Design Considerations for a W-band Josephson Junction Travelling Wave Parametric Amplifier

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***Abstract*—Most Josephson junction Travelling Wave Parametric Amplifiers (JTWPAs) developed so far have been focused on operation below 20 GHz, primarily driven by the choice of the qubit resonance frequency used in quantum computation research. Consequently, there is a lack of effort to extend their operation to higher frequency ranges. However, millimetre (mm)-wave JTWPAs could offer potential significant advantages for astronomy, but their operation in this regime is largely unexplored. In this paper, we describe the design considerations for extending JTWPAs operation to the W-band range. We present two JTWPA designs, one with and one without phase matching elements, and we discuss the design methodology of both approaches, before showing their predicted performance respectively.**

***Keywords*—travelling wave, parametric amplifier, millimetre wave, Josephson junctions, metamaterial, W-band.**

I. Introduction

The design and operation of JTWPAs at frequencies higher than 20 GHz is a relatively unexplored topic, so far. Our interest lies in extending the operation of microwave JTWPAs to the W-band range (75-110 GHz), to pave the way for operation at even higher frequencies into the millimetre (mm) and sub-mm bands. W-band is one of the key windows to astronomical observation, including the Event Horizon Telescopes (EHT). Some of these more demanding observations have driven ALMA (Atacama Large Millimetre/sub-mm Array) to upgrade their band 2 (67-116 GHz) cartridge [1]. However, even state-of-the-art High Electron Mobility Transistors (HEMT) receiver still struggle to achieve the ultimate noise performance [2].

TWPAs exploit the nonlinear reactive properties of superconducting transmission lines for amplification, and have demonstrated broadband high gain with noise approaching the quantum limit in the microwave regime [3, 4]. They can in principle operate at higher frequencies, into the sub-mm wave regime, potentially overhauling the commonly used heterodyne receivers' architecture based on superconductor-insulator-superconductor (SIS) mixers or HEMT amplifiers as first-stage detector. Deployment of an ultra-low noise superconducting pre-amplifier before these detectors would improve the receiver sensitivity [5], especially into the THz region.

While high kinetic inductance films based (K-)TWPAs have shown their potential feasibility in achieving large gain in the W-band [6, 7, 8], a similar demonstration with the Josephson-based metamaterial counterpart has not yet been performed. As JTWPAs generally require much smaller pump powers than KTWPAs, they may be more suitable for operation alongside SIS mixer that require additional high frequency local oscillator source. In this paper, we discuss the design and fabrication considerations of the envisioned W-band JTWPA.

II. W-Band JTWPA with Interdigitated Stubs

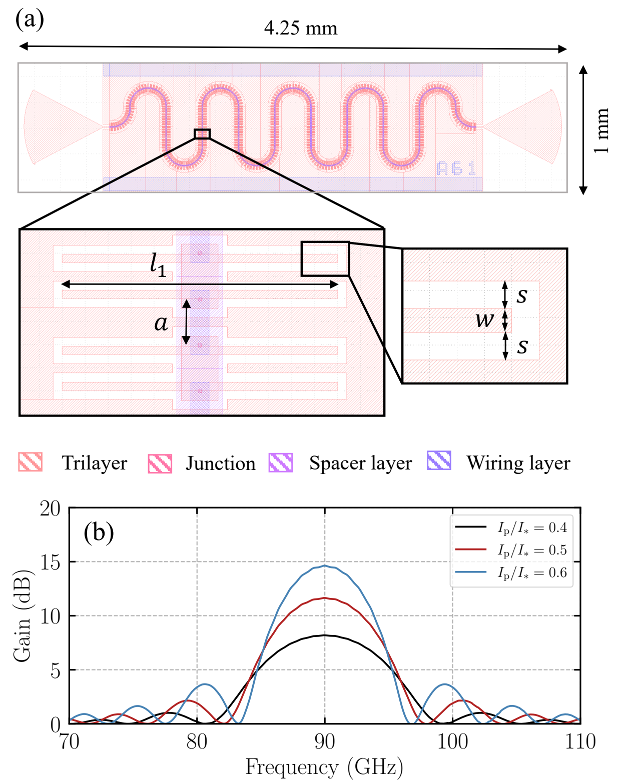

Fig. 1. (a) Layout of the unloaded W-band JTWPA device. Zoom-in shows the structures forming the device, including the junctions and the interdigitated stubs used to match the output impedance of the antennas. The stubs length (l_1), width (w) and gap (s), as well as the distance between the junctions (a) is indicated on the layout. (b) Predicted gain for a pump tone at 90 GHz, with different pump power to critical current ratio (I_p/I_*).

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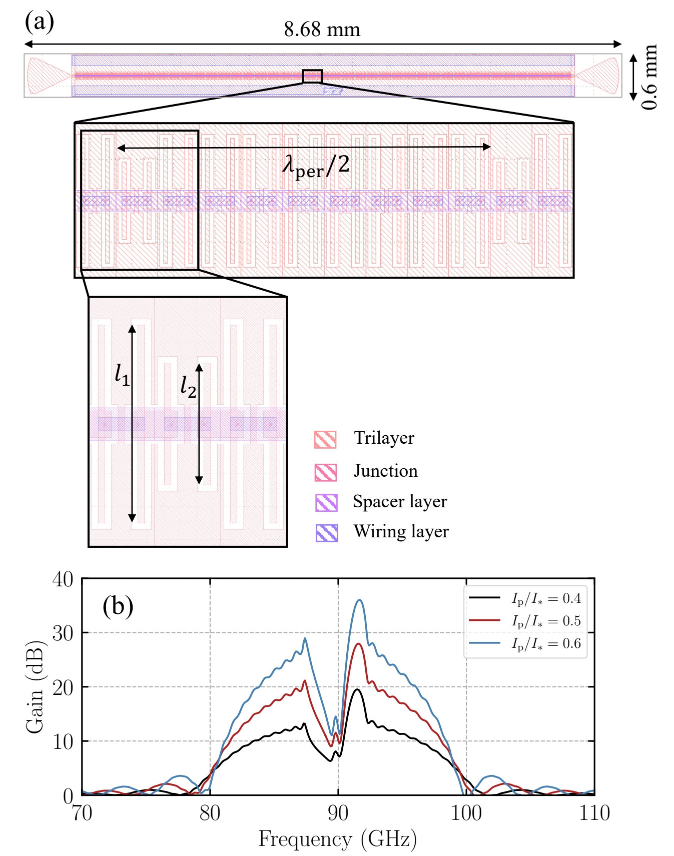

Fig. 2. (a) Layout of the loaded W-band JTWPA device. The zoom-in image shows the variation of the stubs' length (l_1 and l_2) creating the loading section. The loading sections are separated of a distance $\lambda_{\text{per}}/2$, where λ_{per} is the wavelength at $f_{\text{per}} \approx 92$ GHz. (b) Predicted gain for a pump tone at 89.8 GHz, for different pump power to critical current ratio (I_p/I_*).

While recent JTWPA designs utilise aluminium-based junctions [9, 10], harnessing the maturity of the superconducting qubit fabrication techniques, this technology has an operational limit f < 90 GHz due to the aluminium superconducting gap energy. Our designs are based on niobium/aluminium-aluminium oxide/niobium (Nb/Al-AlO_x/Nb) junctions, comprising a larger superconducting gap energy, extending the operational frequency to f < 680 GHz.

A critical parameter to consider for high frequency operation beyond the microwave regime is the plasma resonance frequency of the junctions, which increases inversely with the junction's inductance. As the parametric gain of a JTWPA is directly proportional to the junction inductance, this implies that we may need more junctions to achieve decent gain. Therefore, careful consideration is required to optimise the design of the mm-wave JTWPA. Furthermore, high frequency devices are generally coupled with waveguide connections instead of microwave connectors, hence different deliberation is required for the JTWPA interfaces, as well as the control of the characteristic impedance of the metamaterial line.

TABLE I. DESIGNS CHARACTERISTICS†

Design	J_c (kA/cm^2)	A_{jj} (μm²)	N_{jj}	l_1 (μm)	l_2 (μm)	w (μm)	S (μm)	a (μm)
Unloaded	3.4	0.5	704	60	NA	2	2	10
Loaded	3.4	0.5	704	60	37	1.75	2	10

†Design parameters: critical current density (J_c), junction's area (A_{jj}), number of junctions (N_{jj}), main stubs length (l_1), loading section stub length (l_2), stub width (w), stub gap (S), distance between junctions (a).

As this endeavor is unprecedented, we first opt for a minimalistic design approach. Specifically, we omit dispersion engineering elements that promote exponential gain to ease fabrication. This approach provides us the flexibility in positioning the pump frequency anywhere within the W-band during the experiments without being constrained by the phase matching conditions. It further allows for greater error limits in the fabrication tolerance, particularly these inaccuracies may be a more pronounced effect at higher frequencies compared to microwave designs.

This design, hereafter the unloaded design, is presented in Fig.1(a). It consists of a coplanar waveguide (CPW) Josephson junction array coupled with interdigitated stubs used to match the output impendence of our probe antennas (Z_{out} = 70 Ω), while ensuring the phase velocity remains high to reduce the number of junctions required for high gain. The critical current of the 704 junctions composing our JTWPA is fixed to J_c = 3.4 kA/cm^2, resulting in a cut-off frequency about 180 GHz, high enough to suppress the unwanted pump harmonics while not affecting the amplification bandwidth of the device. The design also includes ground bridges to avoid the generation of higher order modes, and a meandered geometry to reduce the size of the device chip, to limit the substrate resonant modes. We simulated the behaviour of the unit cell and cascaded them to estimate the gain-bandwidth product of the entire chip using our established couple-mode equations (CME) framework [11]. Fig.1(b) shows the expected gain profiles when pumping the device with an 89.8 GHz pump tone at different strength.

In a separate design, hereafter the loaded design, we improve the gain-bandwidth product of the unloaded design by incorporating phase-matching elements, namely periodic loading structures, along the transmission line. This results in a transmission line where the length of the stubs is periodically shortened, as shown in Fig.2(a), with a modulation period of $\lambda_{\text{per}}/2$, where λ_{per} is the wavelength at $f_{\text{per}} \approx 92$ GHz. This modulation creates a stopband around f_{per}, locally distorting the dispersion relation of the device, allowing for phase mismatch

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correction, hence facilitating exponential gain [3, 12]. The predicted gain profiles for this loaded design when pumped at $f_p = 89.8$ GHz is presented in Fig. 2(b), showcasing a significant enhancement in the gain-bandwidth product. The key design parameters of both the unloaded and the loaded designs are summarised in Tab.1.

III. SUMMARY

The operation of JTWPAs at frequencies higher than microwaves is largely unexplored. In this paper, we have presented the design considerations required to extend the operation of JTWPAs to the W-band range. We introduce two JTWPA designs based on Nb/Al-AlO_x/Nb junctions, consisting of a CPW with interdigitated stubs. The two resulting designs, with and without periodic loading modulation of the transmission line, are simulated and their performance calculated for different pump amplitudes. We estimate peak gain values of approximately 15 dB for the unloaded design and 25 dB for the loaded design.

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