TT 49: Superconductivity: Superconducting Electronics I

Time: Wednesday 9:30–13:00 Location: H 2053

Invited Talk TT 49.1 Wed 9:30 H 2053
Parametric Amplification in Josephson Circuits with Non-Centrosymmetric Nonlinearity — •Alexander Zorin, Marat Khabipov, Judith Felgner, and Ralf Dolata — Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

The superconducting technology enabling passive components with extremely low losses and Josephson elements with large nonlinearity makes it possible to engineer various networks possessing remarkable properties for propagating microwaves. We show that nonlinearity of the transmission line based on one-dimensional array of inductively-shunted Josephson junctions, i.e. serially connected rf-SQUIDs, can be effectively controlled by external magnetic flux with crossover from Kerr-like (centrosymmetric) nonlinearity to the pure $\chi^{(2)}$-type, i.e. non-centrosymmetric nonlinearity [1]. The later property, much like in quantum optics with materials having broken inversion symmetry, gives rise to the important effects including second harmonic generation, sum and difference frequency generation, and parametric amplification of microwave light. Due to excellent phase matching, which is possible in this transmission line in a wide frequency range, large parametric gain of traveling microwaves with ultimately quantum-limited performance can be achieved. Recent experiments performed with Nb trilayer circuits [2] have confirmed the validity of our concept and shown great promise for operation in the single-photon regime.
[1] A. B. Zorin, Phys. Rev. Applied **6**, 034006 (2016).
[2] A. B. Zorin, M. Khabipov, J. Dietel, R. Dolata, arXiv:1705.02859.

TT 49.2 Wed 10:00 H 2053
Design of a non-degenerate parametric amplifier based on two coupled Josephson junction arrays — •Ivan Takmakov[1,2], Patrick Winkel[1], Luca Planat[2], Natalia Maleeva[1], Kirill Borisov[1], Alexey V. Ustinov[1,4], Wolfgang Wernsdorfer[1,2,3], Ioan M. Pop[1], and Nicolas Roch[2] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Institut Néel, CNRS and Université Joseph Fourier, Grenoble, France — [3]Institute for Nanotechnology, Karlsruhe Institute for Technology — [4]Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia

We present the design of a parametric amplifier which consists of two identical, capacitively coupled Josephson junction array resonators, referred to as Dimer Josephson Junction Array Amplifier (DJJAA). If design parameters are chosen appropriately, the Josephson Junction array resonators exhibit a dispersion relation with a linear regime including several eigenmodes. Due to the shared coupling capacitance between the arrays, their spectra hybridize to symmetric and antisymmetric pairs of modes, with a level splitting up to several hundreds of MHz. By applying a strong pump tone in-between a pair of hybridized modes we predict non-degenerate amplification, with an instantaneous bandwidth up to 50 MHz and a dynamic range well above the single photon regime. By utilizing several eigenmodes of the same system our approach potentially allows to cover a much larger band of operation.

TT 49.3 Wed 10:15 H 2053
Optical lithography implementation of a non-degenerate parametric amplifier based on two coupled Josephson junction arrays — •Patrick Winkel[1], Ivan Takmakov[1,2], Luca Planat[2], Nataliya Maleeva[1], Kiril Borisov[1], Alexey V. Ustinov[1,4], Wolfgang Wernsdorfer[1,2,3], Nicolas Roch[2], and Ioan M. Pop[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Institut Néel, CNRS and Université Joseph Fourier, Grenoble, France — [3]Institute for Nanotechnology, Karlsruhe Institute of Technology — [4]Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia

We present the implementation of a parametric amplifier which consists of two identical, capacitively coupled Josephson junction array resonators, referred to as Dimer Josephson Junction Array Amplifier (DJJAA). In accordance to our theoretical model we observe non-degenerate amplification in excess of 20 dB, instantaneous bandwidth of approx. 10 MHz and dynamic range exceeding the single-photon regime. The field dependent critical current of the junctions, implemented in the shape of SQUIDs, allows for over 1 GHz frequency tunability. All structures are fabricated using standard two step optical lithography, making the DJJAA fabrication procedure easily accessible to a wide community.

TT 49.4 Wed 10:30 H 2053
Ex vivo continuous Overhauser nuclear dynamic polarization in a SQUID-based ultralow-field magnetic resonance imaging system — •Paul Fehling[1], Rebekka Bernard[1], Rolf Pohmann[1], Matthias Rudolph[1,2], Dieter Koelle[2], Reinhold Kleiner[2], Klaus Scheffler[1], and Kai Buckenmaier[1] — [1]Max Planck Institut for Biological Cybernetics, Max Planck Ring 11, 72076 Tübingen, Germany — [2]Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

Overhauser Dynamic Nuclear Polarization (ODNP) is a hyperpolarization method for magnetic resonance measurements. The polarization of free radicals is transferred to ^{1}H using HF pulses, thus enhancing the ^{1}H signal. Only at UltraLow Fields (ULF) below 10 mT the corresponding HF pulse frequencies are low enough to penetrate large sample volumes, making continuous *in vivo* hyperpolarization possible. Since conventional Faraday coils are not sensitive enough at ULF, a SQUID-based detector is employed as the centerpiece of the ULF-MRI Scanner. With a superconducting second order gradiometric pickup coil the SQUID enables measurements with a sensitivity below $1\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$. First proof-of-principle *ex vivo* images using ODNP enhanced, SQUID based ULF-MRI have been acquired successfully. This is an important step in the direction of a combined ULF MRI and magnetoencephalography system.

TT 49.5 Wed 10:45 H 2053
Nonlinear rf-SQUID metamaterials: two-tone spectroscopy and parametric effects beyond the Duffing regime — •Egor I. Kiselev[1,2], Alexander S. Averkin[2], Mikhail Fistul[4,3], and Alexey V. Ustinov[2,3] — [1]Institut für Theorie der Kondensierten Materie, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany — [3]National University of Science and Technology "MISIS", Moscow, Russia — [4]Center for Theoretical Physics of Complex Systems, Daejeon, Republic of Korea

An experimental and theoretical study of the response of an rf-SQUID metamaterial to strong driving by means of two-tone resonant spectroscopy is presented. The superconducting metamaterial consists of an array of non-hysteretic rf-SQUIDs. We have observed pronounced oscillations of the intrinsic resonance frequency of the meta-atoms with the power of the driving tone. The shapes of these oscillations vary with the frequencies of the driving and probe signals. The response to the probe signal shows remarkable features such as parametric instabilities and sidebands and allows the direct imaging of a bistability. Our theoretical analysis is based on the classical nonlinear dynamics of rf-SQUIDs and in good agreement with experimental observations. We also present first results on parametric amplification by means of an rf-SQUID metamaterial beyond the Duffing regime.

TT 49.6 Wed 11:00 H 2053
Reconstructing Josephson current-phase relations from intermodulation spectroscopy — •Thomas Weissl, Shan W. Jolin, Per-Anders Thorén, Riccardo Borgani, Daniel Forchheimer, and David B. Haviland — KTH- Royal Institute of Technology, Stockholm, Sweden

Two pump tones driving a nonlinear system intermodulate, creating response at integer linear combinations of the their frequencies. With appropriate choice of the pumping frequencies, it is possible to measure not only the amplitudes, but also the phases of these intermodulation products, which depend on the detailed form of the nonlinearity that generates them. We present a method based on pseudo-inversion of a 'mixing matrix' built from the intermodulation response, to reconstruct the non-linear current-phase relation of a superconducting weak link [1,2]. The intermodulation spectra of a Nb-coplanar waveguide resonator with an engineered weak-link was measured as a function of drive amplitude, and the method was applied to obtain the coefficients of a Taylor expansion of the current-phase relation. The method allows for precision characterization of nonlinearities in microwave crcuits without the need of DC connections.
[1] Hutter et al., PRL 104, 050801 (2010).

[2] Platz et. al., Beilstein J. Nanotechnol. 4, 352360 (2013)

15 min. break.

TT 49.7 Wed 11:30 H 2053

Improved quasiparticle thermalization for hybrid single-electron turnstiles — •Joonas Peltonen[1], Dmitry Golubev[1], Antti Moisio[1], Ville Maisi[1], Matthias Meschke[1], Jaw-Shen Tsai[2,3], and Jukka Pekola[1] — [1]Department of Applied Physics, Aalto University School of Science, Espoo, Finland — [2]RIKEN Center for Emergent Matter Science, Wako, Saitama, Japan — [3]Department of Physics, Tokyo University of Science, Kagurazaka, Tokyo, Japan

To advance towards metrologically useful current quantization accuracy in a turnstile based on a single-electron transistor with superconducting aluminium electrodes and a normal metallic island, low density of both residual and drive-induced quasiparticles in the superconducting leads is required. We present measurement results from devices where the thickness of the Al electrodes has been increased by an order of magnitude compared to the maximum allowed by the conventional fabrication process [1]. We further discuss recent experiments where the quasiparticle density at the turnstile junctions is actively lowered by running a current through a nearby voltage-biased tunnel junction between two superconductors with differing energy gaps.

[1] J. T. Peltonen, A. Moisio, V. F. Maisi, M. Meschke, J. S. Tsai, and J. P. Pekola, 1709.09832 (2017).

TT 49.8 Wed 11:45 H 2053

Ultrasensitive Microwave Detector — •Mikko Möttönen[1], Joonas Govenius[1], Roope Kokkoniemi[1], Visa Vesterinen[1,2], Dibyendu Hazra[1], Marton Gunyho[1], Russell E. Lake[1,3], and Kuan Yen Tan[1,4] — [1]QCD Labs, Department of Applied Physics, Aalto University, Aalto, Finland — [2]VTT Technical Research Centre of Finland Ltd, VTT, Finland — [3]NIST, Boulder, Colorado, USA — [4]CQC2T, University of New South Wales, Australia

Intense development of nanobolometers has taken place for well more than a decade with the aim to reach NEP = 1e-20 W/rtHz which is required, for example, in effcient measurements of the cosmic terahertz spectrum in space. Furthermore, observation of single photons at increasingly long wavelengths is a long-standing effort [1]. We present a microwave nanobolometer based on proximity Josephson junctions. Using positive electrothermal feedback, we show that we can achieve a single-shot detection fidelity of 0.56 for 1.1-zJ pulses of 8.4-GHz photons [2]. This is more than an order of magnitude improvement over the previous thermal detectors. Importantly, we also observe that we can reach a sensitivity of NEP = 2e-20 W/rtHz with our detector in the linear continuous mode. This was achieved using a Josephson parametric amplifier in the detector readout chain [3]. In the future, ultrasensitive bolometers and thermometers are expected to play an important role in quantum information processing and quantum thermodynamics.

[1] K. Inomata et al., Nat. Commun. 7, 12303 (2016).
[2] J. Govenius et al., Phys. Rev. Lett. 117, 030802 (2016).
[3] V. Vesterinen et al. , Supercond. Sci. Technol. 30, 085001 (2017).

TT 49.9 Wed 12:00 H 2053

Development of a novel calorimetry setup based on metallic paramagnetic temperature sensors — •Andreas Reifenberger, Matthew Herbst, Sebastian Kempf, Andreas Fleischmann, and Christian Enss — Kirchhoff-Institut für Physik, Universität Heidelberg, INF 227, D-69120 Heidelberg

For the measurement of the specific heat of superconducting mg-sized metallic glass samples in the temperature range down to 10 mK we have developed a new microfabricated platform. It addresses challenging aspects of setups of this kind such as the thermal contact between sample and platform, the necessary thermometer resolution, and an addenda heat capacity exceeding that of the samples of interest (typically nJ/K at 20 mK). Our setup allows us to use the relaxation method, where the thermal relaxation following a well defined heat pulse is monitored to extract the specific heat. The sample platform ($5 \times 5\,\mathrm{mm}^2$) includes a microstructured paramagnetic Ag:Er temperature sensor, which is read out by a dc-SQUID via a superconducting pickup loop. In this way, a relative temperature precision of $30\,\mathrm{nK}/\sqrt{\mathrm{Hz}}$ can be reached, while the addenda heat capacity falls well below 0.5 nJ/K for $T < 300\,\mathrm{mK}$. A gold-coated mounting area ($4.4 \times 3\,\mathrm{mm}^2$) is included to improve the thermal contact between sample and platform. The performance of our setup is presented and discussed.

TT 49.10 Wed 12:15 H 2053

Dc-SQUID readout with high dynamic range and intrinsic frequency-domain multiplexing capability — •Sebastian Kempf, Daniel Richter, Andreas Fleischmann, and Christian Enss — Kirchhoff-Institute for Physics, Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany.

As a consequence of their periodic flux-to-voltage characteristic direct-current superconducting quantum devices (dc-SQUIDs) are intrinsically non-linear devices. The linear flux range of a dc-SQUID is therefore rather small and in most cases a flux-locked loop (FLL) is used both to increase the dynamic range and to linearize the output signal of the SQUID system. However, for FLL operation the requirements on the digitizer sampling the SQUID signal as well as on the readout electronics are challenging. In addition, individual feedback wires have to be routed to the SQUID setting often a practical limit to the implementation of massive multi-channel SQUID systems.

Within this context we present a novel approach for reading out dc-SQUIDs that provides an easy solution for linearizing the SQUID output signal and for increasing the dynamic range. At the same time it intrinsically allows for implementing frequency-domain multiplexing. In relies on applying a periodic sawtooth-shaped magnetic flux signal to the SQUID. The signal amplitude and repetition rate are chosen such that the input signal is transduced into a phase shift of the related SQUID characteristic. We discuss the basics as well as a comprehensive suitability study of our approach and demonstrate the intrinsic multiplexing capability using a customized multiplexer device.

TT 49.11 Wed 12:30 H 2053

Advanced nanoSQUIDs based on sub-micron trilayer Nb/HfTi/Nb Josephson junctions — •Julian Linek[1], Aaron Koser[1], Benedikt Müller[1], Katrin Meyer[1], Maria José Martínez-Pérez[2], Thomas Weimann[3], Oliver Kieler[3], Reinhold Kleiner[1], and Dieter Koelle[1] — [1]Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Germany — [2]Instituto de Ciencia de Materiales de Aragón (ICMA), Universidad de Zaragoza and Fundación ARAID, Zaragoza, Spain — [3]Fachbereich Quantenelektronik, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

We report on the development and performance of advanced Nb nanoSQUIDs for magnetization reversal studies on individual magnetic nanoparticles (MNPs). The nanoSQUIDs are based on trilayer high critical current density Nb/HfTi/Nb Josephson junctions. This offers the unique advantage of combining the realization of SQUIDs with very small loop inductance and hence extremely low flux noise, with a superconductor multilayer approach that offers the fabrication of complex devices with significantly increased functionality for various applications. One example is the recently developed 3-axis vector nanoSQUID [1]. Here, we present the performance of improved vector nanoSQUIDs and first attempts to simultaneously detect at 4.2 K in applied magnetic fields up to a few 100 mT all three orthogonal components of the magnetic moment of individual Co MNPs deposited onto our devices by focused electron beam deposition.

[1] M.J. Martínez-Pérez *et al.*, ACS Nano **10**, 8308 (2016)

TT 49.12 Wed 12:45 H 2053

An argon ion beam milling process for native AlO_x layers enabling coherent superconducting contacts — Lukas Grünhaupt[1], Uwe von Lüpke[1], •Daria Gusenkova[1], Sebastian T. Skacel[1], Nataliya Maleeva[1], Steffen Schlör[1], Alexander Bilmes[1], Hannes Rotzinger[1], Alexey V Ustinov[1,2], Martin Weides[1,3], and Ioan M. Pop[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]Russian Quantum Center, National University of Science and Technology MISIS, 119049 Moscow, Russia — [3]Physikalisches Institut, Johannes Gutenberg University Mainz, 55128 Mainz, Germany

We present an argon ion beam milling process to remove the native oxide layer forming on aluminum thin films due to their exposure to atmosphere in between lithographic steps [1]. Our cleaning process enables integration of complex superconducting quantum circuits without compromising their coherence properties. From measurements of the internal quality factors of superconducting microwave resonators, we place an upper bound on the residual resistance of an ion beam milled contact of $50\,\Omega \cdot \mu\mathrm{m}^2$ at a frequency of 4.5 GHz. Resonators for which only 6% of the total foot-print in areas of high magnetic field was exposed to the ion beam milling showed quality factors above 10^6 in the single photon regime, and no degradation compared to single layer samples.

[1] L. Grünhaupt et al., Applied Physics Letters, 111, 072601 (2017).