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Imaging the electromagnetic response of superconducting metasurfaces

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Abstract – **We present a method to analyze the electromagnetic behavior of superconducting planar microwave metamaterials. Using a laser scanning microscope (LSM), we image the microwave response of two-dimensional arrays of magnetic meta-atoms. This method allows us to investigate contributions of individual meta-atoms to the macroscopic response and thus provides a useful tool for characterization and optimization. The meta-atoms in the present experiment are frequency tunable superconducting quantum interference devices (SQUIDs).**

I. INTRODUCTION

In recent years, two-dimensional metamaterials – so called metasurfaces – have gained an increasing amount of attention [1]. It has been shown that they can, just as their three-dimensional counterparts, manipulate the properties of electromagnetic waves propagating through them. An abundance of potential applications together with the technological advantage in fabrication makes them a very appealing subject. One well-established way to characterize metamaterials and metasurfaces is to measure the electromagnetic scattering characteristics of individual meta-atoms [2, 3] and large structures [4]. This method, however, is insensitive to contributions of individual meta-atoms to the collective response. While this may not seem important for identical and weakly coupled meta-atoms, it can become essential if one or more local parameters are not well known.

In the present experiment, we demonstrate a method to analyze the contribution of individual superconducting meta-atoms to the collective response of a two-dimensional microwave metamaterial. The structure under investigation is an array of 30 × 30 Nb SQUIDs each containing one Nb-AlOx-Nb Josephson junction. For small excitations signals, they be treated as magnetic field tunable resonators [3, 5]. Although they are nominally identical, spatial inhomogeneities in fabrication or magnetic field (i.e. due to Abrikosov vortices occasionally trapped in superconducting films) can lead to a significant spread of their resonance frequencies.

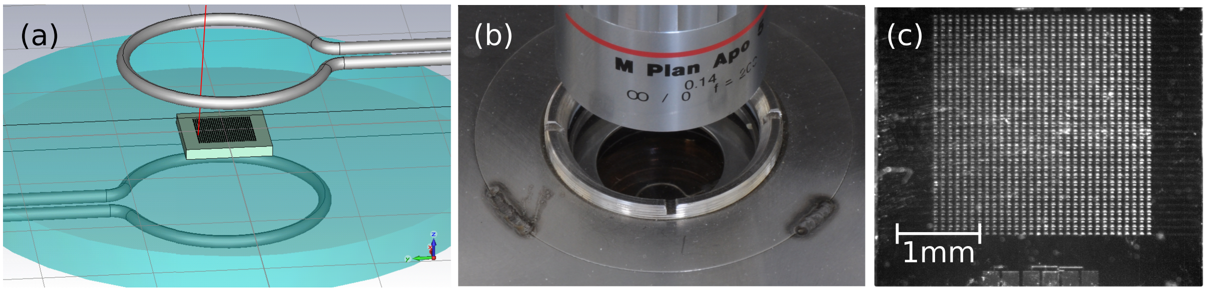

Fig. 1: (a) The sample (array of 30 × 30 SQUIDs on a $4 \times 4\,\mathrm{mm}^2$ silicon chip) is placed on a $4.2\,\mathrm{K}$ cold sapphire cylinder (turquoise). Two pickup-loops above and below excite the sample. The red line symbolizes the laser illumination. (b) Top window of the cryostat with the objective lens. A part of the upper of the two pickup-loops is visible through the window. (c) Microscope image of the sample as seen by the CCD camera of the LSM.

II. EXPERIMENT

Fig. 1(a) shows the setup in which the silicon chip with the SQUID array is placed on a cold sapphire plate located between two pickup loops in a ^{4}He cryostat. In this geometry, the magnetic field generated by the loops is almost perpendicular to the area of the SQUIDs. Additionally, we can also apply a dc magnetic field via a set of large Helmholtz coils outside the cryostat. A modulated, focused laser beam is scanned across the metasurface while we measure the microwave transmission through the two loops as a function of the current position of the laser spot [6]. By locally heating a section of one of the meta-atoms, the illumination causes a slight shift of the resonance frequency of that SQUID. This, in turn, results in a measurable change in the global transmission magnitude which we call photoresponse (PR). For large scale images this allows us to distinguish the SQUIDs that are off resonance (low PR) from those that are close to resonance (high PR) at a fixed frequency. On the level of a single meta-atom, we can image the current flow and the influence of stray magnetic flux.

The SQUIDs used in this structure have outer dimensions of $66 \times 45\,\mu\mathrm{m}^2$ and a pitch of $90\mu\mathrm{m}$. The mutual inductance between neighboring SQUIDs is much smaller than their self inductance so the coupling is very weak. It has been shown in previous experiments that their resonance can be tuned between about $10\,\mathrm{GHz}$ and $20\,\mathrm{GHz}$ by applying a magnetic field on the order of $\mu\mathrm{T}$.

III. RESULTS

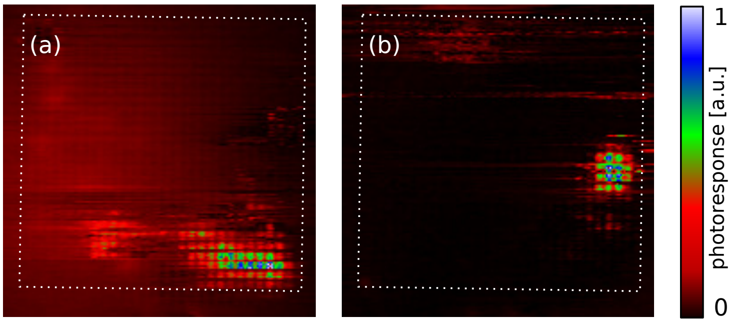

Fig. 2: Two-dimensional photoresponse map of the entire 30×30 SQUID structure shown in Fig.1(c) at (a) $16.74\,\mathrm{GHz}$ and (b) $16.87\,\mathrm{GHz}$ The magnitude of the PR is color-coded using the color-scale on the right where white and black stand for high and low photoresponse, respectively. The white-dotted box indicates the edges of the array in both pictures.

We have measured the photoresponse of the complete array and small subsections. Contrary to the design intentions, no uniform response could be observed over the whole area of the array. Some subsections, however, exhibit a strong collective PR (cf. Fig. 2) at frequencies between 16.7GHz and 17GHz at high excitation power levels. This response is mostly independent of magnetic field. At lower power levels, we were able to image a magnetic field dependent photoresponse, that is periodic for fields on the order of magnitude expected for one flux quantum in the SQUID-loop (cf. Fig. 3). Finally we use this technique to visualize sensitive areas inside individual meta-atoms which is shown in Fig. 4. In this regime we are sensitive to nonlinear and dissipative effects inside the superconductor and junction. Here, sweeping the magnetic field over a larger range also leads to a visible magnetic hysteresis which is most likely caused by flux getting trapped in the SQUID ring.

IV. CONCLUSION

We have demonstrated a technique to investigate spatial properties of two-dimensional, superconducting metamaterials. Using a combination of laser scanning microscopy and microwave transmission measurements we can image the contribution from individual meta-atoms to the collective response of the metasurface. We have shown the versatility of this method by investigating an array of SQUIDs where we were able to visualize the microwave response on length-scales ranging from the whole array down to the individual meta-atom. This method can be

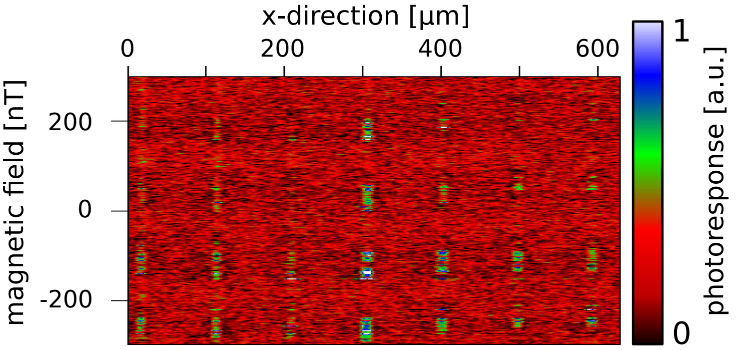

Fig. 3: A one-dimensional scan across seven Josephson junctions as a function of magnetic field. All seven junctions show a periodic modulation in photoresponse. The periodicity is on the expected order of magnitude ($\approx 700\,\mathrm{nT}$) but the field bias appears to be slightly different for every junction.

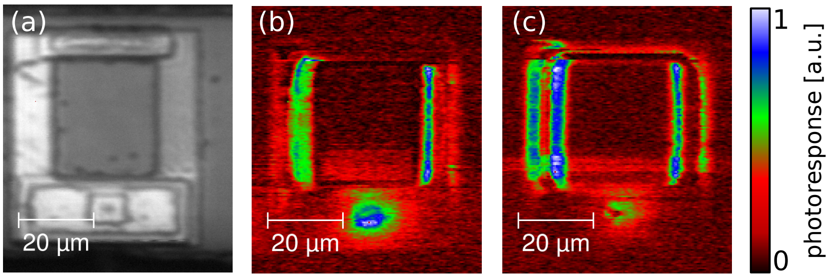

Fig. 4: (a) LSM reflectivity image of a single SQUID meta-atom. (b) Photoresponse at $16.97\,\mathrm{GHz}$ in zero additional magnetic field at $16.994\,\mathrm{GHz}$. (c) A significant hysteresis can be observed after sweeping the magnetic field to $B \approx 2\,\mu\mathrm{T}$ and back.

extended and applied to other superconducting metasurfaces in order to overcome technological and experimental difficulties inherent in this technology.

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