JTWPA parameters. The dotted and solid lines represent a JTWPA with 16 dB and 23 dB gain respectively; the horizontal and vertical grey area mark out the SIS mixer output power range and the usual J_c of SIS tunnel junction respectively. (a) Compression point ($P_{-1\mathrm{dB}}$) and (b) number of junctions (N_{JJ}) as a function of the critical current density (J_c) for different shunt capacitance (C_s) with a fixed junction area of $1\,\mu\mathrm{m}^2$. (c) $P_{-1\mathrm{dB}}$ and (d) N_{JJ} as a function of J_c for different junction area values (A_{JJ}) and a fixed $C_s = 500\,\mathrm{fF}$.

Apart from the above-mentioned parameters, the compression point also depends on the gain of the JTWPA. With everything else being equal, a JTWPA with higher number of junction (hence longer transmission length) would naturally amplify an incoming signal to higher amplitude compare to a lower N_{JJ} JTWPA, assuming a completely lossless transmission line. Consequently, a higher gain TWPA would start to deplete the 'pump' current, and the peak gain starts to deteriorate at lower signal amplitude level, compared to a lower gain TWPA. This effect is illustrated in Fig. 2 (b), where the gains are plotted as a function of the ratio between the signal amplitude against the pump amplitude (I_s/I_p), for three JTWPA models with identical physical parameters except different N_{JJ} to achieve 16, 23 and 30 dB gain respectively. The compression points indicated with squared markers in the plot, represent the points where the signal gain drops by 1 dB, clearly shown to occur at a lower I_s/I_p level as the peak gain is increased. As a lower gain JTWPAs benefited from a reduced number of junctions required, and therefore resulting in higher compression point, it is therefore imperative to further explore the compromise between all these parameters including the peak gain, for the case of using a TWPA for readout of astronomical receiver. In the following section, we present the optimal design parameters for two JTWPA models with a target gain of 16 and 23 dB respectively, to compare the pros and cons between a high- and low-gain JTWPA in terms of the critical parameters listed above.

3.1 High-gain JTWPA

In Fig. 3 (a)&(b), we plot the relation between N_{JJ}, $P_{-1\mathrm{dB}}$ and J_c for different values of shunt capacitance[*] but with a fixed junction area of $1\,\mu\mathrm{m}^2$; and Fig. 3 (c)&(d) for different junction areas but with a fixed shunt capacitance of $C_s = 500\,\mathrm{fF}$. These plots were produced using the coupled mode equations (CME)[11] assuming an artificial perfect phase-matched condition for exponential gain, which can be easily realised at latter stage by adding dispersion engineering schemes such as Resonant Phase Matching (RPM) method[12] or periodic loading structures.[1,13] In this section, we focus on the solid lines in the plot which represent the case for the 23 dB gain JTWPA.

Our target $P_{-1\mathrm{dB}}$ range is highlighted in grey in the $P_{-1\mathrm{dB}}$ vs J_c plots. A similar grey area is shaded on the N_{JJ} vs J_c plots to indicate the typical critical current density values we expect to be able to achieve. The reason we highlight this range of critical current density values is that we expect to fabricate our JTWPA using

[*]The shunt capacitance value is defined per unit cell length, which in our case is 10 µm.

the existing fabrication facilities built for producing SIS mixers, hence they are slightly higher than the typical critical current density value reported in most of the JTWPA in the literatures. To perform these analyses, we fixed the distance between the junctions to 10 µm, facilitating a compact JTWPA design without entailing a fabrication challenge. The pump current amplitude is fixed to $I_\mathrm{p} = 0.5 I_\mathrm{c}$, as higher values could deteriorate the noise performance of the device.

From Fig. 3, it is clear that both N_JJ and $P_{-1\mathrm{dB}}$ increase with higher J_c values. The former relation is straightforward. As J_c increases, I_c becomes higher and hence the junction inductance is lowered. With lower junction inductance, we would therefore need longer transmission length i.e., higher number of junctions to achieve the same gain. The latter relation is unsurprising either. Recall that the gain compression plot shown in Fig. 2 (b) can in fact be approximated[12] as:

$$G = \frac{G_0}{1 + 2G_0 \frac{I_\mathrm{s}^2}{I_\mathrm{p}^2}}. \tag{2}$$

Since we fixed the pump amplitude to $I_\mathrm{p} = 0.5 I_\mathrm{c}$, we can further deduce the equation to:

$$G = \frac{G_0}{1 + 8G_0 \frac{I_\mathrm{s}^2}{I_\mathrm{c}^2}}. \tag{3}$$

From Eq. 3, it is clear that if the critical current I_c is increased as J_c increases, I_s would need to be increased at the same magnitude to achieve the same gain G, which in this case $G = G_0 - 1$ for the $P_{-1\mathrm{dB}}$ point, and therefore the higher $P_{-1\mathrm{dB}}$ point.

Focusing on Fig. 3 (b)&(d), we can also observe a reduction of N_JJ when C_s increases or A_JJ decreases. However, both scenarios also resulting in the reduction of $P_{-1\mathrm{dB}}$ as shown in Fig. 3 (a)&(c), which is undesirable in our case. Nevertheless, one notes that the variations of C_s have a much smaller impact on the compression point value compared to the changes in A_JJ. For example, altering C_s by 10× would only change $P_{-1\mathrm{dB}}$ by about 5 dB but change A_JJ by the same magnitude resulting in change of $P_{-1\mathrm{dB}}$ by almost 15 dB. This therefore suggesting that maximising C_s is a better strategy to achieve high compression points with a small number of junctions.

From these analyses, we conclude that the optimal sets of parameters for achieving 23 dB gain with $P_{-1\mathrm{dB}} = -85$ dBm are as follow: $C_\mathrm{s} = 500$ fF, $J_\mathrm{c} = 9$ kA/cm^2, $A_\mathrm{JJ} = 1$ µm^2 and N_JJ =3,142, as summarised in Tab.1. The chosen C_s value can be achieved conveniently with a compact structure using parallel plate capacitors with a thin layer (≈ 50 nm) of high dielectric constant materials such as aluminium oxide (Al_2O_3). Higher values of C_s could be used to further reduce the number of junctions, but may require too thin a dielectric layer, and more importantly a larger capacitor area which could be detrimental in term of fabrication as well as compactness of the amplifier.

We would like to emphasis that the chosen value of $J_\mathrm{c} = 9$ kA/cm^2 is in fact very close to the typical critical current value we used for fabricating our SIS mixers. This is important as this opens up the possibility to fabricate and integrate both the SIS mixers and the readout amplifier within a single chip, as the technology required to fabricate the tunnel junctions is now the same. Finally, we would like to point out that there are some flexibilities in the choice of J_c and A_JJ, as we can increase/decrease J_c by decreasing/increasing A_JJ to keep the same value of I_c. However, it is important to note that the number of junctions required will not change in either cases.

3.2 Low-gain JTWPA

Although we have shown that a higher than 20 dB gain JTWPA with $P_{-1\mathrm{dB}} = -85$ dBm can be achieved with reasonable physical parameters, we expect that the requirement for more than 3,000 tunnel junctions would still poses a major challenge in fabricating such JTWPA chip. However, it is obvious that if we lower the target gain, we can further reduce the required number of junction, while achieving the needed compression point value. In this section, we explore the possibility of developing a JTWPA with about 10× lower gain, and if we can still utilise such low-gain JTWPA for readout of SIS receiver.

	Gain (dB)	C_s (fF)	J_c (kA/cm^2)	A_{JJ} (μm^2)	N_{JJ}
High gain	23	500	9.0	1.0	3142
Low gain	16	500	9.2	0.3	1317

Table 1. Summary of the parameters describing the high- and low-gain JTWPA models.

For this design, we aim to reach the same $P_{-1\mathrm{dB}} = -85\,\mathrm{dBm}$, hence we fix $C_s = 500\,\mathrm{fF}$ to minimise the number of junctions required, while we explore the required J_c to reach our targeted $P_{-1\mathrm{dB}}$. Referring to the dashed line in Fig. 3 (a), we can see that for the case of $C_s = 500\,\mathrm{fF}$, we can achieve the targeted compression point with $J_c < 4\,\mathrm{kA/cm^2}$.

Although realising tunnel junctions with lower J_c values is certainly feasible, the astronomy community is much familiar with fabrication of higher J_c junctions due to its application for SIS mixers. As this technology is well established within the community, it is therefore preferable not to alter the fabrication recipe too much to ensure good yield. Furthermore, with current e-beam technology, it becomes easier to fabricate smaller junctions ($< 1\,\mu$m), compared to conventional photolithography techniques. Given that we can alter the critical current I_c by either changing J_c or A_{JJ}, we opt for the latter option to adapt to current SIS junction fabrication technique. Following this methodology, we decrease the junction area to $A_{JJ} = 0.3\,\mu\mathrm{m}^2$, so that the target compression point can be reached at a higher J_c value. The final design parameters for achieving a lower 16 dB gain JTWPA with $P_{-1\mathrm{dB}} = -85\,\mathrm{dBm}$ are as follow: $C_s = 500\,\mathrm{fF}$, $J_c = 9.2$ kA/cm^2, $A_{JJ} = 0.3\,\mu\mathrm{m}^2$ and N_{JJ} =1,317, as summarised in Tab.1. It is obvious from the table shown that both designs have very similar fabrication parameters with the exception of the junctions size. However, the low-gain JTWPA requires almost three times less junctions than the high-gain JTWPA, therefore increase the chance of higher yield during fabrication.

As our JTWPA designs are based on Nb/Al-AlO$_x$/Nb junctions technology, the amplifiers can be operated at 4 K environment, similar to the requirement of SIS and/or HEB receivers. Furthermore, the required $J_c \approx 9\,\mathrm{kA/cm^2}$ is similar to the critical current density used for the SIS mixers, therefore allowing the possibility of integrating both the mixer and the JTWPA on a single chip. This would result in a more compact receiver setup and a further reduction of the losses in the receiver chain i.e, better noise performance, as external physical connections would not be required anymore between the SIS mixer chip and the JTWPA. This is important as it may relax the requirement for a 50 Ω JTWPA, due to the high shunt capacitance we required for our design that inevitably lower the characteristic impedance ($Z_0 \propto 1/C_s$). In current design, we expect to utilise a pair of impedance transformer to bridge the impedance of our JTWPA with the 50 Ω environment, or embedding the non-50 Ω section in a periodic loading JTWPA as presented in Ratter et. al.[13] However, if the JTWPA can be connected directly to the output of the SIS mixer, which generally have a lower output impedance, we could develop a JTPWA that would match the output impedance of the SIS mixer directly without going through the 50 Ω intermediate stage (e.g., connecting cables). This would further reducing the need for a circulator and reducing the standing wave issue with the receiver backened, as the impedance mismatch after the high-gain element in the IF chain would have minimal effect on the overall receiver performance.

4. RECEIVER NOISE WITH CASCADED JTWPA & HEMT AMPLIFIER

We have argued that a lower gain ($< 20\,\mathrm{dB}$) JTWPAs could benefit from higher fabrication yield, due to the fewer junctions required, while achieving high enough dynamic range for the readout of SIS mixers; in the case of a 16 dB JTWPA that requires only 1,317 junctions. While a 16 dB JTWPA may not provide enough gain for the readout of astronomical receivers, it can be combined with a HEMT amplifier to further increase the gain. In this section, we extend the analysis performed in Sec.2 to include the noise performance of an SIS receiver using a combination of a 16 dB JTWPA and a 30 dB HEMT for the readout of the signal.

The diagram of the SIS receiver chain considered in this section is shown in Fig. 4 (a). For this setup, Eq. 1 can be re-written as,

$$T_{\mathrm{rec}} = \left(\frac{1}{G_{\mathrm{RF}} - 1}\right) T_{\mathrm{RF}} + \frac{T_{\mathrm{mixer}}}{G_{\mathrm{RF}}} + \frac{T_{\mathrm{JTWPA}}}{G_{\mathrm{RF}} G_{\mathrm{Mixer}}} + \frac{T_{\mathrm{HEMT}}}{G_{\mathrm{RF}} G_{\mathrm{Mixer}} G_{\mathrm{JTWPA}}}, \quad (4)$$

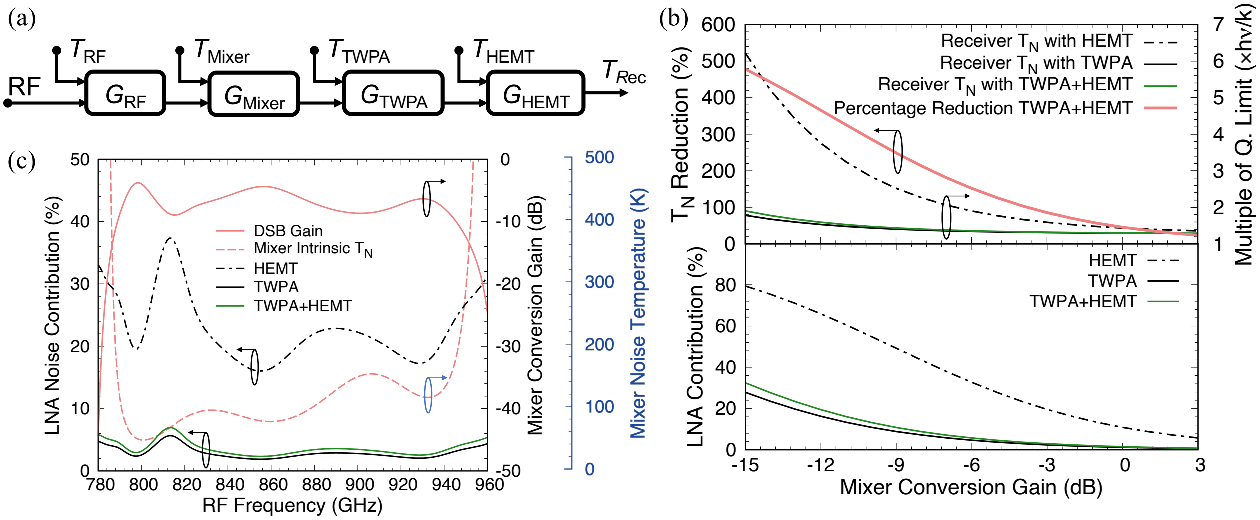

Figure 4. Same plots as depicted in Fig. 1, with the added green curves representing the case of the readout amplifier comprising a cascade of 16 dB gain TWPA and 30 dB gain HEMT amplifier. We assume the noise temperature of the amplifiers remains the same as previous i.e., 0.5 K for the TWPA and 5 K for the HEMT amplifier. (a) Diagram showing the SIS receiver chain with the cascaded TWPA-HEMT amplifiers. (b) Improvement of receiver noise temperature in terms of multiple of quantum limits, comparing the three cases, calculated at 865 GHz. (d) The noise contribution of the readout amplifier(s) to the total receiver noise temperature of the THz SIS receiver for all three scenarios.

where T_{JTWPA} and T_{HEMT} are the noise temperature of the JTWPA and HEMT amplifier respectively; and G_{JTWPA} is the gain of the JTWPA.

Our analysis is based on the same SIS mixer design presented in Sec. 2, with all the calculation parameters remains the same e.g., the noise temperature of the TWPA and the HEMT amplifiers, except the gain of both amplifier which is now 16 dB for our JTWPA and 30 dB for the HEMT. Fig. 4 (b)&(c) reproduce the exact same plots shown earlier, but added with the noise performance of the updated SIS receiver indicated by the green curves that illustrate the case with a combination of a 16 dB JTWPA and a 30 dB HEMT amplifier. Unsurprisingly, this combination has a negligible effect compared to earlier case where we cascaded two 23 dB TWPAs, because from Eq.4 we can see that the noise contribution from the HEMT amplifier is reduced by a factor of 40 already by the gain of the JTWPA, while the noise contribution of the subsequent IF components are dramatically reduced by the HEMT itself. From the bottom graph in Fig. 4 (b), we observe that the effect of combining a JTWPA and HEMT, compared with the cascaded 23 dB JTWPAs is only noticeable for very low conversion gain (∼–15 dB), where the noise temperature contribution is increased from $\sim 28\,\%$ to $\sim 32\,\%$. We can therefore conclude that achieving a high gain (>20 dB) TWPA is not required to produce a significant improvement on the noise temperature of the receiver setup. A TWPA with a decent gain of 16 dB, combined with a HEMT amplifier will have a similar effect on the overall system noise performance, therefore reducing the stringent requirement for the JTWPA fabrication. Nevertheless, ultimately it would still be preferable to master the fabrication processes in the near future, to improve the junction fabrication yield dramatically such that we can fabricate much higher number of junctions; therefore bypass the many restriction presented in this paper to completely replace the use of a HEMT amplifier in astronomical receivers.

5. CONCLUSION

In this paper, we have shown that the noise performance of an SIS receiver can be improved by replacing the HEMT LNA with quantum-limited TWPAs for the readout of the SIS mixer output signal. In order to match the output power of the SIS mixer, we explore different design and fabrication parameter combinations to achieve a higher dynamic range JTWPA with $P_{-1\mathrm{dB}} = -85\,\mathrm{dBm}$. Based on these analyses, we have presented two JTWPA models requiring 3,142 and 1,317 Nb/Al-AlO$_x$/Nb junctions for a gain of 23 dB and 16 dB respectively. One of the main features of our designs is that the required critical current density $J_\mathrm{c} \sim 9\,\mathrm{kA/cm^2}$ is very similar to the J_c used for fabricating SIS tunnel junctions, thus facilitating the implementation of the JTWPA and the SIS mixer on a single chip. We concluded our paper by calculating the noise performance of the SIS receiver considering the combination of a 16 dB quantum-limited TWPA with a HEMT amplifier for the readout of a SIS mixer output signal, and we obtained almost identical results compared with the case of using two 23 dB TWPAs. This suggests that in medium term, a single 16 dB TWPA is sufficient to improve the noise performance of an astronomical receiver, before we could fabricate a JTWPA with much higher number of junction.

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REFERENCES

[1] Ho Eom, B., Day, P. K., LeDuc, H. G., and Zmuidzinas, J., "A wideband, low-noise superconducting amplifier with high dynamic range," *Nature Physics* **8**(8), 623–627 (2012).

[2] Macklin, C., O'Brien, K., Hover, D., Schwartz, M. E., Bolkhovsky, V., Zhang, X., Oliver, W. D., and Siddiqi, I., "A near-quantum-limited josephson traveling-wave parametric amplifier," *Science* **350**(6258), 307–310 (2015).

[3] Esposito, M., Ranadive, A., Planat, L., and Roch, N., "Perspective on traveling wave microwave parametric amplifiers," *Applied Physics Letters* **119**(12), 120501 (2021).

[4] Ranzani, L., Bal, M., Fong, K. C., Ribeill, G., Wu, X., Long, J., Ku, H.-S., Erickson, R. P., Pappas, D., and Ohki, T. A., "Kinetic inductance traveling-wave amplifiers for multiplexed qubit readout," *Applied Physics Letters* **113**(24), 242602 (2018).

[5] Bartram, C., Braine, T., Cervantes, R., Crisosto, N., Du, N., Leum, G., Mohapatra, P., Nitta, T., Rosenberg, L. J., Rybka, G., Yang, J., Clarke, J., Siddiqi, I., Agrawal, A., Dixit, A. V., Awida, M. H., Chou, A. S., Hollister, M., Knirck, S., Sonnenschein, A., Wester, W., Gleason, J. R., Hipp, A. T., Jois, S., Sikivie, P., Sullivan, N. S., Tanner, D. B., Hoof, S., Lentz, E., Khatiwada, R., Carosi, G., Cisneros, C., Robertson, N., Woollett, N., Duffy, L. D., Boutan, C., Jones, M., LaRoque, B. H., Oblath, N. S., Taubman, M. S., Daw, E. J., Perry, M. G., Buckley, J. H., Gaikwad, C., Hoffman, J., Murch, K., Goryachev, M., McAllister, B. T., Quiskamp, A., Thomson, C., and Tobar, M. E., "Dark matter axion search using a josephson traveling wave parametric amplifier," (2021).

[6] Tan, B.-K., K., R., P., K. V., A., K., M., B. A., and G., Y., "Electromagnetic Performance Comparisons of 0.85 THz Integrated Bias-Tee SIS Mixers with Twin-Junction and End-Loaded Tuning Schemes," in [*2022 SPIE Astronomical Telescope and Instrumentations*], SPIE (2022).

[7] Ward, J., Rice, F., Chattopadhyay, G., and Zmuidzinas, J., "Supermix: A flexible software library for high-frequency circuit simulation, including sis mixers and superconducting elements," in [*Proceedings, Tenth International Symposium on Space Terahertz Technology*], 269–281 (1999).

[8] Chaudhuri, S., Li, D., Irwin, K. D., Bockstiegel, C., Hubmayr, J., Ullom, J. N., Vissers, M. R., and Gao, J., "Broadband parametric amplifiers based on nonlinear kinetic inductance artificial transmission lines," *Applied Physics Letters* **110**(15), 152601 (2017).

[9] Tan, B.-K., Rudakov, K., Koshelets, V. P., Khudchenko, A., Baryshev, A., and Yassin, G., "Comparing the performance of 850 ghz integrated bias-tee superconductor-insulator-superconductor (sis) mixers with single- and parallel-junction tuner," *Superconductor Science and Technology* (2022). Submitted for publication.

[10] Navarro, J. M. and Tan, B.-K., "Optimising the design of a broadband Josephson junction TWPA for axion dark matter search experiments," in [*Quantum Technology: Driving Commercialisation of an Enabling Science II*], Padgett, M. J., Bongs, K., Fedrizzi, A., and Politi, A., eds., **11881**, 139 – 148, International Society for Optics and Photonics, SPIE (2021).

[11] Yaakobi, O., Friedland, L., Macklin, C., and Siddiqi, I., "Parametric amplification in josephson junction embedded transmission lines," *Phys. Rev. B* **87**, 144301 (Apr 2013).

[12] O'Brien, K., Macklin, C., Siddiqi, I., and Zhang, X., "Resonant phase matching of josephson junction traveling wave parametric amplifiers," *Phys. Rev. Lett.* **113**, 157001 (Oct 2014).

[13] Ratter, K. and Tan, B.-K., "A dispersion-engineered josephson travelling wave parametric amplifier with periodic impedance perturbation," National Radio Astronomy Observatory (2021).