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Plasmon-induced transparency in metamaterials: Active near field coupling between bright superconducting and dark metallic mode resonators

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Structured plasmonic metamaterial devices offer the design flexibility to be size scaled for operation across the electromagnetic spectrum and are extremely attractive for generating electromagnetically induced transparency and slow-light behaviors via coupling of bright and dark subwavelength resonators. Here, we experimentally demonstrate a thermally active superconductor-metal coupled resonator based hybrid terahertz metamaterial on a sapphire substrate that shows tunable transparency and slow light behavior as the metamaterial chip is cooled below the high-temperature superconducting phase transition temperature. This hybrid metamaterial opens up the avenues for designing micro-sized active circuitry with switching, modulation, and "slowing down terahertz light" capabilities. © *2013 AIP Publishing LLC*.
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Metamaterials have become a burgeoning field of research in the recent years due to their unique capabilities for the manipulation of electromagnetic radiation and the potential of having plethora of practical applications such as perfect lenses, invisibility cloaking, sensors, antennas, frequency selective surfaces, and modulators.[1] The most remarkable feature is the freedom to be able to design the meta-atoms at will in order to have desired resonances at specific electromagnetic frequency so as to have engineered and well controlled optical properties mimicking the natural materials. Optical properties of materials can be drastically modified by using a secondary light beam as pump, for example, an otherwise opaque material can be instantly made transparent in the presence of a pump beam leading to the phenomena of electromagnetically induced transparency (EIT).[2] EIT is a quantum effect caused by interference between coherences excited in the atom by electromagnetic fields. A three-level atomic system coupled to two laser fields usually exhibits interference effects between probability amplitudes at a resonance transition frequency that may either lead to an enhancement or cancellation of absorption. This interference is analogous to constructive and destructive interference observed in the classical waves.

Hau and co-workers achieved record slowing down of light group velocity through EIT at cryogenic temperatures in ultracold atomic cloud.[3] Slow light opens the door to a whole new range of exciting avenues such as nonlinear effects arising from the enhanced timescale of light matter interactions. It could also lead to the development of sophisticated all-optical information processing that can store, delay, and switch optical data bits. There is also a strong demand for the design and development of all-optical buffer memories and routers that could provide an active control over the flow of data in the next-generation telecommunication networks, without the requirement to convert optical signals to electronic data. Additionally, slow-light medium is anticipated to have a far-reaching impact on electromagnetic signal processing, radar systems, and quantum information science.[4]

Recently, classical field interference that mimics the quantum EIT phenomena has been demonstrated as a means for the cancellation of absorption of electromagnetic wave propagating through artificially designed plasmonic metamaterials at a desired frequency which would otherwise be non-transparent.[5–36] This phenomenon has been termed as plasmon-induced transparency (PIT).[7] PIT involves coupling between two distinct resonators in a unit cell of the metamaterial. One of the resonators is highly radiative possessing a broader resonance feature and is called a "bright" resonator, whereas the other resonator is a sub-radiant "dark" resonator since it has a much sharper resonance linewidth. The destructive interference between strongly coupled bright and dark resonators results in a well-defined narrow transparency window. Most of the previous schemes consist of coupling between two passive resonators that would not allow the active tuning of the PIT window. In a recent work, active control of the PIT peak was achieved by integrating a photosensitive material in the split gap of the dark resonator and by exciting the metamaterial with an infrared pump laser.[15]

In this letter, our metamaterial unit cell comprises of a high-temperature superconductor close-ring resonator (CRR) that acts as a bright element and a metal split-ring resonator (SRR) as a dark element. The bright and dark nature of the resonators is determined from the quality (Q) factor of the two resonators. The highly radiative bright superconductor

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resonator has a much broader linewidth dipole resonance with $Q = 0.88$ at the lowest temperature of 27 K. On the other hand, the metal SRR supports sub-radiative inductive-capacitive (*LC*) resonance with a $Q = 7.71$, which is nearly one order of magnitude higher than the Q value of the dipole resonance. It is the destructive interference between two strongly coupled resonators with contrasting Q factor values that causes the plasmon-induced transparency which is a classical analog of the quantum EIT phenomena. The interesting feature of this work lies in the thermal control of the bright mode superconducting CRR dipole resonance. At room temperature, the superconductor acts as a poor metal and thus cannot support the excitation of a resonance in the CRR, whereas the metallic SRR shows a strong *LC* resonance. As the metamaterial chip is cooled down to lower temperatures, the superconductor CRR begins to resonate at exactly the same frequency as the metal SRR leading to a tunable coupling between the resonators. The degree of coupling is controlled through the superconductor active resonator. Thus, with the change in temperature, we experimentally observe a tunable PIT resonance window and the thermal control of group delay of the terahertz pulse propagating through the metamaterial chip. Even though the thermal control is slow compared to electrical and optical tuning, the advantage of using high temperature superconductor is the observation of a temperature dependent switching effect due to the phase change of the superconductor. The phase change in superconductors is unique to the temperature dependence, and the hybrid PIT metamaterial used here inherits this unique behavior in the form of dynamic temperature based switching of the PIT resonance band. Recently, ultrafast switching of resonances in high temperature superconductor metamaterials was observed when the metamaterial was photo-excited using femtosecond infrared light pulses.[37]

The metamaterial array and unit cell consisting of an aluminum metal SRR enclosed within an outer Yttrium barium copper oxide (YBCO) CRR is illustrated in Fig. 1. The metamaterial sample was lithographically fabricated on a commercial (THEVA, Germany) 280-nm-thick YBCO film, which typically has phase transition temperature, $T_c = 85$ K and a critical current density of 2.3 MA/cm^2 grown on a 500-μm-thick sapphire substrate. A 3-μm-thick photoresist layer was first patterned with the outer closed rings on the raw YBCO film as an etching protective layer. The sample was then wet etched in 0.04% nitric acid to remove the YBCO from other parts of the wafer that did not have the photoresist protection, forming the closed ring arrays. The 200-nm-thick aluminum SRRs were aligned and fabricated at the center of the outer closed rings by the conventional optical lithography. The microscopic images and geometric parameters are illustrated in Fig. 1. The size of the sample array is 10 mm × 10 mm and contains about 40 000 unit cells of hybrid SRR-CRR metal-superconductor structures.

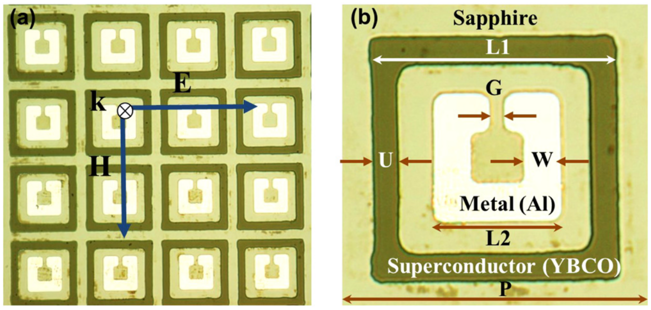

FIG. 1. Microscopic images of (a) a periodic metamaterial array on a sapphire substrate and (b) a metamaterial unit cell with geometrical parameters, L1 = 45 μm, L2 = 22 μm, U = 4 μm, W = 6 μm, G = 3 μm, and a periodicity of P = 50 μm. The incident direction of radiation is normal to the plane and the electric field is parallel to the gap of the inner SRRs.

While designing the metamaterial structure for fabrication, we performed detailed numerical simulations using CST Microwave Studio$^{\mathrm{TM}}$. We simulated the behavior of metal SRR and superconductor CRR independently and ensured that their resonance frequencies are close by and the Q factors are highly contrasting. Figure 2(a) shows the *LC* resonance of inner metallic SRR excited at ∼1 THz with a Q factor of = 7.71 At the *LC* resonance, the excited surface currents in the SRRs are circular and possess a magnetic moment perpendicular to the plane of the metamaterial.[38–41] The *LC* resonance in metal SRRs does not show any significant change by increasing the conductivity of the metal at terahertz frequencies, thus there is no noticeable difference in the response of metal SRRs at room temperature and at liquid helium temperature.[42]

Figure 2(b) reveals the behavior of a superconducting CRR array at different temperatures. Since CRR is a

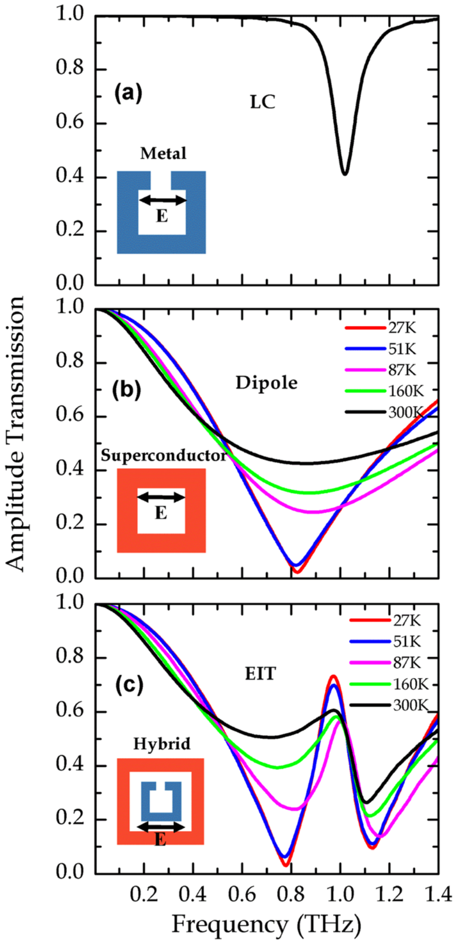

FIG. 2. Simulated transmission spectra of the isolated resonators and coupled PIT structure. (a) LC resonance of metallic inner SRR at room temperature, (b) dipole resonance of outer CRR at various temperatures, and (c) EIT resonance peak in hybrid superconductor-metal structure at various temperatures.

perfectly symmetrical structure, a plasmonic dipolar resonance is excited by the incident terahertz field. At room temperature, a dipole resonance appears to be extremely weak due to the poor conductivity of the superconductor. As the temperature decreases, a resonance gradually evolves due to the increase in YBCO film conductivity and subsequent excitation of strong dipolar surface currents in CRR. At the temperature below Tc, the dipole resonance exhibits a switching effect since resonance amplitude increases dramatically below the superconducting phase transition temperature at which there is formation of Cooper pairs that enhances the imaginary part of the YBCO film conductivity by three orders of magnitude.[43,44] The red shift in the dipolar resonance is due to the kinetic inductance of the superconductor film. A strong dipole resonance can be observed at 51 K and 27 K at 0.83 THz with a Q factor of 0.88. We should note an order of magnitude difference in the Q factors of LC and dipole resonances.

After the two resonator arrays, namely, metal SRR and superconductor CRR are simulated individually, we further bring the two resonator structures together in a unit cell with the CRR enclosing the smaller SRR structure with both structures being concentric in order to achieve strong coupling. Figure 2(c) shows the transmission spectra of the hybrid CRR-SRR metamaterial structure at different temperatures. The CRR-SRR system can be represented as two coupled damped harmonic oscillators. When significant coupling occurs as the temperature is lower than T_c, normal mode splitting results in two separate Lorentzian-like resonances with distinct eigen frequencies and damping rates or resonance line widths. The coupling between the metal SRR and the superconductor CRR is the strongest at the lowest temperature that the metamaterial chip is cooled down to. The coupling occurs due to the strong spatial overlap of near fields of the SRR and the CRR. A temperature tunable transparency resonance band is observed due to the destructive interference between the sub-radiant (dark) metal SRR and the super-radiant (bright) superconducting CRR. The coupling occurs via the near field interaction of the electromagnetic fields at the LC resonance of the metallic split ring resonator and the dipolar resonance of the closed ring superconductor.[45–50] The electromagnetic field in the metal resonator remains strong at room temperature as well as at low temperature due to high conductivity of metals at terahertz frequencies. However, the coupling strength between the resonators increases below the superconducting phase transition temperature due to the excitation of strong dipolar currents in the superconductor CRR. The coupling depends on the Q factor of individual resonators since they must have identical resonance frequency in order to achieve strongest coupling.

The transparency mimics the quantum mechanical EIT phenomena in atomic physics. In order to verify our simulations, we fabricated identical structures of hybrid metamaterial and performed the transmission measurements using terahertz time-domain spectrometer as shown in Fig. 3.[51] We observed the tunable PIT resonance band by decreasing the temperature of the metamaterial chip. The amplitude modulation was more dramatic at much lower temperature of 15 K, thus achieving an active switching and modulation behavior of the PIT window at 1 THz.

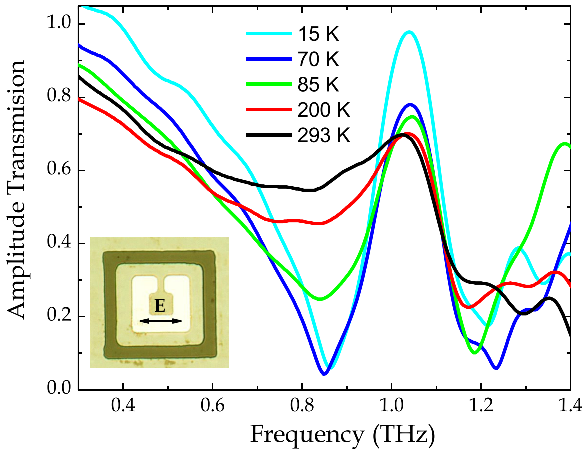

FIG. 3. Experimental transmission spectra of the superconductor-metal hybrid PIT metamaterial, revealing tunable transparency at different temperatures.

In order to elucidate the nature of these resonances, we numerically simulated the surface current distribution and electric fields at the lowest temperature and at resonance frequencies of two dips (0.77 THz and 1.13 THz, respectively) and the transparency peak (0.98 THz). At the resonance dips, as shown in Figs. 4(a) and 4(c), the strong currents are excited in the CRR as well as in the SRR indicating a hybridized mode. At the lower frequency resonance (0.77 THz), the currents in both resonators are antiparallel and at the higher frequency dip (1.13 THz), the surface currents are parallel. On the contrary, in Fig. 4(b), the surface currents are completely suppressed in the outer CRR due to destructive interference between the two resonators. The excitation at the PIT peak is confined only to the inner SRR, expelling the currents completely from the superconducting CRRs. Looking at the electric field simulations, the strongest fields are observed at the PIT peak (0.98 THz) in Fig. 4(e) near the SRR gap which conveys that there is inductive transfer of near field energy from the super-radiative CRR to the dark SRR. The electromagnetic field is coupled back and forth between the bright superconducting CRR and dark metal SRR atoms, leading to a destructive interference and thus, the suppression of field in the super-radiative outer CRR. In Figs. 4(d) and 4(f), the fields at the resonance dips of 0.77 THz and 1.13 THz, respectively, are seen to be distributed on SRR and CRR due to the coupled modes at these eigen frequencies.

From the transmission spectra and the PIT resonance band in Fig. 3, it can be easily recognized that strong dispersion leads to a huge group delay that occurs in the transparency window. This indicates that a light pulse with a central frequency situated in the transparency window will be considerably slowed down while propagating through the hybrid metamaterial. The slow-light feature of the PIT phenomena in metamaterials is extremely attractive for several applications such as strong light-matter interactions and enhanced nonlinear effects. Through our measurements, we demonstrate a thermally *tunable slow-light* effect represented by the group delay (Δt_g) of the terahertz wave packet through the metamaterial sample relative to the sapphire substrate reference. The difference in Δt_g through the EIT metamaterial and reference is retrieved at different temperatures, as

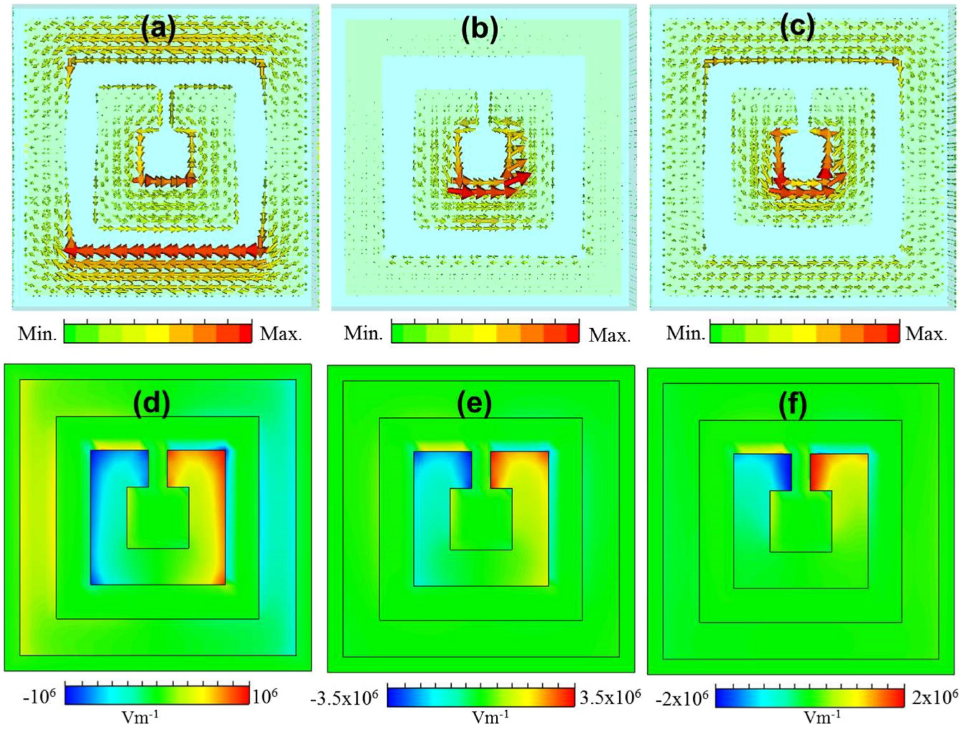

FIG. 4. Simulated surface currents and electric field distributions in the hybrid PIT metamaterial structure at resonance frequencies of (a), (d) 0.77 THz (first dip); (b), (e) 0.98 THz (transparency peak) and; (c), (f) 1.13 THz (second dip) at 27 K.

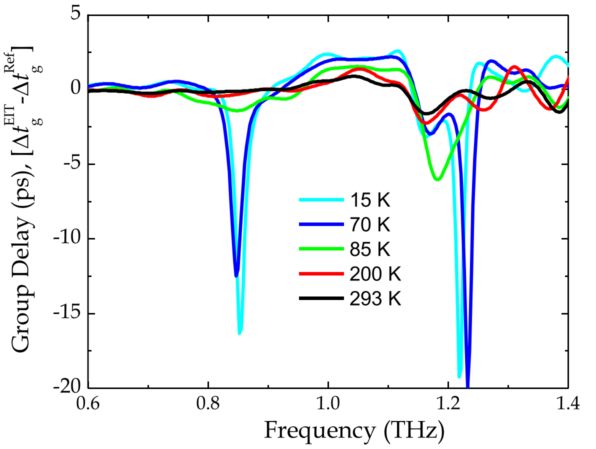

FIG. 5. Thermally tunable active group delay. Group delays retrieved from measured transmission spectra of the hybrid PIT metamaterial at different temperatures.

shown in Fig. 5.[15] We observe that the wave packet with central frequency of ∼1.1 THz is delayed by 2 ps at 15 K. At temperatures above the superconducting phase transition, the slow-light effect is almost negligible. Below T_c, the group delay could be tuned up to 2 ps.

In conclusion, we demonstrate a thermally tunable hybrid metal superconductor EIT metamaterial and slow-light effects. Strong coupling between dark metal SRR and bright superconducting resonator leads to a destructive interference of the scattered fields giving rise to an EIT phenomenon. We have designed and demonstrated a micro-sized subwavelength active circuit device that has the uniqueness to show switching, modulation, and slowing down the terahertz pulse capabilities. This hybrid metamaterial device would find several applications such as regenerators for terahertz communication, light storage, and compact tunable terahertz delay lines. It also offers the opportunity for compressing terahertz signals in free space paving the path for applications in several terahertz devices, such as detectors, modulators, quantum cascade lasers, and amplifiers.

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