Publishable Summary for 20FUN07 SuperQuant
Microwave metrology for superconducting quantum circuits

Overview

Quantum technologies and quantum computing offer exciting new possibilities but also significant challenges that must be overcome to achieve their potential, including the need for fundamental microwave metrology at cryogenic temperatures to support the booming quantum technology industry. The SuperQuant project will establish novel metrological and scientific tools for the measurement of microwave signals in circuits in-situ in cryogenic environments down to the millikelvin range using a combination of superconducting, semiconducting, integrated and conventional photonics, and plasmonic techniques. This includes the development of a quantum standard of microwave power and a quantum-traceable cryogenic sampling oscilloscope with 1 THz bandwidth and an optically integrated quantized arbitrary waveform generator that will enable energy- and cost-efficient generation of thousands of microwave signals at cryogenic temperatures.

Need

All emerging solid-state approaches for quantum computing (QC) and many other quantum technologies (QT) rely on microwave signals. Yet, no established technology exists today that can perform accurate waveform generation and signal metrology under their operating conditions, i.e., at temperatures of 4 K and below, down to a few millikelvins (mK) and for frequencies about 10 GHz.

Driven by the worldwide QT initiatives that require the ultimate precision in signal generation and detection, an increasing number of companies develop miniaturised and tailored microwave components and control electronics specifically for cryogenic temperatures. Many applications set new stringent demands on, e.g., insertion loss, footprint, and spectral characteristics of components. Microwave calibration capabilities exist at room temperature, but they are practically useless for the novel applications since the components undergo major changes as they are cooled from room temperature to temperatures of 4 K and below. Presently, no microwave traceability exists at such temperatures, even though the availability of quantum devices should in principle enable and utilise dramatically better accuracy than can be achieved at room temperature.

There is a race towards Exascale computing (>10^{18} floating point operations per second (flops)). However, the present technology requires far too much electrical power for Exascale computing to be a practical proposition, being close to that generated by a small power plant. Superconducting QC is one of the technologies which might be able to reach this goal. However, scaling up quantum technologies will soon face a fundamental limit of electronic signal and information transfer between room and cryogenic temperatures, as increasing the number/bandwidth of microwave cables will inevitably increase the heat load of cryogenic systems. Although cutting-edge realisations of quantum computers with 50...100 qubits rely on having up to 200 microwave cables in a cryostat, it is impossible to use this approach to build a useful, error corrected- quantum computer that requires about 10^6 qubits (a qubit or quantum bit is the quantum analogy of the classical binary bit). There is thus an urgent need to combine cryogenic microwave techniques with optical signal transfer and ultrafast optoelectronic converters operating at cryogenic temperatures.

Objectives

The overall objective is to establish fundamentally novel metrological and scientific tools for the measurement of microwave signals in circuits in-situ in cryogenic environments down to the millikelvin range using a combination of superconducting, semiconducting, and optical techniques. The specific objectives of the project are:

1. **To develop an optically integrated Josephson Arbitrary Waveform Synthesizer (JAWS) with bandwidth exceeding 100 GHz**, including the development of different ultrafast cryogenic optoelectronic converters based on semiconducting and plasmonic techniques. This is a prerequisite for establishing JAWS as a standard tool of QT outside NMIs by allowing cost- and energy-efficient systems with many output signals and with a bandwidth exceeding 100 GHz.
2. **To develop a quantum-traceable cryogenic 1 THz sampling oscilloscope utilising optoelectronic techniques for in-situ waveform measurements inside cryostats** with sub-picosecond time resolution. To calibrate the oscilloscope with JAWS and to provide the first direct time-domain demonstration of the pulse quantization effect of Josephson junctions.
3. **To develop and validate classical microwave S-parameter measurement capability for microwave devices and components inside dilution refrigerators** enabling traceable vector network analysis to be performed at temperatures below 100 mK. To evaluate the accuracy of these techniques on passive and active components.
4. **To model and develop novel superconducting quantum sensor technology and sensors for measurements of microwave power in the frequency range 1 GHz – 12 GHz in-situ in superconducting circuits in cryogenic environments**, including a full uncertainty estimation to validate the power sensors.
5. **To facilitate the take up of the technology and measurement infrastructure developed in the project by end users** in QT, the metrology community, national metrology institutes, research laboratories, and standards developing organisations (such as IEC).

Progress beyond the state of the art

There is practically no prior art for microwave metrology at cryogenic temperatures, so the project will lay the foundation for a wide microwave toolbox based on two types of approaches: (*i*) cryogenic versions of existing room -temperature techniques will be developed. (*ii*) quantum-based devices will be developed that can operate only at cryogenic temperatures and that will enable superior accuracy compared to any room temperature method.

The basic principle of JAWS is more than 20 years old, but despite plenty of incremental developments, it has remained an expensive niche device that is used only at NMIs to calibrate room temperature equipment. Recently, its frequency range has been extended above 1 GHz, but only for specific waveforms. A radical change in both methodology and philosophy will be adopted, namely an optically integrated JAWS with a bandwidth exceeding 100 GHz targeted to the whole QT community and for applications inside the same cryostat. The project will utilise VTT's recent invention of a silicon photonics (SiPh) based optical pulse pattern generator to create optical drive pulses at room temperature. Two types of novel optoelectronic converters (OEC) for cryogenic temperatures for driving the JAWS circuit will be explored: ETHZ has recently demonstrated ultrafast plasmonic OECs at room temperature, and SuperQuant will pioneer them in cryogenics. Moreover, uni-travelling-carrier (UTC) photodiodes for cryogenic temperatures will be developed. The ultimate goal is to develop JAWS-based on-chip-scale superconducting and optical components that are suitable for mass production.

Waveform metrology based on time-domain electro-optic sampling using femtosecond lasers is an established technology at room temperature. This technique will be extended to create a cryogenic 1 THz sampling oscilloscope which will then be calibrated using JAWS. This quantum-traceable cryogenic sampling oscilloscope will be employed for the first time-domain verification of the pulse quantization effect in Josephson junctions.

SuperQuant will pioneer state-of-art cryogenic microwave metrology for S-parameter measurements up to 20 GHz using three different approaches. Conventional S-parameter, absolute power, and phase calibration measurements will be adapted and migrated to in-situ approaches and their uncertainty at low temperatures estimated. The work will extend existing approaches by, for example, using novel superconductive switches and validating the absolute power and phase calibration at the cryogenic reference plane by advanced modelling of active (i.e., non-linear) devices. Measurement procedures enabling traceability to room temperature standards will be defined and the measurement uncertainty evaluated. Different setups will be compared by means of interlaboratory comparisons.

Finally, quantum sensing will be utilised, in particular, superconducting (SC) quantum bits (qubits) for absolute microwave power measurements. Several quantum sensors are suitable for signal detection, but their applicability for metrology, i.e., absolute power measurement is unknown. Recently, members of the SuperQuant consortium have attempted to relate the measured microwave power to the SI. SuperQuant will optimise the devices, develop measurement protocols, and perform a thorough uncertainty estimation to demonstrate in-situ absolute microwave power measurements. Additionally, the possibility of using JAWS circuits to detect microwave radiation will be studied. These new quantum sensors will be compared to each other and to existing room-temperature microwave power standards.

Results

Optically integrated JAWS with unprecedented bandwidth above 100 GHz:

So far, simulations of new types of UTC and plasmonic photodetectors and their integration have been carried out and the fabrication of first generations has been completed. For plasmonic graphene photodetectors measurements of first devices have been performed at room temperature and a bandwidth exceeding 500 GHz has been observed. The corresponding results have been presented at ECOC 2022 in Switzerland and published in Science [1]. Cryogenic characterisation has been done revealing that the high bandwidth of >100 GHz is retained down to 4K. Furthermore, an increase in response was observed. Different concepts of using JAWS for the generation of RF waveforms are pursued and a system to apply the concepts has been realized. First RF JAWS chips have been designed and fabricated and synthesized signals with frequencies ranging between 1 GHz and 8 GHz have been generated. Additionally, to combine the high-bandwidth photodetectors with the RF JAWS, Silicon photonics devices have been designed, fabricated, and characterised. Current work focuses on the second generation of photodetectors and the further enhancement of Silicon photonics devices.

Cryogenic quantum-traceable 1 THz sampling oscilloscope for in-situ waveform measurements inside cryostats:

An optoelectronic sampling oscilloscope for waveform measurements at room temperature has been built and technologies for fibre-chip mounting have been investigated. The measurements can be carried out using synchronous or asynchronous optical sampling. Based upon this work, the use of the fully-fibre-based optoelectronic sampling oscilloscope was extended to waveform measurements at cryogenic temperatures. This characterization platform has been used to characterise commercial photodiodes with a nominal bandwidth of 20 GHz and 60 GHz. The resulting time traces show a good signal to noise ratio exceeding 40 dB with observable frequency components exceeding several 100 GHz. The corresponding results have been presented at CPEM 2022 in New Zealand and published in a joint journal paper [2]. To further improve hybrid chip integration of superconducting chips, VTT developed flip-chip bonding of superconducting circuits using Indium as a contact material. This technique will prove to be helpful for the realization of hybrid semiconducting and superconducting chips and this is where the current work focuses on.

Scattering-parameter measurements in situ at low temperatures:

For conventional high-frequency measurements under cryogenic conditions, S-parameter measurement setups were designed and simulated. The simulations also evaluated the impact of certain parameters on the accuracy of calibrations using VNAs. Based upon these simulations, critical components were identified and purchased. With respect to on-wafer measurements, VNA measurements on certain calibration substrates have been carried out at ambient temperatures. Substrates have been designed and simulated for cryogenic on-wafer TRL calibration. With respect to measurements in dilution refrigerators, a coaxial S-parameter setup based on electromechanical switches was completed and test measurements were carried out. The simulation of the behaviour of coaxial calibration kits at cryogenic temperatures is still ongoing. This is performed in close collaboration with a company, by means of parameterized replicas of the actual components. The measurement setup based on superconducting switches was designed; first versions of the switches, including suitable planar calibration and test structures, have been fabricated and are currently being characterised in a joint effort between project partners. Results related to this work have been accepted for publication in IEEE Transactions on Applied Superconductivity. Current work concentrates on the set up of uncertainty budgets for on-wafer and dilution fridge measurements.

New quantum sensor technology and sensors for microwave power:

Activities on new power sensors have also proceeded significantly. A corresponding qubit chip, containing flux-tuneable transmon qubits, was designed to cover the 1 GHz to 12 GHz frequency range and fabricated in superconducting Al technology. The first set of qubits was tested at a temperature of 13 mK and a tuneable frequency range of ~3-12 GHz has been obtained. Measurements using qubits of two different designs have been performed, i.e., (i) resonant fluorescence, (ii) Rabi frequency, and (iii) Mollow triplet measurements with the aim to quantitatively deduce the microwave power from these measurements. The second version of a compact ultimate power calibration box was designed and prepared for testing. Some of the results obtained from this work contributed to a recent journal paper [3]. With respect to microwave power standards based on JAWS circuits, first JAWS chips have been fabricated and the critical currents of these chips have been measured. First experimental results demonstrate that JAWS circuits can be used as sensitive probes for microwave power.

Impact

The key dissemination activities undertaken so far are as follows: 1) Liaison with research networks and new projects: Interaction with other international and national projects and consortia, such as the Horizon 2020 project “aCryComm” has been established and is ongoing. Three partners of SuperQuant (INRIM, PTB, VTT) participate in one of the Framework Partnership Agreements (FPAs) for quantum technologies, “Qu-Test”. A proposal for a follow-up project of SuperQuant has been submitted to the recent Call of the European Partnership in Metrology Programme and been accepted. The project will most likely start in June 2024. 2) Standardisation activities: The consortium is pursuing its links to standardisation groups. VTT and PTB are members of the CEN/CENELEC Focus Group “Quantum Technology” and contributed to its roadmap on needs for standardisation for Quantum Technology. Moreover, VTT and PTB introduced the SuperQuant project at meetings of national standardisation meetings. INRIM and PTB introduced the SuperQuant project at EURAMET TC meetings. 3) Conference presentations: So far, 18 presentations linked to the SuperQuant project have been given at national and international conferences and workshops. 4) Journal publications: Three peer-reviewed journal papers have been published, one additional journal paper has been accepted and is awaiting publication, two papers have been submitted for peer review and two additional papers have been drafted.

Impact on industrial and other user communities

The project will support the development of the quantum technologies and quantum computing industries by establishing fundamentally novel microwave metrological and scientific tools for the measurement of microwave signals in circuits in-situ in cryogenic environments down to the millikelvin range.

Cryogenic microwave technology is a rapidly growing field of business, driven by the boom of QC and other quantum technologies. Establishing a European capability of accurate calibration of microwave signals in cryogenic environments will benefit the emerging microwave component, cryogenics, and quantum industry with enhanced measurements and standards. Other industries that are in urgent need of improved signal measurement capabilities and will benefit from the successful development of quantum microwave signal measurement standards include test and measurement, telecommunications, microwave components, space and military communications systems, cryogenic systems for QT, and medical imaging. The project not only addresses QC companies but also cutting-edge- QC projects, such as OpenSuperQ of the EU Quantum Flagship, which relies on an extensive number of microwave cables for the control and readout of the planned 100 quantum bits (qubits). Participation and established contacts to leading public QC consortia are additional strengths to facilitate rapid uptake of technology developed in the SuperQuant project. In addition, stakeholders will also benefit from the dissemination of the project’s outputs through presentations at key conferences, publications in peer reviewed journals, the project website, 2 good practice guides, 2 stakeholder workshops and 3 -web-based- courses.

Impact on the metrology and scientific communities

The SuperQuant project will merge fundamental metrology and QT applications, creating new European capability at the NMI level. This includes high speed (>100 GHz) cryogenic optoelectronic convertors driven by optical pulses, an optically integrated Josephson Arbitrary Waveform Synthesizer (JAWS) for the generation of quantised, arbitrary waveforms with a bandwidth exceeding 100 GHz, a cryogenic 1 THz sampling oscilloscope for in-situ waveform measurements, validated classical microwave S-parameter measurement capability for microwave devices and components inside dilution refrigerators enabling traceable vector network analysis to be performed at temperatures below 100 mK, and novel superconducting quantum sensors for measurements of microwave power in the frequency range 1 GHz –

12 GHz in-situ in superconducting circuits in cryogenic environments. This will lay the foundation for a wide toolbox for cryogenic microwave metrology which is currently missing.

SuperQuant will increase the scientific impact of electrical metrology by supporting quantum technology applications that are being operated in the same cryostat with the metrological standards. The SuperQuant project will contribute to the development of new AC voltage standards up to microwave frequencies. By addressing the challenges of performing accurate microwave waveform and signal generation and measurement at temperatures of 4 K and below and combining optical multiplexing circuits, optoelectronic converters, and the JAWS developed in the project, it is expected that the magnitude of the output voltage and frequency of existing AC voltage standards, which is currently limited to a few volts at an output frequency in the kHz range, will be significantly boosted. This will benefit both low-frequency metrology and microwave metrology, where only calorimetric but not quantum standards exist. Moreover, since electrical quantum effects such as the voltage-frequency relation of the Josephson effect are among the most precisely reproducible relationships with a relative uncertainty of 10^{-19}, the project’s outcomes have direct impact on future universality tests.

SuperQuant arranged its first on-site project meeting at VTT MIKES (Espoo, Finland) on 7–8 April 2022. It was preceded and partly combined with the meeting of the Horizon 2020 project *aCryComm* (attojoule Cryogenic Communication, https://www.acrycomm.eu/), arranged at VTT MIKES on 6–7 April. The combined meeting of more than 30 participants enabled important interactions between the two projects that have a very strong mutual synergy. Additional project meetings took place at PTB (Braunschweig, Germany) in April 2023 and online in December 2023.

Impact on relevant standards

To date, no relevant standards for performing traceable waveform or power measurements or device characterisation in-situ in cryogenic environments exist. The consortium will use the project results to initiate the first steps towards standardisation with respect to microwave power and ultrafast waveform measurements in-situ in superconducting circuits within WG14 of IEC/TC90 “Superconductivity“ and EURAMET EMN-Q. Guidelines for traceable in-situ waveform and power measurements under cryogenic conditions will be disseminated to the relevant stakeholder groups and industrial and scientific societies to underpin future standardisation.

Longer-term economic, social and environmental impacts

The fundamental metrology of this project will support the European quantum technology industry in several ways. Firstly, the fundamental investigations will stimulate innovation and will enable new quantum devices and applications. Secondly, the first steps towards standardisation that are taken in this project will directly underpin European quantum computation innovation and will increase the competitiveness of a key European industry in the global marketplace. Due to its very high power consumption, Exascale computing, with more than 10^{18} floating point operations per second, will require new computational schemes offering orders -of -magnitude improvement in flops per watt over the CMOS technology available today. Yet, in addition to achieving new computing speeds, more energy efficient computing techniques will also contribute to financial saving. With a foreseen energy consumption of data centres of up to 8000 TWh in 2030, a 10% of energy saving of such devices, i.e., 800 TWh per year, would directly result in about €160 billion financial savings.

The European Green Deal aims to create the first climate -neutral continent. The SuperQuant project may also have environmental impact if it contributes to resolving the unsustainable growth of energy consumption of ICT equipment. As noted above energy saving in data centres could eventually be used to shut down more than 90 medium-sized coal-fired power plants and, thus, considerably decarbonising the energy sector.

Society needs technologies based on innovative products and concepts. Quantum computation and communication have the potential to disruptively improve our daily life through the realisation of orders -of -magnitude-improved computational speed and truly secure communication schemes, respectively. Thanks to the rise of QT, electrical metrology can contribute to such developments. Mobile phones will not include a Josephson voltage standard in the near future, but our phones may communicate with a data centre that utilises quantum computers and electrical quantum standards. It is therefore crucial to develop quantum metrology tools that can be automated, mass-produced, and used outside NMIs.

List of publications

[1] Stefan M. Koepfli, Michael Baumann, Yesim Koyaz, Robin Gadola, Arif Güngör, Killian Keller, Yannik Horst, Shadi Nashashibi, Raphael Schwanninger, Michael Doderer, Elias Passerini, Yuriy Fedoryshyn, and Juerg Leuthold, "Metamaterial graphene photodetector with bandwidth exceeding 500 gigahertz", Science 380, 1169-1174 (2023), https://doi.org/10.1126/science.adg8017

[2] Shekhar Priyadarshi, Hao Tian, Alexander Fernandez Scarioni, Silke Wolter, Oliver Kieler, Johannes Kohlmann, Jaani Nissilä, and Mark Bieler, "Cryogenic Fiber-coupled Electro-optic Characterization Platform for High-speed Photodiodes", J. Infrared Milli. Terahz. Waves (2024). https://doi.org/10.1007/s10762-024-00966-1

[3] Teresa Hönigl-Decrinis, Ilya Antonov, Rais Shaikhaidarov, Kyung Ho Kim, Vladimir N Antonov, and Oleg V Astafiev, "Capacitive coupling of coherent quantum phase slip qubits to a resonator", New J. Phys. 25 113020 (2023), https://doi.org/10.1088/1367-2630/ad042e

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 September 2021, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Mark Bieler, PTB, Tel: +49-531-592-2400, E-mail: mark.bieler@ptb.de
Project website address: www.ptb.de/empir2021/superquant/</td></tr>
<tr><td>Internal Funded Partners:
1. PTB, Germany
2. INRIM, Italy
3. TUBITAK, Turkey
4. VTT, Finland</td><td>External Funded Partners:
5. ETHZ, Switzerland
6. RHUL, United Kingdom
7. TAU, Finland
8. TU Delft, Netherlands</td><td>Unfunded Partners:
9. TOBB, Turkey</td></tr>
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