MICROPHOTON

2016

13-14th of April 2016

National Physical Laboratory, Teddington, UK

National Physical Laboratory

EMRP
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MICROPHOTON 2016

Dear Colleagues,

We are pleased to welcome you to the MICROPHOTON 2016 workshop, held at the National Physical Laboratory in London on the 13-14th of April 2016.

This workshop aims to bring together researchers working with very low-level microwave radiation - in particular, methods for controlling and manipulating radiation at the single photon level in solid state systems. These topics will be addressed in seven oral sessions as well as a poster session.

The organisers would like to acknowledge the support of the EMRP. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Tobias Lindstrom and Masaya Kataoka

MICROPHOTON 2016

Wednesday the 13th of April

10:30	**Introduction**	
10:40	**Joint research project MICROPHOTON – Measurement and control of single-photon microwave radiation on a chip**	Antti Manninen *VTT Technical Research Centre of Finland, Centre for Metrology MIKES, Finland*
11:10	**Tunable on-demand photon source based on superconducting quantum systems**	Oleg Astafiev *Royal Holloway, University of London& National Physical Laboratory,UK*
11:40	**A concept of traveling wave parametric amplifier based on Josephson nonlinearity**	Alexander Zorin *Physikalisch-Technische Bundesanstalt, Germany*
12:00	**Microwave Photon Source Driven by Electron Tunnelling in SINIS Junctions**	Shumpei Masuda *Aalto University, Finland*
12:20	**Lunch**	
13:30	**Magnetic resonance at the quantum limit and beyond**	Patrice Bertet *CEA-Saclay,France*
14:00	**Low-loss superconducting nanowires integrated into high-Q NbN resonators using a Ne focussed ion beam**	Jonathan Burnett *University College London,UK*
14:20	**Surface acoustic wave resonators in the quantum regime**	Riccardo Manenti *University of Oxford,UK*
14:40	**Coffee**	
15:10	**Ultra-Low Temperature (ULT) Environments for Research and Industry**	Ziad Melhem *Oxford Instruments,UK*
15:40	**Quantum Circuit Refrigerator**	Kuan Tan *Aalto University,Finland*
16:00	**Single microwave photon detection with SINIS-devices and on-chip filtering of microwave photons**	Janne Lehtinen *VTT Technical Research Centre of Finland, Centre for Metrology MIKES, Finland*
16:20	**Poster session**	
18:30	**End**	

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Thursday the 14th of April

09:30	**Single microwave-photon detection using an artificial Λ-type three-level atom**	Kunihiro Inomata *RIKEN,Japan*
10:00	**Detection of zeptojoule microwave pulses using electrothermal feedback**	Mikko Möttönen *Aalto University,Finland*
10:20	**Superradiant Soliton State of Matter in Quantum Metamaterials**	Alexandre Zagoskin *Loughborough University, UK*
10:40	**Coffee**	
11:10	**Cryogenic InP HEMT Low Noise Amplifiers**	Joel Schleeh *Low-Noise Factory,Sweden*
11:40	**Period-doubling-bifurcation phenomena in superconducting Nb resonators with controlled Josephson nonlinearity at 4.2K**	Marat Khabipov *Physikalisch-Technische Bundesanstalt, Germany*
12:00	**First observations of a Period Doubling Bifurcation in a Josephson cavity resonator**	Katie Porsch *Royal Holloway, University of London UK*
12:20	**Lunch**	
13:30	**Dispersive thermometry with a Josephson junction**	Olli-Pentti Saira *Aalto University,Finland*
14:00	**Nonequilibrium quasiparticles and downconversion of photons and phonons in superconducting microresonators and other thin film devices**	Tejas Guruswamy *Cavendish Laboratory,* *University of Cambridge,UK*
14:20	**Single microwave photon detection based on photon-assisted tunneling phenomena in the Coulomb blockade devices**	Sergey Lotkhov *Physikalisch-Technische Bundesanstalt, Germany*
14:40	**Coffee**	
15:10	**Single-shot qubit readout using a Josephson parametric oscillator**	Jonas Bylander *Chalmers University of Technology Sweden*
15:30	**Protected ground states in short chains of coupled qubits in circuit quantum electrodynamics**	Eran Ginossar *University of Surrey,UK*
15:50	**An artificial atom in front of a mirror: Probing and cancelling vacuum fluctuations**	Per Delsing *Chalmers University of Technology Sweden*
16:20	**Conclusion**	
16:30	**End**	

Abstracts

Wednessday 10:40-11:10

Joint research project MICROPHOTON – Measurement and control of single-photon microwave radiation on a chip

A.J. Manninen

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In May 2013, research groups from four European National Metrology Institutes (MIKES/VTT, INRiM, NPL, PTB) and three universities (Aalto University, Lancaster University, and Royal Holloway, University of London) started a joint research project MICROPHOTON (Measurement and control of single-photon microwave radiation on a chip) in the framework of the European Metrology Research Programme (EMRP). Main objectives of the project include the development of novel cryogenic 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. This presentation is a summary of the project and its main achievements. More detailed presentations of the project results will be given by project partners.

Wednessday 11:10-11:40

Tunable on-demand photon source on superconducting quantum systems

Oleg V. Astafiev[1,2], Z. H. Peng[1,3]

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[2]National Physical Laboratory, Teddington, UK

[3]RIKEN, Wako-shi, Saitama, Japan

Superconducting quantum systems (artificial atoms) provide an opportunity to realize quantum optical effects on-chip with a series of novel interesting properties. Particularly, using strong coupling of the atoms to transmission lines, atomic excitations can be converted into photons with a high efficiency. We demonstrate an on-demand single-photon source using the fully controllable artificial atom. The atom is prepared in the excited state by a short microwave pulse and then emits a photon into the coplanar transmission line. Due to asymmetric coupling of control and emission lines, the excited atom emits the photon into the emission line with a high probability. In our experiments, the yield of the photon generation is found to be not less than 75% and additional control of the atomic energy splitting by external dc fields, allows to tune it in a wide frequency range (with our present device from 7 to 9 GHz and more) without losing the efficiency.

Wednessday 11:40-12:00

A concept of traveling wave parametric amplifier based on Josephson nonlinearity

A. B. Zorin
PTB, Braunschweig

Recently, the field of Josephson traveling wave parametric amplifiers (JTWPAs) operating in the four-wave mixing (4WM) mode and enabling near quantum-limited noise performance is booming. We have developed a new concept of the traveling wave parametric amplifier based on three-wave mixing (3WM) in a superconducting transmission line with an engineered Josephson nonlinearity. Our circuit having ladder-type architecture consists of a serial array of N rf-SQUIDs embedded in the central line of the coplanar waveguide and biased by nonzero external magnetic flux. In contrast to 4WM JTWPAs our device exploits not only cubic (Kerr-like) nonlinearity, but also quadratic nonlinearity allowing 3WM which ensures reliable offset of the large-power pump tone from the signal band, intensive mixing of microwaves and appreciable tolerance to their phase mismatch. Moreover, the analysis shows that our device should exhibit unprecedentedly large bandwidth, excellent gain and power saturation and, therefore, can outperform state-of-the-art 4WM JTWPAs. For example, such amplifier designed for typical technological parameters, the number of cells N = 300 (with total physical length of the amplifier less than 1 cm) and pump frequency of 12 GHz yields a flat (-3 dB) power gain of 20 dB in the bandwidth of 5.6 GHz and the 1 dB saturation power of -93 dBm.

Wednessday 12:00-12:20

Microwave Photon Source Driven by Electron Tunneling in SINIS Junctions

S. Masuda, K. Y. Tan, M. Partanen, R. Lake, J. Govenius and M. Möttönen

QCD Labs, COMP Centre of Excellence, Department of Applied Physics,

Aalto University, P.O. Box 13500, FIN-00076 Aalto, Finland

Microwave photons in a superconducting resonator have been utilized as information carriers and for qubit operations in superconducting quantum computing architectures [1]. In addition, microwave photons provide interactions between qubits and the coupling to a dissipative environment and may transfer heat across macroscopic distances [2]. Therefore, accurate and rapid control of photonic states of microwave resonators are important in the development of quantum information technology.

We increase the number of photons of a microwave resonator using controlled single-electron tunneling across SIN junctions. The device consists of SIN junctions capacitively coupled to a superconducting coplanar waveguide resonator. When an electron tunnels across a junction, photons in the resonator are created or annihilated [3,4]. This device enables electrical control of the output power from the resonator, thus functioning as an on-demand photon source that can readily be integrated into quantum circuits. In our theoretical model, we calculate the power between the resonator and tunneling electrons using P(E) theory [3] and obtain the power between the resonator and the transmission line following Ref. [5].

[1] J. Kelly et al., Nature 519, 66 (2015).

[2] M. Partanen et al., Nature Phys. doi:10.1038/nphys3642 (2016).

[3] G. -L. Ingold and Y. Nazarov, NATO ASI Series B, Vol. 294, Chap. 2 (Plenum Press, New York, 1992).

[4] J. P. Pekola et al., Phys. Rev. Lett. 105, 026803 (2010).

[5] P. J. Jones et al., J Low Temp. Phys. 173, 152 (2013).

Wednessday 13:30-14:00

Magnetic resonance at the quantum limit and beyond

Patrice Bertet

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The detection and characterization of paramagnetic species by electron-spin resonance (ESR) spectroscopy has numerous applications in chemistry, biology, and materials science [1]. Most ESR spectrometers rely on the inductive detection of the small microwave signals emitted by the spins during their Larmor precession into a microwave resonator in which they are embedded. Using the tools offered by circuit Quantum Electrodynamics (QED), namely high quality factor superconducting micro-resonators and Josephson parametric amplifiers that operate at the quantum limit when cooled at 20mK [2], we report an increase of the sensitivity of inductively detected ESR by 4 orders of magnitude over the state-of-the-art, enabling the detection of 1700 Bismuth donor spins in silicon with a signal-to-noise ratio of 1 in a single echo [3]. We also demonstrate that the energy relaxation time of the spins is limited by spontaneous emission of microwave photons into the measurement line via the resonator [4], which opens the way to on-demand spin initialization via the Purcell effect. Finally we report recent results demonstrating that squeezed microwave signals can be used to enhance ESR sensitivity even further [5]

[1] A. Schweiger and G. Jeschke, Principles of Pulse Electron Magnetic Resonance (Oxford University Press, 2001)

[2] X. Zhou et al., Physical Review B 89, 214517 (2014).

[3] A. Bienfait et al., Nature Nanotechnology 11, 253 (2016)

[4] A. Bienfait et al., Nature 531, 74 (2016)

[5] A. Bienfait et al., in preparation (2016)

Wednessday 14:00-14:20

Low-loss superconducting nanowires integrated into high-Q NbN resonators using a Ne focussed ion beam

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Superconducting nanowires embedded within superconducting resonators can find applications as absorbers in kinetic-inductance detectors, detection elements in superconducting single-photon detectors and as quantum phase-slip junctions. In all these cases, low levels of loss are crucial, but a technology for producing high-quality superconducting resonators containing superconducting nanowires has up to now not yet been demonstrated. We have used a neon focussed ion beam to create superconducting nanowires with widths down to 20 nm in NbN superconducting resonators. To investigate the various loss mechanisms, we have characterised the resulting devices over a range of microwave powers and at temperatures down to 300 mK. Measurements of the devices in the low-power limit where parasitic two-level systems are dominating the loss show an intrinsic quality factor at 300mK in the range of 2–5 x 10^5. This level of loss is 100x better than previously demonstrated nanowire-embedded circuits and at least matches state-of-the-art Josephson-junction-based circuits. These results are very promising for achieving low-loss superconducting-nanowire-based architectures for various applications including quantum circuits.

Wednessday 14:20-14:40

Surface acoustic wave resonators in the quantum regime

R. Manenti, M. J. Peterer, A. Nersisyan, E. B. Magnusson, A. Patterson and P. J. Leek

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Surface acoustic waves (SAWs) are mechanical modes confined to the surface of a piezoelectric crystal that can be excited and detected by electric circuits. These mechanical waves can be trapped between two reflectors producing a SAW resonator. In this talk, I will present an experimental study of SAW resonators at 10 mK [1], in which we find that internal quality factors Qi approaching 0.5 million can be reached at 0.5 GHz and that Qi>10^4 is achievable above 4 GHz, making SAW resonators promising devices for integration into quantum circuits. I will discuss the loss mechanisms that may be currently limiting these Q-factors, and report on our progress towards coupling these mechanical resonators to superconducting qubits.

[1] R. Manenti et al., Phys Rev B, **93**, 041411(R) (2016)

Wednessday 15:10-15:40

Ultra-Low Temperature (ULT) Environments for Research and Industry

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Recent advances in cryofree and ultra-low temperature technology is enabling new cryogenic platforms. The new platforms has led the way in ultra-low temperature experiment-readiness with its leading-edge superconducting magnet integration, sample loading mechanisms, and sample wiring options. These platforms come with different sizes and cooling options together with extensive range of electrical and sample access options. This will facilitate different experimental techniques including those requiring large heat load dissipation, such as microwave excitation or solid state NMR, to be performed under the optimum thermodynamic conditions and and allow variety of demanding applications. This talk presents a brief update on the development of ULT platforms for diverse application in research and industry.

Wednessday 15:40-10:20

Quantum Circuit Refrigerator

Kuan Yen Tan, Matti Partanen, Russell E. Lake, Joonas Govenius, Shumpei Masuda and Mikko Möttönen

QCD Labs, COMP Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FI–00076 Aalto, Finland.

Quantum electric circuits promise revolutionizing technological applications in data processing, acquisition, and security. However, these devices suffer from inefficiency in on-demand dissipation of the heat generated in their operation. Here, we introduce a versatile refrigerator for quantum electric circuits and experimentally demonstrate its ability to directly cool a superconducting resonator. In good quantitative agreement with theoretical predictions, the in-situ-controlled operation voltage of the refrigerator gives rise to quantum tunneling of electrons accompanied by absorption of heat from the resonator. In the future, our refrigerator can be integrated with most quantum electric devices, critically enhancing their performance. For the superconducting quantum computer, for example, it potentially provides an efficient way of initializing the quantum bits.

Wednesday 16:00-16:20

Single microwave photon detection with SINIS-devices and on-chip filtering of microwave photons

J. S. Lehtinen[1], A. Kemppinen[1], E. Mykkänen[1], S. V. Lotkhov[2], B. Jalali-Jafari[2], A. B. Zorin[2], A. J. Manninen[1]

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Minimization of microwave background is crucial for improving performance of several cryogenic nanoscale devices. In addition to careful shielding of the sample stage and filtering of the measurement lines, on-chip filtering solutions can dramatically decrease the high energy photon originated disturbances to the measured device.

At low enough temperatures single-electron tunnel rates through superconductor(S)-insulator(I)-normal metal(N) tunnel structures are exponentially suppressed by Bardeen-Cooper-Schrieffer density of states in the superconductor and the Coulomb blockade effect. The dominant tunnelling mechanism originates from the residual photon noise of the junction's electromagnetic environment [1,2,3] making SINIS device viable single microwave photon detector.[4,5]

We've used SINIS devices for characterization of cryogenic environment microwave background with varying shielding levels. On-chip RC- and SQUID-filters have been used to further reduce the background. In new sample design we've incorporated possibility to irradiate the detector with Josephson photon source through transmission line which is equipped with tuneable SQUID-filter.

[1] J. Martinis and M. Nahum, Phys. Rev. B 48, 18316(R), (1993).

[2] J. P. Pekola et al., Phys. Rev. Lett. 105, 026803, (2010).

[3] A. Kemppinen et al., Appl. Phys. Lett. 99, 142106, (2011).

[4] O.-P. Saira et al., Phys. Rev. B 85, 012504, (2012).

[5] S. V. Lotkhov and A. B. Zorin, Appl. Phys. Lett. 100, 242601 (2012).

Thursday 09:30-10:00

Single microwave-photon detection using an artificial Λ-type three-level atom

K. Inomata[1], Z. R. Lin1, K. Koshino[2], J. S. Tsai[1,3], T. Yamamoto[4], and Y. Nakamura[1,5]

[1]RIKEN, Center for Emergent Matter Science (CEMS), Japan.

[2]College of Liberal Arts and Sciences, Tokyo Medical and Dental University, Japan.

[3]Tokyo University of Science, Japan.

[4]Smart Energy Research Laboratories, NEC Corporation, Japan.

[5]Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Japan.

In this presentation, we demonstrate detection of a propagating microwave photon with an artificial Λ-type three-level atom implemented in the dressed states of a driven circuit-QED system where a superconducting flux qubit is coupled to a microwave resonator dispersively [1]. By driving the qubit-resonator coupled system under proper conditions, we realize the impedance-matched Λ system which has two identical radiative decay rates from the upper level to the lower two levels [2, 3]. It has been predicted that a resonant photon input through a waveguide to the Λ system deterministically induces a Raman transition and switches its electronic state [2]. The switching results in the qubit excitation; therefore, we can detect the input single photon by reading out a qubit state before its relaxation [4]. In our experiment, resonant microwave pulses with an average photon number of ~0.1 are input to the Λ system, and the qubit state after each pulse is immediately read out. The photon detection efficiency of 66±6% has been attained [1].
The efficiency limited by a relaxation time (T_1) of the qubit can readily exceed 0.9 by improving T_1 [4].

[1] K. Inomata, Z. R. Lin, K. Koshino, W. D. Oliver, J. S. Tsai, T. Yamamoto and Y. Nakamura, arXiv:1601.05513(2016).

[2] K. Koshino, K. Inomata, T. Yamamoto, and Y. Nakamura, Phys. Rev. Lett. **111**, 153601 (2013).

[3] K. Inomata, K. Koshino, Z. R. Lin, W. D. Oliver, J. S. Tsai, Y. Nakamura, and T. Yamamoto, Phys. Rev. Lett. **113**, 063064 (2014).

[4] K. Koshino, K. Inomata, Z. R. Lin, Y. Nakamura, and T. Yamamoto, Phys. Rev. A **91**, 043805 (2015).

Thursday 10:00-10:20

Detection of zeptojoule microwave pulses using electrothermal feedback

Joonas Govenius, Russell E. Lake, Kuan Yen Tan, Mikko Möttönen

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Superconducting qubits coupled to microwave transmission lines have developed into a versatile platform for solid-state quantum optics experiments [1], as well as a promising candidate for quantum computing [2]. However, in contrast to optical frequencies, at microwave frequencies we still lack efficient detectors for itinerant single-photon pulses [3].

We focus on thermal photodetectors, which have recently been proposed also as monitorable heat baths for experiments on quantum thermodynamics [4]. Recently, Gasparinetti et al. [5] have demonstrated a temperature sensitivity of 90 $\mu K/Hz^{1/2}$ in the readout of such detectors.

We experimentally investigate and utilize electrothermal feedback in a microwave photodetector developed in Ref. [6]. The feedback couples the temperature and the electrical degrees of freedom in the central component of the detector, a metallic nanowire that absorbs the incoming microwave radiation and transduces the temperature change into a radio-frequency electrical signal. We tune the feedback in situ and access both positive and negative feedback regimes with rich nonlinear dynamics. In particular, strong positive feedback leads to the emergence of two metastable electron temperature states in the millikelvin range. We use these states for efficient threshold detection of 8.4-GHz microwave pulses containing approximately $200 \times h \times 8.4$ GHz $\approx$ 1.1 zJ of energy [7]. To our knowledge, this energy resolution is more than an order of magnitude improvement over previous thermal detectors.

[1] A. Wallraff et al., Nature **431**, 162 (2004).

[2] J. Kelly et al., Nature **519**, 66 (2015).

[3] P. D. Nation, J. R. Johansson, M. P. Blencowe, and F. Nori, Rev. Mod. Phys. **84**, 1 (2012).

[4] J. P. Pekola, Nature Phys. **11**, 118 (2015).

[5] S. Gasparinetti et al., Phys. Rev. Appl. **3**, 014007 (2015).

[6] J. Govenius et al., Phys. Rev. B **90**, 064505 (2014).

[7] J. Govenius, R. E. Lake, K. Y. Tan, and M. Möttönen, arXiv:1512.07235 (2015).

Thursday 10:20-10:40

Superradiant Soliton State of Matter in Quantum Metamaterials

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[2]Electronics and Photonics Research Institute (ESPRIT), National Institute of

Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan

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Strong interaction of a system of quantum emitters (e.g., two-level atoms) with electromagnetic field induces specific correlations in the system accompanied by a drastic insrease of emitted radiation (superradiation or superfluorescence). Despite the fact that since its prediction this phenomenon was subject to a vigorous experimental and theoretical research, there remain open question, in particular, concerning the possibility of a first order phase transition to the superradiant state from the vacuum state. In natural atom arrays this transition is prohibited by the ``no-go'' theorem. Here we demonstrate numerically such a transition in a quantum metamaterial - a chain of artificial atoms (qubits) strongly interacting with classical electromagnetic fields - from vacuum state with zero classical electromagnetic fields and all qubits being in the ground state to the superradiant phase with one or several magnetic solitons and varying occupation of ground and excited states of qubits along the transmission line. A quantum metamaterial in the superradiant phase avoids the ``no-go'' restrictions by considerably decreasing its total energy relative to the vacuum state by exciting nonlinear electromagnetic solitons with many nonlinearly coupled electromagnetic modes.

Thursday 11:10-11:40

Cryogenic InP HEMT Low Noise Amplifiers

Joel Schleeh,. Low Noise Factory,
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Low Noise Factory (LNF) was founded in 2005 as a spin-off from Chalmers University of Technology, which was one of the pioneers in the field of InP High Electron Mobility Transistors (HEMTs) already in the 1980's. Today, LNF supplies nearly 200 customer organizations worldwide with more than 800 state-of-the-art low noise amplifiers (LNAs) a year.

LNF offers the lowest noise, highest performance LNAs in the world. Our cryogenic models have become the de-facto standard in physics related research throughout the world thanks to their unprecedented sensitivity.

Our LNAs range from 0.3 GHz to 116 GHz. Our lowest noise models have noise temperatures of less than 2 K. We offer coaxial and waveguide packages, as well as flexible customer optimized solutions with bond bad or solder pin interfaces.

In my presentation I will show our latest products and developments, discuss quality assurance, as well as touch upon the physics behind the low noise temperatures. What are the figure-of-merits? What can STEM images of a cross section of a HEMT tell us about noise performance of the LNA? And why doesn't noise performance improve below 15 K ambient temperature?

Thursday 11:40-12:00

Period-doubling-bifurcation phenomena in superconducting Nb resonators with controlled Josephson nonlinearity at 4.2 K

Marat Khabipov, Judith Dietel, Ralf Dolata, Alexander Zorin

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We have demonstrated and investigated the period-doubling-bifurcation (PDB) phenomena in specially designed superconducting microwave circuits at T = 4.2 K. The PDB effect is characterized by abrupt onset of oscillations at half-frequency of the drive due to parametric excitation caused by odd nonlinearity in the Josephson inductance $L_J(\varphi)$. This phenomenon can be used for detection of small signals due to tiny changes of the circuit or/and the drive parameters. In particular, this effect is suitable for readout of quantum states of superconducting qubits [1] and, presumably, for detecting single microwave photons in a superconducting cavity.

To prove the operation principle of such PDB detector, we designed microwave-driven Nb resonators both of lumped-element and coplanar-waveguide types, incorporating short serial arrays of non-hysteretic one-junction SQUIDs. These circuits allow a variation of the Josephson inductance value $L_{J0}(I_{dc})$ and its nonlinearity in a sufficiently wide range. The circuits with appropriate electric parameters (I_c = 20 μA and $\beta_L \sim 1$ in the SQUIDs) with resonance frequencies around 3 GHz were characterized at the liquid helium temperature. The dependence of the range of the PDB effect on the drive frequency, drive power and external flux bias was investigated. The details of the circuit design and measured results will be reported at this workshop.

[1] A. B. Zorin and Yu. Makhlin, Phys. Rev. B **83**, 224506 (2011).

Thursday 12:00-12:20

First observations of a Period Doubling Bifurcation in a Josephson cavity resonator

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It is generally well understood that under certain conditions of excitation non-linearity in resonators may invoke dynamical bifurcations, the first step towards chaotic behaviour. Combining Josephson junctions with superconducting resonant cavities it is possible to introduce non-linearity in a controlled and non-dissipative way into a well-characterised linear oscillator, providing a model system for the study of fundamental quantum dynamical physics. The so-called Josephson cavity bifurcation amplifier (JBA) [1] has, for example, been used to perform quantum non-demolition measurements on a superconducting qubit [2], to measure directly the noise spectrum of a bath of two level fluctuations [3] and to perform inter-mode spectroscopy [4], mimicking quantum optical experiments but in a more strongly non-linear regime. The approach has so far depended on the cubic non-linearity naturally introduced by unbiased Josephson weak-links. Here we present experimental results exploring a new regime in which a current-biased weak-link induces a quadratic (rather than a cubic) non-linearity [5]. Under certain conditions of drive the system displays a period-doubling bifurcation. The resulting signal is large, rises suddenly from zero to finite value and is well-separated from the drive frequency. It is hysteretic in both drive-power and drive-frequency. All of these features indicate that the Period Doubling Bifurcation may be more suitable as a detector than the JBA. The effect may have wide application in parametric amplification of single and few microwave photons, as readout technology for qubits, in astronomical detection, in ultra-low temperature measurement and elsewhere. We will present results demonstrating the first experimental observation of the effect and characterising the main features.

1) I.Siddiqui et al. Phys.Rev. Lett. **94**, 027005 (2005), R.Vijay, M.H. Devoret and I. Siddiqi. Rev. Sci. Instrum. **80**, 111101 (2009).
2) N. Boulant et al. Phys. Rev. B **76**, 014525 (2007).
3) G. Ithier, G. Tancredi and P.J.Meeson. New Journal of Physics **16**, 055010 (2014).
4) G. Tancredi, G.Ithier and P.J.Meeson. Applied Physics Letters **103**, 063504 (2013).
5) Alexander B. Zorin and Yuriy Makhlin Physical Review B **83**, 224506 (2011).

Thursday 13:30-14:00

Dispersive thermometry with a Josephson junction

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2) Institute of Physics, Polish Academy of Sciences, al. Lotnikow 32/46, PL 02-668 Warszawa, Poland

We have embedded a small-I_c Josephson junction in an engineered multimode electromagnetic environment. First, the low-frequency environment consists of shunting resistors whose thermal noise drives the junction into phase diffusion. Second, we use a high-Q microwave resonance to implement a dispersive readout of the junction. In a suitable range of temperatures, we observe a frequency shift that is an indicator of the the total thermal noise incident at the junction.

We demonstrate thermometry in the range from 300 mK to below 100 mK. In the present design, the system is sensitive to the temperature of an on-chip nanoscale Cu wire (1 µm long) as well as the surrounding cryogenic thermal bath (dominated by macroscopic attenuators outside the sample stage). We demonstrate our ability to distinguish the local and remote contributions by modulating the temperature of the Cu wire with an NIS cooler, or by direct microwave heating.

Using a standard HEMT preamplifier, we achieve a noise-equivalent temperature of < 10 µK/sqrt(Hz) at 50 mK with a power dissipation below 1 fW. The readout bandwidth, given by the resonance linewidth, is 1.6 MHz. This type of thermometer can be used to target various nano-calorimetry experiments in the future.

Finally, we combine DC biasing of the junction with microwave probing for a detailed study of the nonlinear junction-environment interactions. Owing to careful control of the microwave environment, features appear only at voltages corresponding to well-defined resonances. We observe strong modulation of the internal quality factor of the resonator, indicating stimulated microwave emission by the junction. All features are accurately described by a theoretical model with few free parameters.

Thursday 14:00-14:20

Nonequilibrium quasiparticles and downconversion of photons and phonons in superconducting microresonators and other thin film devices

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We have developed a body of work exploring the steady-state quasiparticle and phonon energy distributions evolved in superconducting thin films at low temperatures uniformly absorbing power from photons, or phonons (a recent addition to the model).

We do this with the appropriate calculations of quasiparticle-phonon interactions along with their interactions with low to moderate frequency external sources (much less than material Fermi or Debye frequency). The effects of absorption from multiple sources are considered, both from broadband sources and simultaneous sub superconducting gap frequency (e.g. microwave) and above gap frequency radiation -- highly relevant to readout tone heating of quasiparticles in photon or phonon sensing applications -- and show how this can limit (or in some cases, slightly enhance) detector performance.

We quantify the increases in quasiparticle numbers due to absorbed power for a range of parameters, including for Al, Mo, Ta, Nb, and NbN thin films. Knowledge of the driven distributions also provides information on the downconversion of above gap frequency photons and phonons to quasiparticles near the superconducting gap energy. The efficiency of this downconversion process in a thin film is shown to be frequency and phonon trapping dependent. This has been measured in the frequency response of superconducting detectors to THz radiation.

We believe our model has applications in understanding quasiparticle dynamics, performance and noise in detectors, qubits, and other devices incorporating superconducting thin film resonators, especially those illuminated with microwave radiation.

Some of this work is discussed in the following publications:

D. J. Goldie, S. Withington, Supercond. Sci. Technol. 26, 015004 (2013).
T. Guruswamy, D. J. Goldie, S. Withington, Supercond. Sci. Technol. 27, 055012, (2014).T. Guruswamy, D. J. Goldie, S. Withington, Supercond. Sci. Technol. 28, 054002, (2015).T. Guruswamy, D. J. Goldie, S. Withington, to be published in Supercond. Sci. Technol. arxiv.org/abs/1602.06860 (2016).
P. J. de Visser et al., Phys. Rev. Lett. 112, 047004 (2014).
P. J. de Visser et al., Appl. Phys. Lett. 106, 252602 (2015).

Thursday 14:20-14:40

Single microwave photon detection based on photon-assisted tunneling phenomena in the Coulomb blockade devices

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Activation of single-electron tunneling (SET) due to absorption of microwave photons, so-called *photon-assisted tunneling* effect, provides a fundamental basis for a number of high-sensitive microwave detectors. In our study, we use an Al/AlOx/Al Josephson junction oscillator to irradiate *on-chip* and, on this way, to characterize the detector circuits of three types: an SET trap and an SET transistor, the latter including a superconducting island and either normal-conducting or superconducting leads. Since all the devices include sub-50nm-small superconducting-Al-based tunnel junctions, the relevant frequency scale is $f \sim (\Delta+E_Q)/h \sim 100$ GHz, where Δ and E_Q are the superconducting energy gap of Al and the Coulomb energy of the small SET island, respectively.

In our contribution, we address the principle of operation and the basic properties of the detectors such as the microwave sensitivity, the activation threshold, and the dynamic range of reliable signal detection. The details will be provided of our present-status Josephson-SET integrated circuitry together with its possible development towards future experiments in the field of microwave optics *on-chip*.

Thursday 15:10-15:30

Single-shot qubit readout using a Josephson parametric oscillator

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We have demonstrated a new and simplified single-shot readout technique for superconducting qubits, coupled to a Josephson parametric oscillator (JPO). We modulated the JPO's resonant frequency at twice its value, using a microwave magnetic flux, with modulation amplitude surpassing the threshold for parametric instability. The qubit states then map onto two distinct states of classical parametric oscillation: one oscillating state, with 185 photons in the resonator, and one with zero oscillation amplitude. This high contrast obviates a following quantum-limited amplifier, simplifying the experimental setup compared to other schemes. An error budget indicates that with an optimised device, this method can surpass the fidelity threshold required for fault-tolerant quantum computing.

Krantz et al. (2016) http://arxiv.org/abs/1508.02886
Krantz et al. (2013) New J. Phys. 15, 105002

Thursday 15:30-15:50

Protected ground states in short chains of coupled qubits in circuit quantum electrodynamics

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The quasi-degenerate ground state manifold of the anisotropically coupled spin chain model can encode quantum information in its doubly degenerate ground state, but its degree of protection against local perturbations is known to be only partial. Realisation of such spin chains has been considered theoretically and is under experimental development in superconducting circuits laboratories. We explain how the coupling between the two ground states can be used to observe signatures of Majorana zero modes in a small controlled chain of qubits. We argue that the protection against certain local perturbations persists across a range of parameters even away from the ideal point. Remarkably, when additional non-local interactions, which are available in circuit QED, are considered the system enters a phase where there are two quasi-degenerate ground states and these are fully protected against all local field perturbations.

Thursday 15:50-16:20

An artificial atom in front of a mirror: Probing and canceling vacuum fluctuations

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An artificial atom in the form of a superconducting transmon qubit is placed in front of a mirror and its scattering properties are investigated at microwave frequencies. The mirror allows us to shape the vacuum fluctuations by changing the distance between the atom and the mirror, creating regions in space where the vacuum fluctuations are suppressed. Moving an artificial atom through these regions and measuring the spontaneous emission lifetime of the atom allows us to measure the spectral density of the vacuum fluctuations. In this way we can increase the life time of the atom by a factor of 10.

[1] I.-C. Hoi et al. Nature Physics **11**, 1045 (2015)doi:10.1038/nphys3484

Posters

Poster 1

Angular dependant micro-ESR characterization of a locally doped Gd^{3+}:Al_2O_3 hybrid system for quantum applications

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Rare-earth doped crystals interfaced with superconducting quantum circuitry are an attractive platform for quantum memory and transducer applications. Here we present a detailed characterization of a locally implanted Gd^{3+} in Al_2O_3 system coupled to a superconducting micro-resonator, by performing angular dependent micro-electron-spin-resonance (micro-ESR) measurements at mK temperatures.

The device is fabricated using a hard Si_3N_4 mask to facilitate a local ion-implantation technique for precision control of the dopant location. The technique is found not to degrade the internal quality factor of the resonators which remains above 10^5.

We find the measured angular dependence of the micro-ESR spectra to be in excellent agreement with the modelled Hamiltonian, supporting the conclusion that the dopant ions are successfully integrated into their relevant lattice sites whilst maintaining crystalline symmetries. Furthermore, we observe clear contributions from individual microwave field components of our micro-resonator, emphasising the need for controllable local implantation.

[1] Wisby et al. Appl. Phys. Lett. 105, 102601 (2014)

Poster 2

Thermal photon source: Fabrication @ INRiM

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One of the goals of “Microphoton” EMRP project is the “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.” In such direction, in collaboration with Aalto University, we developed a fabrication process for a thermal photon source working in the range between 11 GHz and 17 GHz. In these latters a nanoscaled normal metal wire acts as a black body radiator having his temperature probed by means of reflection RF measurements.

Fabrication involved the optimization of processes such as accurate etching of Nb for the definition of Coplanar Wave Guides, dielectric deposition for capacitors integration and high resolution multi-step electron beam lithography (EBL) for the SNS inductive elements structure. In this poster we summarize the entire fabrication, focusing on the most relevant aspects that have been faced.

Preliminary high frequency characterization were performed at Aalto University and show resonance frequencies close to expected values but leave still open the question if the device works as designed.

Poster 3

Electron dwell time in a dynamic quantum dot in magnetic field

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Semiconductor electron pump devices have shown promise for current standards due to their high accuracy current transport [1]. Further to this, at higher fields and frequencies these pumps demonstrate excitation states corresponding to energies in the microwave range [2]. This suggests possible applications in microwave and THz photonics, an emerging field with applications spanning from quantum information processing to medical imaging.

The electron pump device was studied as a possible detector for single microwave photons. This would rely on the process where the electron absorbs an incoming photon and leaves the dot. This change in occupancy would be recorded as photon detection. In order to carry out this investigation, an understanding of the dwell time of electrons in the dot is vital.

The device is based on a GaAs/AlGaAs heterostructure, with a dynamic quantum dot formed by surface gates and a quantum point contact (QPC) that probes the dots occupancy [3]. Measurements are performed at below 1 K and various magnetic fields. One electron is loaded into the dot by lowering the entrance barrier. Once loaded, both the entrance and exit barrier are set to a similar height, trapping the electron. The dots occupancy is then monitored using the QPC to determine the decay time of the electron. Varying dwell times ranging from few ms to > 10 s are detected depending on barrier heights and magnetic fields in agreement with theory in Ref [4].

[1] - M.D. Blumenthal *et al*., Nature Physics **3**, 343 (2007).

[2] - M. Kataoka *et al*., Phys. Rev. Lett. **106**, 126801 (2011).

[3] - S.P. Giblin *et al*., APL **108**, 023502 (2016).

[4] - J.D. Fletcher *et al*., Phys. Rev. B. **86,** 155311 (2012).

Poster 4

Towards Hybrid Superconducting-Semiconducting Quantum Multiplexing

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Gate defined macroscopic devices and quantum wires are frequently used as part of integrated circuits in quantum computing and information. We have recently achieved the detailed design, fabrication and initial exploitation of multiplexing circuits that allows us to measure 16X16 split-gate transistors out of GaAs/AlGaAs - where a two dimensional electron gas (2DEG) is formed 90 nm below the wafer surface - at cryogenic temperatures. This quantum multiplexer circuit paves the way for precise and coherent circuits of quantum devices capable of performing quantum logic and processing functions.

In this study we present the initial design of next generation quantum multiplexers based on ballistic 2DEG InGaAs-based superconductor-normal-superconductor (SNS) junctions that could potentially lead to development of novel Majorana fermion devices.

Poster 5

Considerations in the observation of microwave-irradiation coherent quantum phase-slip dynamics in superconducting nanowires

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Coherent quantum phase-slips in superconducting nanowires irradiated by microwaves provide the basis for a potential quantum current standard. To date, experimental efforts by several groups have not led to any published reports of dual-Shapiro steps in microwave-irradiated superconducting nanowires exhibiting coherent quantum phase slips, although one experimental investigation identifies a pertinent but resolvable issue with heating in integrated resistor elements [1]. We report latest measurements under microwave illumination of niobium nitride nanowires with cross-sections as small as ~150 nm^2, compare results for devices with and without integrated resistor elements and discuss the way forward for a microwave-irradiated superconducting-nanowire realisation of a quantum current standard.

[1] C.H. Webster, J.C. Fenton et al. Phys. Rev. B 87 144510 (2013)

Poster 6

Two-level system as a quantum sensor of absolute power

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A quantum system strongly coupled to the environment can act as a quantum sensor of absolute power. We demonstrate this with superconducting artificial atoms coupled to a 1D transmission line. Our artificial atoms have different coupling strengths, are highly nonlinear and can be approximated as two-level systems.

By measuring their coherent emission, we perform quantum oscillation measurements to extract the Rabi frequency and measure their transmission through the coplanar line. In principle, these two quantities are already sufficient to calibrate absolute power. However, coherent emission is affected by dephasing of our artificial atom.

In order to avoid this, we study wave scattering by means of resonance fluorescence and wave mixing. We obtain the Rabi frequency from the resonance fluorescence triplet. The scattered signal is acquired by measuring the side peak that appears due to wave mixing processes.

Our results show that our absolute power calibration is independent of dephasing and the artificial atom as long as it is strongly coupled to the environment.

Poster 7

The Design of a Near-Field Scanning Microwave Microscope Operating in the Quantum Regime

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The design of a Near-Field Scanning Microwave Microscopy (NSMM) is proposed and presented. The device will employ techniques that non-invasively probe dielectric samples at the nano-scale using microwave frequencies. This tool could potentially reach the quantum regime and couple to individual two-level fluctuator (TLF) systems for observation and measurement. These TLFs are atomic scale defects that exist in all dielectric materials and they have a notable influence on decoherence in quantum circuits as well as contributing to signal noise. The design consists of two main components: The first is a piezoelectric quartz tuning fork, which is ideal for ultra-low temperatures, for use as an atomic force microscope and a precision distance control mechanism. The second component is the superconducting microwave resonator tip that is small and compact enough to be mounted onto the tip of one of the tuning fork's prongs, forming the scanning probe tip. The microwave resonator will inductively couple to a coplanar transmission line for signal readouts allowing the tuning fork to be mechanically decoupled from the rest of the system. The microwave resonator will operate in the single-photon regime with frequencies in the region of 6 GHz and will require a high quality factor Q, to operate in the strong coupling regime with TLFs. The whole microscope will be installed on a suspension platform that will minimise the effects from external mechanical vibrations and placed inside of a dilution refrigerator at 10 mK

Poster 8

Microphotonics with Superconducting Qubits

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Here we present recent developments in our work on fabrication and characterisation of transmon qubit devices for use in single microwave photon generation, with an aim to couple the photons to a superconducting nanoscale calorimeter.

The use of superconducting qubit devices for single microwave photon generation has been previously explored in Refs. [1] and [2] within the circuit QED framework. Our transmon qubits consist of a pair of aluminium Josephson junctions with large capacitance across the junction in order to reduce charge noise sensitivity embedded within a niobium resonator structure. Local flux lines allow tuning of the qubit frequency at a nanosecond timescale with each qubit addressable by frequency multiplexing.

Following a Rabi oscillation measurement, we find that for our qubits an energy relaxation time of 2.2 μs and subsequently a phase coherence time of 3.43 μs by means of a Ramsey echo measurement at a flux insensitive operation point. Future work aims at qubit - calorimeter integration and subsequent investigations into the statistics of energy exchange between them [3].

[1] Houck, A. et al. Nature **449**, 328-331 (2007)

[2] Bozyigit, D. et al. Nat Phys **7**, 154-158 (2010)

[3] Pekola, J.P. et al. NJP **15**, 115006 (2013)

Overview of the Period Doubling Bifurcation effect.

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The poster will present some basic characteristics of the Period Doubling Bifurcation (PDB) phenomenon. The use of the PDB effect for qubit state detection was theoretically proposed by Zorin and Makhlin in 2011 [1]. In our experimental implementation the PDB occurs in a superconducting co-planar-waveguide rf cavity into which an additional non-linearity has been imposed by the inclusion of a current biased Josephson junction in the form of a flux biased rf SQUID. The PDB arises only when the microwave drive frequency and the drive power (at twice the signal frequency) as well as the Josephson phase difference are all carefully tuned. The PDB effect is a new effect in superconducting circuits and has many desirable features to exploit as a detector or amplifier, including possible use as a microwave photon detector.

[1] Alexander B. Zorin and Yuriy Makhlin Physical Review B 83, 224506 (2011).