Title: Josephson traveling wave parametric amplifier and its application for metrology

Abstract

Modern solid-state quantum technology requires the characterisation, verification and metrology of extremely small and photonic microwave signals. Major challenges exist in the sufficiently large amplification of such signals, in a sufficiently wide bandwidth and with the lowest possible added noise. Josephson traveling wave parametric amplifiers (JTWPA) have been shown in theory to have the potential to address these challenges. Proposals are invited to develop JTWPA devices for ultra-sensitive microwave signal detection and to demonstrate their usage for the advancement of quantum metrology.

Keywords

Traveling wave parametric amplifier, JTWPA, quantum technology, quantum information processing and communication with microwaves, qubits, three-wave mixing, Josephson metamaterial, quantum limited noise, single-photon detection, non-classical states of microwaves, squeezed coherent states, entangled photon pairs.

Background to the Metrological Challenges

Recent developments in fields such as quantum sensors, quantum information circuits, superconducting quantum bits and more widely in astronomical detection and modern communications, rely on the precision detection of microwave photons. However, the metrological tools for the reliable and sensitive characterisation of solid-state quantum circuits (in particular ultra-low-power and photonic microwave circuits) are significantly lacking. The need is not just for determination of microwave power but for the precise and accurate determination of single photon properties including timing and phase, and multi-photon properties such as coincidence and entanglement. Current state-of-the-art cryogenic amplifiers are inadequate in terms of high noise temperatures, and novel amplifiers are being explored worldwide to operate at the quantum limit of sensitivity. Parametric amplifiers are currently the only known method to achieve quantum limited sensitivity to microwave signals. However, achieving a large enough and sufficiently flat bandwidth ranging e.g. from about 1 GHz to 10 GHz is still a challenging task. Improvement on the current situation is possible in a traveling-wave amplifier with three-wave mixing, but three-wave mixing is only possible in a medium with non-centrosymmetric nonlinearity. The possibility of engineering a nonlinear medium (a quantum metamaterial) with a large and controllable non-centrosymmetric nonlinearity is an important goal in quantum optics and would enable parametric gain, squeezing and generation of entangled photon pairs, paving the way to their application in quantum information processing and communication (QIPC). Such a quantum metamaterial can be engineered with the help of Josephson technology and may allow both excellent characteristics of the JTWPA with three-wave mixing and quantum optics circuits in the microwave domain.

State-of-the-art parametric amplifiers based on Josephson junctions are notable quantum devices, but large dispersion and cross modulation effects do not allow the simultaneous achievement of large gain and flat bandwidth. A wide-band parametric amplifier operating in the regime of three-wave mixing (i.e. when $f_{signal} + f_{idler} = f_{pump}$) has been proposed which relies on the use of a non-centrosymmetric (quadratic) nonlinearity engineered in the underlying Josephson metamaterial and uses the travelling wave concept, so freeing the device of the usual resonator and enabling wide-bandwidth operation. The pump-tone is widely separated from the signal, considerably reducing the need for output filtering. It is expected that the intrinsic gain is larger, reducing the length of the transmission line and considerably reducing the dephasing effects. The net result is a high-gain quantum-limited amplifier of simpler construction, wide bandwidth and with a flat gain response free of cross-modulation effects. The availability of such an amplifier, together with associated new and fundamental developments in Josephson quantum metamaterials (due to the further exploitation of a non-centrosymmetric nonlinearity), would enable a wide range of fundamental and new quantum optical experiments in the microwave regime. Further, the integration of JTWPAs with existing quantum-based sensors has the potential to enhance their overall sensitivity beyond what can currently be realised using semiconductor electronics.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the practical realisation and characterisation of Josephson traveling wave parametric amplifier devices, and to assess their usage in quantum measurement.

The specific objectives are:

1. To develop a broadband Josephson traveling wave parametric amplifier (JTWPA) utilising three-wave mixing, with a power gain of 20 dB and flatness of ±3 dB in a one octave range centred on 5 to 6 GHz. The amplifier should include optimisation of circuit design parameters and physical layout, the preparation of functional samples and optimisation of the fabrication technology.
2. To analyse the amplifier noise and demonstrate noise-squeezing (up to 5 dB) and quantum-limited performance (noise better than $hf/2k_B$ ~ 0.3 K), and to clarify the role of device parameters (nonlinearity and dispersion, signal gain, bandwidth and dynamic range) in order to optimise the amplifier operation.
3. To develop reliable and validated quantum amplifier metrology (components and processes) for the characterisation of the JTWPA device and other devices such as cryogenic amplifiers and photon generators.
4. To improve the sensitivity and readout of the JTWPA device to quantum levels with minimum backaction, through integration with quantum sensors and macroscopic quantum systems. In particular, to combine the JTWPA-based preamplifier with nanoSQUID sensors operating in a dispersive mode and rf-single-electron-transistor (SET) charge detectors optimised for error counting in single electron pumps. Further, to demonstrate frequency multiplexing in these circuits, and flux and charge sensitivities approaching the standard quantum limit.
5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the measurement supply chain (quantum technology professionals) and end users (electronics, healthcare, information and communications industries) including demonstration of the application of the JTWPA device in at least two quantum measurement case studies.

Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 40 % of the total EU Contribution to the project.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.