Experiments With Tunable Superconducting Metamaterials

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***Abstract*—The paper reviews experiments with networks of compact thin-film superconducting microwave resonators. Superconducting circuits offer low loss properties, well-controlled nonlinearity, and frequency tunability in the microwave and mm-wave frequency ranges. An interesting spin-off of superconducting metamaterials is going to be quantum metamaterials comprised of arrays of superconducting qubits. This direction is an emerging new field for fundamental studies in quantum optics using microwaves.**

***Index Terms*—Josephson junctions, microwave metamaterials, microwave resonators, superconducting quantum interference devices (SQUIDs), superconductors, superconducting electronics.**

I. Introduction

THIS paper briefly reviews a series of experiments performed within recently established collaboration between German and Russian laboratories[1] [2] [3] jointly working on various aspects of superconducting and quantum metamaterials. The fascinating research field of superconducting metamaterials opened up only few years ago and is presently rapidly developing [1]. The focus of our experimental studies is on ultra-low loss electromagnetic metamaterials comprised of networks of superconducting elements.

How small are the losses in a superconducting meta-atom? The quality factors for superconducting resonators at microwave frequencies vary between several hundreds and several millions. At temperatures close to the critical transition temperature from normal to superconducting state, the losses at microwave and mm-wave frequencies are limited by the finite surface impedance of a superconductor. The high-frequency impedance remains non-zero due to the presence of normal electron excitations, so-called quasi-particles, in a superconductor. At lower temperatures, the number of quasi-particles drops down exponentially and their contribution to losses becomes negligibly small. Here, the main source of energy dissipation are dielectric losses in Josephson junction oxide barriers and oxidized surface layers of superconducting films, near edges with the highest magnitude of electrical field. By using high-quality dielectrics and surface layer cleaning, Q-factors of up to 10^7 and even high are achieved at temperatures below 1 K.

The design flexibility of superconducting thin-film networks and circuits allows for utilizing small structures down to the nanoscale while maintaining low loss properties, very strong and well-controlled nonlinearity, and frequency tunability. This approach opens up an opportunity to develop novel superconducting devices with non-trivially tailored and employed electromagnetic properties, which can be functionalized as ultra-compact antenna arrays, phase modulators, integrated tunable isolators, active emitter arrays, novel bolometers, etc. [2]. Expanding towards these novel applications in space research, communication and sensing technology will become one of the priorities for this research field in the nearest future. Superconducting quantum metamaterials comprised of arrays of superconducting qubits are emerging new field for fundamental studies in quantum optics, opening a possibility to explore collective quantum dynamics under very strong coupling between electromagnetic field and artificial atoms.

II. Classical Superconducting Metamaterials

Using superconductors as replacement for normal metals in metamaterials allows reducing losses by several orders of magnitude, shrinking the size of artificial meta-atoms, and achieving tunable frequency of operation. The losses in superconductors remain extremely small at photon energies below the superconducting energy gap, which corresponds to frequencies ranging from several 100 GHz to several THz, depending on the choice of the superconducting material. Superconducting metamaterials can be composed of superconducting thin films, transmission lines and resonators. Embedding Josephson junctions in superconducting thin-film structures make it extremely easy to tune the resonance frequency in a broad range by applying an external magnetic field. Arrays of Josephson junctions enclosed in superconducting loops are thus very attractive candidates for frequency-tunable low-loss metamaterials. Josephson junction acts as a parametric inductor that depends on superconducting current flowing across it.

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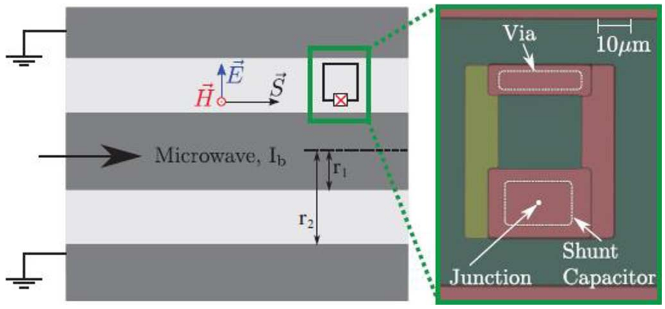

Fig. 1. Sketch of a single SQUID embedded into a coplanar transmission line. The darker areas represent the Nb electrodes. The inset on the right shows an optical microscope image of the SQUID [3].

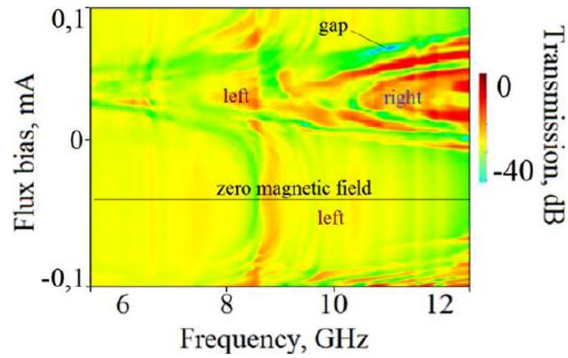

Fig. 2. Measured transmission for tunable left-handed transmission line as function of magnetic field [8].

A. One-Dimensional Tunable Magnetic Metamaterial Using SQUIDs

We have designed and experimentally tested low-loss tunable transmission lines based superconducting circuits with Josephson junctions. In these structures, split-ring resonators used in conventional metamaterials are replaced by superconducting loops with Josephson junctions, forming superconducting quantum interference devices (SQUIDs). Like the split-ring resonators, these elements can be seen as LC-resonators that couple to the magnetic field. The advantage of superconducting thin-film metamaterials is that, due to the tunable intrinsic inductance of the Josephson junction, the resonance frequency of the rf-SQUID can be changed by applying an external dc magnetic field. We obtained first experimental results that demonstrate the tunability of the resonance frequency of individual SQUIDs [3] (Fig. 1) and arrays of SQUIDs [4]. We have also studied in detail the effects of stray magnetic fields which are crucial for coherent response and overall tunability on the performance of the SQUID-based metamaterials [5].

B. Nonreciprocal Cryogenic Microwave Circuits

Isolators protect microwave circuits from harmful effect of standing waves—for example, prevent a microwave source from an unwanted signal reflected by a metamaterial. We have studied the bidirectional propagation of microwaves through a long Josephson junction in a flux-flow regime. We have demonstrated that the transmitted microwave power depends on the direction of microwave propagation relative to the direction of the flux flow [6]. This nonreciprocal behavior is explained by the interaction of the microwave signal with the moving fluxon chain inside the junction. Thus a long junction may act as an on-chip isolator for external microwave signals, with its transmission properties being fully controlled by the bias current and in-plane magnetic field. We have also studied this problem analytically and numerically within the framework of the perturbed sine-Gordon model [7].

C. Left-Handed Tunable Transmission Lines

The tunable microwave filters are the basic devices in the high-frequency technology. The cloaking device—the most popular example of an interesting microwave metamaterial—is a kind of a filter tuned for a specific spatial shape. Our research on microwave transmission lines with integrated superconducting structures has demonstrated their feasibility for constructing tunable RF metamaterials.

We have studied microwave properties of a superconducting tunable coplanar waveguide (CPW). Pairs of Josephson junctions are forming SQUIDs, which shunt the central conductor of the CPW. The Josephson inductance of the SQUIDs is varied in the range of 0.08–0.5 nH by changing an external dc magnetic field. The central conductor of the CPW contains Josephson junctions connected in series that provide extra inductances; the magnetic field controlling the SQUIDs is weak enough not to influence the inductance of the chain of the single junctions. The circuit is designed to have left-and right-handed transmission properties separated by a variable rejection band; the band edges can be tuned by the magnetic field. Transmission measurements were made on CPWs composed of up to 120 Nb–AlO_x–Nb Josephson junctions. At zero magnetic field, we observed no rejection band in the frequency range of 8–11 GHz. When applying the magnetic field, a rejection band between 7 and 9 GHz appears, see Fig. 2. The experimental data were compared with numerical simulations, demonstrating a good qualitative agreement [8].

D. Compact Multi-SQUID Split Ring Resonators

The split ring resonators (SRRs) became very popular for realization of microwave metamaterials. We have proposed and studied experimentally compacted yet tunable superconducting SRRs employing nonlinear inductance of Josephson current [9]. A fraction of SRR is replaced by Nb–AlO_x–Nb Josephson tunnel junctions connected in parallel and forming a dc SQUID, which inductance is sensitive to the external magnetic field, see Fig. 3. By adding Josephson junctions, SRR can be made more compact, and its resonance frequency can be tuned via application of magnetic field.

We have developed the EM-model and performed experiments with Josephson SRR weakly coupled to a transmission line within frequency range 11–13 GHz. The experimental results presented in Fig. 4 are in good quantitative agreement with the model [9].

The suggested modification of traditional SRR brings at least two advantageous features: 1) the metallization area can be reduced at least by six times making SRR more compact at given

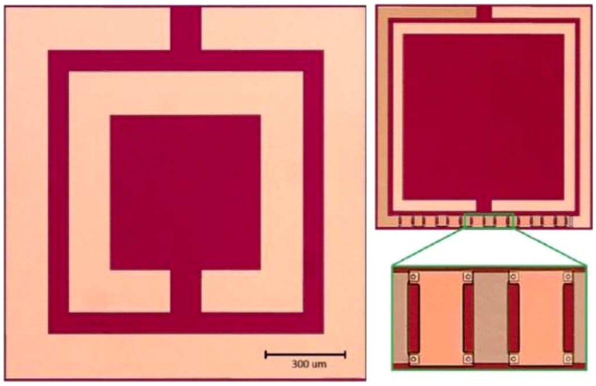

Fig. 3. Size comparison of the fabricated conventional SRR and tunable JSRR containing 15 SQUIDs. Both meta-atoms where designed to operate around 11.5 GHz and are shown using the same spatial scale. Bottom inset shows a the SQUID array; small circles are Josephson junctions [9].

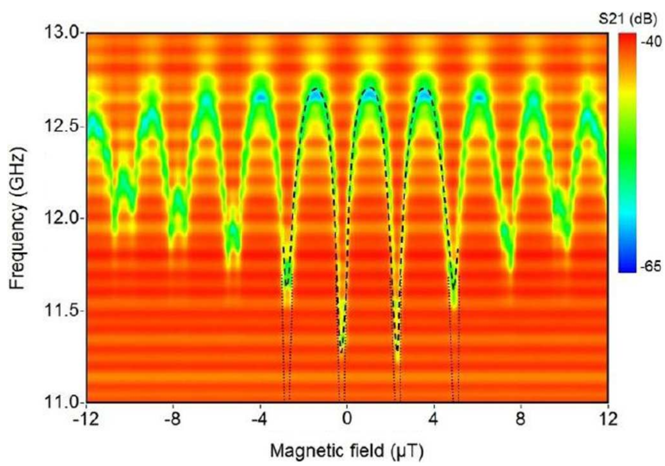

Fig. 4. The characteristics of Josephson SRRs formed by 15 SQUIDs. The black dashed lines are fits for nonuniform field distribution [9].

frequency, thus reducing the density of metal in the artificial electromagnetic media and 2) the new device can be tuned by at least 10% in frequency using small magnetic fields. All these makes the SRR with embedded JJ a promising substitute for the conventional SRR employed at cryogenic temperatures.

E. Nonlinear Switchable SQUID Metamaterials

The nonlinear effects occur in the circuits containing SQUIDs at the high level of the RF-induced current, comparable to the critical current of Josephson junctions [10]. We studied nonlinear properties of SQUIDs integrated into a CPW. Since the SQUID is a part of a resonator inside the waveguide, the RF current through the Josephson junction can be comparable with the critical current that may result in the inductance of the critical current dependent on the instantaneous value of the signal current in the ring. In the simple approach, the critical current drops down by the value of the induced RF current. It is clear that such process is highly nonlinear, and the harmonics of the probe current have to appear.

Strong microwave driving of a Josephson junction leads to a bifurcation on the lower side of its resonance. Using a single junction, this bifurcation has been employed to implement a Josephson bifurcation amplifies [11]. The strongly driven

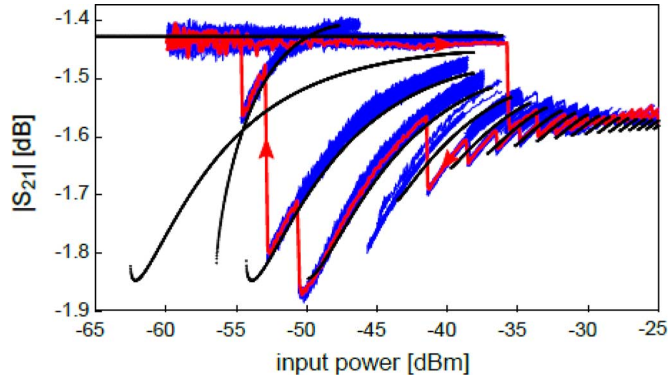

Fig. 5. Calculated (black) and measured (blue and red) transmission through a single SQUID. The red data show a hysteresis loop from low to high power and back. The blue data are a collection of different power sweeps of varying length and initial conditions [12].

Josephson junction enters the bi-stable regime with two stable non-dissipative dynamical states, which differ by both amplitude and phase. The low-amplitude state oscillates nearly in phase with the driving signal, while the high-amplitude state is characterized by the phase shifted approximately by π. We have recently implemented a SQUID-based metamaterial operated in such a bi-stable manner [12], for which the in-phase response corresponds to positive magnetic permeability μ and the out-of-phase response translates into having μ negative. For properly chosen driving frequency and power, these states are stable and switching between them achieved by changing the driving power or frequency. As these two states with $\mu > \mathbf{0}$ and $\mu < \mathbf{0}$ are both locally stable for a given set of driving signal parameters, they may coexist in a way that some part of meta-atoms oscillate at phase close to 0 and another part at phase close to π. Having these groups of meta-atoms mixed together and randomly distributed in the metamaterial should produce birefringence for waves incident on such a metamaterial. Once the two parts are separated by design parameters, they will form an interface between two metamaterials, one with positive and another with negative permeability. An example of experimental multi-stable states measured for a single SQUID is shown in Fig. 5.

F. Two-Dimensional SQUID-Based Metamaterials

Two-dimensional metamaterials (so-called metasurfaces) have recently gained an increasing attention. They can be used, just as their three-dimensional counterparts, to manipulate the properties of propagating electromagnetic waves. The meta-atoms in our experiments are frequency tunable SQUID-resonators aggregated in a metasurface. The structure under investigation is an array of 30×30 Nb SQUIDs each containing one Nb–AlO_x–Nb Josephson junction. For small excitations signals, they may be treated as magnetic field tunable resonators as above. At first step, we developed a method to analyze the electromagnetic behavior of superconducting planar microwave metamaterials using a laser scanning microscope (LSM). We have mapped the laser-to-microwave response of two-dimensional arrays of magnetic meta-atoms [13]. This method allows us to investigate contributions of individual meta-atoms to the macroscopic response and thus provides

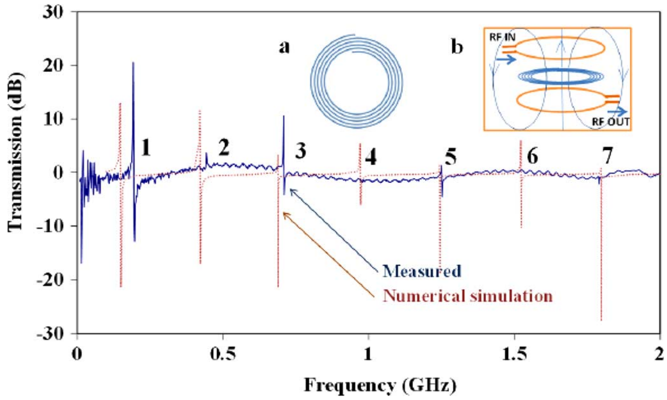

Fig. 6. Experimental and numerically simulated RF response of a ring-shaped superconducting monofilar Archimedean resonator. The numbers at the peaks denote the mode number n. The resonator is a superconducting 40-turn Nb spiral with external diameter of 3 mm and internal diameter of 2.2 mm. A simplified view of the spiral (with less turns) is shown in insert (a). These results are obtained by measuring transmission magnitude $|S_{21}|$ through a spiral resonator in a setting shown in insert (b).

a useful tool for characterization and optimization. We have shown the versatility of this method with an array of SQUIDs visualizing its microwave response on the scale ranging from the whole array down to the individual meta-atoms. This method can be extended to various superconducting metasurfaces in order to detect and eventually overcome technological and experimental difficulties inherent in this technology.

G. Ultra-Compact Spiral Metamaterials

The general concept of a metamaterial presumes that the size of meta-atoms should be much smaller than the wavelength at the frequency of operation. The spiral resonators are offering a particularly compact design for the magnetic-type meta-atoms. The superconducting spiral is even more attractive object as its operation is not limited by the active (resistive) loss.

We studied theoretically and experimentally electrodynamics of the Archimedean spiral, shaped as a flat ring—with no central part. We developed analytical solution for the spectrum of the resonance modes of the spiral and obtained analytical expression for the waveform of the current at the resonance modes [14]. The current distribution inside the spiral satisfies a particular Carleman type singular integral equation, solution of which yields a set of resonant frequencies. The calculated resonance frequencies and the waveform current distributions are in good agreement with experimental data and the results of our numerical simulation. Despite of the nearly identical boundary conditions for electromagnetic fields at the extremities of the resonator, the relative frequencies of the resonant modes of the spiral approximately follow the sequence of the odd numbers as $f_1{:}f_2{:}f_3{:}f_4\ldots = 1{:}3{:}5{:}7\ldots$ This particular set of resonant modes is also well explained by our analytical model. The developed analytical model gives both the near-field and the far-field structure of the resonator modes. As the result, the evaluation and characterization of a metamaterial designed of such microresonators can be facilitated essentially. An example of experimentally measured and numerically simulated RF response of a spiral resonator is presented in Fig. 6.

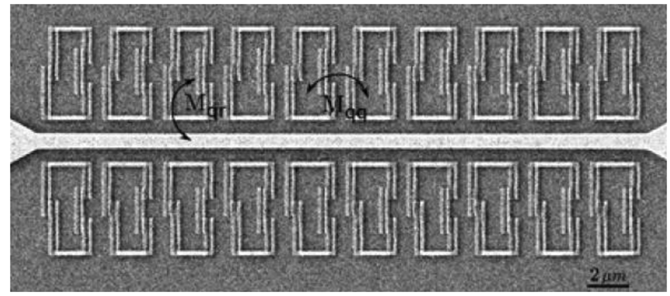

Fig. 7. Scanning electron micrograph of the sample showing the central part of the coplanar waveguide resonator. 20 qubit rings are situated between the central conductor line and the ground plane of the resonator. Each qubit is individually coupled to the resonator by the mutual inductance M_{qr} and to its neighbour by M_{qq}. The system effectively constitutes n mutually non-interacting spins coupled to the photon field of the resonator [15].

III. Quantum Superconducting Metamaterials

Atoms of natural materials interact with electromagnetic field as two-level quantum systems. Recently, artificially made quantum two-level systems have been reported in many experiments with superconducting nonlinear resonators cooled down to their ground state. At ultra-low temperatures, superconducting loops containing Josephson junctions behave as macroscopic two-level quantum systems often referred to as qubits. The typical energy level separation of these quantum meta-atoms is of the order of few GHz, which requires using for experiments with them temperatures below 1 K. In contrast to the case of natural atoms or molecules, superconducting qubits allow for a very strong effective dipole coupling to the external electromagnetic field. This opens unique opportunities of designing artificial quantum structures made of meta-atoms that have ultra-strong and coherent coupling to the electromagnetic fields in a transmission line or a cavity. The major technical challenge for artificially made quantum superconducting metamaterials will be making as close as possible the energy level separation of many physically different and, therefore, not exactly identical meta-atoms. This problem can be circumvented by utilizing very strong coupling of the meta-atoms to the electromagnetic field, similar to the way of overcoming the effects of inhomogeneous broadening in lasers made of natural atoms. This should allow for novel ways of generating and controlling non-classical electromagnetic waves (light squeezing, coherent down- and up-conversion, etc.). This emerging field will be driven by very interesting coming experiments in the near future.

In our first experiment with a prototype quantum metamaterial [15], we have measured the microwave properties of an array of 20 superconducting flux qubits embedded into a microwave resonator shown in Fig. 7. The phase of the signal transmitted through the resonator revealed the collective resonant coupling of up to 8 qubits. Quantum circuits of many artificial atoms based on this proof-of-principle experiment offer a wide range of prospects, from detecting single microwave photons to phase switching, quantum birefringence, super-radiance and quantum phase transitions.

IV. Conclusion

This brief review outlined recent developments in the field of superconducting metamaterials based on circuits with Josephson junctions. A Josephson junction is a unique example of a very compact inductor which inductance can be easily varied *in situ* by applying a weak external magnetic field. Moreover, Josephson junctions are the core components of superconducting qubits, which offer a possibility of creating truly handmade quantum metamaterials.

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