Progress in the development of a KITWPA for the DARTWARS project

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Abstract

DARTWARS (Detector Array Readout with Traveling Wave AmplifieRS) is a three years project that aims to develop high-performing innovative Traveling Wave Parametric Amplifiers (TWPAs) for low temperature detectors and qubit readout. The practical development follows two different promising approaches, one based on the Josephson junctions (TWJPA) and the other one based on the kinetic inductance of a high-resistivity superconductor (KITWPA). This paper presents the advancements made by the DARTWARS collaboration to produce a first working prototype of a KITWPA.

1. Introduction

Nowadays, many applications rely on the faithful detection of low power microwave signals at cryogenic temperatures. This is especially true in the field of the superconducting quantum computation, where quantum-limited noise microwave amplification is paramount to infer the qubit state with high fidelity.

For these applications, the goals are to maximize the signal to noise ratio of microwave extremely feeble signals while allowing a broad readout bandwidth. The latter is extremely relevant in all the applications where the devices are required to be multiplexed over large bandwidths. To solve this problem, parametric amplification with superconducting circuits, a well known technique used for low noise amplifiers, will be exploited and developed to its technical limits.

DARTWARS [1](Detector Array Readout with Traveling Wave AmplifieRS) aims to develop two type of traveling wave parametric amplifiers: TWJPA and KITWPA. The technical goal is to achieve a gain value around 20 dB, comparable to the currently used semiconductors low temperature amplifiers (HEMT), with a high saturation power (around -50 dBm), and a quantum limited or nearly quantum limited noise ($T_N < 600$ mK). These features will lead to the readout of large arrays of detectors or qubits with virtually no noise degradation.

2. Parametric amplification and KITWPA

A traveling wave parametric amplifier is physical implementation of a parametric oscillator. By by carefully modulating the properties of the oscillating system, the oscillator will absorb energy from the surroundings, resulting in an exponential growth of the oscillation amplitudes. A parametric amplification of a current signal I can thus be achieved by making the signal travel through a transmission line (TL) made of a non-linear inductors $L(I)$, resulting in a wave equation which is equal to the one of the parametric oscillator. In particular, KITWPA exploits the nonlinear kinetic inductance of a superconducting coplanar waveguide (CPW) to generate parametric interaction between a strong RF input pump at a frequency ω_p and signal at a frequency ω_s ($\omega_s < \omega_p$) , resulting in a signal amplification and generation of idler(s) product(s) ω_i [2].

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The inductance of the superconducting line can in fact be divided into a geometric inductance L_g and a kinetic inductance L_k. The former depends on the geometry of the circuit, while the latter depends on the supercunducting material and it is related to the inertia of the Cooper pairs. The kinetic inductance makes the overall inductance of the line non-linear, and along the direction x of the CPW can be modeled as

$$L(x,t) = L_0(x)\left[1 + \left(\frac{I(x,t)}{I^*}\right)^2\right] \quad (1)$$

where $L_0(x)$ is the linear kinetic inductance.

The fact that a superconducting line has zero *dc* resistance at $T < T_c$ suggests the motivation for the use of superconducting parametric amplifiers: a very low power dissipation and an added noise that approaches the minimum set by quantum mechanics.

One of the goal of DARTWARS is to make a KITWPA amplifiers that operate in a three-wave mixing (3WM) fashion when biased with a dc current I_d. In this scheme, the pump exchange its energy with a signal and idler products when the phase-matching conditions are satisfied

$$\omega_p = \omega_s + \omega_i \quad ; \quad k_p - k_s - k_i = \frac{\chi I_{p0}^2}{8}(k_p – 2k_s - 2k_i) \quad (2)$$

where k_p, k_s, k_i are the wavenumbers of the corresponding signals and $\chi = 1/(I^{*2} + I_d^2)$.

3. Preliminary results from the KITWPA fabrication

To achieve the phase matching condition of eq (2), DARTWARS will exploit a lumped-element transmission line for the KITWPA design. In this picture the characteristic impedance of the TL is periodically modified to form both a wide stopband at $3\omega_p$ and a narrow stopband near ω_p. Placing the pump tone below this narrow stopband allow to easily match the conditions of eq (2) while suppressing higher pump harmonics, which would result in a gain and noise degradation. In addition, the lumped elements TL allow to achieve a high gain with a shorter TL (tens of cm compared to few meters of a periodic loading TL).

The KITWPA will be made of NbTiN films produced at the FBK-CMM facility. The critical temperature of the film produced can be seen in Figure 1.

Even if the critical temperatures measured suggest that new sputter targets will be required to achieve the best literature values (~ 15 K), the results of the sputtering fabrication processes are encouraging, indicating that a wide range of L_k can be easily achieved with the current setup.

To characterize the produced films, the NbTiN has been patterned into lumped element resonators [3]. The kinetic inductance was assessed on three different wafers with two techniques. One, labeled as L_k-Sim, evaluates L_k as the value required to match the measured resonant frequency of the KID with the one extracted from simulation, which takes into account only L_g. The other, indicated as L_k-T_c, compute L_k from

$$L_k = \frac{\hbar}{1.76\pi k_b T_c} R_n \quad (3)$$

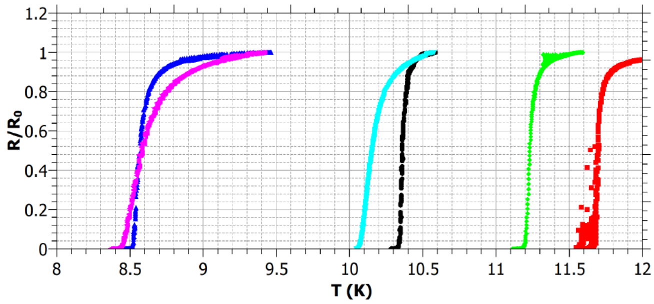

Figure 1: Normalized transition shape of the NbTiN films fabricated at FBK.

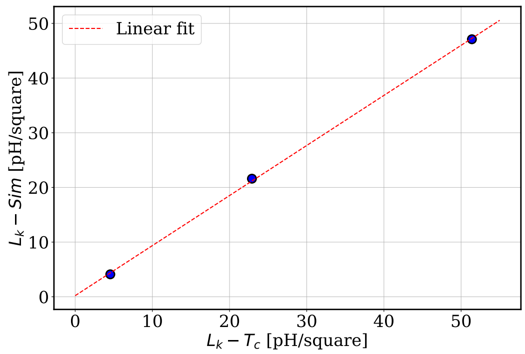

Figure 2: Comparison between the two different methods adopted to measure the kinetic inductance of the supeconducting films.

The two techniques are comparable, as shown in Figure 2.

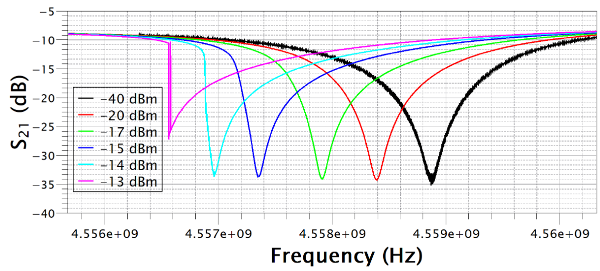

Figure 3: Example of different resonant profiles due to the different powers of the RF signal.

Finally, the maximum achievable non-linearity of the film I_c/I^* was assessed from eq (1). The resonance frequency f_0 was measured by changing the power P of the RF probe tones (Fig 3), while the conversion between P and I^2 was assessed through Sonnet and Qucs simulations. The following relation $(2\pi f_0)^{-2} = (L_k + L_g)C$ was used to evaluate L_k.

Figure 4 shows the results achieved for one of the produced resonators. Overall, the maximum achieved non-linearity from the different wafer produced was roughly 0.25, close to the target value of 0.34. Upon these promising results, the first KITWPA prototypes will be produced during the last quarter of 2022.

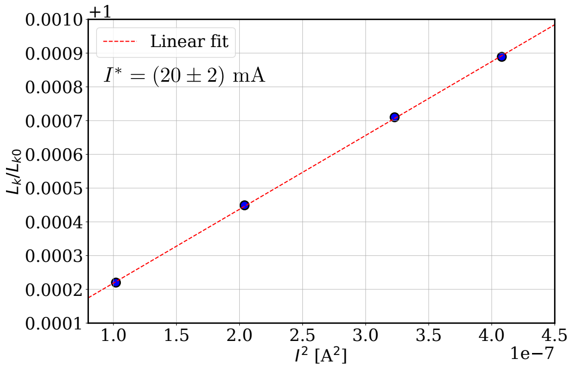

Figure 4: I^* measurement of the KID with the highest kinetic inductance

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