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Investigation of Tunable, Electrically Coupling Meta-Atoms in a Coplanar Waveguide

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Abstract – **We present a one dimensional superconducting metamaterial, which employs meta-atoms electrically coupled to a coplanar waveguide. The meta-atom is of resonant nature with a tunable resonance frequency due to built-in two-junction (dc-) superconducting quantum interference devices (SQUIDs). We present simulated and measured results of the transmission data.**

I. Introduction

Using rf-SQUIDs as magnetic field tunable meta-atoms instead of the commonly employed split ring resonators (SRR) has proven to be a viable addition to the wide field of metamaterials. Both theoretical discussions [1]–[3] and experimental realizations in different waveguide geometries [4]–[6] showed a large tunablility of resonance frequency and thereby magnetic permeability. However, the nonlinear inductance of the Josephson junction offers not only an additional degree of freedom to tune the resonance frequency. As shown recently [7, 8], it also enables - at higher microwave powers - to access and switch between multiple stable states, each corresponding to a different amplitude and phase of the meta-atoms' response.

In this work, we stay in the low power regime and take the next step towards a tunable negative index material: We introduce a component suitable for the 1D coplanar waveguide (CPW) geometry that couples to the electric instead of the magnetic field component. The novel electrical dipole meta-atom includes a dc-SQUID that has a magnetic field tunable inductance. In the future, we intend to combine tunable electric and magnetic meta-atoms, thus offering the possibility to open and close negative index pass bands at will.

II. Setup

The metamaterial under investigation consists of a one-dimensional (1D) coplanar waveguide which contains 26 rod-like meta-atoms. A optical micrograph of part of the waveguide is shown in Fig. 1(a). Figure 1(b) shows the single meta atom turned by 90°. The rectangles visible in the ground planes (beige) and central conductor (light blue) are parallel plate capacitors C_{ground} and C_{cen} between the structure and the waveguide. The capacitors are connected via a niobium electrode into which a dc-SQUID and a single junction are inserted. The structure is symmetric with respect to the central conductor. The single junction serves as an additional inductance to the geometric inductance of the strip; the dc-SQUID serves the same purpose, however, its inductance is tunable.

The equivalent electric circuit of the single meta atom (cf. Fig.1(c)) is a resonant structure. Unlike the rf-SQUID or the SRR, it couples to the electric field component of the wave (the magnetic coupling of the built-in, small dc-SQUID is calculated to be small compared to the electric coupling). Due to the tunable inductance of the dc-SQUID, the resonance frequency of this dipole is also tunable. In the following, we shall use the term rod for this meta-atom.

The inductance of the dc-SQUID is tuned by applying a magnetic field perpendicular to the area of the SQUID loop. Therefore, two bias tees before and after the sample are used to superpose the microwave signal in the central conductor with a constant current I_b. The latter produces the external magnetic flux threading the SQUIDs.

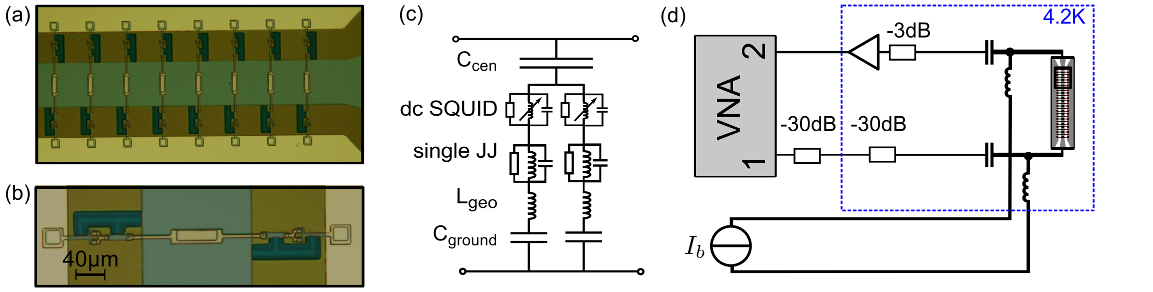

Fig. 1: (a) Optical micrograph (top view) of part of the coplanar waveguide containing electrically coupled structures. (b) Zoom of one structure consisting of parallel plate capacitors to both ground planes and central conductor, one dc-SQUID and one single junction in each gap. The blue F-shaped structures are necessary for fabrication but irrelevant for the experiment.(c) Electric circuit equivalent of the single meta-atom. (d) Sketch of the experimental setup.

As shown in Fig. 1(d), the sample including part of the microwave setup is immersed in liquid helium, i.e. at a temperature of $T = 4.2\,$K. The two ports of a vector network analyzer are connected to either end of the setup and the complex transmission is measured as a function of frequency and magnetic flux.

III. Results

The main difference between the rods and the rf-SQUIDs investigated in Ref. [5, 4] as magnetically coupled meta-atoms (apart from the nature of the coupling) is, that the rods affect the transmission through the waveguide at any frequency and not only when in resonance. Calculating the dispersion relation for such an infinite periodically loaded line [9] shows that the phase velocity is strongly decreased. Additionally, propagating waves are only allowed below the stop band which starts for zero external flux at $\nu_{\text{stop}} = 10.2\,$GHz. Since our transmission line contains only a finite number of unit cells, each containing one rod, only discrete frequency values within the first pass band $0 < \nu < \nu_{\text{stop}}$ are allowed. By cascading the ABCD matrices of 26 unit cells, the transmission matrix for our system can be calculated. The resulting frequency dependent transmission magnitude $|S_{21}|$ is shown in Fig. 2(a) for different flux values. The horizontal axis shows the external flux in units of flux quanta in the loop of the dc-SQUID. The decrease of the onset of the stop band is due to the magnetic flux dependent inductance. The response of the dc-SQUIDs is a periodic function of magnetic flux with a period of flux quantum $\Phi_0 = h/2e$. It approaches infinity as the flux enclosed by the SQUID loop approaches half a flux quantum.

The features which are visible around $\Phi_{\text{ext}} = \pm 0.5\Phi_0$ and go up to 20 GHz are the third pass band. The second pass band is very narrow and therefore not visible. Additionally, it exists only at flux values close to zero. This is due to the resonance nature of the rods.

The aforementioned discrete frequencies where propagation and thus high transmission is possible are clearly visible in Fig. 2(a) and (b). They correspond to the lighter (yellow, white) stripes in the lower frequency region between 1 GHz and 10 GHz in Fig. 2(a).

When comparing the simulation to the measured transmission magnitude (Fig. 2(b)), we also find the discrete frequencies at which transmission is allowed as in the simulation. The features of the third band around $\Phi_{\text{ext}} = \pm\Phi_0$ are reproduced, too. Clearly missing in the measured picture is, however, the stop band. This may be due to parasitic modes in the sample holder that offer a transmission band or other unwanted effects in the sample mounting. However, since the transmission through this band shows no dependence on magnetic field, it does not seem to be an intrinsic property of this meta-atom design.

IV. Conclusion

A novel electrically coupled meta-atom intended for application in a coplanar waveguide geometry was introduced. Since part of the total inductance is tunable, the onset of the stop band can be adjusted by applying a constant magnetic field. The transmission through a 1D metamaterial consisting of 26 such meta-atoms was investigated. Simulation and measurement agree very well apart from the finite transmission in the stop band. Once the

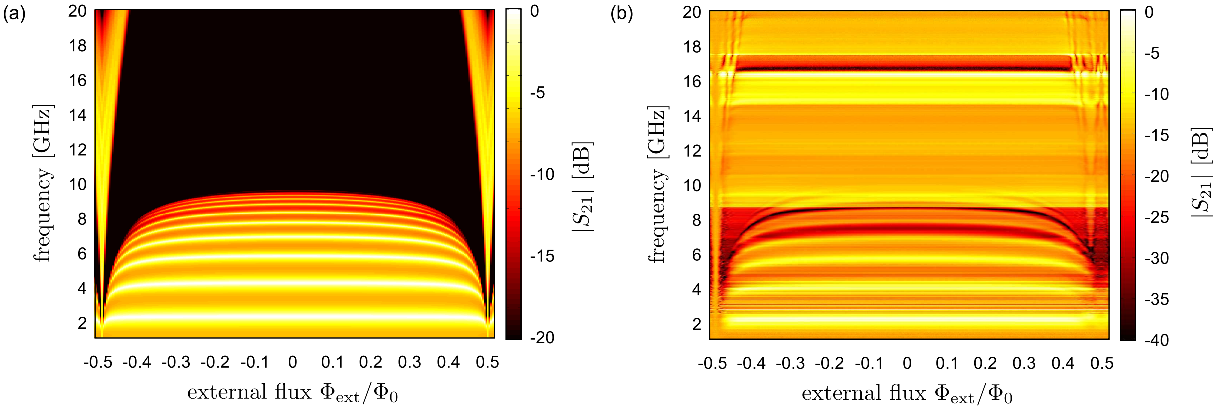

Fig. 2: (a) Simulated transmission magnitude through a periodically loaded coplanar waveguide containing 26 rods. (b) Measured transmission through the experimentally fabricated circuit. Note the difference in color scales.

issue of the missing stop band is solved, the rods will be combined with tunable, magnetically coupled rf-SQUIDs in order to obtain a tunable negative index pass band.

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