Realising tunable, quantum and low-loss metamaterials and plasmonics with superconductors

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Abstract

The use of superconductors over normal metals offers a significant reduction in ohmic losses, providing interesting opportunities for metamaterials and terahertz plasmonics. Superconducting Josephson junction metamaterials and other metamaterial quantum interference devices are inherently nonlinear, making them promising candidates for use in sensor and switching application as well as quantum information processing.

1. Introduction

Metamaterials fabricated from superconductors are characterized by significantly reduced ohmic losses then in their normal-metal counterparts, opening the door to the realisation of low-loss and high *Q*-factor metamaterials. This sharp dispersion makes superconducting metamaterials promising media for use in various sensor and switching applications. Accordingly superconducting metamaterials have received significant attention since their first practical demonstration [1], and recently we reported the first free-space measurements of metamaterials fabricated from the high-critical temperature (T_C) superconductor $YBa_2Cu_3O_{7.5}$ [2]. Significant and non-linear enhancement of the Fano and dipole resonances was observed as the metamaterial temperature was decreased below T_C, owing to the ohmic resistance being replaced by a more dominant kinetic inductance, permitting the existence of plasmonic excitations [3]. The concept of plasmonic excitations in the microwave and terahertz part of the spectrum gives rise to the potential for superconducting waveguides supporting low-loss plasmon waves for the transport of information in compact data processing circuits. Furthermore, the intrinsic nonlinear nature of superconducting metamaterials render them ideal candidates for sensor applications, their applicability enhanced only further by the concept of superconducting Josephson junction (JJ) quantum metamaterials.

2. Tunable, quantum metamaterials

Several groups [4, 5, 6] have proposed using the quantum properties of the superconducting state to generate a nonlinear response of metamaterials on the quantum level. These suggestions revolve around the use of JJ and their associated non-linear properties and strong response to small external stimuli. To realise such a material, we translate the classical metamaterial into a truly quantum system by replacing the traditional split ring resonator (SRR) with a JJ ring device. The fundamental property associated with the JJ is that of magnetic flux quantization. Our JJ-based SRRs trap magnetic flux within each ring leading to flux quantization. The behaviour of the magnetic flux threading through the ring (Φ) is governed by the non-linear differential equation:

$$\ddot{\Phi} + \gamma\dot{\Phi} + \beta\sin(2\pi\Phi) + \Phi = \Phi_{ext} \quad (1)$$

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where γ represents dissipation within the system, β is related to the inductance, critical current and the flux quantum, and Φ_{ext} is a magnetic flux generated by an external source. This elegantly and simply explains the non-linear response of the JJ-based metamaterial. Practical realization of large arrays of JJ-based superconducting metamaterials is a highly sophisticated process, but the design and fabrication hurdles have been overcome and we present the first experimental results based upon such a large-scale quantum metamaterial made from a Nb process. Example micrographs of these metamaterials are given in Fig. 2 and Fig. 2.

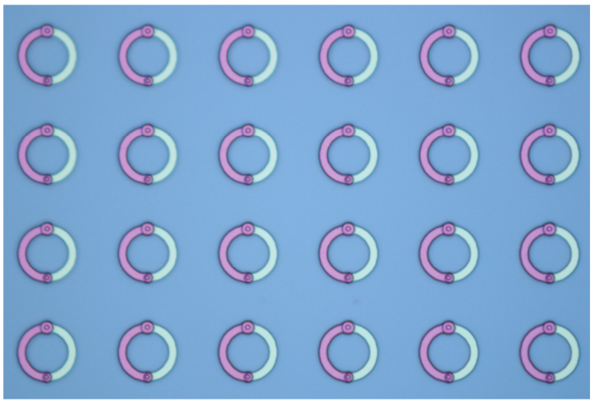

Fig. 1: Optical micrograph of an array of JJ metamolecules. The complete array consists of over 10,000 elements. The ring diameter is 20 μm and the JJ diameter is 1.5 μm.

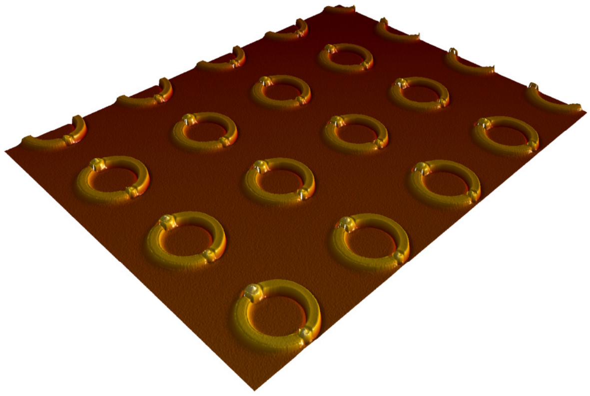

Fig. 2: 3D optical micrograph of a single JJ metamolecule. The JJ sits in the plane of the material. Dimensions are given in Fig. 1.

The response of this JJ-based metamaterial is analysed as a function of temperature and applied RF and DC magnetic fields. Example data showing the response of the metamaterial to temperature is given in Fig. 3, where the largest response of the material is shown to be close to the T_C (9.0 K).

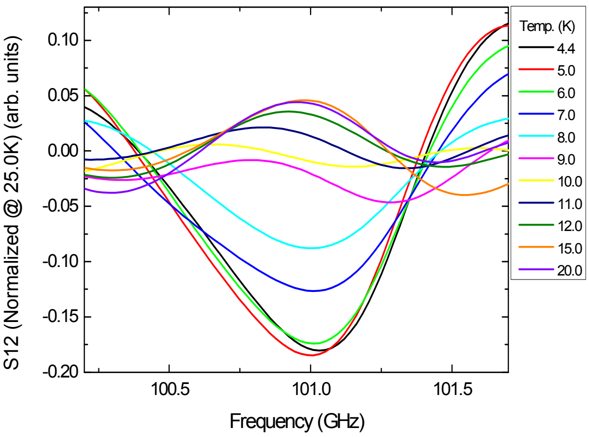

Fig. 3: Experimental data showing response of a JJ-based metamaterial resonance to changes in temperature. As expected for a Nb-based metamaterial, the largest change occurs close to T_C.

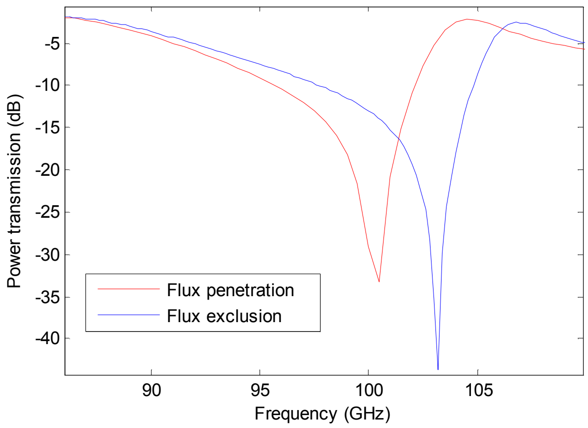

Fig. 4: Graph of computational modelling results for the FLEXMET, in both full magnetic flux exclusion (blue) and full flux penetration (red) configurations.

In such a JJ-based metamaterial, for some values of applied magnetic field the concept of magnetic flux quantization leads to complete magnetic field exclusion within the structure. Flux quantization and exclusion may be engineered in uniquely designed metamaterial structures other than those based upon JJs. Here we use such novel materials to study nonlinearities stemming from magnetic flux quantization and exclusion in larger, more traditional superconducting metamaterials (FLEXMET), based upon metamolecules of SRRs and intra-structure elements. In FLEXMETs, a SRR is driven by an external microwave field, establishing an oscillating magnetic field. The intra-structure in the FLEXMETS will only allow penetration by a quantized number of magnetic flux quanta, Φ_0. Due to the intra-structure's small area, even a single quantum of flux corresponds to a significant local magnetic field at low enough microwave powers. In this regime, the response of the metamolecule will be altered due to the expulsion of magnetic field from most of its area. The confinement of oscillating magnetic field between the SRR and the intra-structure will result in more energy stored in the magnetic field which in turn will shift the resonant frequency. This is confirmed in the results of computational simulations, plotted in Fig. 4. In FLEXMETs we may accurately engineer flux quantization and exclusion, providing us with an alternative paradigm for achieving nonlinearities in metamaterials.

4. Superconducting plasmonics

The plasmonic regime in the noble metals manifests itself just below the plasma frequency, when the free electrons driven by an electromagnetic wave oscillate so rapidly that almost no collisions happen during one oscillatory period. Correspondingly, oscillations of all of the electrons become coherent and their acceleration is determined by the strength of the incident field and the kinetic inductance. On the other hand, in the superconducting state, the absence of electron scattering and the dominant kinetic inductance of the charge carriers are natural, resulting from the formation of Cooper pairs, which permit the existence of efficient plasmonic excitations (much like optical plasmons) at frequencies ranging from few Hz up to the superconducting gap frequency (around a few THz for high T_C superconductors). In general, electromagnetic fields at the surface of superconductors are almost completely expelled from the medium, making plasmon-polariton like excitations loosely bounded to the surface weekly localized and thus unsuitable for waveguide applications. However, we show that plasmonic fields can be spatially squeezed on the scale of just few tens of nanometers in structured superconducting waveguides; here plasmons remain able to propagate for hundreds of wavelengths, adding up to several centimetres. This opens up the opportunity for low-loss superconducting waveguides to be incorporated into data processing circuits, providing a crucial link between optical and electronic circuitries. Moreover, since the electromagnetic characteristics of superconductors may be readily altered by external stimuli such as magnetic field, electrical current, optical illumination or temperature, the plasmon signal may be efficiently controlled in data processing and interconnect applications.

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