Dynamic tuning in metamaterials exhibiting electromagnetically induced transparency

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Abstract

Metamaterials designed to display electromagnetically induced transparency (EIT) have potential applications in telecommunication because of their large phase shifts and delay-bandwidth products. Therefore, the ability to tune the performance of these metamaterials is crucial in terms of their functionality in various applications. Here we demonstrate a precise and sensitive control on EIT response of a mematerial composed of superconductor/normal metal hybrid structure through temperature and RF magnetic field.

1. Introduction

Electromagnetically induced transparency (EIT) is a coherent optical process observed in quantum mechanical systems rendering the light with no absorption and steep dispersion [1]. The characteristics of EIT have been classically reproduced with engineered metamaterials [2, 3, 4]. Those metamaterials have employed combinations of carefully designed special resonators, called dark and radiative elements, to demonstrate EIT-like effects [5, 6]. Radiative elements directly couple to the external electromagnetic field, whereas dark elements have vanishing dipole interaction with it. Opening a transparency window in the transmission spectrum requires significant loss contrast between two types of elements forming the metamaterial.

The EIT metamaterials implemented with solely normal metal components lack sufficient loss gradient. Here, we introduce a design jumping that hurdle by employing superconducting thin films in the dark element and normal metal films in the radiative element. The proposed EIT metamaterial is made of double planar Nb split ring resonators (SRRs) symetrically located around a Cu strip (see the inset of Fig.1b). The details of the fabrication and design can be found in Ref [7]. Below the transition temperature, T_c, of Nb [8], the dark element (Nb SRRs) shows almost no resistance whereas the radiative element (Cu strip) remains lossy, this contrast develops a transparency window and gives rise to a very large group delay [7].

The microwave measurements are done by mounting the single chip of EIT metamaterial at the center of a Nb X-band waveguide of length 10.3 cm. Ideal alignment of the Cu strip with the electric field of

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the fundamental waveguide mode results in a single EIT resonant feature in the simulated transmission spectrum. However, small deviations (which are inevitable in experiments) cause two extra dark modes to emerge which are uncoupled to the Cu strip in the presence of perfect symmetry [7]. The 2x2 scattering matrix and group delay data are obtained via a network analyzer for a range of temperatures from room temperature down to 4.2 K.

2. Tuning the EIT Response with Temperature

Since the mechanism of the classical EIT-effect presented here is basically based on maintaining the loss contrast between the dark and radiative elements, modification of the resistance difference between the elements tunes the response. One way to achieve it is by changing the superfluid density of the Nb thin film via temperature. Fig. 1(a) and (b) show the evolution of transmission and group delay data for a set of temperatures. At the lowest temperature (4.4 K) one can see three very intense EIT-like resonant peaks, since the surface resistance of Nb differs from that of Cu significantly. The enhancement in both data get weaker with increasing temperature [9], because of the increase in ohmic loss of the dark element (see the inset of Fig. 1a). Finally, at T_c (9.26 K), Nb becomes a normal metal and can not maintain a significant loss contrast with Cu, which results in closing the transparency window and no enhancement in group delay.

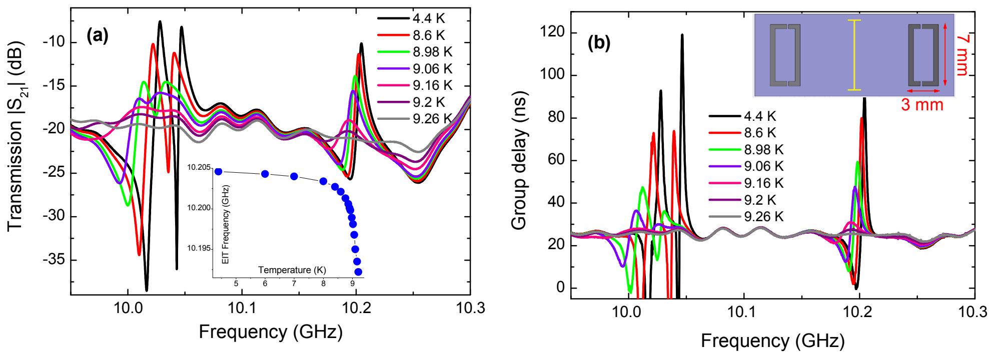

Fig. 1: (Color online) (a) Transmission $|S_{21}|$ vs frequency of EIT metamaterial for a set of temperature, the excitation power is -10 dBm. The inset shows the highest EIT resonant frequency as a function of temperature. (b) Group delay vs. frequency for the same sample. The inset is the cartoon picture of the EIT sample showing Nb split rings around a Cu strip.

3. Tuning the EIT response with RF input power and Nonlinearity

Superconducting thin films show non-linear response to incident electromagnetic waves. This response can be controlled by the power of the electromagnetic waves, because the superfluid density also depends on the magnetic field.

Superconductors create screening currents resisting the applied magnetic field. Fig. 2(a) shows the tunability of the highest frequency/main EIT feature with a set of RF input powers ranging from -40 dBm to +18 dBm. The ambient temperature at which experiments were conducted is 4.4 K. With increasing microwave power, the magnetic penetration depth will increase due to reduction of the density of superconducting carriers. In addition, RF magnetic vortices can enter the structure and change the inductance and loss of the dark element. This causes a reduction in transmission along with systematic jumps with progressing input. At +15 dBm, the main EIT peak collapses, but the spectra still do not reach the backgroud until +18 dBm where Nb is driven into the normal state and the transparency window closes. This

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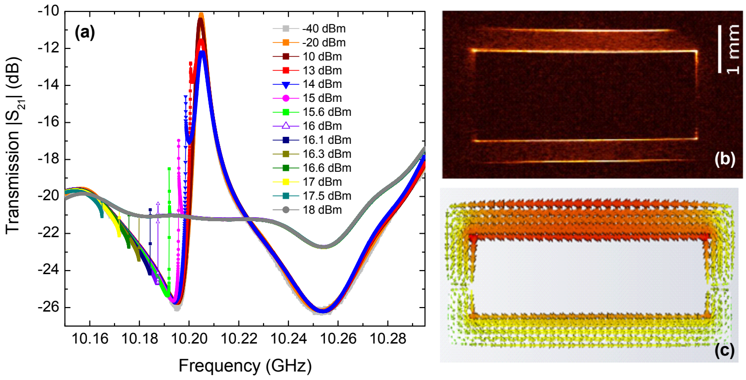

Fig. 2: (Color online) Transmission $|S_{21}|$ vs frequency for the same EIT sample at 4.4 K for a set of RF input powers. (b) The LSM image on one of the Nb split rings at the EIT resonance. Light areas correspond to large current density. The image was acquired at a frequency of 9.747 GHz, input power of +18 dBm, and a temperature of 7 K. (c) The numerical simulations run for the same geometry showing the RF current distributions on the EIT sample.

implies that local Joule heating accompanies magnetic field effects on EIT characteristics between +15 and +18 dBm.

We examined the distributions of RF currents on the surface of the sample at EIT resonance with Laser Scanning Microscopy (LSM). For this, the sample is excited in a similar way as a laser beam illuminates a spot on the sample surface. The local heating generated by the laser creates a change in transmission characteristics which is proportional to RF current density. Fig. 2b presents an LSM image showing RF current distributions of one of the SRRs in the metamaterial. The clearest photoresponse contrast is seen at the inside and outside edges of Nb thin film conductor. The microwave current density is enhanced there to maintain the Meissner state in the interior of the superconductor [10]. Note the similarity between the LSM photoresponse image and the calculated current distributions [7] at EIT resonance shown in Fig. 2c.

4. Conclusion

In conclusion, we have demonstrated dynamic and sensitive tunability of superconductor/normal metal hybrid EIT metamaterial through changes in superfluid density. Either temperature or RF magnetic field modifies the loss contrast between the elements of the sample enabling precise control of the EIT response.

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