EMPIR Call 2020 – Fundamental, Industry and Normative

Selected Research Topic number: **SRT-f16**
Version: 1.0

Title: Microwave metrology for superconducting quantum circuits

Abstract

The advancement of quantum technologies and quantum computing implies a significant increase of high frequency cabling and components operated at cryogenic temperatures down to tens of millikelvin. Scaling up quantum computing puts stringent requirements on heat-load, space, and signal integrity under these extreme conditions. Yet, no established technology exists today that can perform accurate waveform generation and signal metrology in-situ at cryogenic temperatures. Proposals addressing this SRT should focus on developing and establishing fundamentally novel metrological and scientific tools for the measurement of microwave signals in circuits in-situ at cryogenic temperatures down to millikelvin range. This platform will establish a strong European capability by utilising novel quantum sensors and dissemination of in-situ signals traceable to the SI.

Keywords

Microwave metrology, superconducting (SC) quantum technologies (QT), cryogenic systems, dilution refrigerators, signal generation and detection, waveform metrology, superconducting circuits, quantum circuits, quantum sensors, microwave power calibration, optoelectronic measurements, microwave power standards, microwave scattering parameters.

Background to the Metrological Challenges

As quantum technology develops further and quantum computing scales up, there will be a significant increase in the use of microwave components and signals inside cryogenic systems. As a result of this, better knowledge and in-situ control of the electrical signals used to control these quantum circuits is required to advance these technologies. Yet, the fundamental capability of accurate in-situ signal metrology in a cryogenic system is currently far behind what is needed and has only been demonstrated in a few bespoke experiments.

Microwave signals for SC quantum computing are currently generated using bulky and expensive synthesisers based on room-temperature electronics. Novel solutions are needed for scalability, signal quality, and economics. When quantum systems are scaled beyond hundreds of control lines, delivering these signals without exerting excess heat loads and maintaining signal integrity becomes a significant challenge. For example, quantum computing based on SC qubits requires ultra-high-quality arbitrary waveforms with frequencies of about 10 GHz. An ultimate way to generate such signals would be the Josephson Arbitrary Waveform Synthesiser (JAWS) based on delta-sigma modulation of quantised voltage pulses obtained from a SC Josephson device, but generating 10 GHz signals is well beyond the present state of the art. Similar methods would also be urgently needed in room-temperature waveform metrology to increase the output voltage of JAWS up to 10 V level. That requires fundamental research and breakthroughs in generation and cryogenic detection of pulse waveforms.

In the last years we have seen an increase in the number of companies that develop miniaturised and tailored microwave components and control electronics, as many applications set new stringent demands on e.g. insertion loss, footprint, and spectral characteristics of components. Yet a metrology framework to support this need is lacking, and signal generation and calibration accuracy is mainly limited by the significant changes that components undergo as they are cooled from room temperature (where calibration and traceability to the SI exists) to millikelvin temperatures (where no such traceability currently exists). This can be addressed using a bulky switched cryogenic standard, but even so this relies on the quality of switch calibration, which is not trivial at low temperatures, and achieving accuracies better than 0.5 dB becomes very challenging and certainly not practical for systems consisting of hundreds of signal lines and components.

An alternative approach, utilising quantum sensors for absolute signal detection at millikelvin temperatures, has recently been demonstrated using SC qubits in a variety of proof-of-concept implementations, as well as other platforms. Most of these implementations demonstrate the capability of signal detection and only recently have there been further efforts to establish stringent error bounds (uncertainties) and relate the measured quantities to existing SI. Furthermore, SQUID arrays made of either high- or low-temperature superconductors have been fabricated and employed for sensing applications. Yet, the possibility to use such circuits for metrological applications, i.e., absolute signal detection at very low power levels has not been investigated.

Key to supporting the development of quantum technologies is the ability to both synthesise and validate electrical signals in-situ at cryogenic temperatures. To this end, novel approaches, which combine SC, semiconducting, and optical techniques, need to be implemented.

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 developing and establishing fundamentally novel metrological and scientific tools for the measurement of microwave signals in circuits in-situ at cryogenic temperatures down to millikelvin range.

The specific objectives are

1. To model, develop and validate techniques for generation and traceable detection of ultrafast waveforms with frequency components exceeding 100 GHz in-situ in cryogenic systems. To demonstrate optoelectronic waveform measurements in superconducting (SC) circuits at cryogenic temperatures with traceability to the SI.
2. To develop and validate microwave measurement capability for calibration of S-parameters and electrical signals in devices and components in-situ at millikelvin temperatures (inside dilution refrigerators), based on existing state of the art microwave metrology techniques. Demonstrate calibration of a DUT cooled to millikelvin temperatures with traceability to the SI.
3. To model, develop and validate novel SC quantum sensor technology for measurements of microwave power, waveforms and microwave electric fields in the frequency range 1-12 GHz in cryogenic environments.
4. To perform a full error estimation of the sensor(s) from objective 3 with traceability to primary electrical standards and evaluate the performance of the sensor(s) for applications in low-temperature environments. To compare the quantum sensors with current state of the art microwave power measurement techniques.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, research laboratories), standards developing organisations (IEC, CEN, ISO) and end users (quantum technologies).

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 across all selected projects in this TP.

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,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to the quantum technologies sector.

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.