Publishable Summary for 17FUN10 ParaWave
Josephson travelling wave parametric amplifier and its application for metrology

Overview

The emerging field of microwave quantum optics has gathered significant interest for the launch of technologies taking advantage of quantum mechanical phenomena, but its progress critically depends on the availability of cryogenic low noise amplifiers. This project has developed a favourable type of the Josephson Travelling Wave Parametric Amplifier (JTWPA) based on the three-wave mixing principle, offering high gain, large bandwidth and potentially quantum limited noise performance. The associated quantum amplifier metrology for the characterisation of JTWPAs was established and applications of the JTWPA to enhance the sensitivity of quantum sensors and as a source for quantum illumination were explored.

Need

Quantum technologies offer a step change in sensitivity or accuracy not attainable with classical devices. They promote transformative advances to science and society and have the capacity to improve the competitiveness of European industry and SMEs by creating new commercial opportunities in many of the world's biggest markets. Areas that will benefit the most include quantum computing, quantum communication and "quantum non-demolition" measurements. In addition, recent developments in quantum sensing, quantum information circuits, astronomical detection and modern communications rely on the precision detection of microwave photons. Furthermore, the emerging field of microwave quantum optics could be used to provide ultra-precise and metrological measurement. This is needed for the precise determination of single photon properties including timing and phase, and quantum properties such as squeezing and entanglement.

However, all these developments critically depend on the availability of cryogenic amplifiers with sufficient gain and bandwidth as well as added noise no larger than that determined by quantum-mechanical principles. Current state-of-the-art cryogenic semiconductor amplifiers have (at GHz frequencies) an electrical noise that is at least a factor of ten too high for quantum sensitive applications. Current superconducting quantum-limited microwave amplifiers available both commercially and in research laboratories all suffer from compromises in specification and hence a broadband quantum-limited microwave amplifier is urgently needed.

The Josephson Travelling Wave Parametric Amplifier based on the three-wave mixing, whose fundamentals were developed within this project, will achieve significant advances in the state-of-the-art gain, in bandwidth and simplicity of construction. Additionally, there is a need for a reliable metrological characterisation of JTWPA and similar devices, what will be established within this project. Investigating the capabilities of the JTWPA is a first step towards the advancement of microwave quantum optics, which could impact many fields of science and technology, such as artificial intelligence, cryptography, and brain scans.

Objectives

The overall goal of this project was to develop a novel and practical broadband microwave amplifier capable of operation at and beyond the fundamental, or standard quantum limit, of sensitivity.

The specific objectives of this project were:

1. **To develop a broadband JTWPA** utilising three-wave mixing, with a power gain of 20 dB and flatness of $\pm$3 dB in a one octave range centred on 5 GHz to 6 GHz. The amplifier development will include optimisation of circuit design parameters and physical layout, the preparation of functional samples and optimisation of the fabrication technology. JTWPA circuits will be developed in Nb, Al and Nb-Al hybrid technology according to the intended application.
2. **To analyse the amplifier noise and demonstrate thermal noise-squeezing (up to 5 dB) and quantum-limited performance** (noise temperature better than, at least $hf/k_B \sim 0.3$ K), and to clarify the

role of device parameters (nonlinearity and dispersion, signal gain, bandwidth and dynamic range) 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 cryogenic amplifiers. The envisaged metrology platform will allow the characterisation of devices in terms of their gain, bandwidth and harmonic generation. Standard room temperature microwave sources and thermal noise sources will be used for metrological characterisation.
4. To improve the sensitivity 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 (rf-SET) charge detectors optimised for error counting in single electron pumps. Both, the SQUID and the superconducting SET (i.e., Cooper-pair transistor) are examples of macroscopic quantum sensors/systems since their behaviour involves a macroscopically large number of Cooper pairs. 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.

Progress beyond the state of the art

Within this project a new type of JTWPA was developed, consisting of a microwave transmission line formed by a serial array of nonhysteretic one-junction SQUIDs. These so called rf-SQUIDs are flux-biased such that this one-dimensional metamaterial possesses a large quadratic nonlinearity, which allows the use of the favourable three-wave mixing principle (in contrast to the four-wave mixing in common parametric amplifiers). The project’s JTWPA outperforms current state-of-the-art parametric amplifiers in the following features: 1) The pump tone is widely separated from the signal band, considerably reducing the need for output filtering. 2) Efficient operation with reduced pump power due to large gain. 3) High dynamic range in wideband operation by using the travelling wave concept.

Analysis of the JTWPA operating in both degenerate (signal phase sensitive) and non-degenerate (phase insensitive) regimes was carried out by the project. Additionally, the project’s JTWPA capabilities to enable squeezed microwave radiation generated in both monochromatic and broadband (or multimode) regimes were explored and the concept of using the JTWPA as a Non-Classical Light Source for Microwave Quantum Illumination was developed.

A metrology platform was finalised to compare the characteristics of different cryogenic amplifiers. The project carried out fundamental metrology of the JTWPA using standard room temperature microwave sources and thermal noise sources and developed a validated test facility for comparison of JTWPA measurements against an analytical and numerical model for JTWPA behaviour. Metrological characterisation of the gain, bandwidth, and harmonic generation of the JTWPA and other cryogenic amplifiers can be provided.

Several concepts for the integration of the project’s new type of JTWPA together with quantum-based sensors were developed to demonstrate the overall advancement beyond what can currently be realised using state-of-the-art amplifiers. Such integrated circuits are expected to achieve improved sensitivity close to the standard quantum limit, show minimised backaction and higher bandwidth.

Results

1. ***To develop a broadband 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 GHz to 6 GHz. The amplifier development will include optimisation of circuit design parameters and physical layout, the preparation of functional samples and optimisation of the fabrication technology.*

The circuit parameters and the design of a three-wave mixing JTWPA have been optimised for fabrication in niobium and aluminium technology. Several samples have been tested, showing a clear proof of principle for the operation of a three-wave mixing JTWPA. The experimental results and intensive circuit simulations have proven the necessity to include a defined dispersion in the JTWPA to avoid the amplification of signals with frequencies above the pump frequency, limiting the achievable gain. The project explored several alternative strategies to mitigate the creation of higher order mixing products and to ensure good phase matching between the pump and the low frequency signals to be amplified.

a) Resonant-Phase-Matching
The unwanted phase difference between the pump and the signal to be amplified can be compensated for by using Resonant-Phase-Matching: i.e., the periodic inclusion of resonators with resonance frequency slightly below the pump frequency into the serial array of SQUIDs.

b) Gap-Engineering
The concept of Gap-Engineering was examined theoretically and by circuit simulations. By a periodic variation of circuit parameters, a gap in the rf-transmission of the JTWPA is created, modifying the phase velocity in the vicinity of the frequency gap, and compensating the phase difference between the pump and the signal.

c) Quasi-Phase-Matching
Another alternative approach was studied theoretically and by simulations. It is based on the Quasi-Phase-Matching concept and just requires a periodic change of the spatial orientation of the basic rf-SQUID elements.

Additional simulations have been performed to optimise the gain, bandwidth, and dynamic range and to investigate the effects of parameter variations and defects in JTWPA circuits.

Objective 1 was almost completely achieved. The obtained results clearly demonstrate that it should be possible to create a high performance three-wave mixing JTWPA based on the available state of the art fabrication technology and to reach the targeted high gain in a wide bandwidth. Unfortunately, it was not possible to validate the simulation results experimentally since no defect free devices could be verified before the end of the project due to multiple delays in the fabrication resulting from the COVID pandemic.

2. ***To analyse the amplifier noise and demonstrate thermal noise-squeezing (up to 5 dB) and quantum-limited performance*** *(noise temperature better than, at least $hf/k_B \sim 0.3$ K), and to clarify the role of device parameters (nonlinearity and dispersion, signal gain, bandwidth and dynamic range) to optimise the amplifier operation.*

A low-temperature dilution-cryostat setup at RHUL was put into operation for the characterisation of both resonator and travelling wave parametric amplifier devices at the many photon level at mK temperatures. This setup with a bandwidth of 4 to 8 GHz is optimised for noise squeezing experiments and measurements at the quantum limit. All necessary microwave equipment to support noise squeezing measurements is available for deployment on the low temperature measurement system. A further low-temperature measurement setup at PTB, also based on a dilution refrigerator, has been completed with the aim of characterising JTWPA circuits at a temperature of about 20 mK with a focus on their linearity, dynamic range, and noise.

NPL has constructed a complete quantum amplifier metrology system with a base temperature of 300 mK for rapid screening and testing of devices fabricated in aluminium or niobium technology. This low-temperature cryostat system will be used for wide bandwidth characterisation at 4 to12 GHz, see objective 3 for details. Moreover, NPL and PTB are operating simple ^{4}He dip probes for a quick characterisation of Nb devices.

Several parametric amplifier samples fabricated in niobium and in aluminium technology were characterised so far in terms of bandwidth, gain and their output spectrum. Feedback was given on the need for an appropriate modification of the dispersion within the JTWPA to avoid the creation of strong higher order mixing products and second harmonic generation, limiting the achievable gain. The results of the sample characterisations also helped to improve the device layout and the fabrication technology.

Objective 2 was only partially achieved. The setup for noise measurements has been completed, but the final experimental demonstration of thermal noise-squeezing was not possible since no defect free devices with sufficient gain could be verified before the end of the project.

3. ***To develop reliable and validated quantum amplifier metrology*** *(components and processes) for the characterisation of the JTWPA device and other quantum devices such as semiconductor cryogenic amplifiers.*

The ultimate noise performance of a parametric amplifier can only be demonstrated at a temperature ≤ 30 mK. However, all other parameters can be measured at a temperature of 300 mK which is easier to realise. NPL therefore specified and constructed a complete quantum amplifier metrology system with a base temperature of 300 mK for rapid screening and testing of devices fabricated in aluminium or niobium technology by the project partners. It is configured for wide-band (4-12 GHz) characterisation of JTWPA and other cryogenic devices. The installation includes cryogenic RF coaxial switches so that different amplifiers can be selected in one experiment together with calibration circuits for standardisation of the gain measurements.

The instrumentation located at room temperature for metrological measurements comprises RF signal sources, spectrum analysers and network analysers. Measurement software was specially developed and facilitates frequency and power sweeps of different parameters in different instruments through a simple user interface panel. Traceable measurement of amplifier parameters is assured by using calibrated instruments at room temperature in combination with reference calibration lines at low temperature and a variable-temperature cryogenic noise source.

A validated test facility allows for comparison of JTWPA measurements against an analytical and numerical model for JTWPA behaviour. Metrological characterisation of the gain, bandwidth, and harmonic generation of the JTWPA and other cryogenic amplifiers can be provided. The system was used to characterise several devices fabricated by partners during the project.

Objective 3 was fully achieved. The finalised experimental setup and the developed evaluation processes allow for the reliable metrological characterisation of cryogenic microwave amplifiers and related instruments.

4. *To improve the sensitivity 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-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.*

Rf-SETs in Al technology have been designed and fabricated. The rf measurement setup in a cryogen-free dilution refrigerator for high-frequency characterisation of rf-SETs has been accomplished and several SET devices have been characterised. Two types of matching schemes were considered to match the high impedance rf-SET to the 50 Ohm transmission line or JTWPA. First, a stub matching scheme was designed, and a prototype has been fabricated by multistep electron-beam lithography. The second approach is based on a quarter-wavelength impedance transformer (QWT). A multi-QWT approach was developed and realised on a PCB. It allows to match the 10 kΩ load to 50 Ω at a frequency of 4.5 GHz in the bandwidth of 1 GHz. The final measurement setup is based on the rf-reflectometry technique and includes attenuators and a directional coupler in the drive line and a directional coupler, isolators, and cold semiconductor amplifiers in the receiver line. The JTWPA's will be inserted in between the isolators and the cold semiconductor amplifiers.

Designs for Al and Nb based nanoSQUIDs were optimised and test samples have been fabricated. The characterisations of DC nanoSQUIDs in Nb technology was accomplished at 4.2 K. In addition to this, Nb rf-nanoSQUIDs (both single Josephson Junction and arrays), incorporated in resonators, have been designed and fabricated. Two different coupling schemes for impedance matching of the SQUID sensors to the JTWPA have been elaborated in detail. For the Nb devices, a dispersive microwave readout was developed by embedding the nano-SQUID into a lumped element LC resonator with a resonance frequency of about 5 GHz and coupling it to the JTWPA with a passive directional coupler. For the Al nanoSQUIDs the designs developed for coupling to parametric amplifiers include distributed resonant structures at GHz frequencies. The SQUID modulates the frequency of the resonator with a periodicity of the magnetic flux quantum. In this scheme, the resonator is pumped with an external frequency source and the output coupled directly to a parametric amplifier. Both schemes easily allow the combination of several SQUID sensors and frequency multiplexing.

Objective 4 has been achieved to a large extend. Although quantum sensors and coupling schemes have been finalised, it was not possible to complete the ultimate measurements before the end of the project due to multiple delays in fabrication of devices and laboratory access restrictions resulting from the COVID pandemic.

Impact

The project website has been updated regularly, as well as a ResearchGate Project Webpage. A stakeholder group was formed with more than 30 individual members from universities, research institutions, NMIs and small and large companies located in and outside of Europe. The stakeholder group includes the National Institute of Standards and Technology (NIST, USA), The National Institute of Advanced Industrial Science and Technology (AIST, Japan) and the Institut de radioastronomie millimétrique (IRAM, France).

The consortium has given more than 45 posters and presentations on the results of the project at national and international conferences such as the International Scientific Conference on Superconducting Quantum Technologies, the 14th and 15th European Conference on Applied Superconductivity, EUCAS 2019 and 2021, and the Applied Superconductivity Conference, ASC 2020. In addition, the project has published 12 open access peer-reviewed publications in scientific journals such as Applied Physics Letters, Phys. Rev. Applied, Nature Nanotechnology and IEEE Transactions on Applied Superconductivity.

The project organised an international online workshop on “Superconducting Parametric Amplification” for stakeholders and interested participants. Eight presentations were given by consortium members and five talks by international experts. The project received positive feedback from the participants, and the event stimulated interesting discussions and follow-on projects.

Impact on industrial and other user communities

The project's development of the JTWPA will have a major impact on the field of quantum computing in the long term, it will be of particular interest to high-tech industries (e.g., project stakeholders Google LLC and IBM) who require simultaneous measurement of the states of a large number of qubits. The project’s JTWPA, when integrated with quantum sensors will also allow the amplification of extremely small microwave signals with the lowest possible noise, which is critical for the next generation of cryogenic measurement equipment needed for delicate quantum measurements.

The project produced parametric amplifier designs, external microwave circuits for operating the amplifiers and techniques for interfacing the amplifiers to different quantum-based sensors. It also developed unique cryogenic parametric amplifiers that will be of interest to high-tech companies engaged in quantum computing and the manufacture of ultrasensitive instruments using quantum devices and systems such as Magnicon, Germany and York Instruments Ltd, UK.

Inspired by this project, the SME SeeQC.EU, based in Italy, started its own JTWPA research program. SeeQC.EU is developing the first digital quantum computing platform for global businesses and it presented its first results at the Applied Superconductivity Conference 2018 in Seattle, USA.

Impact on the metrology and scientific communities

Single-photon real-time detection is essential in technologies such as: quantum computing with solid-state circuits and microwave photons; quantum key distribution for secure communication; ultrasensitive spectrum analysis of microwave components; and quantum interference experiments with non-classical photon states (beating the standard quantum limit). The use of the JTWPA in the qubit readout circuits will substantially improve manipulation and characterisation of quantum circuits and facilitate the development of a quantum processor. This project will also advance quantum information processing and communication with microwave frequencies, where high-fidelity detection of single microwave photons is indispensable.

Fundamental and new quantum optical experiments in the microwave regime are of considerable interest to the scientific community. The experiments include, the second harmonic generation, parametric down conversion with squeezing and the generation of entangled photon pairs as a source for quantum illumination. The availability of this project’s JTWPAs, together with associated new and fundamental developments in Josephson quantum metamaterials (due to the further exploitation of a non-centrosymmetric nonlinearity), would enable these experiments to be realised by the scientific community after this project’s lifetime.

The project has received several invitations to present its results at various prestigious events including the international workshop on ‘Use-cases from quantum technologies for sensing and metrology’, held in December 2018 in France and at various research centres such as the Karlsruhe Institute of Technology (KIT), in Germany (July 2019) and the Center for Axions and Precision Physics Research, Institute for Basic Science in Korea (October 2019).

Other research groups picked up the idea of a three-wave mixing JTWPA developed within this project, e.g., VTT Technical Research Centre of Finland and Aalto University published work on applications of three-wave mixing and Kerr-free Josephson metamaterials and a group from the Lomonosov Moscow State University presented a niobium based JTWPA on the EUCAS 2021 conference.

Several follow-up projects in cooperation with stakeholders of the scientific communities were acquired, among others the project DARTWARS (Detector Array Readout with Traveling Wave AmplifieRS) and AHEAD2020, aiming to develop multiplexed SQUID arrays for radio astronomy with potential application of the JTWPA as a low noise wide band amplifier.

Impact on relevant standards

Due to the early stage of electronic quantum technologies mainly realised in scientific laboratory environments, there are still no standards for superconducting quantum devices or for single microwave photons. This project has helped to generate the necessary skills and experience within the participating NMIs and spread knowledge into a wider metrological community to create the basis for future standardisation activities.

Information on progress and on the results of this project was regularly disseminated to relevant standardisation committees such as BIPM Consultative Committee for Electricity and Magnetism (CCEM), the EURAMET TC-EM (Electricity and Magnetism), including the Working Group on Strategic Planning and the sub-committee 'DC and Quantum Metrology (DC&QM)' by presentations and through several progress reports.

Two good-practice guides covering the application of the JTWPA as a versatile two-port amplifier for quantum technologies have been prepared and submitted to CCEM and TC-EM. They are available on the ParaWave website.

Longer-term economic, social and environmental impacts

Superconducting quantum devices are accepted world-wide to be a leading contender in the development of future quantum technologies, including sensing, metrology, and computing. Quantum computing can also be used to solve complex problems in a wide range of areas of impact, such as the discovery of new medicines, optimising complex networks (e.g., global supply chains), and artificial intelligence. However, the transition of quantum technologies into commercial products requires a new generation of quantum engineers who are conversant in multi-disciplinary approaches. Specific research into JTWPAs and their applications within this project supported this by developing knowledge and research expertise within Europe, together with trained scientists and engineers.

A longer-term outcome of the project will be the building of a dedicated low-temperature setup for the characterisation of parametric amplifiers and related circuitry within PTB's new Quantum Technology Competence Center (QTZ, due for completion in 2023). The QTZ will focus on the development of user-friendly and robust components for quantum sensing and metrology and on providing calibrations, services, and facilities accessible for end users. Furthermore, QTZ will offer hands-on training and seminars for quantum technology.

The new Advanced Quantum Metrology Laboratory (AQML) at NPL in Teddington is nearing completion with occupation due in 2023. Its overall aim is to expand NPL's ground-breaking research in quantum technologies. Quantum metrology at NPL will play a crucial role in bridging the gap between quantum science and industry to help grow a profitable and sustainable quantum industry deeply rooted in the UK. The AQML forms part of Quantum Metrology Institute which brings together all of NPL's leading-edge quantum science and metrology research and provides the expertise and facilities needed for academia and industry to test, validate, and ultimately commercialise new quantum research and technologies. The ParaWave Metrology Platform will be located in the AQML with close proximity to related research in quantum technologies and will form part of NPL's showcase for quantum technologies with industry in the UK and further afield.

In addition, INRIM has developed the Piemonte Quantum Enabling Technology (PiQuET, completed 2020, www.piquetlab.it) and transferred this project's fabrication processes into PiQuET. PiQuET provides 400 m^2 of clean room space for the development of new quantum, micro and nano devices, and will bring together and expand the knowledge of European scientists, engineers, and industry in Quantum Enabling Technologies.

List of publications

[1] S. V. Lotkhov, R. Dolata, M. Khabipov, "*DC measurement of dressed states in a coupled 100 GHz resonator system using a single quasiparticle transistor as a sensitive microwave detector*", Appl. Phys. Lett. 115, 192601 (2019) https://doi.org/10.1063/1.5119220

[2] A. B. Zorin, "*Flux-Driven Josephson Traveling-Wave Parametric Amplifier*", Phys. Rev. Applied 12, 044051 (2019) https://doi.org/10.1103/PhysRevApplied.12.044051

[3] L. Fasolo, A. Greco, and E. Enrico, "*Superconducting Josephson-Based Metamaterials for Quantum-Limited Parametric Amplification: A Review*", Condensed Matter Physics, Edited by InTech Open (2019) https://doi.org/10.5772/intechopen.89305

[4] T. Dixon, J.W. Dunstan, G.B. Long, J.M. Williams, P.J. Meeson, and C.D. Shelly, "*Capturing Complex*

Behavior in Josephson Traveling-Wave Parametric Amplifiers", Phys. Rev. Applied 14, 034058 (2020) https://doi.org/10.1103/PhysRevApplied.14.034058

[5] I. Golokolenov, A. Guthrie, S. Kafanov, Yu. A. Pashkin and V. Tsepelin, "*On the origin of the controversial electrostatic field effect in superconductors*", Nat Commun 12, 2747 (2021) https://doi.org/10.1038/s41467-021-22998-0

[6] A. Greco, L. Fasolo, A. Meda, L. Callegaro and E. Enrico, "*Quantum model for rf-SQUID-based metamaterials enabling three-wave mixing and four-wave mixing traveling-wave parametric amplification*", Phys. Rev. B 104, 184517 (2021) https://doi.org/10.1103/PhysRevB.104.184517, click here for open access full text

[7] A. B. Zorin, "*Quasi-phasematching in a poled Josephson traveling-wave parametric amplifier with three-wave mixing*", Appl. Phys. Lett. 118, 222601 (2021) https://doi.org/10.1063/5.0050787, click here for open access full text

[8] L. Fasolo, A. Greco, E. Enrico, F. Illuminati, R. Lo Franco, D. Vitali, P. Livreri, "*Josephson Traveling Wave Parametric Amplifiers as Non-Classical Light Source for Microwave Quantum Illumination*", Measurement: Sensors 18, 100349 (2021) https://doi.org/10.1016/j.measen.2021.100349

[9] L. Fasolo, C. Barone, M. Borghesi, G. Carapella, A. P. Caricato, I. Carusotto, W. Chung, A. Cian, D. Di Gioacchino, E. Enrico, P. Falferi, M. Faverzani, E. Ferri, G. Filatrella, C. Gatti, A. Giachero, D. Giubertoni, A. Greco, C. Kutlu, A. Leo, C. Ligi, P. Livreri, G. Maccarrone, B. Margesin, G. Maruccio, A. Matlashov, C. Mauro, R. Mezzena, A. G. Monteduro, A. Nucciotti, L. Oberto, S. Pagano, V. Pierro, L. Piersanti, M. Rajteri, A. Rettaroli, S. Rizzato, Y. K. Semertzidis, U. Uchaikin, A. Vinante, "*Bimodal Approach for Noise Figures of Merit Evaluation in Quantum-Limited Josephson Traveling Wave Parametric Amplifiers*", IEEE Transactions on Applied Superconductivity 32 (4) 1700306 (2022) https://doi.org/10.1109/TASC.2022.3148692

[10] M. Khabipov, V. Gaydamachenko, C. Kissling, R. Dolata and A. B. Zorin, "*Superconducting microwave resonators with non-centrosymmetric nonlinearity*", Superconductor Science and Technology 35, 065020 (2022) https://doi.org/10.1088/1361-6668/ac6989

[11] S. Wolter, J. Linek, T. Weimann, R. Kleiner, D. Koelle, R. Kleiner and O. Kieler, "*Static and dynamic transport properties of multi-terminal, multi-junction microSQUIDs realized with Nb/HfTi/Nb Josephson junctions*", Superconductor Science and Technology (2022) https://doi.org/10.1088/1361-6668/ac782b

[12] AP. Livreri, E. Enrico, L. Fasolo, A. Greco, A. Rettaroli, D. Vitali, A. Farina, F. Marchetti, D. Giacomin, "*Microwave Quantum Radar using a Josephson Traveling Wave Parametric Amplifier*", 2022 IEEE Radar Conference RadarConf22 (2022) https://doi.org/10.1109/RadarConf2248738.2022.9764353, click here for open access full text

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 July 2018, 42 months	
Coordinator: Ralf Dolata, PTB Project website address: https://sites.google.com/inrim.it/parawave/home	Tel: +49 531 592 2247	E-mail: Ralf.Dolata@ptb.de
Internal Funded Partners: 1 PTB, Germany 2 INRIM, Italy 3 NPL, United Kingdom	External Funded Partners: 4 LanU, United Kingdom 5 RHUL, United Kingdom	Unfunded Partners:
RMG1: INRIM, Italy (Employing organisation); NPL, United Kingdom (Guestworking organisation)		