Imaging Coherent Response of Superconducting Metasurface

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***Abstract*—We study microwave response of the individual metaatoms of a superconducting metasurface formed by a two-dimensional array of superconducting quantum interference devices (SQUIDs). In our experiment, RF currents in the metasurface are directly imaged by using the laser scanning microscopy (LSM) technique. We tested a sample with 21 × 21 SQUID array in a waveguide cavity designed to achieve a uniform microwave distribution over the entire array. The demonstrated tunability of 2D SQUID metasurface resonance frequency by external magnetic field is about 56%, covering 8–12.5-GHz range. The obtained LSM images of the RF current distributions over the SQUID array confirm a high degree of coherence of the entire metasurface. The SQUID-based metasurfaces combine low losses and frequency tunability and can be useful for designing compact cryogenic RF systems.**

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

I. Introduction

At the actual stage of superconductive RF metamaterials research, the option of superconducting metasurface is gaining a significant attention [1], [2]. The two-dimensional array of Radio Frequency Superconducting QUantum Interference Devices (RF SQUID) has a number of useful features in this regard. As a SQUID may be used as a magnetically coupled RF micro-resonator, it is a good candidate for a role of magnetic meta-atom with the resonance frequency tunable with external magnetic field when single, or collectively in an array. Recently the RF SQUID array response has been studied theoretically [3]–[5] and, to some extent, experimentally [6]. A possibility of tuning of the resonance frequency of a moderate size array of RF SQUIDs by the constant magnetic field, temperature and microwave signal was demonstrated in [6]. In such experiment, based on measurement of transmission of RF signal through entire sample with SQUIDs, it is difficult to estimate the actual number of the SQUIDs involved in synchronized RF response. The degree of uniformity of the response and the dynamics of a large array of RF SQUIDs also remains unclear.

The cryogenic laser scanning microscope (LSM) gives an excellent opportunity for direct observation of RF currents in planar superconductive array of SQUIDs [7]. In LSM experiments we are obtaining the distribution of the RF resonant currents in a planar superconductive circuit, and can see the responses of the individual SQUIDs in the array to the probing laser beam, and may estimate on the uniformity of the RF response. In this work we study experimentally the individual responses of RF SQUIDs in the two dimensional array to incoming RF signal with the use of cryogenic Laser Scanning Microscope.

II. Experimental Setup

The SQUID coupling to the RF wave may be efficient when the magnetic component of the incident wave is perpendicular to the SQUIDs' plane. Also, a natural requirement for the test setup would be a uniform level of RF excitation over a SQUID array. These two requirements may be met when a moderate size ($d \ll \lambda$) SQUID array is placed in a vertical plane of symmetry of a rectangular waveguide, operating in a regime of running TE_{10} wave (with low level of standing waves). As known, in a standard rectangular waveguide the magnetic field component of fundamental TE_{10} mode is always perpendicular to the vertical plane of symmetry, i.e. to the plane of symmetry parallel to the narrow wall of the waveguide. A similar type of waveguide test cavity was recently used for a study of collective response of a SQUID array in [6].

Additionally, the designed waveguide test chamber allows studying the uniformity of RF response of the individual SQUIDs of an array, when coupled to the Laser Scanning Microscope. The connection with the laser microscope optics is made via a small round hole in the waveguide narrow wall, with the diameter below cut-off for RF signal. Our test cavity

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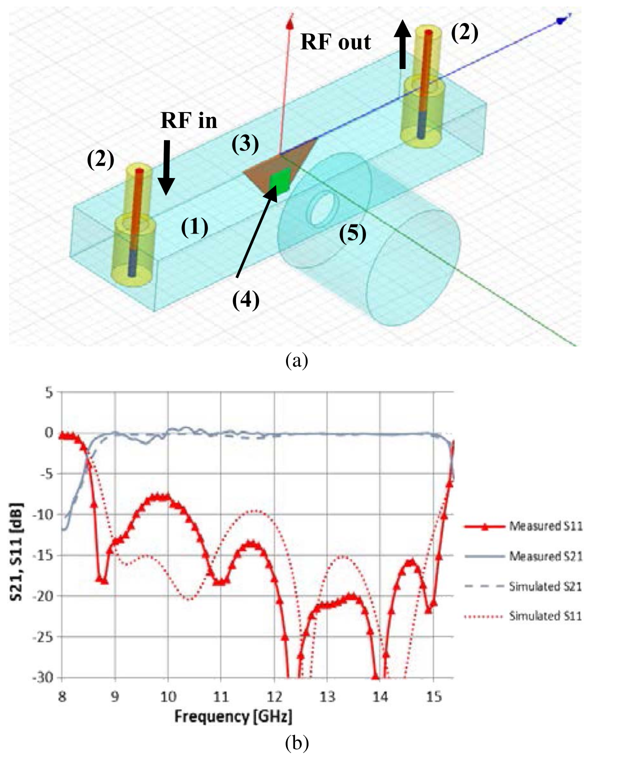

Fig. 1. (a) Waveguide chamber used for the cryogenic test of the RF SQUID metasurface. In the sketch, a section of the 19 mm × 9.5 mm waveguide (1) is shown. The waveguide section is terminated with the two waveguide-to-coaxial adapters (2) letting the RF signal in and out of the chamber, and the sample mounting plate (3) in the center. When the SQUID array is mounted at the support plate (3), the sample (4) is being installed inside of the waveguide facing the optical window (5). The window (5) lets in the waveguide the optical probing beam of the laser scanning microscope and is not transparent for the RF probing signal. (b) Measured (solid line) and HFSS simulated (dotted line) transmission and reflection coefficients of the test chamber versus frequency of the probing RF signal show the convenience of the developed chamber for the SQUID metasurface characterization in the 8.5–15.5-GHz band.

[Fig. 1(a)] has a section of rectangular 19 mm × 9.5 mm waveguide (1) with the two coaxial to waveguide adapters (2) and a sample mounting plate [(3) in Fig. 1(a)]. The optical window is in the sidewall of the rectangular waveguide [(5) in Fig. 1(a)]. In the cavity the sample (4) is glued at the Sapphire mounting plate (3) in the vertical plane of symmetry of the waveguide, facing the optical window in the sidewall (5). The Sapphire was chosen for the sample mounting because of its good thermal conductivity. The waveguide test design was optimized with ANSYS HFSS CAD software[1] in order to reduce the level of the standing waves at the sample location. The HFSS simulated and measured transmission through the test cavity is plotted in Fig. 1(b). In the 8.5–15.5 GHz band the transmission is high enough to insure low level of the standing waves in the cavity and allowing the use of the test chamber. During the cryogenic tests the test chamber with SQUID array is covered with Permalloy magnetic shield and installed in a liquid Helium cryostat with optical window for LSM beam coupling. The Helmholtz coils are installed outside of the waveguide (and inside of the magnetic shield) in order to apply the uniform magnetic field to the SQUIDs.

[1]http://www.ansys.com

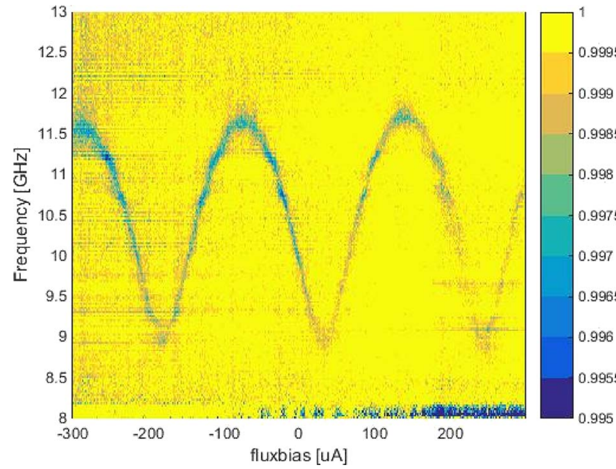

Fig. 2. Measured transmission through the cavity with 21 × 21 SQUIDs array versus frequency and versus external magnetic field. The probing RF signal power level is set low enough (−70 dBm) to keep the response linear (RF power independent). The data show a possibility of 21 × 21 SQUID array tuning in 8–12.5-GHz range. The resonance response of SQUID array seems to be synchronous, with no additional branches (parasitic resonances) visible, as for a singular RF SQUID, with periodical variation of resonance frequency versus magnetic field.

III. Experiment and Discussion

We prepared the samples with arrays of 21 × 21 RF SQUIDs. Each RF SQUID is formed as Nb thin film rectangular loop with outer dimensions of $70 \times 50\ \mu m^2$ and with a single Nb/AlOx/Nb Josephson junction. The inner loop area is $2000\ \mu m^2$, the junction critical current is about 1.9 μA, and the junction shunting capacitance is about 2 pF. The distance between the SQUIDS is 5–10 μm, about 1/10 of their size, and so, the SQUIDs coupling is relatively strong.

First, we observed the collective response of the SQUID array as a function of frequency of the probing signal and of the applied magnetic field (magnet current) (Fig. 2). Here we measure transmission through the test chamber with the array installed at 4.2 K when the level of probing RF signal low enough to keep the SQUIDs response linear (power independent). The S21 data is normalized against the transmission at the temperature above the critical temperature of Nb, at about 10 K. The absorption at the resonance frequency is visible as darker spots. In Fig. 2 the resonance response of SQUID array seems to be synchronous, with no additional branches (parasitic resonances) visible, as for a singular RF SQUID, with periodical variation of resonance frequency versus magnetic field.

Next, we use the Laser Scanning Microscope in order to spatially resolve the resonance response of the individual SQUIDs acting as meta-atoms in the 2D metamaterial sample. This would clarify an intriguing question of the modal structure in the resonances in the array of SQUIDs [5]. The LSM image gives the variation of the RF transmission through a planar superconductive sample (δS21) as a function of the laser beam position at the sample (δS21(x, y)). As the laser beam affects the superconductor locally, and as the effect depends on the local RF current level, the resulting LSM image gives the 2D plot of the RF currents in the sample at a fixed RF frequency

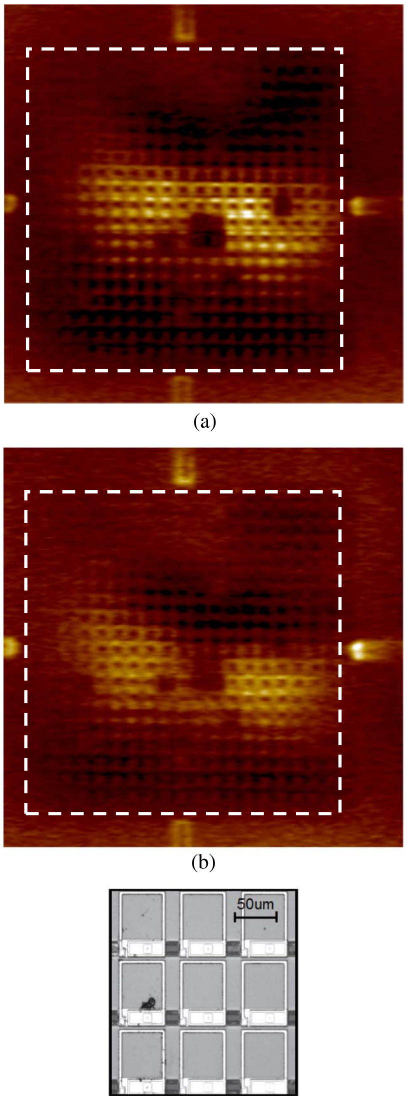

Fig. 3. LSM-generated images of the RF currents in the 21 × 21 SQUIDs array at the RF frequency close to the maximum resonance frequency of SQUIDs (Fig. 2). (a) and (b) LSM data at F max—two independent measurements. In figures, the light color coding corresponds to the maximum of LSM response, showing the area with the superconductive circuit with the strongest RF current. The dotted line shows the limit of the SQUID filled area of about 1 × 1 mm. (c) Optical image of close up view of 9 SQUIDs in the tested array, about 1/50 of the total area. The two dark spots in the center of views (a) and (b) (no RF currents) are likely to be the two defective SQUIDs. One can note that about 50% of the SQUIDs in the array participating in the resonance (bright color). The remaining question of the resonance modal structure in the SQUID array requires RF phase information unavailable in LSM experiments.

[Fig. 3(a) and (b)] [8], [9]. The measurement is done at the fixed frequency close to the maximum SQUID resonance frequency. In Fig. 3(a) and (b) the bright regions correspond to high LSM response (more laser beam induced loss) with higher RF current density, whereas the dark regions correspond to areas with low RF current density, or to the areas with no superconductor. It is clear that the RF response substantially varies over the SQUID array. The two dark spots in the center (no RF currents) are likely to be the two defective SQUIDs. One can note about 50% of the SQUID in the array participating in the resonance (bright color). The remaining question of the resonance modal structure in the SQUID array [5] requires RF phase information unavailable in LSM experiments.

IV. Summary

It has been shown that SQUID array based superconductive metasurface may have nearly synchronized resonance, which can be tuned from 12 GHz to 8.5 GHz by applying a constant magnetic field. A carefully developed test chamber allowed us avoiding parasitic resonances and to couple the tested SQUID array with Laser Scanning Microscope. We obtained 2D LSM the picture of collective RF response in 2D SQUID array, where nearly 50% of the SQUIDs is participating in the coherent response. The observed resonance mode of the SQUID array has a rather complex structure. The lack of the RF phase information in LSM data is somewhat limiting the mode analysis.

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