# Development of a Superconducting Platform for the Manipulation of Quantum States in the Microwave Regime

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## PhD Dissertation Synthesis

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This dissertation reports on the personal research activity conducted from November 2019 to January 2023 in the Quantum Electronics sector of the Italian National Institute of Metrology (INRiM) in Turin. The primary goal of this activity was to establish and characterize a cryogenic microwave measurement setup within a newly acquired dilution refrigerator. The purpose of this setup was to enable a traceable characterization of quantum superconducting electronics at millikelvin temperatures. The successful accomplishment of this objective marked a significant milestone in the history of INRiM, as it enabled the internal realization of a quantum engineering cycle for superconducting microwave devices. This iterative process encompasses device modelling, design, fabrication, and characterization, along with the implementation of improvements based on the analysis of the device characteristics.
The opportunity to implement such a cycle was utilized to develop an initial prototype of an rf-SQUID-based Josephson Traveling Wave Parametric Amplifier (JTWPA), which was personally modelled, designed and micro-fabricated as a

part of the research activity. JTWPAs are a class of superconducting amplifiers that utilizes the peculiar nonlinear characteristics of an array of Josephson junctions embedded in a transmission line to amplify low-power microwave signals. Their operation is based on the parametric amplification principle, where an input signal is mixed with a pump tone to generate an amplified output signal. At the time of writing this dissertation, these nonlinear metamaterials represent the most promising solutions as first-stage cryogenic amplifiers due to their wide bandwidth, high gain and quantum-limited noise performance. These exceptional characteristics make them highly sought after by the research community due to their essential role in various applications in quantum information processing, sensing and communication systems. Furthermore, these amplifiers have the potential to revolutionize the field of quantum technologies by facilitating the manipulation and detection of microwave photons, allowing for the implementation of complex quantum circuits and networks.

The manuscript is structured into five chapters. Chapter 1 provides a concise introduction to the fundamental quantities used to describe linear and non-linear microwave networks, focusing also on the essential calibration techniques needed to de-embed the device under test's characteristics from those of the measurement setup. Additionally, the chapter reports a brief historical overview of JTWPAs and an examination of the main nonlinear properties exhibited by Josephson junctions, emphasizing their critical role as key components for parametric amplification. Chapter 2 introduces an original description of an rf-SQUID-based JTWPA within the circuit-Quantum Electrodynamics (c-QED) theoretical framework. The chapter begins by defining the energy stored in each component of the device and proceeds to construct its Hamiltonian. By employing second-quantization techniques, an input-output relation is derived, which serves as a foundation for evaluating various metrics associated with the amplifier. These metrics, which include gain and noise properties, are crucial for evaluating the performance of the JTWPAs and have been assessed for key study quantum input states. Chapter 3 provides a comprehensive discussion of the design of the cryogenic setup specifically tailored for the characterization of microwave two-port networks at cryogenic temperatures. The setup was successfully installed and tested in INRiM's first-ever dry-dilution refrigerator, which became operational in the second half of 2022. Chapter 4 details the experimental work conducted in parallel to develop, fabricate, and test a first prototype of an rf-SQUID-based JTWPA incorporating a resonant phase-matching scheme. This endeavour involved several important intermediate steps, including the construction of a cryogenic-compatible sample holder, the establishment and standardization of a cutting-edge UV lithography-based fabrication protocol for Al/AlOx/Al junctions, and the verification of finite-element simulation accuracy through comparisons between simulations and experimental results obtained from lumped LC resonators. The chapter proceeds by presenting the proposed layout for the rf-SQUID-based JTWPA and its subsequent characterization at cryogenic temperatures. Despite the evidence of the presence of intermixing products, an effective gain was not observed in this prototype. The chapter concludes by discussing the possible causes of the non-ideal performance and proposing potential solutions to address these issues. These proposed solutions lay the foundation for future research and development, aiming to enhance the performance of the rf-SQUID-based JTWPA and overcome the challenges encountered in this initial engineering cycle. Lastly, Chapter 5 provides a brief discussion on the importance of JTWPAs as microwave quantum light emitters, highlighting their potential beyond their use as quantum-limited amplifiers.