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Strong magnetic annihilation of the dark mode in a bright-dark coupled terahertz metamaterial

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Dark mode in metamaterials has become a vital component in determining the merit of Fano type of interference in the system. Its strength dictates the enhancement and suppression in the amplitude and *Q*-factors of resulting resonance features. In this work, we experimentally probe the effect of strong near field coupling on the strength of dark mode in a concentrically aligned dipole (bright) and the split ring (dark) resonator system exhibiting classical analog of electromagnetically induced transparency effect. A strong magnetic (inductive) coupling between the bright-dark resonators destructively interferes with the inherent magnetic field of the dark mode to completely annihilate the effect of dark mode in the coupled system. Moreover, the observed annihilation of the dark mode can be the basis of resonant optical cloaking effect, wherein under the strong magnetic interactions, the split ring resonator becomes invisible to the incoming terahertz wave.

In recent years, metamaterials have gained a significant interest in controlling and manipulating the light matter interactions over a wide band of electromagnetic (EM) spectrum, ranging from radio waves to the ultraviolet frequencies. Metamaterials [1,2] are artificial sub wavelength periodic structures and they attain their properties from the geometry and structural arrangement of their unit cells called meta-atoms. The possibility of tuning the effective material parameters such as permittivity and permeability in these materials has led to some astonishing discoveries that include the pioneering works on perfect lens [3], invisibility cloaks [4,5], negative refraction [6] and artificial magnetism at terahertz frequencies [7]. The near field interactions in these metamaterials have a tremendous impact on establishing the classical analogy of quantum effects such as electromagnetically induced transparency [8-12] and Fano resonances [13-15].

Electromagnetically induced transparency (EIT) is a coherent phenomenon wherein, the destructive interference between bright and dark excitations results in a sharp transparency peak at the resonance. This effect was first seen in a three level atomic system [16] and later was also extended to several classical systems [17] including the metamaterials. Unlike in the atomic systems, EIT like effects in metamaterials result from the classical interference between the near fields of coupled resonators. The fundamental essence for EIT is the presence of non-interacting dark state (mode) in the system, wherein its strength dictates the intensity of the resulting transmission peak. In classical systems, the effect of bright-dark coupling on the EIT type of resonance has been demonstrated in the context of a strong and weak coupling regime of near field interactions [18-20]. In the strong coupling regime, EIT peak possesses stronger intensity due to the enhanced interaction of bright-dark modes. Whereas, in the weak coupling regime, as the bright-dark resonators are kept far apart, the weak interaction between them results in the disappearance of the EIT effect. In this work, we study the influence of strong magnetic coupling on dark mode, wherein the existence of the dark mode is completely suppressed in a strong near field coupling regime. This observation is in contrast with other studies, where the physical separation between bright and dark resonators is so large (weak coupling regime) that the effect of the dark mode is negligible. In our case, coupling between the bright and dark resonators exerts a very strong and opposing magnetic field back on to the dark resonator thereby rendering it ineffective and results in a complete disappearance of the EIT peak. This observation is analogous to the effects in Delta(Δ)-type of atomic EIT systems[21,22], wherein the EIT peak can be modulated by enhancing or destroying dark state using the magnetic component of microwave field connecting the electric dipole forbidden transition of the atomic states.

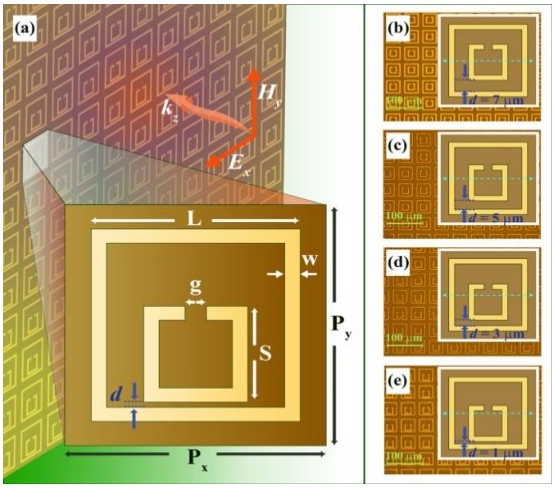

Fig. 1. **(a)** Graphical representation of EIT metamaterial sample along with its unit cell dimensions. Length of CRR, L : 40 μm; length of SRR, S : 20 μm; width, w : 3 μm; SRR gap, g : 4 μm, square periodicities, P_x and P_y : 50 μm and *d* is the varying coupling distance between the SRR and the lower CRR arms. **(b)-(e)** are the optical microscope images of the fabricated samples for *d* = 7, 5, 3 and 1 μm, respectively along with the schematic of corresponding unit cell.

The proposed metamaterial design is illustrated in Fig. 1(a). As shown, the unit cell (meta-molecule) of the structure is composed of a split ring resonator (SRR), termed as the 'dark mode' and is placed inside a closed ring resonator (CRR) structure, termed as the 'bright mode', with a varying coupling distance between them given by '*d*'. Fig. 1(b)-(e) represent the optical microscope images of the fabricated metamaterial samples with gradually decreasing coupling distances *d* = 7 μm, 5 μm, 3 μm and 1 μm, respectively. Instead of using conventional photolithography, where the resolution is typically limited to >2 μm, we chose to use a laser based scanning lithography technique to obtain the required resolution of 1 μm between the resonators. The AZ1518 photoresist mask was written on a 500 μm thick silicon substrate (ρ > 5 kΩ-cm) using a 405 nm laser followed by development and thermal evaporation of 200 nm thick aluminium metal. Finally, the desired metamaterial patterns were achieved by performing lift-off process using acetone. For the incident THz wave of polarization $\boldsymbol{E_x}$, the SRR resonator supports the LC type of magnetic resonance and the CRR being a square symmetric structure supports the broad dipolar resonance. The structural parameters of SRR and CRR are chosen such a way that both the LC and dipolar resonance resonate at the same resonance frequency but possess contrasting line widths. The SRR structure displaying a LC resonance with sharper line width (higher quality factor (Q)) is termed as the 'dark mode', where the CRR structure with broad (low Q-factor) dipolar resonance is termed as the 'bright mode'. The presented concentric alignment of the SRR (dark mode) and CRR (bright mode) resonators manifests the metamaterial induced transparency effect, which has been demonstrated in our earlier works [12,23]. It is well established that the capacitive gap in the SRR structure signifies the electric nature of the field confinement that favors the strong electric coupling between the adjacent resonators [23]. On the other hand, the currents flowing through the inductive arm of the SRR resonator give rise to the effective magnetic response with the magnetic dipoles oriented perpendicular to the metamaterial plane favors the magnetic coupling with the adjacent resonators. Unlike the other classical EIT designs [11,18,19], the current concentric arrangement of resonators provides unique topography to investigate the effect of strong electric (capacitive) as well as strong magnetic (inductive) interactions on the resulting transparency peak. In this work, we thoroughly investigate the competition between the electric and the magnetic near field interactions in enhancing and destroying the transparency effect in the proposed structure. Our results show the complete annihilation of the SRR (dark) resonance in the strong magnetic (inductive) coupling regime of SRR and CRR resonators, thereby destroying the transparency in the composite metamaterial system.

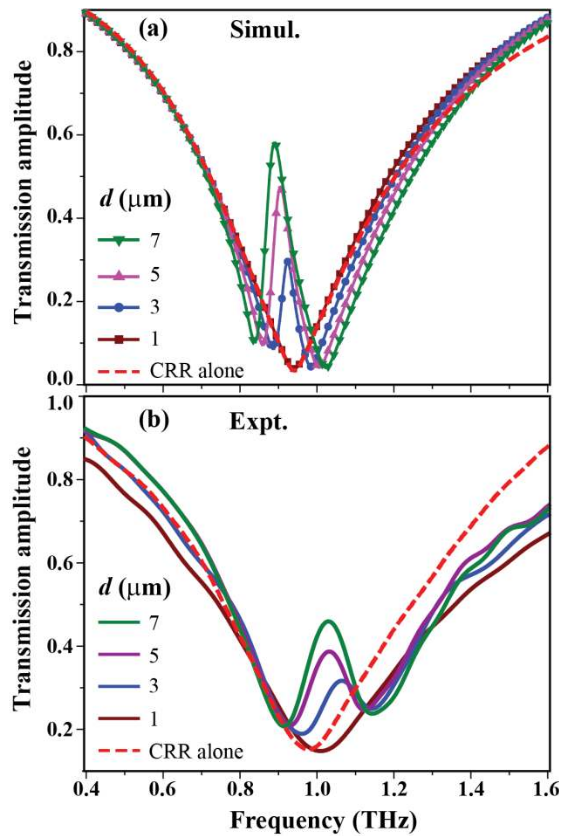

Fig. 2. **(a)** Numerically calculated THz transmission spectra depicting the gradual disappearance of the transmission peak with decrease in the coupling distance *d*. **(b)** Experimentally measured THz transmission spectra for varying coupling distances that show a good agreement with the corresponding simulation data.

In Fig. 2, we present the terahertz transmission spectra of the composite metamaterial structure (concentric arrangement of SRR and CRR) for *d* = 7 μm, 5 μm, 3 μm, 1 μm and for the metamaterial with CRR structure alone. The transmission measurements were performed in dry N_2 environment using the standard photoconductive antenna based terahertz time domain spectroscopy (THz-TDS) system. The transmitted time signals through the sample (E_S) and the reference (silicon) substrate (E_R) were Fourier transformed and normalized using the expression, T(ω)= |(ES (ω))/(ER (ω))|. Fig. 2(a) depicts the numerically simulated transmission spectra performed using the commercially available CST microwave studio software. For the simulation, aluminium metal with σ_{dc} = 3.56 × 10^7 S/m is used as metallic resonator and the silicon (ε_r = 11.7) is considered as the transparent substrate at THz frequencies. The transmission spectrum for *d* = 7 μm signifies an existence of sharp transparency peak at the centre (around 0.9 THz) of broad absorption dip. The transparency is a result of the destructive interference between the opposing near fields of the SRR and CRR resonators [23]. To investigate the effect of strong magnetic interactions between SRR and CRR arms on the transparency peak, we displaced the base arm side of SRR structure towards one of the CRR's arm. As we reduce coupling distance (*d*) between the inductor arm and the CRR arm, amplitude of the transparency peak gradually decreases and ultimately disappears at *d* = 1 μm (blue line + solid squares in Fig. 2(a)).

The most striking feature of the resonance spectrum at *d* = 1 μm is that it ideally coincides with the dipolar spectrum of the CRR alone (shown by red dashed curve in Fig. 2(a)). These overlapping resonances signify the complete cancellation in the contribution of SRR resonance (dark-mode) effect on the near field interactions in the composite metamaterial structure. The experimentally measured transmission spectra shown in Fig. 2(b) for the samples with *d* = 7 μm, 5 μm, 3 μm, 1 μm and CRR alone agree well with our simulation results shown in Fig. 2(a). The experimentally observed mismatch in the resonance line widths of the composite (*d* = 1 μm) and the CRR alone metamaterial structure can be presumably due to the structural irregularities in the respective fabricated samples that can greatly affect the strength of the near field interactions in the metamaterial structures. The gradual reduction in the amplitude of the transmission resonance with decreasing *d* in the composite structure essentially signifies weakening of the dark mode (SRR) resonance, which is more evident from the electric field and surface current distributions shown in Fig. 3.

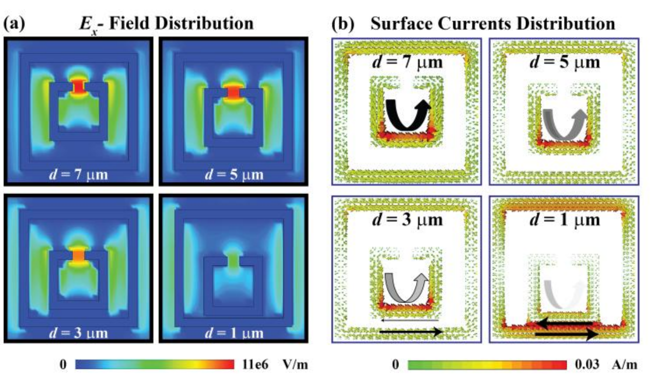

Fig. 3. **(a)** ***x***-component of the simulated electric field distribution at the transmission frequency showing a gradual decrease in the confined field strengths at the SRR gap for decreasing coupling distance *d*. **(b)** Corresponding simulated surface currents that shows the decrease in current density of the SRR resonator due to the increased magnetic interaction between the SRR and the lower CRR arms. Black arrows signify the direction of the surface currents.

Electric field distribution plot shown in Fig. 3(a) provides a clear visual indication of the annihilation of SRR resonance, which shows the gradual diminishing of electric field confinement within the SRR gap region for decreasing *d*. For instance, at *d* = 1 μm, the electric field density in the SRR gap is significantly reduced, whereas the fields across the CRR dipolar arms show larger gain compared to that of the metamaterial structure with *d* = 7 μm. This indicates that the composite structure gradually attains the dipolar characteristics as the SRR arm comes in close proximity of the CRR arm. The underlying near field interaction mechanism can be clearly explained by investigating the nature of the surface current distributions given in Fig. 3(b). In our previous study [23], we established that in the composite structure (*d* = 7 μm) the destructive interference between the surface currents of SRR and the CRR resonators results in a sharp transparency peak with an anomalous dispersion in the system. Here, as we decrease d, an opposing current loop develops (shown in Fig. 3(b) with black straight arrows) on the edge of the SRR arm that gradually grows in strength and destructively interferes with the inherent surface currents of the SRR. As a result, the surface current density on the SRR resonator slowly diminishes and a strong cancellation of the SRR effect is seen when the separation between the SRR arm and the CRR arm is *d* = 1 μm.

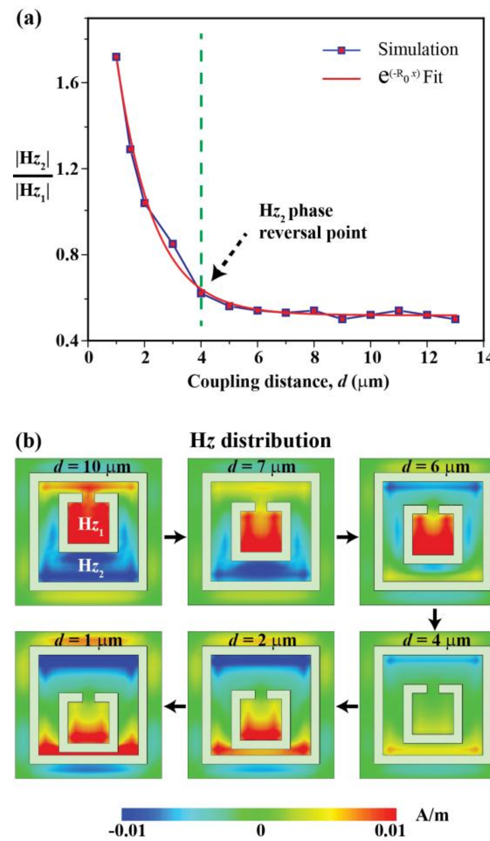

Fig. 4. **(a)** Depicts the varying strengths in the competing magnetic fields Hz_1 and Hz_2 with respect to the coupling distance (*d*), where Hz_1 and Hz_2 are the strengths of the ***z***-component of the magnetic field within the SRR and between SRR-lower CRR arm, respectively. The vertical green dotted line signifies the phase reversal point of Hz_2, where the phase of Hz_2 flips from negative to positive sign. The solid red curve represents the exponential fit to the Hz_2/Hz_1 data with the value of rate constant, R_0 = 0.76. **(b)** Simulated Hz distribution showing gradual strength and phase change in the Hz_2 component, indicating the influence of the strong magnetic interaction on the SRR excitation.

In Fig. 4(a), we articulate the near field interactions responsible for the annihilation of the SRR resonance in the form of change in the ratio of magnetic fields ($\frac{|Hz_2|}{|Hz_1|}$), where Hz_1 is the *z*-component of the magnetic field within the SRR resonator and Hz_2 is the *z*-component of the magnetic field in between the SRR and CRR arms. From the field simulations, we observe that, as the base arm side of the SRR resonator is displaced towards the CRR arm, there is an exponential increase in the strength of magnetic coupling between the SRR and CRR arms. Magnetic field inside the SRR structure ($|Hz_1|$) stays higher than the field between the SRR and CRR resonator arms ($|Hz_2|$) (i.e $|Hz_2|/|Hz_1| < 1$) for the coupling distances greater than 2 μm, indicating the influence of the SRR (dark mode) in the system. On the other hand, as $d \leq 2$ μm, the magnetic field Hz_2 becomes monotonically larger than the Hz_1 and hence the field within the SRR resonator is completely suppressed, thereby annihilating the SRR effect in the composite metamaterial structure at $d = 1$ μm. In Fig. 4(b) we show the magnetic field distribution (H*z*), where the fields inside SRR (Hz_1) and the fields between the SRR and CRR arms (Hz_2) show gradual variation in their field strengths. As the coupling distance (*d*) decreases, field inside the SRR structure gradually diminishes and becomes extremely weak at the phase reversal point of Hz_2 (around $d = 4$ μm). Below the Hz_2 phase reversal point ($d < 4$ μm), field between the CRR and the SRR arm (Hz_2) undergoes the phase flip and grows in strength to eliminate the SRR resonator effect at $d = 1$ μm. Thus, the interplay between the magnetic fields Hz_1 and Hz_2 in the composite concentric resonator system is largely responsible for the annihilation of the SRR effect in the strong magnetic (inductive) coupling regime.

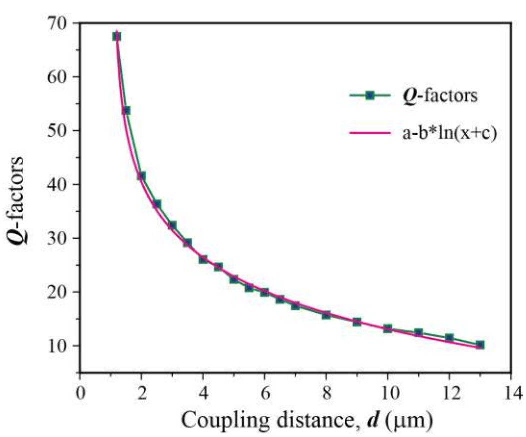

Fig. 5. Graph depicting the *Q*-factors of the transmission peak with respect to coupling distance. Variation in *Q*-factors follows the logarithmic behavior indicating the influence of both strong electric and magnetic coupling in the system. The fitting parameters for the logarithmic curve are; a = 39, b = 11.86, c = -1.1 and 'x' is the variable.

Competing electric and magnetic interactions in the proposed composite metamaterial structure dictates the variation in the quality (*Q*)-factor values. *Q*-factor of the transmission resonance is 67 for $d = 1.2$ μm and it decreases logarithmically with increase in the coupling distance (*d*), as shown in Fig. 5. The logarithmic decay in the *Q*-factors signifies the delayed saturation in the near field interactions within the structure that deviates from the normally observed exponential behavior. This is because the SRR exists within the dipolar ring (CRR), the system stays in the influence of either strong electric/weak magnetic (strong capacitive) or weak electric/strong magnetic (strong inductive) coupling regime. Hence, the presence of both the electric and magnetic fields (both inductive and capacitive) leads to a slower decay in the *Q*-factor, which follows the logarithmic behavior.

In conclusion, we demonstrated the strong magnetic coupling induced annihilation of LC resonance (SRR effect) at terahertz frequencies. The proposed composite metamaterial structure that includes a concentric arrangement of SRR and the CRR resonators can enact both strong electric as well as magnetic interaction that respectively enhances and destroys the EIT type of transmission resonance in the system. Suppression in the resonant transmission peak is due to the annihilation of the SRR's LC resonance (dark mode) in the proximity of the strong magnetic coupling regime. The observed strong magnetic annihilation of resonances could have direct implications on realizing near field based resonant magnetic switches, slow light devices and could enable controlled manipulation of effective permittivity and permeability of the medium in realizing resonant cloaking devices at terahertz frequencies.

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