TT 50: Superconducting Electronics: SQUIDs, Qubits, Circuit QED II

Time: Thursday 15:00–18:30 Location: H36

TT 50.1 Thu 15:00 H36

Development of ultrasensitive dc SQUIDs with sub-micrometric circuit elements — •Mauro Esattore[1], Michael Paulsen[2], Jörn Beyer[2], Oliver Kieler[1], Mark Bieler[1], Patryk Krzysteczko[2], and Rainer Körber[2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Physikalisch-Technische Bundesanstalt, Abbestraße 2-10, 10587 Berlin, Germany

The dc SQUID is one of the most established applications of superconductor technology. Their sensitivity to magnetic flux allows for numerous applications, such as low-temperature thermometry or current sensing for electrical metrology. In this contribution, we present superconducting "fine-pitch" input coils with sub-micrometric parameters to be integrated into existing Nb/Al-AlO_x/Nb-based SQUID sensor designs. The aim is to reduce inductive losses of the signal-to-SQUID coupling, without compromising the overall device layout. In a SQUID current sensor, to maximize the inductive coupling constant k between the signal input coil and the SQUID loop means to achieve a low coupled energy sensitivity $\epsilon_c = (1/k^2)\times\epsilon$ - where ϵ is the SQUID-intrinsic energy sensitivity. Fine-pitch input coils will increase k, as well as extend the range of input coil inductances for our existing devices. The energy sensitivity $\epsilon \propto \sqrt{C}$: reduced Josephson junction (JJ) sizes will lower the capacitance C and improve ϵ_c. Thus, we are refining our JJ definition process to obtain JJs with sub-micrometric lateral size. The contribution will provide details on the fabrication process and design aspect of the sensors, as well as characterization results.

TT 50.2 Thu 15:15 H36

Superconducting Pb stripline resonators: Role of coupling and applications in spectroscopy — Elies Ben Achour, Cenk Beydeda, Gabriele Untereiner, Martin Dressel, and •Marc Scheffler — 1. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany

Planar superconducting microwave resonators play an important role for various research directions in solid state physics and quantum technologies. Here we investigate superconducting lead (Pb) stripline resonators, which we probe at various harmonics between 0.7 GHz and 6 GHz and at temperatures between 1.5 K and 7 K.

We discuss on general grounds how the loaded quality factor Q_L of a planar microwave resonator made of a conventional superconductor should depend on temperature and frequency. We consider contributions due to dissipation by thermal quasiparticles Q_{QP}, due to residual dissipation Q_{Res}, and due to coupling Q_C. We focus on the role of coupling, and we compare resonators with different coupling capacitance. For the Pb resonators, we find a strongly frequency- and temperature-dependent Q_L, which we can describe by a lumped element model. For certain resonators at the lowest studied temperatures we observe a maximum in the frequency-dependent Q_L when Q_{Res} and Q_C match, and here the measured Q_L can exceed 2×10^5.

We also present the application of such Pb stripline resonators for microwave spectroscopy at temperatures down to the mK range.

TT 50.3 Thu 15:30 H36

Hybrid Microwave Resonators Integrated with van der Waals Superconductors — •Yejin Lee[1], Haolin Jin[1,2], Giuseppe Serpico[1,3], Tommaso Confalone[2,4], Berit Goodge[1], Edouard Lesne[1], Kornelius Nielsch[2,4], Nicola Poccia[3,4], and Uri Vool[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]Technische Universität Dresden, Germany — [3]University of Naples Federico II, Italy — [4]Leibniz Institute for Solid State and Materials Science Dresden, Germany

Superconducting microwave resonators are highly coherent devices that are extensively used in quantum circuits. Their robustness and sensitivity also make them excellent probes for exploring novel materials, which are coupled to them in a hybrid system. Particularly good candidates are van der Waals materials, whose microscopic size makes them incompatible with conventional bulk measurement methods. However, such hybrid platforms require the development of a new process to maintain the high quality of the circuit. We present a technique to integrate a microwave resonator with a superconducting thin van der Waals flake with a crystalline-preserved interface. We investigate their microwave response as a function of temperature under various microwave powers and magnetic field. The hybrid resonator exhibits a significant modification in its resonant mode with the presence of the flake while maintaining a high-quality factor. Hybrid superconducting circuits integrated with vdW crystals offer an extensive potential in probing materials' unique properties and for developing high-quality devices for quantum technology.

TT 50.4 Thu 15:45 H36

Two-level system involved nonlinear response in van der Waals hybrid microwave resonators — •Haolin Jin[1,3], Giuseppe Serpico[1,2], Yejin Lee[1], Berit Goodge[1], Edouard Lesne[1], Nicola Poccia[2,3], and Uri Vool[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]University of Naples Federico II, Italy — [3]Leibniz Institute for Solid State and Materials Science Dresden, Germany

Two-level system (TLS) bath is considered as the main loss channel in coplanar superconducting microwave resonators and is often associated with an upshift in resonance frequency as the temperature increases. The individual TLS can be saturated at the high input power, improving the quality factor of the resonator. However, the resonance frequency upshift remains unaffected by driving power because all TLS at different energy can contribute to the frequency shift, whereas only those close to the resonance frequency can be saturated. Here, we observed a positive nonlinearity in a van der Waals superconductor integrated hybrid resonator device. The hybrid device exhibited a significant upshift in resonance frequency with increasing temperature, indicating strong coupling to a TLS bath. It maintained a high-quality factor despite this coupling. These findings suggest that the resonance mode in the hybrid device is coupled to an off-resonant TLS bath and the hybrid system provides a new source of lossless nonlinearity unrelated to the Josephson effect. This work opens a path towards high quality hybrid superconducting circuits with vdW materials and highlights the development of new devices for quantum technology.

TT 50.5 Thu 16:00 H36

Dielectric waveguide setup tested with a superconducting millimeter-wave Fabry-Pérot interferometer at milli-Kelvin temperatures — •Jakob Lenschen[1], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut (PHI), Karlsruher Institut für Technologie — [2]Institut für Quantenmaterialien und Technologie (IQMT), Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany

Superconducting quantum circuits operating at mm-wave frequencies of around 100 GHz may offer many interesting new possibilities. The order of magnitude higher photon energy compared to current implementations and the wider bandwidth would not only improve the resilience to thermal fluctuations, but could also speed up qubit manipulation. Millimeter-wave measurements at ultra-low temperatures are largely unexplored due to several technical difficulties, such as a difficult signal path isolation and thermalization. We have developed a cryogenic setup consisting of dielectric waveguides and a superconducting Fabry-Pérot cavity located at the dilution cryostat base temperature. We show that the quality of the mm-wave signal guided to and from a temperature of 10 mK is sufficient to measure resonator cavity quality factors of over one million at 110 GHz in the few photon limit.

TT 50.6 Thu 16:15 H36

Resonant escape in Josephson tunnel junctions under millimeter-wave irradiation — •Jonas N. Kämmerer[1], Sergei Masis[1], Karo Hambardzumyan[1], Philipp Lenhard[1], Urs Strobel[1], Jürgen Lisenfeld[1], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut (PHI), Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany — [2]Institut für Quanten-Materialien und Technologien (IQMT), Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany

Operating superconducting quantum circuits at mm-wave frequencies around 100 GHz promises several advantages. For example, it may allow for much higher operating temperatures above 1 K and faster qubit manipulation. We study the microwave-driven dynamics of a superconducting phase qubit made of Nb/AlO_x/Nb junction. In particular, we have measured the switching current distributions at radiation frequencies above 100 GHz and observed clear double-peak structures. The data indicate a resonant escape of the phase as well as an irradiation-induced suppression of the potential barrier. This behavior is well described by the strong-driving model of the resonant escape[1]. While being measured in the quasi-classical regime of thermally activated escape, our results point towards a feasibility of operating phase qubits at mm-wave frequencies.

[1] M.V.Fistul,A.Wallraff,A.V.Ustinov, Phys.Rev.B**68**, 060504 (2003).

15 min. break

TT 50.7 Thu 16:45 H36

Heat transport in the quantum Rabi model: Universality and ultrastrong coupling effects — Luca Magazzu[1], Elisabetta Paladino[2,3], and •Milena Grifoni[1] — [1]University of Regensburg — [2]Università di Catania, Italy — [3]INFN, Sez. Catania, Italy

Heat transport in a qubit-oscillator junction weakly coupled to heat baths displays a rich variety of effects depending on the junction parameters. Signatures of the transition to the regime of ultrastrong qubit-oscillator coupling appear in the thermal conductance, current, and rectification. For example, upon increasing the coupling, the conductance as a function of a bias applied to the qubit undergoes a transition from a resonant to a broadened, zero-bias peak behavior. At low temperatures, coherent heat transfer via virtual processes yields a universal power-law behavior in the linear conductance as a function of the temperature. In addition, the low-temperature conductance is modulated by a prefactor which unravels the multilevel nature of the junction: A coherent suppression arises in the presence of quasi-degeneracies in the spectrum. At higher temperatures, sequential processes dominate heat transfer and a scaling regime is found when quantities are scaled with a coupling-dependent Kondo-like temperature.

[1] L.Magazzù, E.Paladino, M.Grifoni, Phys.Rev.B110, 085419 (2024);
[2] L.Magazzù, E.Paladino, M.Grifoni, arXiv:2403.06909 (2024).

TT 50.8 Thu 17:00 H36

Gauging away the ground-state photon content of the quantum Rabi model — •Arka Dutta, Daniel Braak, and Marcus Kollar — Theoretische Physik III, University of Augsburg

The quantum Rabi model (QRM) features the simplest type of coupling between a single cavity light mode and an atomic electron. It is integrable if the electronic degree of freedom is truncated to just two states [1]. The derivation of the effective Hamiltonian leads to different forms depending on the chosen gauge [2]. In the dipole gauge, the ground state of the QRM exhibits non-zero photon number in contrast to its weak coupling approximation, the Jaynes-Cummings model. We compute the exact photon content for all eigenstates in an arbitrary gauge and obtain a gauge for which the ground state contains no photons. Thus only this gauge fits the intuitive understanding that the cavity should be empty in the lowest energy state even for strong light-matter interaction.

[1] D. Braak, Phys. Rev. Lett. **107**, 100401 (2011).
[2] O. Di Stefano et al., Nat. Phys. **15**, 803 (2019).

TT 50.9 Thu 17:15 H36

Dispersive and dissipative interactions in niobium-based photon-pressure circuits — •Zisu Emily Guo, Mohamad el Kazouini, Janis Peter, Kevin Uhl, Dieter Koelle, Reinhold Kleiner, and Daniel Bothner — Physikalisches Institut, Center for Quantum Science (CQ) and LISA$^+$, Universität Tübingen

Photon-pressure (PP) circuits consist of one superconducting microwave resonator in the GHz range and one low-frequency (LF) circuit in the MHz range and are the cQED analog of cavity optomechanics. The LC circuits in a PP device are coupled to each other via a superconducting quantum interference device (SQUID), emulating an optomechanical interaction and offering access to sensing and control of MHz photons with potential applications in axion dark matter detection and quantum information technologies. Here, we report the realization of niobium- and nanoconstriction-based photon-pressure circuits operated in the thermal regime. In contrast to previous implementations, we observe in our experiments both dispersive and dissipative PP coupling - meaning that not only frequency but also linewidth modulations contribute significantly to the overall interaction. We investigate dynamical backaction effects with these dissipative contributions as well as sideband-cooling of the LF mode, measured through photon-pressure-induced transparency and output noise thermometry, respectively. Additionally, our circuit design with on-chip flux-bias line allows the parametric modulation of the LF mode resonance frequency, which may be used for LF squeezing and (phase-sensitive) amplification of the PP coupling rate.

TT 50.10 Thu 17:30 H36

Exact and Dispersive Models for Superconducting Networks — •Adrian Parra-Rodriguez — Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — Institute of Fundamental Physics IFF-CSIC, Calle Serrano 113b, 28006 Madrid, Spain — Institut Quantique and Département de Physique, Université de Sherbrooke, Sherbrooke, Quebec J1K 2R1, Canada

In this presentation, I will address the construction of exact quantum mechanical models for quasi-lumped electrical networks [1,2], comprising (nonlinear) capacitors, inductors, nonreciprocal elements (circulators), and transmission lines (TLs). Traditional quantization methods, such as node-flux or loop-charge approaches, often lead to singularities and unphysical predictions, stemming from incorrect identification of the TLs' infinite-dimensional Hilbert space. Using a geometrical description [1] and the Faddeev-Jackiw method, we resolve these issues via a mixed charge-flux first-order quantization. I will also introduce a systematic method to construct effective dispersive Lindblad master equations for weakly anharmonic superconducting circuits coupled by generic linear nonreciprocal systems, deriving coupling parameters and decay rates from the coupler's immittance parameters [3]. Extending the work of Solgun et al. (2019) on reciprocal couplers, this approach includes nonreciprocal elements, stray coupling, and collective dissipative effects from external environments, while avoiding potential singularities.

[1] A. Parra-Rodriguez et al., Quantum 8, 1466 (2024);
[2] A. Parra-Rodriguezet al., arxiv:2401.09120;
[3] Labarca et al., Phys. Rev. App. 22, 034038 (2024).

TT 50.11 Thu 17:45 H36

Nonlinear High-Kinetic-Inductance Microstrips for Integrated Non-Reciprocal Devices — •Niklas Gaiser[1], Ciprian Padurariu[1], Björn Kubala[1,2], Nadav Katz[3], and Joachim Ankerhold[1] — [1]ICQ and IQST, University of Ulm, Ulm, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [3]The Racah Institute of Physics, The Hebrew University of Jerusalem, Israel

Superconducting microwave circuits offer a rich platform for many quantum information devices and quantum-technological applications. Recently, nonlinear properties of circuit elements have become of increasing interest as they allow new functionalities, such as frequency mixing or self-interaction of waves. Microstrip waveguides with high-kinetic-inductance, as experimentally realized in [1], possess strong nonlinear features. Moreover, they yield a greatly reduced phase velocity which addresses the challenge of long wavelengths in the microwave regime and enable highly compact and integrated on-chip solutions.

Here, we present a theoretical proposal for a devices that utilizes a nonlinear high-kinetic-inductance to achieve a non-reciprocal effect. Diode-like behaviour is proven with markedly dissimilar transmission spectra for signals propagating through the device in different directions. We discuss the nonlinearities' power dependence as well as the special boundary conditions posed by the nonlinear propagation problem.

[1] S. Goldstein, G. Pardo, N. Kirsh, N. Gaiser, C. Padurariu, B. Kubala, J. Ankerhold, N. Katz, New J. Phys. 24, 023022 (2022).

TT 50.12 Thu 18:00 H36

Observation and Modelling of Self-Sustained Oscillations in Non-Linear Cavity-Optomechanics — •Korbinian Rubenbauer[1,2], Shivangi Dhiman[4], Thomas Luschmann[1,2], Achim Marx[1,2], Rudolf Gross[1,2,3], Anja Metelmann[4,5], and Hans Huebl[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]School of Natural Sciences, Technical University of Munich, Garching, Germany — [3]Munich Center for Quantum Science and Technology, Munich, Germany — [4]Institute for Theory of Condensed Matter and Institute for Quantum Materials and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany — [5]Institut de Science et d'Ingénierie Supramoléculaires, University of Strasbourg and CNRS

Quantum sensing uses quantum elements or quantum principles to detect an external stimulus. In this context, cavity-electromechanics focuses on mechanical sensor elements dispersively coupled to a microwave resonator. This setting typically uses linear mechanical elements and linear microwave cavities. Here, we discuss the case of a non-linear or Kerr microwave resonator as a readout circuit. Our device integrates a mechanically compliant nanostring into a superconducting quantum interference device (SQUID), which is part of a flux-tunable superconducting resonator. This enables large tunable single-photon optomechanical coupling. We present an experimental and theoretical study investigating the impact of the Kerr nonlinearity on the device performance, particularly in the context of mechanical instabilities. We find excellent quantitative agreement.

TT 50.13 Thu 18:15 H36

Engineering Cooper Pair Bunching Using an Anharmonic Environment — •Surangana Sengupta[1], Björn Kubala[1,2], Joachim Ankerhold[1], and Ciprian Padurariu[1] — [1]ICQ and IQST,Ulm University,Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

The electromagnetic environment of superconducting circuits provides exciting opportunities to engineer the tunneling of Cooper pairs. The simplest example is a dc biased Josephson junction in series with a microwave cavity. There has been extensive work showing that when the dc bias is chosen to be resonant with a well-defined cavity mode, the transport of Cooper pairs has the same statistics in the long time limit as that of the photon emission from the cavity mode [1].

In my talk, I extend this study to the case when the cavity mode is anharmonic. I investigate the case when the voltage bias is detuned from the transition between Fock states 0 and 1. Due to the anharmonicity however, this voltage can be resonant with half the transition between Fock states 0 and 2. Therefore, the process of coherent two-Cooper pair tunneling accompanied by two-photon creation is favored compared to single Cooper pair tunneling and single photon creation. This results in bunched Cooper pair tunneling, with Fano factor approaching $F = 2$, and in a squeezed cavity state. I will compare this effect to a similar and competing inelastic co-tunneling process arising from second-order rotating wave approximation.

[1] M. Hofheinz *et al.*, Phys. Rev. Lett. **106**, 217005 (2011).