TT 42: Quantum Coherence, Quantum Information Systems 2

Time: Wednesday 15:00–19:15 Location: H18

TT 42.1 Wed 15:00 H18

Magnetic hysteresis effects in superconducting coplanar microwave resonators — •D. Bothner[1], T. Gaber[1], M. Kemmler[1], M. Grünzweig[1], B. Ferdinand[1], S. Wünsch[2], M. Siegel[2], P. Mikheenko[3], T. H. Johansen[3], D. Koelle[1], and R. Kleiner[1] — [1]Universität Tübingen, Germany — [2]Karlsruher Institut für Technologie, Germany — [3]University of Oslo, Norway

We present experimental data regarding the impact of external magnetic fields on quality factor and resonance frequency of superconducting microwave resonators in a coplanar waveguide geometry. In particular we focus on the influence of magnetic history and show with the assistance of numerical calculations that the found hysteretic behaviour can be well understood with a highly inhomogeneous microwave current density in combination with established field penetration models for type-II superconducting thin films. Furthermore we have used magneto-optical imaging techniques to check the field distribution which we have assumed in our calculations. Finally, we demonstrate that and how the observed hysteretic behaviour can be used to optimize and tune the resonator performance for possible hybrid quantum sytems in magnetic fields [1].

[1] D. Bothner et al., Phys Rev. B 86, 014517 (2012)

TT 42.2 Wed 15:15 H18

Anisotropic rare-earth spin ensemble strongly coupled to a superconducting resonator — •Sebastian Probst[1], Hannes Rotzinger[1], Ivan Protopopov[2], Stefan Wünsch[3], Philipp Jung[1], Markus Jerger[1], Michael Siegel[3], Alexey V. Ustinov[1], and Pavel Bushev[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, D-76128 Karlsruhe, Germany — [2]Institut für Nanotechnologie, Karlsruher Institut für Technologie, D-76021 Karlsruhe, Germany — [3]Institut für Mikro- und Nanoelektronische Systeme, Karlsruher Institut für Technologie, D-76189

We report on ESR spectroscopy of an erbium spin ensemble strongly coupled to a superconducting lumped element microwave resonator. Er^{3+} ions are distinct from other spin ensembles due to their optical transitions inside the telecom C-band at 1.54 μm. This feature makes them most attractive for interfacing optical and microwave photons by using a hybrid quantum architecture [1]. However, in contrast to NV-centers or ruby crystals, rare-earth ions possess a magnetic anisotropy due to the host crystal field. This results in a strong angular dependence of the spin g-factor and of the collective coupling strength with respect to the orientation of the DC magnetic field. We have probed this anisotropy at millikelvin temperatures by performing on-chip ESR spectroscopy. The strong coupling regime with a collective coupling of 36 MHz and 11 MHz linewidth has been reached at a resonator frequency of 4.9 GHz for spin transitions with a g-factor of 1.4.

[1] P. Bushev et al., Phys. Rev. B 84, 06051 (R) (2011)

TT 42.3 Wed 15:30 H18

Tunable Coupling between Two Resonators Controlled by a Flux Qubit: the Quantum Switch — •E. Hoffmann[1], M. Haeberlein[1], A. Baust[1], M. Schwarz[1], E.P. Menzel[1], H. Huebl[1], David Zueco[2], J.-J. García Ripoll[3], E. Solano[4], F. Deppe[1], A. Marx[1], and R. Gross[1] — [1]TU München, Garching and Walther-Meißner-Institut, Germany — [2]CSIC-Universidad de Zaragoza, Spain — [3]IFF-CSIC, Madrid, Spain — [4]Universidad del Pais Vasco UPV/EHU and Ikerbasque, Spain

Superconducting quantum circuits have developed into a promising platform for quantum information processing. To this end, systems consisting of a few qubits and/or harmonic oscillator circuits have been investigated. When scaling up these systems, elements allowing for a controlled coupling/decoupling of circuit parts are mandatory. A possible implementation of such an element is the Quantum Switch, where a controllable coupling between two superconducting transmission line resonators is mediated by a superconducting flux qubit. In this presentation, the experimental characterization of such a device and spectroscopic evidence for the switching behavior will be discussed.

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TT 42.4 Wed 15:45 H18

Tunable gradiometric flux qubits in circuit-QED experiments — •J. Goetz[1], M. J. Schwarz[1], Z. Jiang[1,2], F. Sterr[1,2], M. Häberlein[1], F. Deppe[1,2], A. Marx[1], and R. Gross[1,2] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching — [2]Physik Department, TU München, Garching

Gradiometric flux qubits with tunable minimal transition frequency have strong potential for scalable quantum circuits as well as for the realisation of various coupling schemes between qubits and coplanar waveguide resonators. We have systematically studied the tuning of the minimal transition frequency, the so called qubit gap, of single qubits depending on fabrication parameters [1]. In addition we investigate how the special geometry of these qubits allows us to switch between the ultrastrong-coupling regime and negligible coupling strength. We discuss the application of tunable gradiometric flux qubits in establishing strong σ_x coupling between a resonator mode and the qubit enabling the simulation of relativistic quantum systems.

This work is supported by the DFG via SFB 631, the Excellence Initiative via NIM, as well as by the EU-projects CCQED and PROMISCE.

[1] M. J. Schwarz et al., arXiv:1210.3982

TT 42.5 Wed 16:00 H18

Path Entanglement of Continuous-Variable Quantum Microwaves — •E. P. Menzel[1], R. Di Candia[2], F. Deppe[1], P. Eder[1], L. Zhong[1], M. Ihmig[4], M. Haeberlein[1], A. Baust[1], E. Hoffmann[1], D. Ballester[3], K. Inomata[5], T. Yamamoto[5,6], Y. Nakamura[5,7], E. Solano[2], A. Marx[1], and R. Gross[1] — [1]Walther-Meissner-Institut and TU Muenchen, Germany — [2]Universidad del País Vasco UPV/EHU and Ikerbasque, Spain — [3]University College London, UK — [4]TU Muenchen, Germany — [5]RIKEN Advanced Science Institute, Japan — [6]NEC Smart Energy Research Laboratories, Japan — [7]The University of Tokyo, Japan

Entanglement is a quantum mechanical phenomenon playing a key role in quantum communication and information processing protocols. Here, we report on frequency-degenerate entanglement between continuous-variable quantum microwaves propagating along two separated paths. In our experiment, we combine a squeezed and a vacuum state via a beam splitter. We reconstruct the squeezed state and, independently from this, detect and quantify the produced entanglement via correlation measurements[1]. Our work paves the way towards quantum communication and teleportation with continuous variables in the microwave regime.

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[1] E. P. Menzel *et al.*,arXiv:1210.4413

TT 42.6 Wed 16:15 H18

Fast microwave beam splitters from superconducting resonators — •M. Haeberlein[1,2], D. Zueco[3], P. Assum[2], T. Weissl[4], E. Hoffmann[1,2], B. Peropadre[5], J.J. García-Ripoll[5], E. Solano[6], F. Deppe[1,2], E. Xie[1,2], A. Marx[1], and R. Gross[1,2] — [1]Walther-Meißner-Institut, Garching, Germany — [2]Technische Universität München, Garching, Germany — [3]CSIC-Universidad de Zaragoza, Spain — [4]CNRS, Grenoble, France — [5]CSIC-Instituto de Física Fundamental, Madrid, Spain — [6]Universidad del País Vasco and IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

Coupled superconducting transmission line resonators have potential applications in quantum information processing. Experimentally, high coupling strength are often desirable. One example is the fabrication of fast beam splitters, which however is hampered by non-negligible two-mode squeezer terms. In this work, we experimentally study superconducting microstrip resonators which are coupled over one third of their length. We alter position of this coupling region, thereby changing the relative weight between inductive and capacitive coupling. As a consequence, the beam splitter terms reach a coupling strength of 800 MHz, which is a significant fraction of the resonance frequency of 5.44 GHz. Nevertheless, the relative weight of the two-mode squeezer terms decreases to 20%, enabling the construction of a fast beam splitter.

This work is supported by DFG via SFB 631, the German excellence Initiative via NIM, EU projects SOLID; CCQED, and PROMISCE, Basque Government IT472-10, Spanish MICINN FIS2009-12773-C02-01, and DZ granted by ARAID.

TT 42.7 Wed 16:30 H18

Coupling a donor based spin ensemble to superconducting circuits — •Christoph W. Zollitsch[1,2], Moritz Greifenstein[2], Alexander Backs[2], Felix Hoehne[3], Martin S. Brandt[3], Rudolf Gross[1,2], and Hans Huebl[1] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching — [2]Physik-Department, Technische Universität München, Garching — [3]Walter Schottky Institut, Technische Universität München, Garching

The realization of solid state based quantum systems has been successful using various approaches, e.g. superconducting qubits, NV centers or quantum dot systems. The coupling of different systems in hybrid systems allows to exploit their individual advantages. To allow a coherent information transfer between two quantum systems strong coupling is required, i.e. the effective coupling g_{eff} needs to exceed the loss mechanisms of both contributing systems. We study the coupling between a superconducting coplanar niobium microwave resonator and an ensemble of uncoupled electron spins of phosphorus donors in natural silicon. We perform microwave transmission spectroscopy of the resonator at millikelvin temperatures as a function of the magnetic field and observe the onset of an avoided level crossing. By analyzing the evolution of the linewidth near the level degeneracy we find $g_{\mathrm{eff}}/(2\pi) = 1.3$ MHz. The loss rate of the spin system and the resonator are determined to $\gamma/(2\pi) = 10$ MHz and $\kappa/(2\pi) = 0.3$ MHz, respectively. We also discuss the temperature and power dependence of g_{eff}.

Financial support via SFB 631 and NIM is gratefully acknowledged.

15 min. break

Invited Talk TT 42.8 Wed 17:00 H18

Orbitronics in Silicon — •Gabriel Aeppli — London Centre for Nanotechnology, University College London, UK

Control of magnetic interactions as well as localised spin sates is a prerequisite for spin-based quantum computing. Interactions can be induced via photons or exchange interactions mediated through atomic orbitals. We have consequently carried out optical and scan probe measurements demonstrating control over donor impurity orbitals in silicon and at its surface. The experiments are analogous to experiments performed in atom traps, where silicon plays the role of the vacuum and the impurity that of the atoms.

[1] N. Q. Vinh et al., PNAS **105**, 10649 (2008); and submitted (2012)
[2] P. T. Greenland et al., Nature **465**, 1057 (2010)
[3] S. R. Schofield et al., submitted (2012)

TT 42.9 Wed 17:30 H18

Decoherence due to quasiparticle tunneling in circuit QED — •Andreas Heimes[1], Michael Marthaler[1], Juha Leppäkangas[2], and Gerd Schön[1] — [1]Institut für Theoretische Festkörperphysik, Karlsruher Institut für Technologie, Wolfgang-Gaede-Str. 1, D-76128 Karlsruhe, Germany — [2]Microtechnology and Nanoscience, MC2, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

In recent years great effort in screening envoironmental decoherence sources lead to an increased coherence time of Josephson based qubits. Temperature dependent decay time measurements in phase and transmon qubits suggest that nonequilibrium quasiparticles have become one of the major limiting factors. We theoretically investigate this nonequilibrium situation and show that quasiparticle tunneling through Josephson junctions influences the excitation and relaxation dynamics of such quantum information devices.

TT 42.10 Wed 17:45 H18

Making optimal control work for superconducting qubits — Daniel Egger[1], Fadi Abu Dagga[1], Daniel Sank[2], and •Frank K. Wilhelm[1,3] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken — [2]Physics Department, University of California, Santa Barbara, USA — [3]IQC and Department of Physics and Astronomy, University of Waterloo, Canada

Optimal control is a powerful tool to find pulse sequences and shapes that implement quantum gates on given realistic hardware, such as superconducting qubits. For practical applicability, the intense filtering as well as the challenge of precise calibration need to be met. We illustrate this challenge along the example of the implementation of a controlled phase shift gate between transmon qubits coupled by a resonator. The pulse sequence reaches a high fidelity gate in short time but is highly sensitive to the characterization of the transmon frequencies. We show how a combination of robust optimal control, genetic algorithms, and plain debugging help meet these challenges.

15 min. break

TT 42.11 Wed 18:15 H18

Quantum process tomography of phase and energy relaxation through adaptive measurements — •Markku Stenberg[1] and Frank Wilhelm[1,2] — [1]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany — [2]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, ON, N2L 3G1, Canada

Quantum process tomography tends to be very time consuming when multiple degrees of freedom are studied simultaneously. We present a method of efficient quantum process tomography to estimate the phase and energy relaxation rates in qubits. The method applies Bayesian inference to adaptively choose measurements based on the previously obtained measurement outcomes. We adopt sequential Monte-Carlo approach to perform the Bayesian updates and make use of a fast numerical implementation of the algorithm. We compare the performance of our method to conventional offline (implemented after experimental data collection) strategies and illustrate how our method can speed up quantum process tomography.

TT 42.12 Wed 18:30 H18

Generation of Nonclassical States of Microwave Radiation via Single Photon Detection — •Luke C.G. Govia, Emily J. Pritchett, and Frank K. Wilhelm — Saarland University, Saarbrücken, Germany

We describe the creation of nonclassical states of microwave radiation via single photon detection, using an ideal dichotomic detector. Ideally, such a detector only indicates the presence or absence of photons and, as such, will have a back action in the form of the subtraction operator. Using the non-linearity of this back action, it is possible to create nonclassical states of microwave radiation, including squeezed and cat-like states, starting from a coherent state. One such dichotomic single photon detector is the Josephson Photomultiplier (JPM), as discussed in [1]. We discuss the implementation of this protocol using JPMs and their necessary regime of experimental operation.

[1] Phys. Rev. A 86, 032311 (2012)

TT 42.13 Wed 18:45 H18

Understanding and utilizing phase qubit decoherence channels for microwave photon detection — •Emily Pritchett, Luke Govia, and Frank Wilhelm — Saarland University

Superconducting phase qubits are a leading platform for storing and processing quantum information. While extremely promising, phase qubits experience unexpectedly short lifetimes as compared to other superconducting qubits (e.g, the transmon), which is explained by the experimental observation of densely packed anti-crossings in the phase qubit's spectrum. While currently thought the result of interactions between the qubit and spurious defects in its environment, we show that these anti-crossings exist between the qubit state and other nearly-degenerate eigenstates of the circuit even before interaction with the environment is considered. We discuss how the instability introduced by these in-circuit resonances can be utilized for high-efficiency, high-bandwidth single microwave photon detection.

TT 42.14 Wed 19:00 H18

Engineered circuit QED with dense resonant modes — •Daniel Egger and Frank Wilhelm — Universität des Saarlandes, Saarbrücken, Germany

Meta-materials are systems engineered at a wavelength smaller than the radiation considered but larger than the atomic scale; they gain their properties from their structure. Of notable interest are left-handed meta-materials. They exhibit negative permittivity and permeability[1]. On chip quantum optics routinely use right-handed transmission lines, made of a microwave strip-line, as information mediators[2]. In this work, we discuss the properties of a left-handed/right-handed hybrid transmission line. The resulting mode structure presents a mode pile-up at a lower cut-off frequency. Placing a qubit near the hybrid line results in strong to ultra-strong coupling to a quasi-continuum of modes. This system generates strongly entangled multi-mode states and also serves as quantum simulator for a spin-boson model with a sub-sub-ohmic density of states.

[1] V. Veselago, Sov. Phys. Usp. **10**, 517 (1968)
[2] A. Blais *et al.*, PRA **69** 062320 (2004)