

# Measuring the nonlinearity of titanium nitride film for applications as kinetic inductance travelling wave parametric amplifiers

Joseph C. Longden<sup>\*‡</sup>, Faouzi Boussaha<sup>†</sup>, Christine Chaumont<sup>†</sup>, Nikita Klimovich<sup>\*</sup> and Boon-Kok Tan<sup>\*</sup>

<sup>\*</sup>*Department of Physics (Astrophysics), University of Oxford, Keble Road, Oxford OX1 3RH, UK*

<sup>†</sup>*GEPI (CNRS UMR 8111), Observatoire de Paris, PSL Université, Paris, France.*

<sup>‡</sup>Contact: joseph.longden@physics.ox.ac.uk, phone +44 1865 273 303

**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/millimetre (mm)/sub-mm astronomy, dark matter search experiments, absolute neutrino mass determinations, and qubit readout platforms. To date, only a limited number of successful kinetic inductance (KI-)TWPA devices have been reported, with the majority of them fabricated from niobium titanium nitride (NbTiN) thin films; although in principle, any highly nonlinear low loss superconducting film can be used to construct a KITWPA. In this proceeding, we explore the suitability of using a different type of superconducting film, titanium nitride (TiN) for such application. We report on the detailed analysis of the nonlinear behaviour of TiN films to ascertain the film’s suitability for application as KITWPA. We experimentally characterised TiN transmission lines at cryogenic temperatures to compare the results predicted with electromagnetic simulations. This characterisation and analysis allows us to understand the fundamental physics governing the behaviour of the TiN films, their merits and limitations, and whether they are well suited for applications as KITWPAs.

## I. INTRODUCTION

KINETIC inductance travelling wave parametric amplifiers (KITWPAs) [1], [2], [3], [4], [5], [6] are quantum devices that can achieve high gain over broad bandwidth by efficiently transferring power from a strong ‘pump’ wave to an incoming weak ‘signal’ wave via the wave-mixing mechanism in a nonlinear medium comprising a high kinetic inductance wire. 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 nonlinear kinetic inductance of the thin superconducting films from which the device is constructed. Kinetic inductance is an equivalent series inductance that manifests from the mobile charge carriers in an alternating electric field, which to the lowest order Taylor expansion varies quadratically with current,  $L(I) = L_0 \left(1 + \frac{I^2}{I_*^2}\right)$ , where  $L_0$  is the zero-current inductance and  $I_*$  is a term that sets the scale of nonlinearity [7].

The majority of KITWPAs reported in the literature comprise a long superconducting transmission line patterned using a niobium titanium nitride (NbTiN) film cooled to sub-Kelvin

temperatures. In principle, a KITWPA can be fabricated from any superconducting film provided that it displays a high kinetic inductance and low loss [8], such as titanium nitride (TiN). TiN films have found applications in superconducting micro-resonator detectors e.g., microwave kinetic inductance detectors (MKIDs) [9], due to their high kinetic inductance, controllable critical temperature ( $T_c$ ) and physical robustness [10]. TiN films have additionally been shown to display extremely low-loss compared to other superconducting films [11]. Despite this, NbTiN films have proven to be a popular choice for KITWPA fabrication due to their high  $T_c$ , making them better suited for applications at higher bath temperatures and higher frequency ranges, such as the readout or pre-amplification of millimetre (mm) heterodyne receivers. A plethora of microwave applications at sub-Kelvin temperatures remain, however, e.g., readout of astronomical bolometric receivers and first-stage sensor for axion search experiments. The negligible heat dissipation of KITWPAs also 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 film for such applications and investigate if there are additional advantages and/or limitations comparing to the conventional NbTiN film. In particular, if such TiN-KITWPA technology holds the potential to be directly integrated with front-end detectors made up of the same material, such as TiN-MKIDs array [9].

Before venturing into developing a KITWPA using the TiN film, it is important to fully understand the behaviour of the thin film as well as our fabrication capabilities. Therefore, in this paper, we present a theoretical and experimental investigation of the various properties of our TiN film using a set of simple transmission line structures, which allow us to probe the characteristics related to their application as KITWPAs. We chose co-planar waveguide (CPW) as the main form of our transmission line due to their ease of fabrication, being a single deposition layer, and are typically less lossy when compared to microstrip structures with dielectric layers.

## II. DEVICE DESCRIPTION & EXPERIMENTAL SETUP

We designed a set of these simple CPW line structures using Ansys High Frequency Structure Simulator (HFSS). The devices were subsequently fabricated in the clean-room

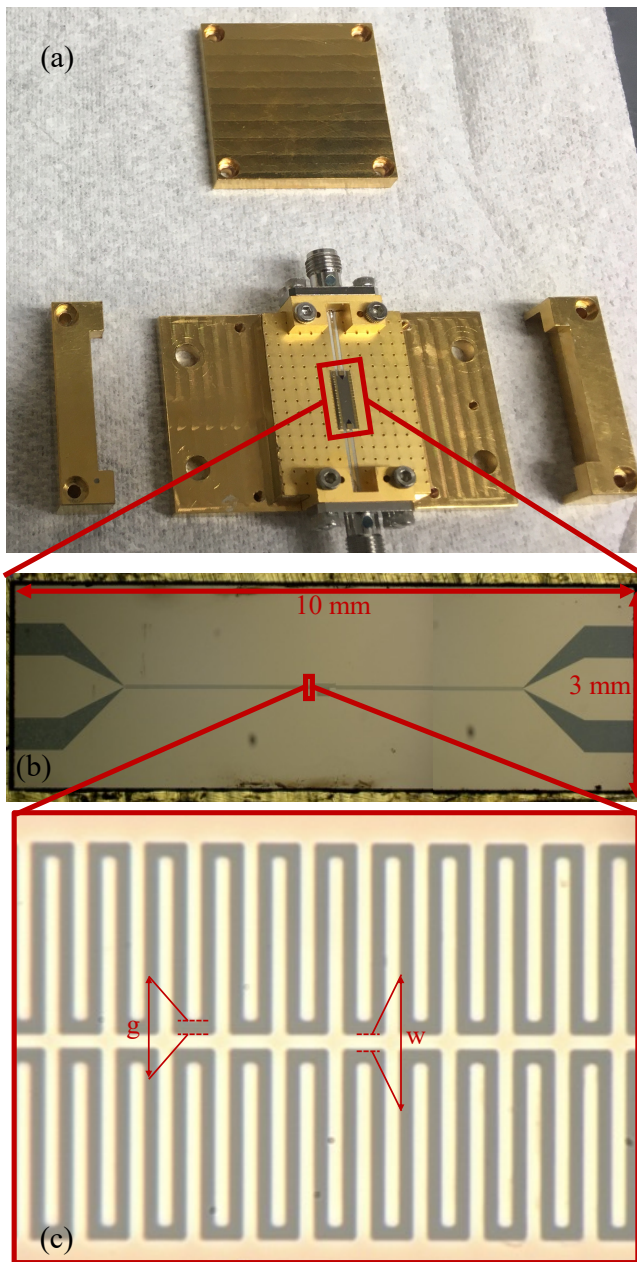


Fig. 1. (a) Photograph of transmission line device housed within sample holder. (b) Photograph of a short CPW transmission line chip. (c) Zoom-in of the CPW line section, highlighting the ‘fishbone’ transmission line structure.

facilities at the Observatoire de Paris comprising 100 nm thick TiN film sputtered onto a 3 inch, 500  $\mu\text{m}$  thick sapphire substrate, which was then patterned photo-lithographically. We expect the film to have a  $T_c = 4.39$  K, and a normal state resistivity,  $\rho_N = 140 \mu\Omega \text{ cm}$ . Each of these test-structure devices comprise a CPW line shunted with additional stubs for impedance matching [4], where the length of the stubs was optimised to give a characteristic impedance ( $Z_0$ ) of 50  $\Omega$ . Fig. 1 shows the full CPW device, with a segment of the ‘fishbone’-style transmission line highlighted in Fig. 1(c). Each chip has a physical length of 10 mm with a width of 3 mm, and the CPW width ( $w$ ) and gap ( $g$ ) dimensions are varied from chip to chip to better understand the effect of the geometrical

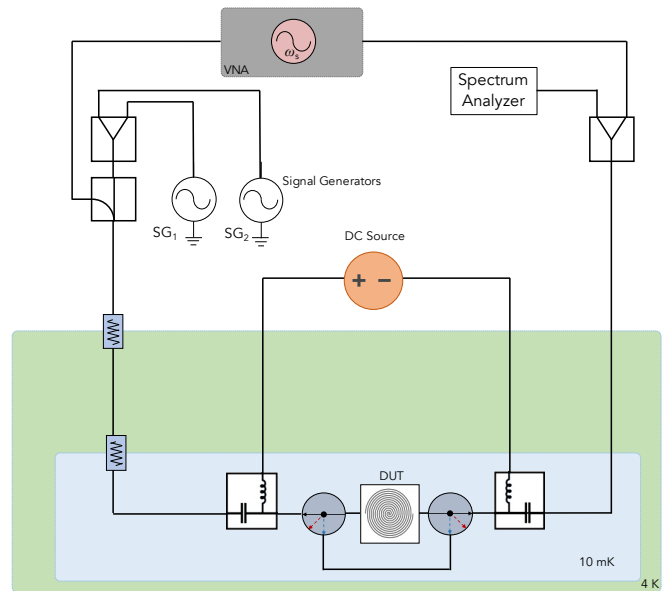


Fig. 2. Schematic of experimental setup used to test the CPW transmission line chips. The versatile setup allows us to switch between S-parameter measurements using the vector network analyser (VNA) and inter-modular distortion measurements using a signal generator (or multiple signal generators) and a spectrum analyser.

topology of the CPW on the transmission line performance. The fabricated transmission line chips are mounted onto a gold-plated copper box and wire-bonded to a Rogers Duroid 4350B grounded-CPW printed circuit board, which provides a connection to the external circuitry via SMA end-launchers, as shown in Fig. 1(a).

We experimentally characterised our devices in a 10 mK dilution refrigerator. A schematic of our experimental setup is shown in Fig. 2. A vector network analyser (VNA) is used to provide a sweeping signal tone, which after a series of warm and cold attenuations, injected into the device under test (DUT), with the output signal then routed back via low-loss RF line to the VNA. This configuration allows us to perform a frequency sweep of the signal, allowing an  $S_{21}$  transmission spectrum to be obtained. Alternatively, we could generate the signal tone using a signal generator and probe the output spectra with a spectrum analyser. This allows us to perform harmonic and inter-modular distortion (IMD) measurements to explore the wave-mixing behaviour of the DUT. A DC current can also be provided along the length of the transmission line using a pair of bias tees, which allows us to probe the critical current,  $I_c$ , and nonlinearity of the devices. A pair of 6-way coaxial switches were utilised at either side of the DUT to switch between multiple DUTs and a through line, to allow for in-situ cryogenic calibration.

### III. NONLINEARITY MEASUREMENTS

We first probed the nonlinearity of a 50  $\Omega$  CPW transmission line by measuring the phase shift as a function of the DC current through the line. The VNA was used to measure the magnitude and phase of the  $S_{21}$  transmission through the CPW at zero current, then with a pair of bias tees, a DC current was

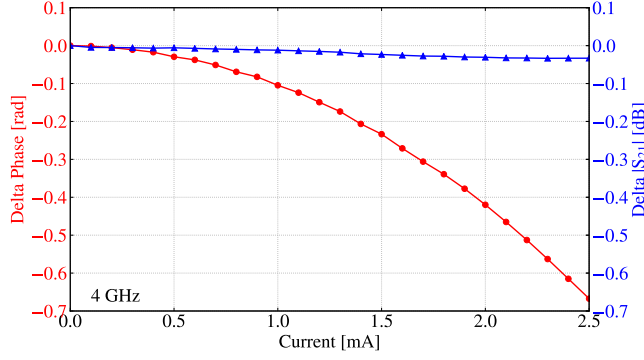


Fig. 3.  $S_{21}$  at 4GHz for transmission line as a function of applied DC current. The phase of the  $S_{21}$  is shown in red and the magnitude in blue. These results were obtained for transmission line dimensions of  $w = 10 \mu\text{m}$  and  $g = 5 \mu\text{m}$ .

introduced along the length of the CPW centre strip and the shift to the magnitude and phase was measured. The results of this investigation are shown in Fig.3 and clearly shows the phase of the transmission varying with applied current, whilst the magnitude remains relatively constant within a small current range. This result, which depicts the same behaviour as seen in [1], suggests that the TiN CPW is operating as a low-loss, nonlinear transmission line as expected. Additionally, the dependence of the phase shift with current is consistent with a quadratically varying kinetic inductance.

Having verified the nonlinearity of the transmission lines, we then explored the wave-mixing properties of the film. As a Kerr<sub>3</sub> nonlinear material with a power dependent kinetic inductance relation, it is expected that injecting strong tone into the device will produce a third harmonic of the input tone. We experimentally reproduced this, and the result is shown in Fig. 4, where a 4 GHz tone from a signal generator was injected into the DUT and the amplitude of the third harmonic at 12 GHz is measured with a spectrum analyser. As expected, we found a linear relation between the input power and the third harmonic's amplitude. A second harmonic was also observed if an additional DC current was passed along centre conductor, again confirming the nonlinearity of the film as expected.

To further explore the wave-mixing properties of the transmission lines, we subsequently performed inter-modular distortion (IMD) measurements. The IMD measurements involved injecting two RF tones at frequencies  $f_1 = 7.995 \text{ GHz}$  and  $f_2 = 8.000 \text{ GHz}$  into the device and measuring the output with a spectrum analyser. If the transmission line displays a purely linear behaviour, one would expect to only see the two input frequencies,  $f_1$  and  $f_2$ , present at the output. In contrast, if the transmission line displays a nonlinear behaviour consistent with a power dependent kinetic inductance, then one would expect to see 3<sup>rd</sup>-order wave mixing terms at the output, as well as the input frequencies. The results of the IMD measurements are shown in Fig.5, which shows the output containing many 3<sup>rd</sup>-order cross-harmonics, which is consistent with a nonlinear material exhibiting four-wave

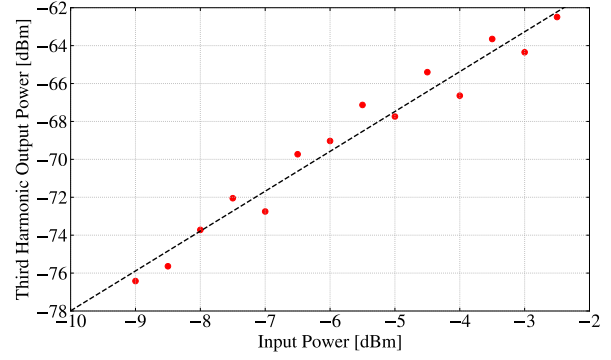


Fig. 4. Output power of the third harmonic as a function of the input power of the primary tone set at 4GHz.

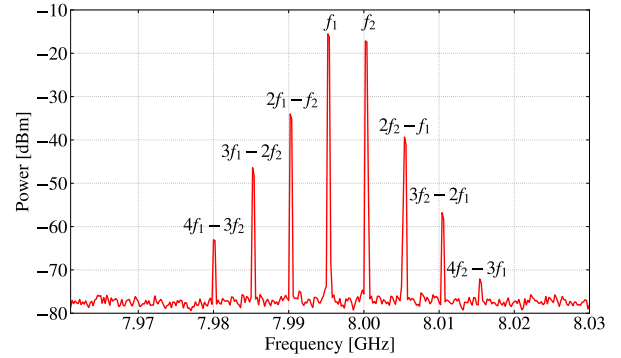


Fig. 5. Output inter-modular distortion (IMD) spectrum with two input tones at  $f_1 = 7.995 \text{ GHz}$  and  $f_2 = 8.000 \text{ GHz}$ , respectively.

mixing.

#### IV. DIMENSION COMPARISON

It is desirable to make the  $w$  and  $g$  dimensions as small as possible to produce the most compact KITWPA, however, smaller dimensions are also more prone to fabrication defects. To ascertain the limitations of our photo-lithographic fabrication capabilities, we fabricated the CPW lines with several different  $w$  and  $g$  dimensions to measure and compare their  $|S_{21}|$  behaviour. The results are shown in Figs.6(a-d). For CPW  $w : g$  ratios of 10:5, 6:3, and 4:2  $\mu\text{m}$ , we observe a close to 0dB transmission up to approximately 10 GHz, with relatively small ripples in the spectrum. This indicates that the devices are defect-free and the characteristic impedance is reasonably well matched to  $50 \Omega$ , in agreement with our simulations.

The  $|S_{21}|$  of the 2:1  $\mu\text{m}$  CPW, shown in 6d, is found to be much less than 0dB and varies significantly with frequency. Subsequent time-domain reflectometry (TDR) and DC measurements revealed that the device was short-circuited, suggesting that a TWPA made with these dimensions using our photo-lithography techniques may result in a low yield. Similar results for all 4 designs were also found for longer transmission line samples, up to one third of the length of

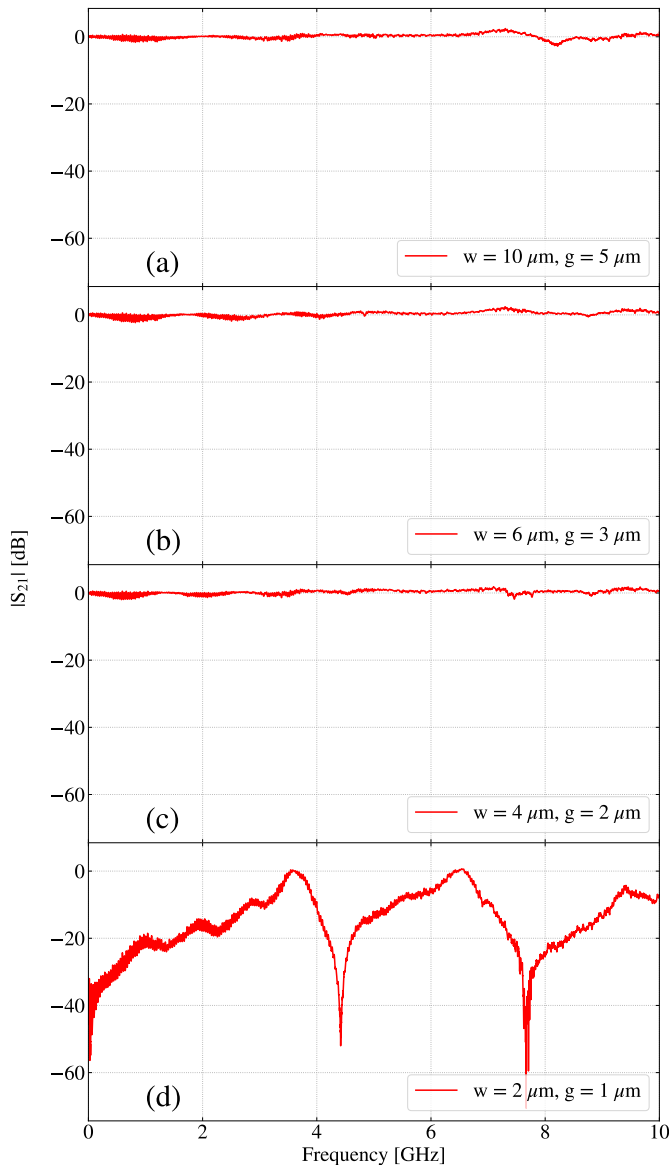


Fig. 6.  $|S_{21}|$  transmission spectra for different CPW transmission line dimensions. Input power to the devices was levelled at approximately -50 dBm.

a real KITWPA device, however, note that we only tested a handful of DUTs, hence the conclusion is indicative instead of definitive.

## V. CONCLUSIONS

We have presented the preliminary analysis of the non-linearity of a series of TiN transmission lines to ascertain the suitability of TiN films for use as KITWPAs. We experimentally characterised our simple TiN CPW transmission line structures and we found that they display the necessary nonlinearity and wave-mixing capabilities that are necessary for KITWPA operation. Our analysis on the CPW dimensions also suggests that we can make KITWPAs with a good yield provided  $w$  and  $g \geq 2 \mu\text{m}$ . Our next steps are to proceed to a full KITWPA design and measurement, to fully characterise the gain behaviour of a TiN KITWPA.

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