# Imaging Coherent Response of a Superconducting Metasurface

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**Abstract**— We study microwave response of the individual meta-atoms 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 Laser Scanning Microscopy (LSM) technique. We tested a sample with $21 \times 21$ 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.

**Introduction:** A two-dimensional array of SQUIDs is an example of a tunable superconducting metasurface [1]. Here the SQUIDs are playing a role of magnetically coupled meta-atoms, tunable with external magnetic field [2]. Recently the microwave response of SQUID arrays has been studied theoretically [3,4] and also experimentally [5,6]. In published experiment it is difficult to estimate the actual number of the SQUIDs involved in synchronized RF response. We are using a cryogenic LSM [7] in order to observe the responses of the individual SQUIDs in the array, and to characterize the spatial distribution of the coherent response of the array to microwave signal.

**Experiment and Results:** In the test setup, the probing microwave signal should be uniform and have magnetic field component directed orthogonal to the plane of the SQUID array. To achieve this, we place the SQUID array sample in the plane of symmetry of a rectangular waveguide, where the magnetic field of the fundamental $TE_{10}$ mode is perpendicular to the sample plane. The designed waveguide test section has two coaxial adapters for the broadband connection to the network analyzer. The LSM access is made via a small hole in the waveguide wall, with the size much smaller than the cutoff wavelength for RF. The test sample is an array of $21 \times 21$ SQUIDs, where each SQUID is a Nb thin-film rectangular loop, with outer dimensions of $70 \times 50\,\mu\mathrm{m}^2$, interrupted by a single Nb/AlO$_x$/Nb Josephson junction.

In transmission experiment with the SQUID array, the array collective response is visible as a resonance peak tunable over 56% band (8.5–12 GHz). The resonance peak is narrow, about 20 MHz wide, and resembles a response of a single resonator. We used LSM to visualize the RF currents in the individual SQUIDs at the resonance frequency of the array. The LSM imaging shows that about 50% of the SQUIDs in the array are resonating coherently.

**Conclusion:** Our experimental study of superconducting metasurface with $21 \times 21$ SQUID array indicates a nearly synchronized resonant response of the array and a broad frequency tuning range of the metasurface. The LSM imaging of the currents in the individual SQUIDs shows a partial uniformity, where about 50% of the SQUIDs participate in the coherent response. The spatial structure of the SQUID array response will be discussed. SQUID-based metasurface has low losses and a good frequency tunability, and can be useful for designing compact cryogenic RF systems.

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