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Electromagnetically Induced Absorption in Metamaterials in the Infrared Frequency

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Abstract—In this paper, the author studies, through numerical simulation, the classical analog of the electromagnetically induced absorption/reflection (EIA) in a planar metamaterial structure in the near infrared spectral region. The structure is designed by transforming an electromagnetically induced transparency (EIT) structure into an EIA structure using Babinet's principle. The structure exhibits a coupling between a bright mode (a complementary ring resonator (CRR)) and a dark mode (pair of parallel straight slits) imprinted on a glass substrate. A narrow absorption window, induced in a wide transparent window, is achieved by the structure and the strength of coupling is tuned by the degree of breaking symmetry and relative displacement of the two mode elements.

1. INTRODUCTION

Electromagnetically induced transparency (EIT) is a quantum mechanical phenomenon in which an absorption is transformed into a transparency, and this is associated with strong dispersion that reduces the group velocity [1–3]. This phenomena has many potential applications in signal processing, optical filtering and sensing technologies [4–7]. The classical analog of the EIT has been achieved and reported by many researchers using a planar metamaterial structures that are generally composed of two metallic elements imprinted on a dielectric substrate. The two elements are metallic resonators that act either as two bright modes or a bright and dark mode. A bright mode element couples strongly with the incident excitation field while the dark element does not couple with the incident field but couples with the magnetic field induced by the bright element. Several EIT metamaterial structures have been employed and reported in the microwave, terahertz and optical frequency regions [8–14].

In this paper, we propose a new EIT structure that achieves a more pronounced narrow transparency window sandwiched between two absorption bands compared with a similar structure proposed in [14]. Also compared with [14], the structure proposed here is independent of the polarization orientation with respect to the bright mode element. Then we transform this structure into an EIA structure using Babinet's principle [15, 16], where a narrow absorption/reflection window is sandwiched between two transparency bands. The structures proposed here may be used as obscurant particles that allow the passage of a specific window/windows of the electromagnetic spectrum and obscure the neighboring frequencies, for this reason the transmission spectrum will be discussed and addressed for the potential obscurant applications. Although the orientational average response of the structure is what matters, it is of good benefit to get the behavior in a given orientation. The EIT structure is composed of a metallic ring resonator (RR) which acts as a bright mode and a pair of metallic rods that act as a dark mode. Here we overlap the RR wide antenna resonance and the narrow line width quadrupole rod resonance, which in turn produces the EIT-like effect. The structure is transformed into an EIA structure by replacing the metallic RR and the pair of rods resonator with complementary ring resonator (CRR) and

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a pair of parallel slits and rotating the structure by a 90 degrees according to Babinet's principle [15, 16]. We will also show that the coupling strength between the bright and dark modes can be adjusted by varying the degree of symmetry and their relative displacements.

2. STRUCTURES GEOMETRY AND NUMERICAL SIMULATIONS

Figure 1 shows the geometry of the proposed EIT structure which is composed of a metallic RR and a pair of metallic rods. The k-vector of the incident light is perpendicular to the plane of the structure with the electric field perpendicular to the pair of rods, so only the RR couples with the incident excitation

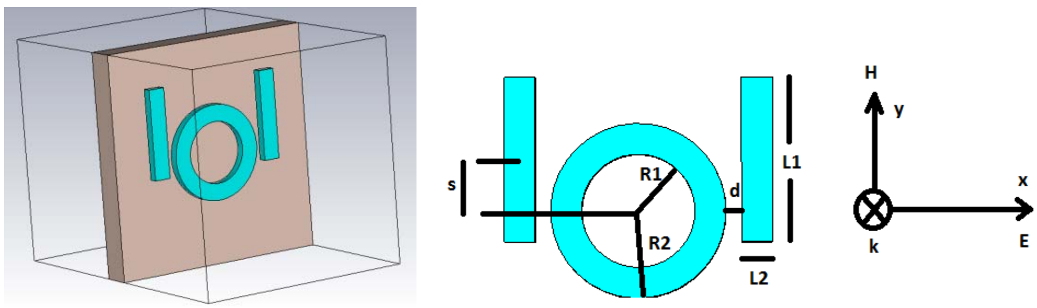

Figure 1. Unit cell, geometry and incident light polarization of the EIT structure. $L1 = 320\,\mathrm{nm}$, $L2 = 60\,\mathrm{nm}$, $R1 = 110\,\mathrm{nm}$, $R2 = 170\,\mathrm{nm}$, $d = 30\,\mathrm{nm}$, $s = 100\,\mathrm{nm}$.

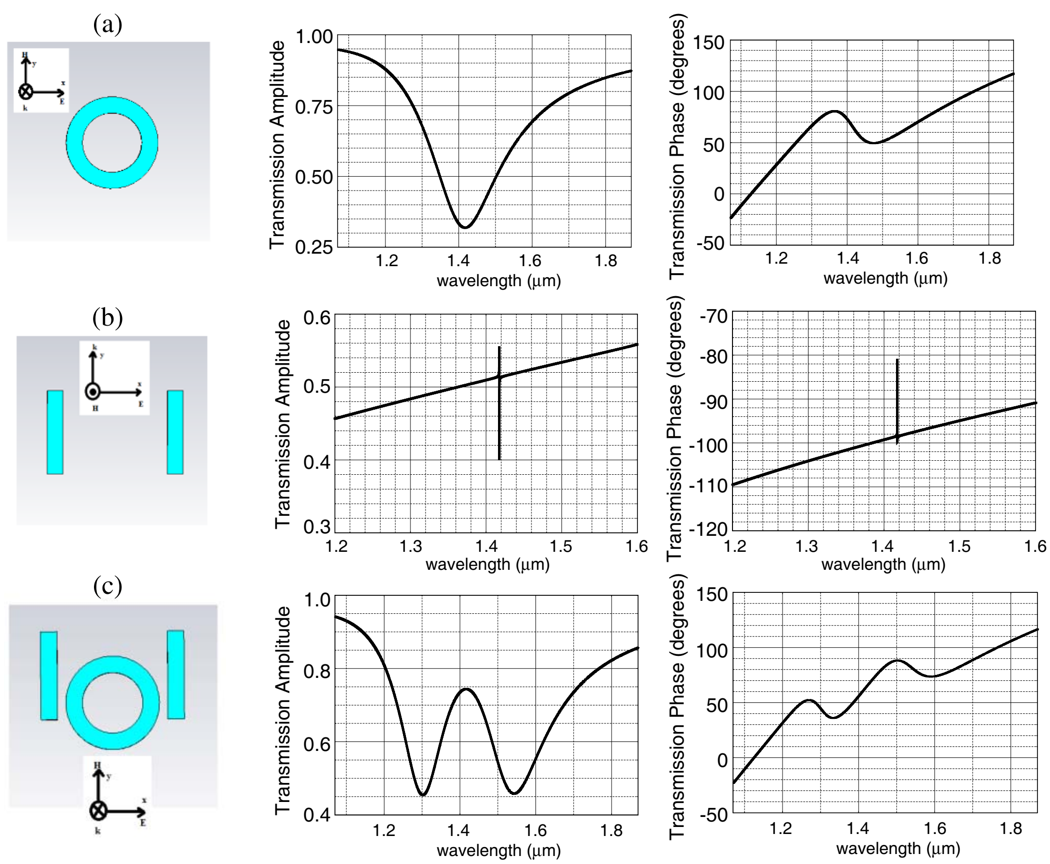

Figure 2. Transmission spectra (amplitude and phase) versus wavelength for (a) the bright, (b) dark and (c) EIT structures.

field giving an antenna resonance, while the pair rods couple with the magnetic field induced by the externally induced current of the RR bright mode. The dimensions of the elements have been chosen to overlap the resonances at the same frequency in the near infrared region. The unit cell is composed of 30 nm thick metal on a 100 nm thick glass substrate. The permittivity of glass was taken as 2.0 and the metal permittivity was modeled using the Drude model with plasma frequency 2.18×10^{15} Hz and collision frequency 3.07×10^{13} Hz.

The simulation spectra were performed using the CST microwave studio suite solver where periodic boundary conditions were applied in the x and y directions [17]. When the two absorption resonances overlap, an EIT like effect is achieved as shown in the simulation spectra in Figure 2. Here to excite an anti-parallel current mode in the pair of rods a break of symmetry is required and this is represented by the parameter (s) in Figure 1. In Figure 2, we plotted the transmission spectra (amplitude and phase) of the bright mode alone (Figure 2(a)), the dark mode alone (Figure 2(b)) and the EIT structure (Figure 2(c)) which is achieved when the bright mode element placed in proximity of the dark mode element. As seen in Figure 2(c), when the bright and dark modes resonances hyperdized, an EIT like effect is produced where a transparency window is induced in an absorption/reflection wide window. Since we are using periodic boundary condition, the k vector is rotated by a small angle in the k-H plane for the simulation spectra of Figure 2(b) [14, 17]. Figure 3 shows the distribution of the magnetic field amplitude for $s = 0$ nm and $s = 100$ nm of the EIT structure at the resonance wavelength 1.418 µm. This figure shows that the dark mode is only excited when the symmetry is broken (i.e., $s = 100$ nm).

Next we transform the structure using Babinet's principle, as mentioned above, to achieve an EIA like effect. The geometry and simulations of the EIA structure are shown in Figures 4 and 5. Figure 5 shows the amplitude of transmission and reflection. According to the simulation, a narrow

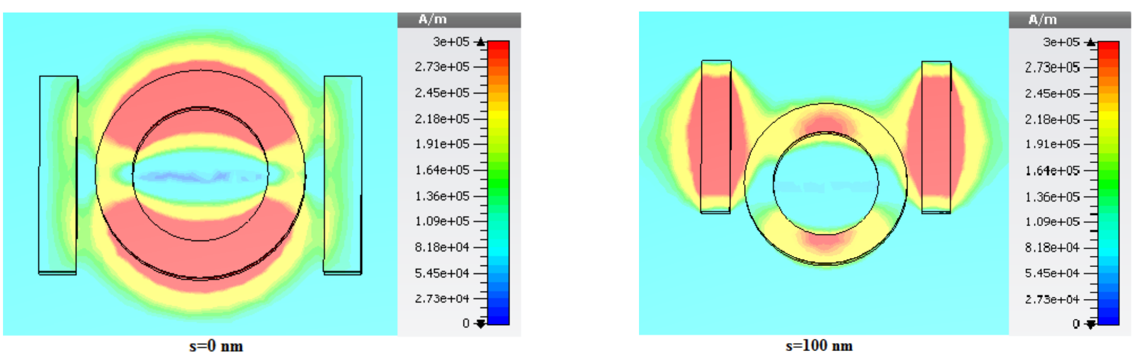

Figure 3. Distribution of magnetic field amplitude for the EIT structure for $s = 0$, 100 nm at the resonance wavelength 1.418 µm.

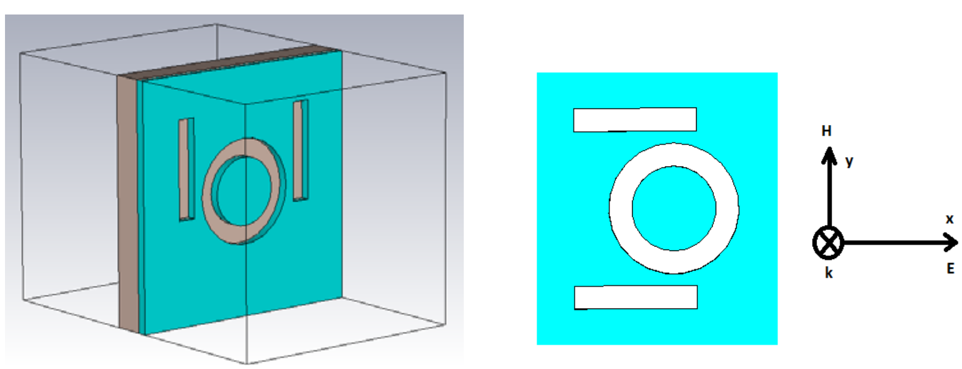

Figure 4. Unit cell and incident field polarization of the EIA structure. Dimensions are the same as in Figure 1.

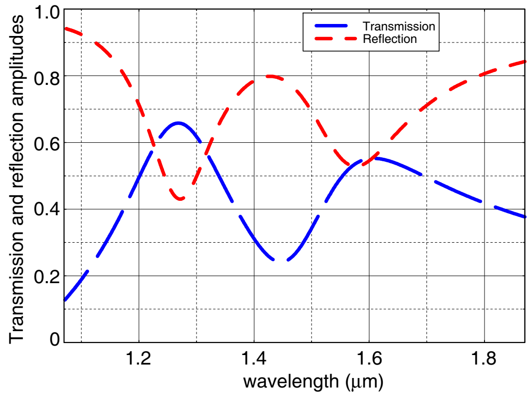

Figure 5. Transmission and reflection spectrums of the EIA structure in Figure 3 for $s = 100\,\text{nm}$.

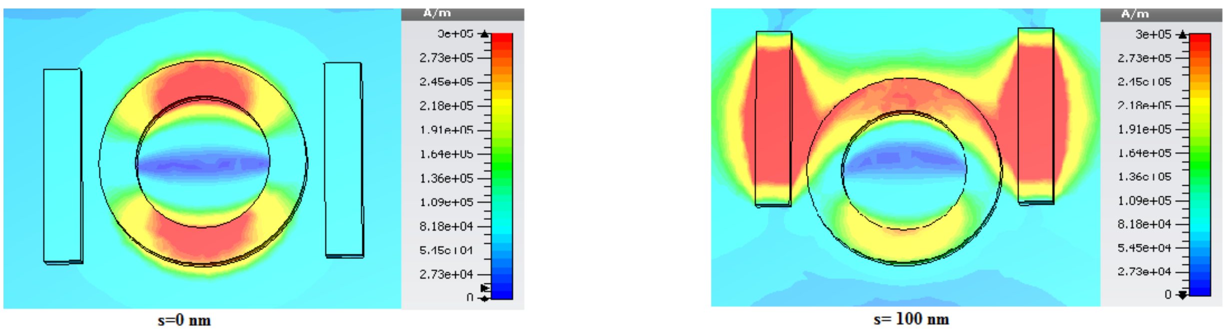

Figure 6. Distribution of magnetic field amplitude for the EIA structure for $s = 0$, $100\,\text{nm}$ at the resonance wavelength $1.448\,\mu\text{m}$.

absorption/reflection (low transmission) window is achieved and sandwiched between two transparency windows. One can see that the resonance frequency of the EIA structure is slightly shifted from the resonance frequency of the EIT structure and this can be attributed to the fact that Babinet's principle assumes an infinitely thin conductor [16]. Also the dielectric substrate affects the resonance frequency differently in the two structures. Figure 6 shows the distribution of the magnetic field amplitude for $s = 0\,\text{nm}$ and $s = 100\,\text{nm}$ respectively, again we see that that the dark mode is only exited when the symmetry is broken.

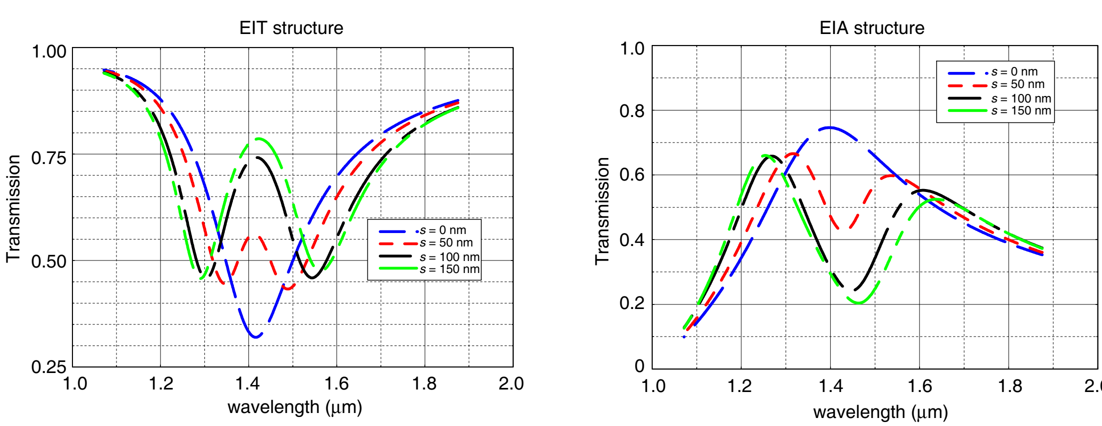

Figure 7. Transmission spectra versus symmetry parameter s for relative displacement $d = 30\,\text{nm}$.

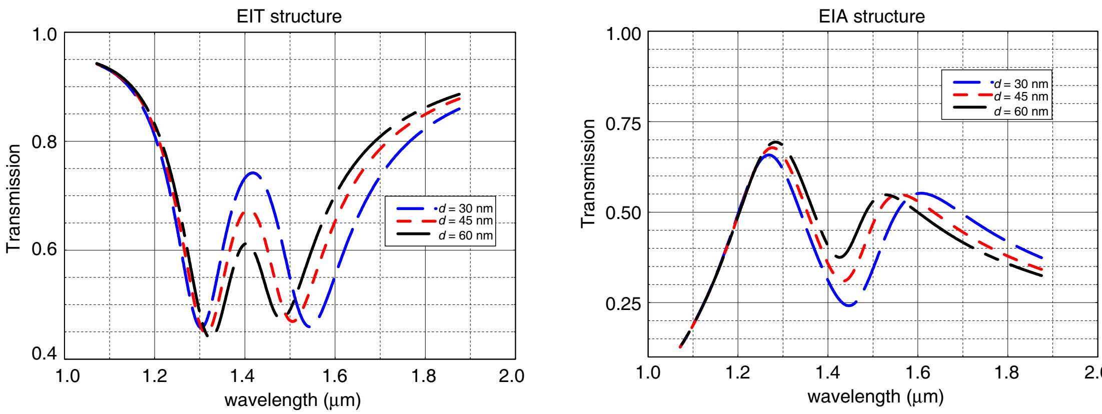

Figure 8. Transmission spectra versus relative displacement d for symmetry parameter $s = 100\,\mathrm{nm}$.

3. DISCUSSION

Figure 7 shows the transmission spectra of the EIT and EIA structures as a function of the symmetry parameter s, we see that the narrow transmission/absorption window becomes more pronounced and shifted to lower frequencies for the EIA structure as the s parameter increases. For $s = 0$ the EIT and EIA disappear as breaking symmetry is a requirement for both the EIT and EIA effects [8–14]. Next we study the effect of the relative displacement between the bright and dark elements on the EIT and EIA effect, this displacement is represented by the parameter d. Figure 8 shows the transmission spectra as a function of d and we see that as d decreases the coupling becomes stronger and more pronounced transmission/absorption window are achieved. Also the resonance frequency is shifted to lower frequencies for the EIA structure as d increases, and this shift is attributed to the slight change of the effective dielectric function of the structure.

4. CONCLUSION

A new metamaterial structure is proposed at the near infrared frequencies to mimic the electromagnetically induced transparency. The structure is transformed to an electromagnetically induced absorption using the Babinet's principle. The structure is composed of a bright element (RR/CRR) and a dark element (pair of rods/slits), the bright element couples strongly with the excitation field while the dark element couples with the magnetic field of the bright mode. Coupling between the two elements gives rise to a narrow transparency window in the absorption band for the EIT structure and a narrow absorption window in the transparency band for the EIA structure. The coupling strength between the two modes can be tuned by changing the symmetry degree and the relative displacement. These structures have many potential applications in signal processing, optical filtering and sensing technologies.

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