Tunable Frequency-Selective Surface Based on Superconducting Split-Ring Resonators

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***Abstract* – We study a possibility to use the 2D superconducting metamaterial as a tunable frequency-selective surface (FSS). The proposed FSS is made of sub-wavelength size (λ/14) metamaterial unit cells, where a split-ring resonator is embedded in a small iris aperture in a metal plane. The split-ring resonator is made of NbN film, and its resonance frequency is tuned by the temperature of the sample, changing the kinetic inductance of NbN film. The Ansoft HFSS simulation predicts the FSS tuning range of about 10-20 %. The developed superconducting FSS may be used as a tunable band-pass filter or modulator.**

I. INTRODUCTION

The frequency-selective surfaces (FSS) are known to be useful as quasi-optical filters or diplexers at millimeter and submillimeter wavelengths [1], [2]. The most of FSS filters are designed to work in a fixed frequency band. However, for a variety of applications, an electronically controllable FSS may be desirable. Typically, the tunable FSSs are used as tunable filters switching between reflection and transmission at a fixed frequency [3], [4], or as a filter with gradually shifting the transparency band [5], [6]. The different methods can be used for tuning FSS working frequency, e.g., mechanical tuning by micro-electromechanical switches (MEMS) [7], [8] or electrical tuning by varactor diodes [9], [10].

In the past, a possibility to change resonance frequency in superconducting metamaterials has been demonstrated by adjusting the Josephson inductance of junctions embedded into resonators [11], [12]. In this work, we are proposing using a thin superconducting film kinetic inductance, which is tunable by the temperature, in order to control the transmission band. This solution has a technological advantage, as it requires only a single-layer circuit, which is easier to implement compared to three layers needed for Josephson junctions. For a normal metal nanowire, the resistive component of the impedance dominates the kinetic inductive component up to THz frequencies. In a superconductor, however, the DC resistance is zero and the impedance from DC to GHz frequencies can be dominated by the kinetic inductance of the supercurrent. It is possible to control the kinetic inductance of the superconductor by the temperature, by current through the resonator, or by magnetic field. In NbN thin-film circuits, the kinetic inductance L_k can be tuned substantially, by more than factor of three [13]. Below we present the HFSS simulation of the designed FSS.

II. FREQUENCY-SELECTIVE SURFACE DESIGN AND SIMULATION RESULTS

The proposed unit cell of FSS metamaterial has a sub-wavelength size and consists of a split-ring resonator (SRR) etched of NbN thin film. SRR is placed into a small aperture in a metal screen, which is normally not transparent at the resonance frequency of SRR. A resonance in SRR makes it possible for the RF signal transmission to propagate through. The width of the split ring resonator line is made small in respect of its length, making the contribution of the kinetic inductance prevailing that of the geometric inductance.

A high number of squares (or a strong aspect ratio) of the SRR superconducting line is required to achieve a good tunability of the NbN resonator by temperature. In the studied example, we use a circular single line SRR with the width of the line $w = 10$ μm, with the SRR diameter $D = 3$ mm, with the radial gap $s = 0.5$ mm, and with resulting length of $l = 8.92$ mm. The number of squares of the resonator line is $n = 892$. The kinetic inductance per square of NbN film in the superconducting state at temperature well below the superconducting transition temperature T_c is expected to be

$$\mathrm{L_{k\square}} = 1.3 * 10^{-11}\mathrm{H}/\square \ , \quad (1)$$

and the total kinetic inductance of the SRR is thus

$$\mathrm{L_k} = \mathrm{L_{k\square}} * \mathrm{n} = 11.6 * 10^{-9}\mathrm{H} \ . \quad (2)$$

Simulation of transmission (S21) for normal incidence of a flat wave through FSS has been performed with Ansoft HFSS software. An image of a unit cell of the FSS metamaterial is shown in Fig. 1. In calculations, we assumed the entire FSS to be covered with the identical cells located at a common Si substrate with a common metallization plane. The unit cell aperture diameter is D_A=3.5 mm, while the NbN SRR diameter is D=3 mm and SRR line width is w=10 μm (Fig. 1). At the central frequency of 4 GHz, the FSS metamaterial unit cell size (5x5 mm^2) is about $\lambda/14$.

The "perfect conductor" boundary conditions are assumed at the surface of the metallic screen. The "impedance" boundary condition is assigned at the surface of the NbN SRR. The real part of the SRR surface impedance is set to $Z_{re} = 10^{-10}\ Ohm/\square$, corresponding to a superconductor in the low frequency limit. The imaginary part of the impedance is set to $Z_{im} = 2\pi f L_{film}$, where f – is the signal frequency, L_{film} – is the inductance per square of the film in units of $H/\square$. Simulations have been performed with the different values of the inductance L_{film} , modeling tuning of the kinetic inductance of the film by temperature. On the sidewalls of the FSS's unit cell, a conventional HFSS's periodically "master and slave" boundary conditions are assigned to simulate an infinitely large 2D array composed of the unit cells. At the top and at the bottom sides of the unit cell, the HFSS's "Floquet" ports are assigned.

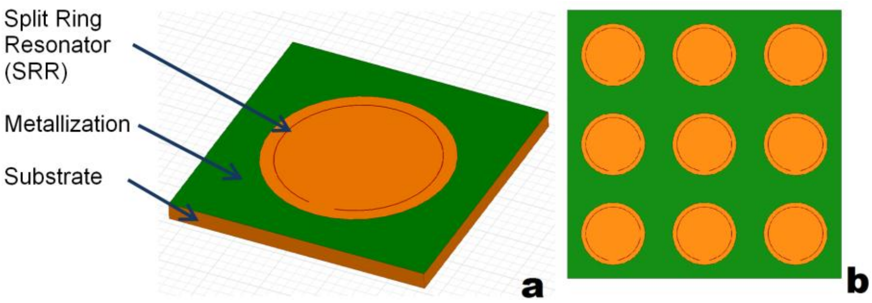

Fig. 1. (a) General view of the FSS unit cell. Unit cell consists of a silicon substrate (orange) and of metallization with a round aperture (green). The NbN split ring resonator is placed into the aperture (red). (b) A top view of the FSS with 3x3 unit cells.

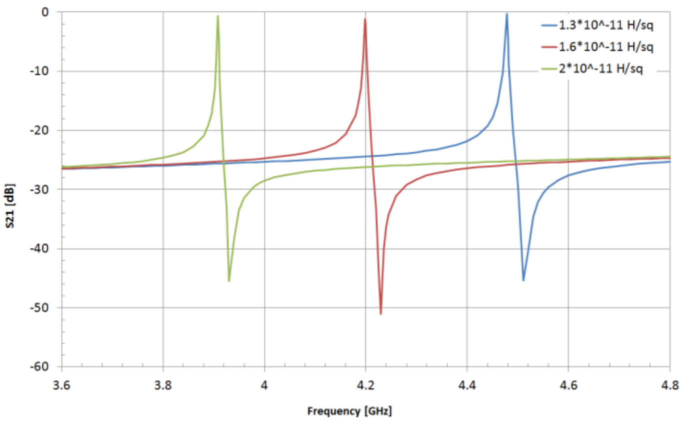

Fig. 2. Transmission (S21) through the designed FSS simulated with HFSS software for the normal incidence of a flat wave. The transmission is calculated for the kinetic inductance value at the temperature far below the critical temperature T_c (L=13 pH/sq (blue line)) and for the temperature near T_c (L=20 pH/sq (green line)). Predicted resonance frequency shift is about 15%, from 4.5 GHz to 3.9 GHz. Note a 100 % transmission at the resonance frequency of the tunable FSS.

III. Conclusion

We studied a tunable frequency selective surface based on a 2D superconducting metamaterial composed of split ring resonators made of a thin film of NbN. The resonance frequency of the NbN FSS is tuned by changing temperature. In contrast to the previously discussed tunable superconducting metamaterials using Josephson junctions as tunable elements, our approach here benefits from a simpler technology.

Numerical simulation using Ansoft HFSS confirms the possibility to tune the working frequency of FSS by the temperature of the sample by at least 15%. A high quality factor of superconducting resonator gives a possibility to create tunable narrow band filters with high selectivity and low loss.

The proposed superconducting frequency selective surface could be used in two different modes of operation: as a modulator for a fixed frequency of the signal, or, alternatively, as a continuously tunable band-pass filter. The proposed FSS design demonstrates enhanced transmission through small sub-wavelengths apertures as in [14, 15], but now with a capability of frequency tuning. Currently, the sample preparation is under way for performing experimental verification.

The proposed FSS could find applications, e. g., in radio-astronomical detectors and in superconducting electronics.

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