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Original
Ultra low noise readout with traveling wave parametric amplifiers: The DARTWARS project / Rettaroli, A., Barone, C., Borghesi, M., Capelli, S., Carapella, G., Caricato, A.P., Carusotto, I., Cian, A., Di Gioacchino, D., Enrico, E., Falferi, P., Fasolo, L., Faverzani, M., Ferri, E., Filatrella, G., Gatti, C., Giachero, A., Giubertoni, D., Granata, V., Greco, A., et al.. - In: NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT. - ISSN 0168-9002. - ELETTRONICO. - 1046:(2023), p. 167679. [10.1016/j.nima.2022.167679]

Availability:
This version is available at: 11583/2973316 since: 2023-01-11T11:24:44Z

Publisher:
Elsevier

Published
DOI:10.1016/j.nima.2022.167679

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12 October 2026

Ultra low noise readout with travelling wave parametric amplifiers: the DARTWARS project

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Abstract

The DARTWARS project has the goal of developing high-performing innovative travelling wave parametric amplifiers with high gain, large bandwidth, high saturation power, and nearly quantum-limited noise. The target frequency region for its applications is 5 − 10 GHz, where the expected noise temperature is below 600 mK. The development follows two different approaches, one based on Josephson junctions and one based on kinetic inductance of superconductors. This contribution mainly focuses on the Josephson travelling wave parametric amplifier, presenting its design, preliminary measurements and the test of homogeneity of arrays of Josephson junctions.

Keywords: microwaves, low noise, parametric amplification, detector arrays, superconductors, Josephson junctions

1. Introduction

Ultra-low noise detection near the quantum limit and amplification over a large bandwidth are fundamental requirements in forthcoming particle physics applications operating at low temperatures, such as neutrino measurements, x-ray observations, CMB measurements, and light dark matter detection, as well as in quantum computing applications, where high fidelity readout is key. In these fields, arrays of detectors are being used, such as arrays of MKIDs (microwave kinetic inductance detectors), arrays of TESs (transition edge sensors), microwave resonant cavities and arrays of qubits, all requiring multiplexed readout.

The readout sensitivity of arrays of detectors with a high number of channels in the microwave range (MKIDs, TES mu-MUX, qubits, mw cavities) is currently limited by the noise temperature and bandwidth of available cryogenic amplifiers such as HEMTs (high-electron-mobility transistors) or JPAs (Josephson parametric amplifiers). Comparing the two technologies, HEMTs have the advantages of providing high gain (> 30 dB), large bandwidth (few GHz) and high dynamic range, while JPAs have typical gain of about 20 dB, a small dynamic range (< -100 dBm) and a small instantaneous bandwidth (~ 100 MHz). Nevertheless, JPAs allow to significantly boost the sensitivity of the detection since their added noise reaches the quantum limit, whereas HEMTs noise is 10–40 times above that limit [1, 2].

DARTWARS (Detector Array Readout with Travelling Wave AmplifieRS) aims to develop a device with large bandwidth and nearly quantum-limited noise at the same time, exploiting the concept of parametric amplification with microwaves travelling along a transmission line with embedded superconducting non-linear lumped elements.

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2. The project

A parametric amplifier is a type of parametric oscillator, which is a harmonic oscillator where its parameters are varied with time:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \beta(t)\frac{\mathrm{d}x}{\mathrm{d}t} + \omega^2(t)\,x = 0. \qquad (1)$$

$\beta(t)$ and $\omega(t)$ are the damping coefficient and the resonance frequency. If these parameters are varied at about twice the resonance frequency by a pump signal, the oscillator absorbs energy from it. If the loss is not sufficient to dampen this energy, the oscillations grow exponentially, whereas, below this limit, the pumped energy is transferred to the signal that is amplified.

A TWPA is designed as a transmission line with tunable embedded reactive elements, as inductances. The nonlinear inductance is implemented by means either of Josephson junctions (JJs) or the kinetic inductance (KI) of superconductors, for which the relationship with the current is, at the first order, $L(I) \simeq L_0(1 + (I/I_c)^2)$, where in JJs I_c is the junctions' critical current, while in KI devices I_c is the superconductor critical current. Both three-wave mixing (3WM) and four-wave mixing (4WM) are possible: in 3WM a single pump photon converts into signal and idler photons, $\omega_p = \omega_s + \omega_i$, whereas in 4WM two pump photons convert into signal and idler photons, $2\omega_p = \omega_s + \omega_i$ [3].

The development of Josephson travelling wave parametric amplifiers (JTWPAs) and of kinetic inductance TWPAs (KITWPAs) has been already investigated and demonstrated, as for example in [4, 5] and [6, 7] respectively. In these cases, gain values up to 15 dB over a bandwidth of a few GHz have been reached, but significant progress is still needed. The purpose of DARTWARS is to investigate the fabrication of both JTWPA and KITWPA devices [8].

JTWPAs are made of a coplanar waveguide (CPW) embedding a chain of rf-SQUIDs (see Fig. 1), which can be biased by a DC current or a magnetic field to activate the 3WM or 4WM nonlinearities. The design follows the coupled mode equation approach developed by INRiM (Istituto Nazionale di Ricerca Metrologica) [9, 10]. To avoid power leakage into higher frequency tones, the CPWs are equipped with a modified dispersion relation following two different approaches, the Resonant Phase Matching (RPM) and the Quasi-Phase Matching (QPM). RPM uses a reduced plasma frequency mixed to a periodic load of LC resonators to create mismatch among the travelling tones, in order to suppress higher harmonic generation, then the signal tone that is meant to be amplified is re-phased through the opening of a bandgap in the dispersion relation. On the contrary, QPM uses a mix of low plasma frequency and a sign modulation of the nonlinearity into the medium to suppress higher harmonic generation and stimulate amplification by changing the phase of the travelling waves of π after a coherence length has been reached.

In the KITWPA devices (Fig. 2), the momentum conservation can be achieved in two ways: *a)* dispersion engineering the CPW with periodic loadings creating a frequency gap; *b)* building an artificial transmission line, that uses lumped-element inductors and capacitors. The characteristic impedance of the transmission line is modified every one-sixth of a wavelength at a frequency slightly above the pump frequency f_p to form a wide stopband at $3f_p$, allowing suppression of the third armonic of the pump. In addition, every third loading is modified in length (longer or shorter relative to the first two) to create a narrow stopband near f_p; this allows the pump to fulfill the phase-matching condition. The CPW-type amplifiers are made of NbTiN and are meter-long transmission lines, causing impedance mismatches which are the likely cause of large ripples in the gain profile, with the result that the amplifiers suffer from self-heating due to the strong pump tone, creating an excess of thermal noise. On the other hand, the lumped-element approach brings the advantage of having a shorter transmission line resulting in a higher fabrication yield.

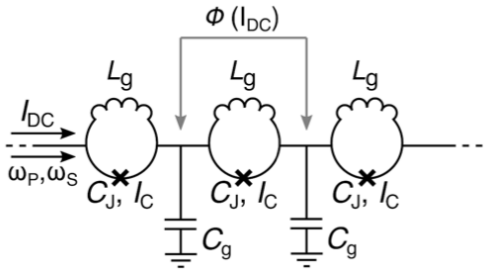

Figure 1: Circuit schematic of the Josephson metamaterial. The central conductor of the coplanar waveguide is made by a chain of rf-SQUIDs composed by a geometrical inductor L_g and a Josephson junction of critical current I_c and capacitance C_J. The line is capacitively shunted to ground by capacitors C_g.

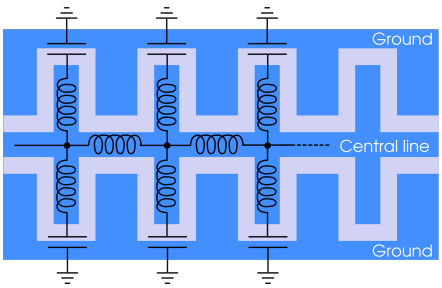

Figure 2: Circuital schematic of a unit cell of a superconducting artificial line made of CPW sections. Each cell is composed by a series inductance L_d and two resonators with inductance L_f and capacitance to ground $C/2$.

The goals of the DARTWARS project within 2024 are: *a)* the development of high-performing parametric amplifiers by exploring new design solutions, new materials and fabrication processes, to achieve a gain value around 20 dB, a high saturation power (around −50 dBm), a large bandwidth (in the 5–10 GHz range), noise near the quantum limit ($T_n \lesssim 600$ mK at these frequencies) and to reduce the gain ripples; *b)* the readout demonstration of different detectors and devices involved in the next-generation particle physics experiments, such as MKIDs, TESs, microwave resonant cavities and qubits.

3. Preliminary measurements on JTWPA protorype

The device was fabricated by INRiM and tested at LNF (Laboratori Nazionali di Frascati) in a dry dilution refrigerator with

the lowest temperature stage at $T = 15$ mK. It is composed of 15 sections of coplanar waveguide embedding 990 nonhysteretic rf-SQUIDs connected by bended sections of CPW. The values of the circuit parameters of the Josephson metamaterial, by design, are a ground capacitance $C_g = 13.0$ fF, a geometrical inductance $L_g = 45$ pH, a Josephson capacitance $C_J = 25.8$ fF and a Josephson critical current $I_c = 1.5$ μA. The Josephson junctions were fabricated exploiting an electron beam lithography process on a double layer polymeric mask, followed by an Aluminum e-gun evaporation.

The characterization of the JTWPA consists in evaluating its 3WM capabilities and its gain through pump-on pump-off measurements. Two-tones measurements are possible by supplying in input a weak signal tone and a driving pump tone, coupled together by a directional coupler. The stage of amplification is composed by a low-noise cryogenic HEMT (put at 4 K) and a room-temperature FET, providing a gain of 30 dB each. An rf splitter allows to send the output both to a spectrum analyzer, to perform power spectra, and to a vector network analyzer, to measure scattering parameters. Finally, a current generator connected to the device through bias tees provides the DC current bias to the device. (More details in [11]).

Nonlinear effects generate idler tones that have different frequencies depending on the order of nonlinearity that causes them. Fig. 3 reports the power of the output idler tone P_{Idler}, generated via 3WM, as a function of the DC bias current I_{DC}. The pump tone is at $\nu_p = 6.75$ GHz, with three different power values (-90, -85 and -80 dBm), and the signal tone is at $\nu_s = 3.3$ GHz with a power of $P_s = -67$ dBm. For this mixing process the idler is generated at $\nu_i = \nu_p - \nu_s = 3.45$ GHz. The 3WM idler should present a minimum at zero I_{DC}, as expected from the Kerr nonlinearity of an rf-SQUID, but here we note a shift of the minima, which is attributed to magnetic field trapping during the cooling of the dilution refrigerator. Moreover, the suppression of the 3WM idler tone is not complete, since the data in Fig. 3 do not reach the noise floor of the setup (dashed line). It has to be noticed that the modulation of the 3WM process here reported is limited to around 10 dB, since it is reasonably affected by nonidealities of the JTWPA and the surrounding environment.

Then, parametric amplification has been quantified with gain measurements, by means of the pump-on pump-off technique. The gain is studied both in the degenerate ($\nu_p = \nu_s$) and nondegenerate mode, as a function of the pump power. Although we do not observe a constant gain over a large bandwidth, values between 25 and 30 dB are reached for particular values of pump frequency and power, as shown in Fig. 4 for $\nu_p = 17.975$ GHz and $\nu_s = 9$ GHz (nondegenerate mode). Unfortunately, the minimum measured noise temperature was $T_n = 3.63$ K. This was in part due to a malfunctioning of attenuators at very low temperatures, causing an excess thermal noise at the device input. Also, the nonhomogeneity of the JJs on the chip, discussed in the Conclusions, could have played a role.

After the prototype was characterized, a study of the homogeneity of the Josephson junctions fabricated with the same process was carried out, to improve the performances of future devices. For this reason, a sample of 960 JJs with critical

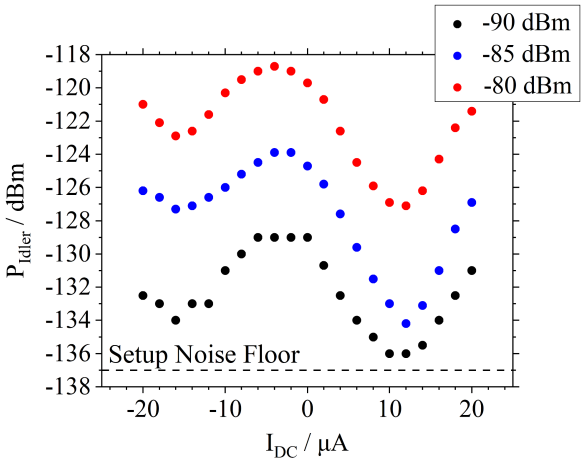

Figure 3: Modulation of the output idler tone power (P_{Idler}) generated via 3WM as a function of the bias current I_{DC}. Here the JTWPA is excited with a signal tone at frequency $\nu_s = 3.3$ GHz , for three different values of the driving pump tone at frequency $\nu_p = 6.75$ GHz.

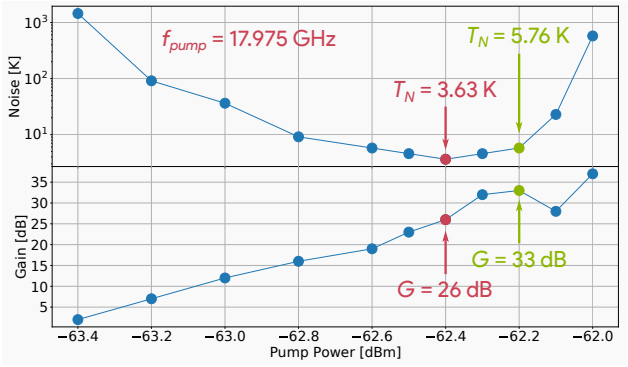

Figure 4: *Top:* Noise temperature as a function of the input pump power for frequencies $\nu_p = 17.975$ GHz and $\nu_s = 9$ GHz (nondegenerate mode). *Bottom:* Signal gain as a function of the pump power with the same tone frequencies, evaluated with the pump-on pump-off technique.

current $I_c = 4$ μA, self-capacitance $C = 225$ fF and expected normal resistance $R_n \simeq 80$ Ω was fabricated. Two oxidation techniques were used, a dynamic oxidation with an O_2 pressure of 4.30×10^{-4} Torr for a time of 660 s, and a static oxidation at 1.58×10^{-3} Torr for 344 s. The two processes should bring to similar oxide barrier thicknesses and similar resistances.

The normal resistances of JJs were tested with a probe station, which performs four-terminal measurements (see Fig. 5). As a result, the resistance values are distributed around about 12 Ω, with a spread around 5%$-$10%. There are also ascending or descending gradients depending on what is the position of the arrays of junctions along the wafer. Finally, junctions fabricated with the static oxidation process show higher overall resistances than the dynamic oxidation ones.

4. Conclusions

TWPAs are promising candidates of quantum-limited microwave amplifiers for applications in fundamental physics and

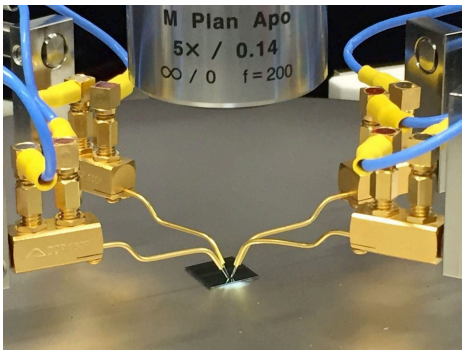

Figure 5: Probe station used to perform four-terminal resistance measurements on the sample of 960 Josephson junctions.

quantum computing. DARTWARS aims at developing nearly-quantum limited TWPAs exploiting Josephson junctions and kinetic inductance of superconductors, exploring new designs and materials, and demonstrating the readout of several devices (TES/MKIDs/RF cavities/qubits). With the preliminary characterization of a prototype of JTWPA we demonstrated the 3WM modulation, although with some nonhomogeneities, as well as good capabilities of parametric amplification, measuring gain values between 25 and 30 dB for particular frequencies.

The results show that there is room for improvement. In fact, INRiM is committed to implement the design with the modified dispersion relation given by the RPM technique in the JTWPA structure, to reduce the phase mismatch between the travelling tones. Furthermore, numerical studies on the QPM approach are being performed. On the fabrication side, a new realization technique is being investigated, consisting in a two-step lithography; moreover, to reduce the single JJ areas nonhomogeneity due to the overlap of unpredictable rounded edges, a new design exploiting a double-layer mask is under development. New tests of the homogeneity of samples of JJs are being performed, without observing better results with respect to Section 3 at the moment.

Finally, progress has been made in the development of KITWPAs. In fact, NbTiN patterned into micro-resonators was characterized to estimate the kinetic inductance of the material and its nonlinearity. The kinetic inductance was evaluated measuring the resonance frequency of the resonators, and then it was related to the nonlinearity in the current. The KITWPA device design is close to completion, and the first prototype is foreseen for summer 2022.

Acknowledgments

This work is supported by the Italian Institute of Nuclear Physics (INFN), within the Technological and Interdisciplinary research commission (CSN5), by the European Union's H2020-MSCA Grant Agreement No. 101027746, and by the Joint Research Project PARAWAVE of the European Metrology Programme for Innovation and Research (EMPIR). PARAWAVE received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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