# Experimental characterisation of titanium nitride transmission lines for applications as kinetic inductance travelling wave parametric amplifiers

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***Abstract*— Travelling wave parametric amplifiers (TWPAs) made from highly nonlinear reactive superconducting thin films have been demonstrated to be a potentially viable quantum-noise-limited amplifier technology for various fundamental physics platforms, including microwave/mm/sub-mm astronomy, dark matter search experiments, neutrino mass experiments and qubit readout. To date, only a limited number of successful kinetic inductance TWPA devices have been reported, with the majority fabricated from the same material, niobium titanium nitride (NbTiN), although in principle any highly nonlinear superconducting film can be used for kinetic inductance TWPA fabrication. Here, we present a detailed analysis of titanium nitride (TiN) transmission lines, to ascertain their suitability for use as kinetic inductance TWPAs. We will experimentally characterise our transmission line structures at cryogenic temperatures and compare the results with electromagnetic simulations. This characterisation and analysis would allow us to understand the advantages and limitations of TiN films, and whether they are suitable for applications as kinetic inductance TWPAs.**

Keywords— ***Low-noise, Amplifier, Superconducting, RF, Microwave, Travelling-wave***

## I. Introduction

Kinetic inductance travelling wave parametric amplifiers (KITWPAs) [1, 2] are quantum devices, which can achieve high gain over broad bandwidth. They exhibit quantum-limited noise performance with negligible heat dissipation and their ease of fabrication makes them readily scalable to arrays for large pixel count applications, such as the readout of astronomical detector arrays.

The operation of a KITWPA, is reliant on the inherent non-linearity of the kinetic inductance of thin superconducting films. The majority of KITWPAs reported in the literature comprise a long superconducting transmission line patterned with a niobium titanium nitride (NbTiN) film [3], which is typically cooled to sub-Kelvin temperatures during operation. In principle, a KITWPA can be fabricated from any superconducting film that displays a high kinetic inductance, such as titanium nitride (TiN). TiN films have found applications in superconducting micro-resonator detectors, such as MKIDs, due to their high kinetic inductance, controllable critical temperature ($T_c$) and physical robustness [4]. TiN films have additionally been shown to display extremely low losses compared to other superconducting films [5]. Despite this, NbTiN films have proved a popular choice for KITWPA fabrication due to their high $T_c$ making them better suited for applications at 4 K, such as heterodyne receivers. However, a plethora of applications at sub-Kelvin temperatures remain e.g., bolometric receivers and axion search experiments, and the negligible heat dissipation of KITWPAs allows for closer placement of the amplifier to the detector at the sub-Kelvin stage to further reduce signal loss. We, therefore, intend to explore the use of lower $T_c$ TiN films for such applications and investigate additional possible advantages and/or limitations compared to the NbTiN film.

Before venturing into designing a KITWPA using the TiN film, it is important to fully understand the behaviour of the thin film. Therefore, in the first part of the paper, we present an experimental investigation of the various properties of our TiN film using a set of simple transmission line structures to probe their characteristics, which are related to their application as KITWPAs. We further investigate and report on how the transmission line geometries and topologies would affect the performance of the KITWPA. Finally, following comprehensive film and design geometry characterisation results, we conclude the paper by reporting on the preliminary measurement results of a TiN KITWPA operating from 4-12 GHz range.

## II. Results

In this paper, we focus our study on a 100 nm thick TiN film with $T_c$ = 4.39 K and resistivity $\rho_N$ = 140 $\mu\Omega$cm, deposited on a 500 $\mu$m thick sapphire substrate. Preliminary DC measurements of the thin film behaviour have already been performed to explore the IV characteristics of our TiN film. Preliminary results yield a maximum DC current allowed to transverse through the TiN strip before it quenches of about 1.8 mA at 400 mK, which is consistent with the expected critical current ($I_c$) value for our TiN superconducting film of ~1 mA. The maximum current as a function of bath temperature is shown in Fig. 1a. Fitting a linear trend to this data gives a max current of 2.2 mA at 0 K and zero current at 4.21 K, which are close to the expected $I_c$ and $T_c$ values, respectively. These preliminary DC measurement results suggest that our TiN films are behaving as we would expect,

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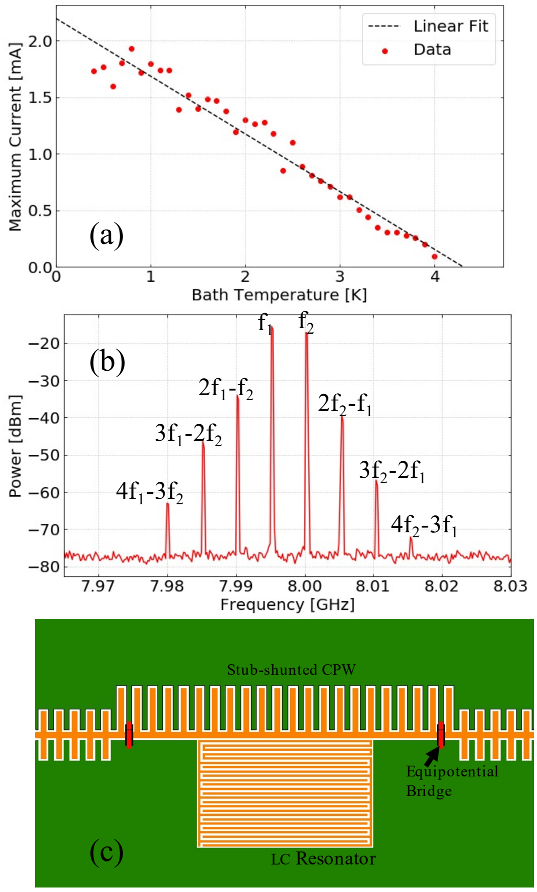


Fig. 1. (a) Maximum current through the superconducting strip as a function of the strip bath temperature. (b) IMD spectrum for TiN superconducting strip at 10 mK. (c) CAD image of an example resonator test structure.

allowing progression onto RF characterisation of our TiN transmission line structures.

In order to investigate the nonlinearity of the film, we have performed intermodular distortion (IMD) measurements, which involves sending two signals at different frequencies across a narrow band and measuring the non-linear cross terms. The signal levels are set below the $I_c$ and $T_c$ of the film. The results of this experiment are shown in Fig. 1b, which show the primary tones at frequencies $f_1$ and $f_2$ and the resultant third-order mixing terms. No gain was observed during this experiment and the peak heights of all tones were lower than expected. We can, therefore, confirm that there is nonlinearity present in our TiN films, but losses are higher than expected.

To further investigate the broadband behaviour and loss/nonlinearity performance of our TiN film, we have designed a series of simple test structures using a commercial 3D electromagnetic (EM) simulation software to obtain the required network parameters. An example test structure is a lumped-element LC resonator, shown in Fig. 1c, which is a particularly useful probe of the film properties, since the changes in the current dependence inductance would lead to a shift in the resonant frequency as the applied current is varied. The magnitude of the frequency shift can be used as a measure of the strength of nonlinearity, whilst the change in the depth of the resonance can be used to probe how lossy the film is. An ideal KITWPA film would exhibit a strong frequency shift with minimal change in the depth of the resonance.

The broadband performance of a KITWPA could also be affected by various design issues, such as the choice of transmission line and its corresponding dimensions. Most of the transmission line structures included in this study are based on co-planar waveguides (CPW) and include various combinations of the centre-strip and gap width ratio to explore the effect of geometry on KITWPA performance. To control the characteristic impedance of the transmission line, the CPW is shunted with additional capacitive stubs [6] (same width and gap dimensions as the main CPW), with their length optimised for a 50 Ω line. We additionally employ equipotential bridges for the suppression of parasitic transmission modes. A simple measurement of the $S_{21}$ parameter will, therefore, confirm the feasibility of a particular dimension of test structure as a broadband transmission line and will also reveal the extent of losses in a long transmission line.

Our investigation also explores different transmission line topologies. Ideally, a KITWPA transmission line would be completely straight, however, the necessary long lengths make it impractical to achieve sufficiently high gains on a practical-sized chip. In practice, the transmission line must instead be wrapped into a compact arrangement, such as a spiral or hairpin-style pattern. The compactness of these arrangements may affect the performance of a KITWPA, due to cross talk between adjacent lines, so it is important that this effect is fully studied and understood.

Finally, based on the detailed analysis of our test structures, we conclude the paper with a KITWPA design, which includes its predicted gain-bandwidth product and preliminary experimental results including gain and noise temperature measurements.

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