# Plasmonic Behavior of Deep Sub-Wavelength Superconducting RF Metamaterials

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**Abstract**

We have designed and built ultra-small RF metamaterials with magnetically active spiral elements made of superconducting Nb films [1]. RF transmission measurements on single, 1-D and 2-D arrays of spirals show robust magnetic response when Nb is in the superconducting state [2] at frequencies as low as 14 MHz (corresponding to wavelength ~ 3000 ×'meta-atom' size). Numerical simulations capture the main features of the experimental spectra. The resonant features are tunable via variations in temperature and RF magnetic field [3]. As temperature approaches $T_c$, the superconducting kinetic inductance contribution to the total inductance increases, placing this RF metamaterial in the plasmonic limit. We study this approach to the plasmonic limit and compare to the analogous situation of frequency approaching the plasma edge in normal metal metamaterials [4].

## 1. Introduction

Superconducting metamaterials can be made highly compact without significantly increasing Ohmic losses [1]. Spiral-shaped self-resonant *meta-atoms* have strong magnetic response that extends to frequencies as low as 14 MHz in the radio frequency (RF) spectrum. Despite their low resonant frequency and compact size (diameter $D_0$ = 6 mm) these meta-atoms have quality factors on the order of $10^3$ or more. Their resonant properties are strongly tuneable with temperature, and both RF and static magnetic fields, in part through the kinetic inductance of the superconducting electrons [3]. The spirals are fabricated with thin films of the conventional superconductor Nb deposited on single crystal dielectric substrates. The 200-nm thick films are patterned by a dry etching process and can be made in large numbers through wafer-scale integration.

## 2. Plasmonic Behavior of Superconducting Metamaterials

Metals loose their ability to screen electric and magnetic fields as the frequency approaches the plasma frequency ($\omega_p$) from below. For a resonant object that creates artificial magnetism, one can define a plasmonic parameter $R_{Plasma} = U_{Kinetic}/U_{Magnetic}$ , in terms of the ratio of energy stored in kinetic forms to magnetic forms in the resonant structure [4]. Artificial magnetism is strong for small values of $R_{Plasma} \ll 1$, but degrades in the limit $R_{Plasma} \gg 1$ as $\omega \to \omega_p$.

Superconductors have a superfluid plasma frequency ($\omega_{ps}(T,B,J)$) which is a function of temperature, magnetic field and current, through the superfluid density $n_s(T,B,J)$. Superconducting meta-atoms operating at approximately fixed frequency can be tuned from the limit $R_{Plasma} \ll 1$, to the limit of $R_{Plasma} \gg 1$, simply by varying a parameter such as temperature.

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## 3. Scale Invariance in the Plasmonic Regime

We exploit the scale invariance of Maxwell's equations and find that for a given value of the dielectric function of the superconductor, there is a specific value of $K = \omega D_0/c$ at which magnetic resonance is achieved. We have fabricated a series of scaled spiral meta-atoms (Fig. 1) and studied their resonant properties as a function of temperature from the metallic to the plasmonic regime.

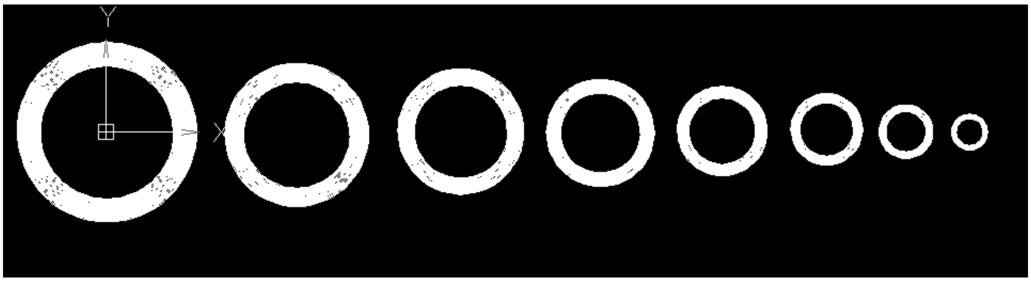


Fig. 1: Image of the lithographic mask used to produce the scaled spiral meta-atom resonators with diameters ranging from 12 mm on the left to 3 mm on the right.

Preliminary data for the resonant frequency versus temperature for three of the scaled spirals are shown in Fig. 2. The data scale together approximately by plotting the scaled frequency versus the scaled temperature. However near $T_c$, in the plasmonic regime, the data separate. Here we expect the product $n_s(T)D_0^2$ to remain constant. From this, one can extract the superfluid density evolution versus temperature and compare to the expected Ginzburg-Landau temperature dependence near $T_c$.

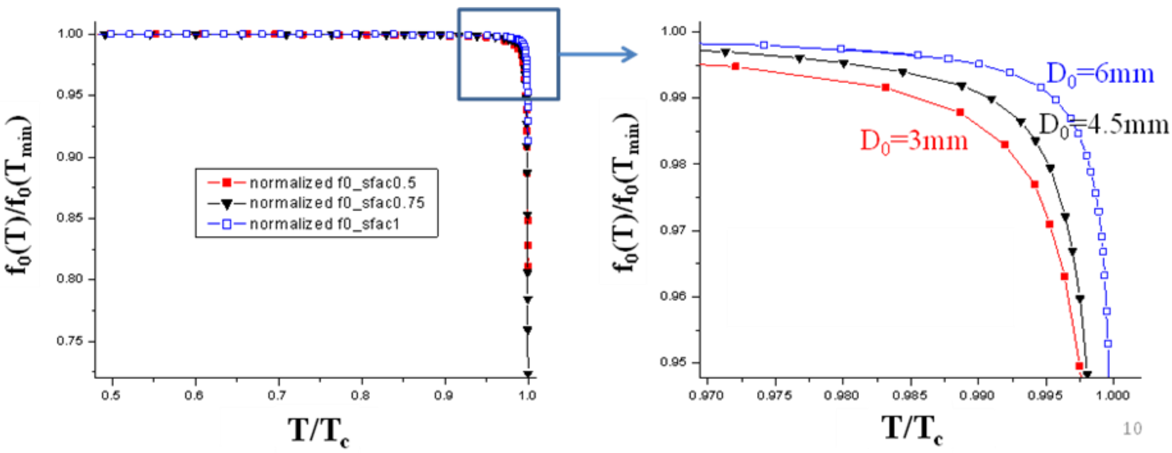


Fig. 2: Scaled resonant frequency versus scaled temperature for three scaled spirals of diameters 3 mm ($f_0(T_{min})$ = 150 MHz), 4.5 mm ($f_0(T_{min})$ = 101 MHz), and 6 mm ($f_0(T_{min})$ = 76 MHz). The critical temperature was approximately $T_c$ = 9.2 K in all cases.

## 4. Conclusion

We have exploited the analogy between the superfluid plasmonic properties and ordinary metal plasmonic physics to study the loss of artificial magnetism upon approach to the plasmonic limit. The extreme sensitivity of the superfluid density to external perturbations allows us to carefully examine the loss of screening properties with a series of scaled magnetically active superconducting meta-atoms.

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