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rf SQUID Metamaterials: A Rich Nonlinear Setting for Applications

Jingnan Cai, Seokjin Bae, Steven M. Anlage
Physics Department
Center for Nanophysics and Advanced Materials
University of Maryland
College Park, MD 20742-4111 USA
anlage@umd.edu

Alexander P. Zhuravel
B. Verkin Institute for Low Temperature Physics and Engineering
Kharkov 61103, Ukraine

***Abstract*— We summarize work on the nonlinear properties of radio frequency Superconducting Quantum Interference Device (rf SQUID) based metamaterials and discuss how this platform enables new applications. The metamaterials show extreme tunability of their resonant response, ranging in principle from 10's of GHz to zero frequency, all within the tuning parameter range of one half flux quantum of magnetic field. They also display strong and tunable intermodulation response and can be used for amplification and mixing. We also investigate the "dark modes" of oscillation of the rf SQUID metamaterial through a microscopic investigation of the status of each SQUID in the array while in operation under cryogenic conditions. These images reveal very complex behavior of the metamaterial in the low excitation strength limit. Surprisingly, we find that large rf flux amplitudes change the metamaterial response and tend to erase defects and disorder to create coherent oscillations of the array.**

Keywords—rf SQUID, Metamaterial, Intermodulation, Laser Scanning Microscope, Chimera

I. Introduction

Metamaterials are made up of closely-spaced "meta-atoms," each of which is nominally identical and is designed to create some non-trivial interaction with electromagnetic fields. The meta-atoms are much smaller than the wavelength of the electromagnetic waves, and thus create a coarse-grained collective response to the fields. One can thus create effective media that are endowed with new properties not available in nature, such as negative refraction or the ability to re-direct and manipulate light in novel ways.

In the distant past rf SQUIDs were used to measure low-frequency magnetic fields through the change in mutual inductance between the (non-resonant) SQUID and a nearby resonant rf tank circuit. The simplest rf SQUID is a superconducting loop that is interrupted by a single Josephson junction. We have taken the rf SQUID in a new direction by treating it as a stand-alone resonant meta-atom which is driven by external dc and rf magnetic flux [1-6]. The rf SQUID combines two macroscopic quantum phenomena, namely flux quantization and the Josephson effect. This allows one to utilize an external flux in the loop to effectively control the gauge-invariant phase difference δ on the Josephson junction. This in turn allows one to control the Josephson inductance $L_{JJ}=\Phi_0/(2\pi\, I_c(T) \cos\delta)$, where Φ_0 is the magnetic flux quantum, $I_c(T)$ is the temperature dependent critical current of the junction, and the gauge invariant phase δ runs from 0 to 2π as the dc magnetic flux in the SQUID loop varies from 0 to Φ_0. The rf SQUID is thus an LC-resonant circuit with variable inductance. The Josephson inductance can be tuned through positive and negative values as the dc magnetic flux is varied, creating an extreme degree of tunability. We can design the SQUID such that the geometric inductance of the loop can be exactly canceled by the negative Josephson inductance, which permits tuning of the SQUID self-resonance from the microwave domain to dc [6].

II. Overview

Through experiments, numerical simulations, and analytical theory we have explored the behavior of strongly nonlinear 0D, 1D, and 2D rf SQUID metamaterials, which show extreme tunability and nonlinearity [6-8]. Because the rf SQUIDs are intrinsically nonlinear, it is interesting to study the collective nonlinear properties of large ensembles of strongly coupled meta-atoms. The coupling is achieved by mutual inductance of the SQUID loops, and this interaction can be of long range. Through this coupling we expect to create non-trivial collective response of the metamaterial.

III. Experiment

The rf SQUID metamaterials are measured in a waveguide geometry that provides a uniform rf magnetic flux bias to the SQUIDs by means of the passing electromagnetic wave that is used to measure the transmission scattering parameter S_{21}. For a single SQUID, the transmission shows a sharp dip as a function of frequency when an rf SQUID resonance is achieved. For the full rf SQUID metamaterial, there are many collective modes of oscillation. There is one such mode that involves a strongly phase-coherent oscillation of all the SQUIDs and results in a sharp absorptive minimum in S_{21} vs. frequency. Many other modes of oscillation of the metamaterial exist [9], but these have very small scattering cross section with the passing electromagnetic waves [8, 10].

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These "dark modes" of oscillation can be visualized and studied by means of our laser scanning microscope [10].

IV. Intermodulation Results

We investigate the SQUID metamaterial as a nonlinear medium through detailed two-tone intermodulation (IM) measurement over a broad range of tone frequencies and tone powers [11]. A sharp onset followed by a surprising strongly suppressed IM region near the resonance is observed. Using a two time-scale analysis technique, we present an analytical theory that successfully explains our experimental observations. The theory predicts that the IM can be manipulated with tone power, center frequency, frequency difference between the two tones, and temperature [11].

V. LSM Imaging of rf SQUID Metamaterial Dark Modes

The spatial response of the rf SQUID lattice under cryogenic conditions and rf and dc flux bias is investigated with a laser scanning microscope (LSM). LSM photoresponse images at zero dc flux and low rf flux bias show no evidence of large-scale coherent response from the rf SQUID lattice. Instead we find small clusters of coherent SQUIDs adopting a variety of resonant frequencies. Spatial synchronization of the rf SQUIDs occurs under increased rf flux bias,[10] in agreement with our earlier results based on global transmission measurements and simulation [8, 12]. Motivated by many new theoretical studies based on our experiments [13 - 20], we expect that many other interesting collective behaviors, such as Chimera states,[13 – 15, 17, 19 - 20] will be discovered in this remarkable nonlinear metamaterial.

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References.

[1] C. Du, H. Chen, and S. Li, "Quantum Left-Handed Metamaterial from Superconducting Quantum Interference Devices," Phys. Rev. B vol. 74, 113105 (2006).

[2] C. Du, H. Chen, and S. Li, "Stable and Bistable SQUID Metamaterials," J. Phys. Condens. Matter vol. 20, 345220 (2008).

[3] N. Lazarides and G. P. Tsironis, "rf Superconducting Quantum Interference Device Metamaterials," Appl. Phys. Lett. vol. 90, 163501 (2007).

[4] A. I. Maimistov and I. R. Gabitov, "Nonlinear Response of a Thin Metamaterial Film Containing Josephson Junctions," Opt. Commun. vol. 283, 1633 (2010).

[5] N. Lazarides and G. P. Tsironis, "Multistability and Self Organization in Disordered SQUID Metamaterials," Supercond. Sci. Technol. vol. 26, 084006 (2013)

[6] M. Trepanier, D. Zhang, S. M. Anlage, O. Mukhanov, "Realization and Modeling of Metamaterials Made of rf Superconducting Quantum-Interference Devices," Phys. Rev. X vol. 3, 041029 (2013).

[7] D. Zhang, M. Trepanier, O. Mukhanov, and S. M. Anlage, "Tunable Broadband Transparency of Macroscopic Quantum Superconducting Metamaterials," Phys Rev. X vol. 5, 041045 (2015).

[8] M. Trepanier, D. Zhang, O. Mukhanov, V. P. Koshelets, P. Jung, S. Butz, E. Ott, T. M. Antonsen, A. V. Ustinov, S. M. Anlage, "Coherent Oscillations of Driven rf SQUID Metamaterials," Phys. Rev. E vol. 95, 050201(R) (2017).

[9] M. Eleftheriou, N. Lazarides, and G. P. Tsironis, "Magnetoinductive breathers in metamaterials," Phys Rev E vol. 77 (3), 036608 (2008).

[10] A. P. Zhuravel, S. Bae, A. V. Lukashenko, A. S. Averkin, A. V. Ustinov and S. M. Anlage, "Imaging collective behavior in an rf-SQUID metamaterial tuned by DC and RF magnetic fields," Appl. Phys. Lett. vol. 114, 082601 (2019).

[11] D. Zhang, M. Trepanier, T. M. Antonsen, E. Ott, S. M. Anlage, "Intermodulation in Nonlinear SQUID Metamaterials: Experiment and Theory," Phys. Rev. B vol. 94, 174507 (2016).

[12] M. Trepanier, Ph.D. thesis (University of Maryland, 2015), http://drum.lib.umd.edu/handle/1903/17290.

[13] N. Lazarides, G. Neofotistos, and G. P. Tsironis, "Chimeras in SQUID metamaterials," Phys Rev B vol. 91, 054303 (2015).

[14] J. Hizanidis, N. Lazarides, and G. P. Tsironis, "Robust chimera states in SQUID metamaterials with local interactions," Phys Rev E vol. 94, 032219 (2016).

[15] N. Lazarides and G. P. Tsironis, "SQUID metamaterials on a Lieb lattice: From flat-band to nonlinear localization," Phys Rev B vol. 96, 054305 (2017).

[16] J. Hizanidis, N. Lazarides, and G. P. Tsironis, "Flux bias-controlled chaos and extreme multistability in SQUID oscillators," Chaos: An Interdisciplinary Journal of Nonlinear Science vol. 28, 063117 (2018).

[17] Amitava Banerjee and Debopriya Sikder, "Transient chaos generates small chimeras," Phys Rev E vol. 98, 032220 (2018).

[18] N. Lazarides and G. P. Tsironis, "Multistable dissipative breathers and collective states in SQUID Lieb metamaterials," Phys Rev E vol. 98, 012207 (2018).

[19] J. Hizanidis, N. Lazarides, and G. P. Tsironis, "Chimera states in networks of locally and non-locally coupled SQUIDs," arXiv:1902.02158 (2019).

[20] N. Lazarides, J. Hizanidis, and G. P. Tsironis, "Controlled Generation of Chimera States in SQUID Metasurfaces using DC Flux Gradients," arXiv:1902.01711 (2019).