Final Publishable JRP Summary for EXL03 MICROPHOTON
Measurement and control of single-photon microwave radiation on chip

Overview

Applications of quantum technology are expanding in fields such as medical imaging (e.g. magnetoencephalography), airport security and telecommunications. Single-photon microwave sources and detectors are examples of precisely controllable quantum devices needed especially in quantum information processing and communication (QIPC). The lack of such sources and detectors has been a major limitation, for instance in QIPC based on circuit quantum electrodynamics (cQED). To address this need, this project developed several types of microwave detectors and sources suitable for operation at the single (or near single) photon level. Quantum devices are operated at cryogenic environments, as the quantum mechanical nature of materials becomes most apparent at low temperatures. Therefore the project provided tools for cryogenic experiments that will lead to a better understanding of quantum devices and thus improve their performance.

Need for the project

In the quantum revolution, new types of quantum devices are being developed that promise unprecedented capabilities for a wide range of applications. One particularly active and important research field is the development of quantum information processing and communication (QIPC) using quantum bits (qubits) based on superconducting devices and other cryoelectronic components.

The development of any future superconducting quantum computing technology will depend on the availability of on-chip single-photon and few-photon microwave components. Yet, electromagnetic metrology for microwave frequencies at very small signal levels is still in its infancy.

Quantum device technology requires the development of microwave photon detectors and sources at the single-photon level. Photons at microwave frequencies offer advantages over optical frequencies as normal microwave components can be used together with special superconducting electronics. For example, in QIPC single microwave photons can be generated and used as qubits in quantum computing and measured using single-photon detectors. Thus, 'on-demand' sources of microwave photons with known qualities, and detection of these photons in a reliable way at the single-photon level is essential.

At the start of this project, 'on-demand' generation of single microwave photons had been demonstrated in only a few experiments, and single-photon detectors for microwave frequencies were not available at all. This was because the energy of a microwave photons is much lower than that of optical photons, meaning that detection of microwave photons at the quantum level needs extremely sensitive detectors operating in ultra-low noise environments.

The development of such cryonanoelectronic devices requires ultrasensitive microwave sensors to tackle the problem of the residual microwave photons, which can distort measurements. An ultraquiet microwave environment minimising noise and thermally excited microwave photons is needed to study the effects of background microwave radiation on quantum nanodevices in cryogenic environments.

Scientific and technical objectives

The objectives of this project included the development of novel microwave detectors and sources down to the single-photon level, and the improvement in the performance of cryoelectronic quantum devices by understanding and eliminating the detrimental effects caused by microwave radiation coming from the electromagnetic environment. The specific objectives were:

1. Development of single-microwave-photon detectors, which give spectral information about radiation. The aim was to develop sensors covering a wide frequency range from below 10 GHz up to approx.

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300 GHz and that the methods would be based on superconductor and semiconductor nanodevice technologies.

2. Development of cryogenic sources of microwave photons to cover frequencies between 4 GHz and 300 GHz and their use in the characterisation of the developed photon detectors.
3. Characterisation and minimisation of background microwave radiation in the cryogenic measurement systems of nanoelectronic devices.
4. Demonstrations of improved performance of cryoelectronic quantum nanodevices such as SINIS-SET (S Superconductor I Insulator N Normal metal I Insulator S Superconductor - Single-Electron Transistor) based components and other devices.

Results

Single -photon microwave detectors

Single-photon microwave detectors and sources are needed for quantum information and processing applications. The single photon sources can be used as qubits in quantum computing, and single-photon detectors can be used for measuring these qubits. Several versions of ultrasensitive cryogenic microwave detectors on frequency ranges from 10 GHz up to 200 GHz were studied and developed to increase single-photon sensitivity. Even though single-photon sensitivity with good fidelity could not be demonstrated during the lifetime of the project, there was significant progress beyond the state-of-the-art towards this goal.

With a SINIS single-electron trap detector it is already possible to observe events caused by individual microwave photons, but with a very low quantum efficiency. Such SINIS detectors can be used, for example, to obtain spectral information of microwave radiation penetrating quantum devices.

With SNS (S Superconductor N Normal metal S Superconductor) detectors, the state-of-the-art of microwave photon detection sensitivity of thermal detectors was improved by more than an order of magnitude, to approx. 200 photons at 8.4 GHz frequency, and reaching single-photon sensitivity is now feasible. A special property of such thermal detectors is that they typically have a wide bandwidth and a large dynamic range. Operation of a new type of a superconducting bifurcation amplifier, a period-doubling bifurcation (PDB) amplifier, was demonstrated for the first time by the project. PDB detectors are expected to have better tuneability than the already developed amplitude bifurcation amplifiers, but without compromising the feasibility of single-photon sensitivity.

Sources of microwave photons

Microwave photon sources are an important element for quantum technologies. Two types of qubit-based on- demand sources of single microwave photons were developed in this project. One of the sources was based on a transmon qubit (i.e. a superconducting qubit) and is similar to qubit-based single-photon sources. The other source had a novel design and was unique in the sense that the frequency of generated photons could be tuned over a wide frequency range from 6.7 GHz to 9.1 GHz. Both sources (devices) are suitable for integrating with on-chip detectors. Detection of microwave photons generated with on-chip on-demand sources would be a breakthrough in circuit quantum electrodynamics. Additionally, an on-chip microwave generator based on the Josephson generation phenomenon was developed by the project and used in the characterisation of SINIS trap detectors on the same chip.

Background microwave radiation in cryogenic measurement systems

Cryogenic quantum devices are extremely sensitive to environmental fluctuations, for example quasiparticles excited by background microwave radiation are a serious problem for single-electron devices. The project developed methods to characterise and minimise the background microwave radiation in cryogenic measurement systems. A measurement system with variable level of microwave filtering and shielding was developed for systematic studies of the effects of microwave background radiation on cryoelectronic devices. The measurement system is available for measurements and has the potential to improve the performance of cryoelectronic quantum devices. However, quantitative measurements of the effects of different microwave background level on double SINIS-SET devices could not be performed due to sample fabrication problems. The project also demonstrated the usefulness of a SINIS trap detector as a tool for obtaining spectral information of microwave radiation, as part of the characterisation of superconducting on-chip filters.

Improved performance of cryoelectronic quantum nanodevices

The aim of this objective was to use a double SINIS-SET device as a tool to demonstrate improved performance when increasing the filtering and shielding of the sample chamber. However, the work was frustrated by technical problems with device fabrication. But the project did manage to obtain further evidence of the improved performance of SINIS single-electron devices in experiments with a SINIS single-electron trap detector.
In the newly developed and specially filtered and shielded measurement chamber, the hold times of electrons in the trap were at least an order of magnitude longer than in a conventionally filtered and shielded cryostat. Moreover, a dramatic effect of filtering on the performance of SINIS single-electron devices was demonstrated in an experiment in which a SINIS single-electron trap was filtered by a (Superconducting QUantum Interference Device) SQUID array. The hold time could be increased by two orders of magnitude when on- chip filtering was improved by adjusting the external magnetic field to a value at which the SQUID array filter was blocked, thus preventing microwave photons penetrating via the on-chip leads.

Impact

The impact of this project is mostly in the scientific community, however, in the long-term, there will be financial and social impacts. The cryoelectronics market has already a significant volume of commercial applications, and this is expected to increase dramatically in future as the recent progress in cryogen-free refrigeration and on-chip coolers is making cryoelectronics more attractive for practical applications. Easy-to-use commercial methods for signal line filtering and radiation shielding of quantum nanodevices will benefit the manufacturers of cryogenic refrigerators and components.

Dissemination activities

Results of the project have been reported in 19 peer-reviewed publications and proceedings including highly ranked scientific journals such as Nature Communications and Physical Review Letters. A more general article about controlling single microwave photons was published in the Microwave Journal, which reaches 50,000 readers from all over the world. Project results have also been presented in 47 presentations or posters at scientific conferences and workshops.

In addition, the MICROPHOTON 2016 workshop covered quantum, microwave and cryogenic developments from the project and was attended by more than 60 participants from universities, research institutes, and the cryogenic and microwave industries.

The project website www.microphoton.eu and a newsletter were set-up as well as a stakeholder group. The stakeholder group was used to enhance dissemination of the outputs of the project and to provide opportunities for communication with target audiences.

On-line training on ‘Shielding out high-energy photons inside a cryostat’ was developed by the project and given to a group that actively works in this field at the University of Copenhagen. The training material is also available for stakeholders on the project website.

A good practice guide for microwave radiation detection, shielding and filtering within cryogenic systems has been produced and is available on the project website and via arXiv.

Impact on standards

Even though the work carried out in the project was of fundamental nature and not yet at the stage that needs standardisation, there was regular exchange of information about the project’s progress with relevant technical committees particularly in the fields of electrical metrology and microwave science. The project was presented to the CIPM Consultative Committee for Electricity and Magnetism (CCEM) and to EURAMET Technical Committee for Electricity and Magnetism (TC-EM). More detailed results from the project have been given to the EURAMET TC-EM Subcommittee on DC and Quantum Metrology in 2015 and 2017. Project results were also presented for the International Union of Radio Science in the URSI Atlantic Meeting on Radio Science.

Early Impact

In this project, several nano- and cryoelectronic devices were developed which are important steps towards microwave photon detectors and on-demand sources. Substantial progress beyond the state of the art was achieved, and the work published in high-impact scientific journals has stimulated important further research in the field. Examples include:

- Demonstration of on-demand generation of single microwave photons with a tuneable frequency between 6.7 GHz and 9.1 GHz using a novel superconducting source based on a flux qubit coupled to a pair of transmission line waveguides. The result was published in Nature Communications has already been cited in at least 5 scientific articles.
- Improvement of the state-of-the-art of the sensitivity of thermal microwave photon detectors to the level of 1 zeptojoule (10^{-21} Joules), corresponding to approx. 200 photons at 8.4 GHz frequency, using an SNS detector. The result has already been cited in at least 7 published scientific articles.

The impact of the project for European quantum metrology is also significant:

- The project's new measurement capabilities for second-order correlation functions of single microwave photon sources will be an important tool in further research in microwave quantum optics.
- The project developed a measurement system which is available for studies of the effects of microwave background radiation on cryoelectronic devices.
- The project's research on the PBD amplifier lead to invention of a novel type of a Josephson traveling wave parametric amplifier.
- The project's development of a microwave photon detector based on a semiconductor quantum dot single-electron device has given important insight not only for microwave photon detection but also for applications of a similar device in so-called electron quantum optics.

Potential impact

Even though single-photon real-time detection with good fidelity was not achieved during the lifetime of the project, the achievement of this end goal is now closer. The microwave photon detectors and sources developed in this project have the potential to enable the realisation of a practical quantum computer based on solid-state qubits, which will be a revolutionary breakthrough.

List of Publications

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