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Ultra-compact superconductive resonator with double-spiral structure

A. S. Averkin[1], **A. P. Zhuravel**[2], **A. Karpov**[1], **S. M. Anlage**[3], **and A.V. Ustinov**[1,4]

[1]National University of Science and Technology (MISIS), Leninskiy prosp. 4, 119049 Moscow, Russia
[2]Verkin Institute for Low Temperature Physics and Engineering, NAS of Ukraine, 61103 Kharkov, Ukraine
[3]CNAM, Physics Department, University of Maryland, College Park, Maryland 20742-4111, USA
[4]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
e-mail of the presenter: mrvar@yandex.ru

***Abstract* – We discuss the characteristics of an ultra-compact double-spiral superconductive Nb micro-resonator as a potential magnetic metamaterial element. This resonator consists of two superconducting Nb spirals, sandwiched face to face, with a small gap. We study the resonator spectral response by using numerical simulation. The resonator modal structure has been also examined with a laser scanning microscope. The achieved resonator size with respect to the wavelength in our experiment is about λ/4200. Compared to the single-spiral resonator, the frequency of the fundamental mode of the double-spiral one is lowered by a factor of six. Small size and the ease of manufacturing make the double-spiral resonator an attractive solution for magnetic the component of a metamaterial.**

I. INTRODUCTION

A number of potential applications of a medium with simultaneous negative permittivity ε and permeability μ was theoretically described by Veselago in 1968 [1]. About 30 years later, a practical example of a material with negative effective permeability μ was demonstrated by Pendry *et al*. [2]. In order to create the negative permeability μ, Pendry *et al.* used an array of split ring resonators (SRR). SRRs interacts mainly with the magnetic component of the electromagnetic (EM) field and gives the possibility to create a medium with effective negative μ. The first demonstration of a medium with both negative ε and μ was done by Smith *et al*. in 2000 [3]. They called this artificial media a metamaterial. The metamaterial was constructed of layers of copper SRR and layers of wires. SRRs have strong coupling with the magnetic component of the EM field, while the wires have a strong coupling with the electric component of the EM field, acting as electrical dipoles.

The spiral resonator, as compared to an SRR, has equally strong coupling to magnetic field, but much smaller size than SRR, because of the dense placement of turns. Earlier experiments [4], [5] were made with planar spirals made of thick Cu films (~0.35 thick in [4] and ~0.25 mm thick in [5]) on dielectric substrates. Such a thick coating is required to minimize the Ohmic losses, making the design intermediate between 2-D and 3-D. Another approach to reduce the size of the spiral resonator is the introduction of the structure with two sandwiched spirals, studied recently by Chen *et al*. [6]. The demonstrated twin-spiral magnetic metamaterial component size is below λ/1300 [6].

A further miniaturization of normal-metal spiral resonators has its natural limitation due to the scaling of Ohmic dissipation with spiral length [7]. In order to demonstrate a deep sub-wavelength size resonator, it appears promising to utilize ultra-compact superconductive spiral resonators. A superconducting spiral resonator and one-dimensional planar array of spiral resonators made of Nb film was studied by Kurter *et al*. [8]. This resonator has a fundamental resonance frequency of 74 MHz, and its size is as small as λ/675.

In this work, we are using the two superconductive Nb spirals, sandwiched face to face with a small gap in between. The two spirals of the resonator have a strong capacitive coupling. As result, the frequency of the fundamental mode is lowered by more than 5 times with respect to a single resonator. The resonators are produced by photolithography. We demonstrate that the resonator diameter is only a small fraction of the wavelength size, below λ/4000.

II. SAMPLE PREPARATION

The spiral resonators made from 200 nm Nb thin film on a 350 μm thick quartz substrate [9]. The dimensions of a single spiral are the inner diameter R_i=4.26 mm, the external diameter R_e=6.0 mm. The spiral is ring-shaped with no central part. The width of the spiral line is 10 µm, while the space between lines is 10 µm, and the number of turns is 44. Two identical 44-turn Nb spirals are glued face-to-face by using Apiezon grease. The centers of the spirals are aligned precisely. In the resonator, the two spirals are wound in opposite directions.

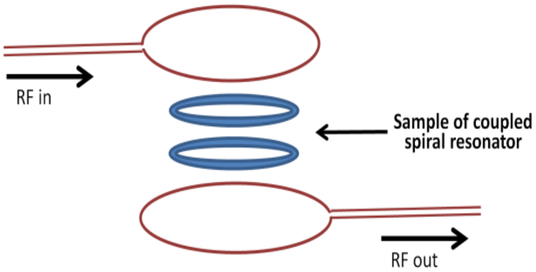

Fig. 1. Schematic of the test setup of a two-spiral resonator sample mounted between two magnetic loop probes. The probing signal is injected through the upper loop and received at the lower magnetic probe. The loops (magnetic probes) are weakly coupled, and at the resonance frequencies of the two-spiral structure a sharp variation in transmission occurs.

III. Simulation And Experimental Results.

The sample is mounted inside of a copper holder between the two RF magnetic loop probes (Fig. 1) and installed inside a cryostat. Probe loops are connected to an Agilent PNA-X network analyzer. Measurements are performed at the temperature of 4.5 K, when Nb is in the superconducting state. The measured transmission coefficient $|S_{21}|$ versus frequency for the coupled spiral resonators is shown by dashed line in Fig. 2. The distribution of RF current density in the spirals at the resonance frequencies was checked with a laser scanning microscope (LSM) [10,11]; data are not shown here due to space limitations.

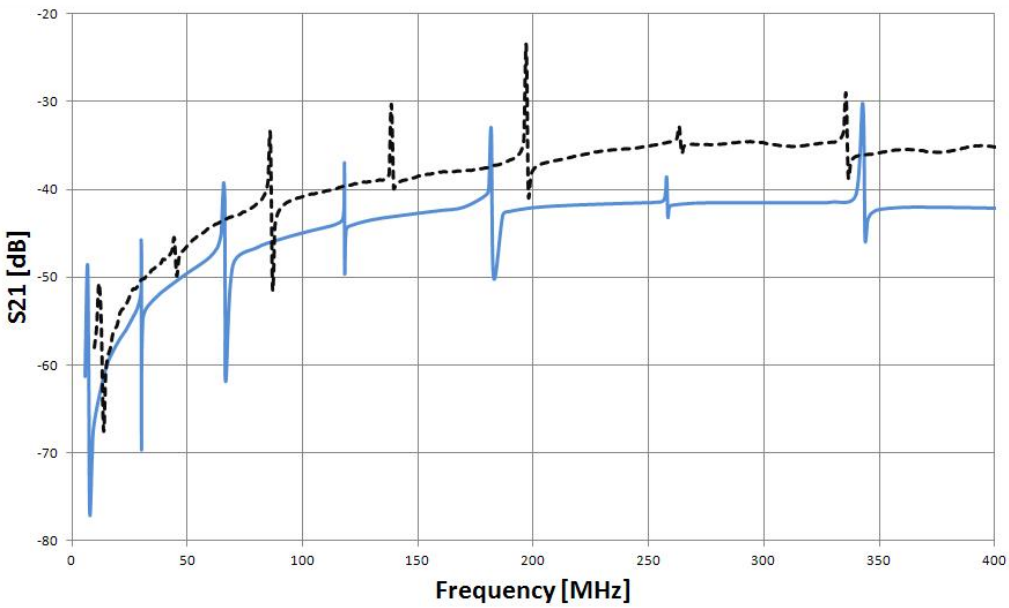

Fig. 2. Measured (dashed line) and simulated (bold line) transmission $|S_{21}|$ of the double-spiral resonator at T=4.5 K in the configuration shown in Fig. 1.

The simulated transmission is shown in Fig. 2 by bold line. The fundamental resonance is at 8 MHz, which differs from the measured value of 12 MHz. Differences between simulation and experiment decrease with rise of frequency. The discrepancy might have been caused by the simplified configuration of RF probes in simulation and the fact that the simulation was performed inside the box with walls covered with ideal EM wave absorber. In reality, measurements were performed inside the sample holder made of copper.

The higher resonances are nearly equidistant in frequency, with a strong reduction of the coupling at the even modes, leading to weaker response. The resonator diameter to the wavelength ratio is as low as 1/4200.

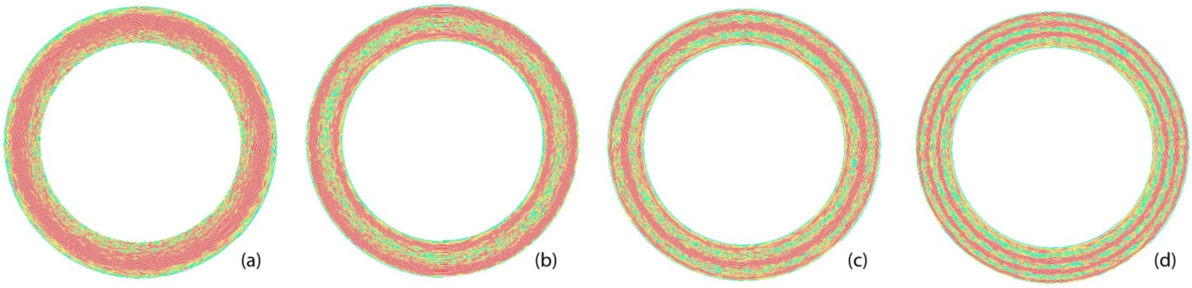

Fig. 3. The simulated RF current distributions inside the top spiral in double-spiral resonator at the different frequencies. (a) fundamental mode at 8 MHz, (b) second mode at 30.5 MHz, (c) third mode at 66 MHz, (d) forth mode at 118 MHz. The dark color corresponds to the higher current amplitudes.

VI. CONCLUSION

An ultra-compact superconducting micro-resonator was proposed, simulated, produced and tested. The resonator consists of two superconducting Nb spirals, sandwiched face to face, with a small gap. We explain the resonator spectral response using numerical simulations. The simulated resonator modal structure was verified with the scanning laser microscope. The achieved resonator size relative to the wavelength is about 1/4200.

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