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The Effect of Antenna Movement and Material Properties on Electromagnetically Induced Transparency in a Two-Dimensional Metamaterials

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Abstract: Increasing development of nano-technology in optics and photonics by using modern methods of light control in waveguide devices and requiring miniaturization and electromagnetic devices such as antennas, transmission and storage as well as improvement in the electromagnetic tool, have led researchers to use the phenomenon of electromagnetically induced transparency (EIT) and similar phenomena in metamaterials. In this work, we introduce a metamaterial structure in nanometer dimensions and THz frequency region. Moreover, by broking the geometrical symmetry structure, we offer EIT with high transmittance and more Q-factor in comparison, to our knowledge, with previous studies of two-dimensional structure, in the infrared region. These achievements can be a good choice for slow light applications and can be used to amplify light in nanostructure and also to detect the infrared light. Finally, we study the effect of changing the metal on the proposed metamaterial. Moreover, in this study, numerical calculations and simulations are done by FDTD method.

Keywords: electromagnetically induced transparency, metamaterials, breaking geometric symmetry, slow light.

1. Introduction

Electromagnetically induced transparency (EIT) phenomenon which is well described by quantum optics is a coherent optical nonlinearity feature which is a result of destructive superposition of two laser beams, when passing through an opaque atomic environment and leads to transforming the region to a transparent environment in a narrow spectral region. The famous effect of this phenomenon is the light speed reduction in materials and substances. Recently, EIT, has also been developed in metamaterials. The phenomenon was first reported experimentally over the radio frequency region [1] and theoretically over the optical frequency region [2] in 2008. Since then, many structures have been proposed, exhibiting EIT in different frequency regions. This effect underlies many interesting ideas such as the transfer of quantum correlations [3], nonlinear

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optical processes at low light levels, and ultraslow light propagation [4-5]. Moreover, this phenomenon is of numerous potential applications regarding filters, sensors and optical switches. The recent years' researches indicate that observing such an effect in classic models is simpler than the atomic models. Super substances are artificial structures the single unit cell dimensions of which are smaller in comparison with the wave length; and the electromagnetic features exhibited by them are absent in natural substances. These substances electromagnetic features can be controlled through designing suitable geometrical parameters for their structures [6]. The first of the experiments in which EIT phenomenon led to light production was proposed by Hau et al. [5] in which light speed was reduced to 17 m/s. Generally the fundamental condition for the EIT phenomenon to take place is the bimodal resonance destructive interaction with different Q-factors [7-8].

2. Suggested Nanostructure

Fig. 1 shows the suggested super substance single unit cell scheme in a symmetrical state along with its antennas geometric parameters. This single cell includes three Nano strip L1, L2 and L3 which are 40 nm thick and made of Silver with electrical properties described by Drude model. The plasma frequency of Silver equals $\omega_p=1.4\times10^{16}$ s^{-1} and the impact frequency (entropy constant) $\gamma=3.2\times10^{13} s^{-1}$ which are placed on a 100 nm thick glass layer with refractive index n=1.55. This single unit cell is reiterated on XY surface in a periodical manner so it creates a 2D super substance blade. The single unit cell length along X, Y is 850 nm and the metal strips width is 80 nm and the clearance from L2 and L3 strips to L1 is 60 nm, L1 strip length is 460 nm and L2 and L3 strips lengths are 230 nm. Light is vertically radiated on the strips surface and the electrical field is formed along X vector (x-polarized).

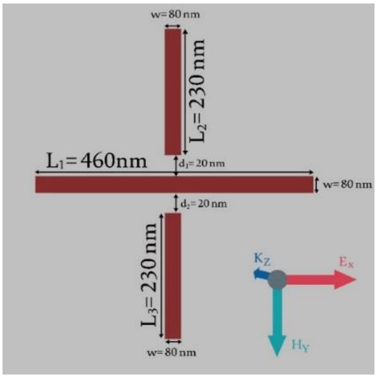


Fig. 1: Super substance single unit cell and structural geometrical parameters

3. Symmetrical State Nanostructure Evaluation

In symmetrical state, the L3 and L2 antenna's bright modes strongly couple with the radiated light but it suffers from radiation great losses and has low quality factor. Small Q-factors are a result of radiation slump originating from electrical dipoles created along the two metal strips (Fig. 2b). In fact, the electrical field which is horizontal along the metal strip causes an electrical dipole to form along L1 and L2 strips. The created dipoles are identical and of the same direction in two strips; therefore, interference these two strips emitted fields is constructive and increases the dispersion. Also, since the magnetic field is located on the strips surface it is not possible to create anti-symmetrical mode through the magnetic field. Due to the structural symmetry, L1 antenna dark mode cannot directly be coupled with the external light; therefore, there would be a thin spectral response in comparison with the bright mode and consequently there exists lower losses and higher quality coefficients (Fig. 2b). Inter-antenna coupling happens when the structural symmetry is broken and the second order modes begin stimulating (Fig. 2b). In case that the structure is symmetrical we will only bear witness to a single resonance about 243.2 THz (Fig. 2a).

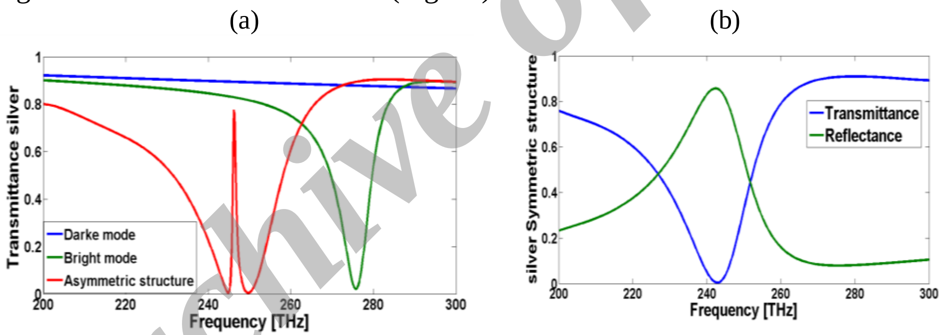


Fig. 2. a) Transmission and reflection diagrams of Silver structure, b) Transmittance versus frequency curve of Silver structure for dark mode related to L_1 strip (blue line), bright mode related to L_2 and L_3 strips (green line) and the case of symmetry breakdown (red line). L_1 and L_5 equal to 225 nm,d_1=45 nm and d_2=55 nm.

4. The Nanostructure Symmetry Breaking

EIT phenomenon is studied by the vertical and horizontal displacement of L1 and L2 strips. As it was illustrated in asymmetrical structure scheme in Fig. (3) L1 and L3 metal strips which are placed in a 60-nm distance from L1 strip are displaced to right side and left side, respectively, by 10 nm.

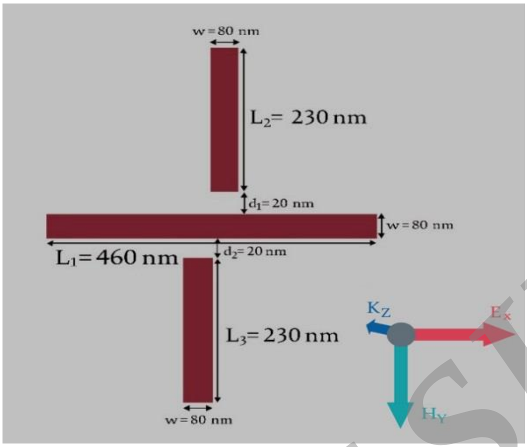


Fig.. 3. Super substance single unit cell and the structural geometrical parameters when the symmetry of the structure is broken.

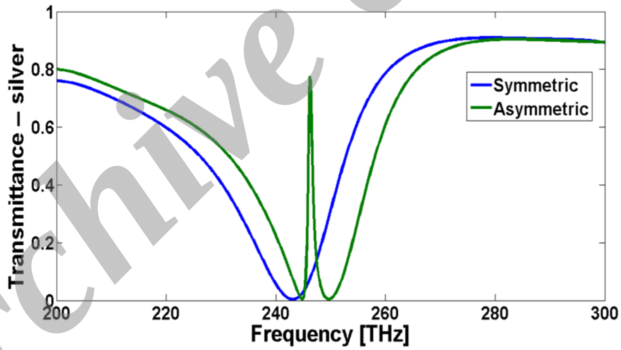


Fig. 4. Transmittance versus frequency curve of the structure in symmetrical state (blue line) and in asymmetrical state (green line), $L_2=L_1=230$ nm, $d_2=d_1=60$ nm.

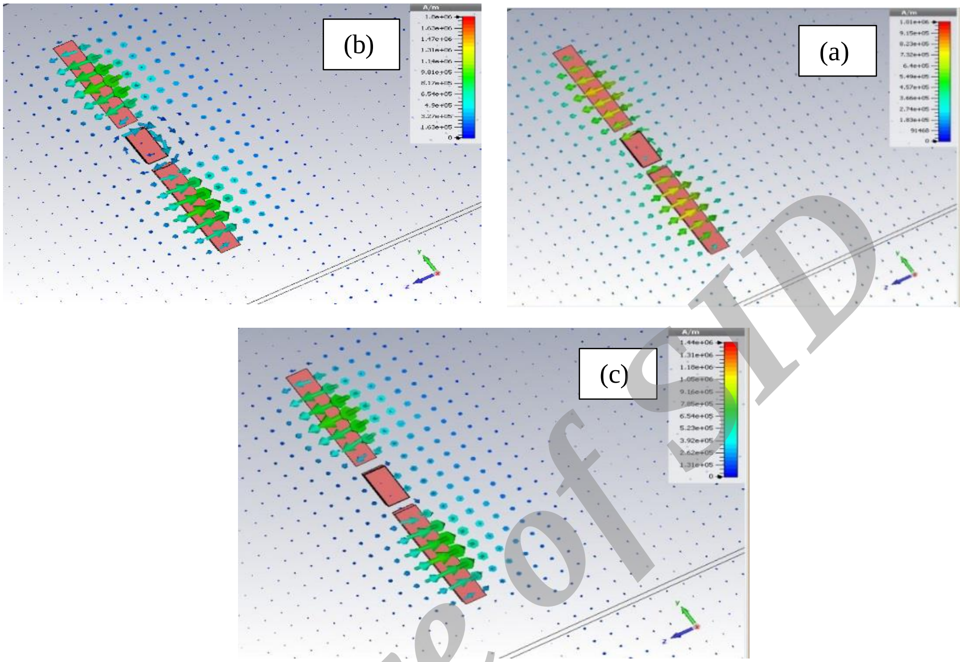


Fig. 5. Exhibition of the surface currents in bright and dark modes of the structure in a) 245 THz frequency, before resonance, b) 246.35 THz frequency, resonance frequency, c) 250 THz frequency, after resonance.

In fact, the emergence of such resonances is associated with the excitement of anti-asymmetrical mode. The reason for the losses reduction (here, the reflection) and the transmission increase is that equal currents are created in two vertical L2 and L3 strips in opposite directions relative to one another. These two currents' radiated electromagnetic fields interference is destructive, so the dispersion is decreased. But, because the metal vertical strips are located in a very short distance from L1 strip, dark mode will be indirectly excited by the bright mode. EIT is the result of the destructive interference between these two modes. The observed effect according to the figures on the transmission diagrams is known as the electromagnetically induced transparency which is obtained by breaking the structure geometrical symmetry.

To completely understand the subject matter, the field distribution manner and the surface currents in asymmetrical state, in resonance frequency, and also in a frequency after and before are illustrated in Fig. 5. In asymmetrical state, the surface currents flow in opposite directions to one another in L2 and L3 metal strips (bright mode). With this explanation it is well illustrated in Figs 5-a and 5-

b that in resonance and before and after resonance the surface currents' direction does not change in L2 and L3 strips but in L1 strip (dark mode) the surface current direction before the resonance, Fig. 5-a, is counterclockwise but in resonance conditions, Fig. 5-b, and afterward, Fig. 5-c, it's direction is clockwise.

5. Change of Metal substance

In this section the effect of antenna material on the EIT of the proposed nanostructure is investigated. According to Fig. 5 it is seen that when we make use of different metals the resonance behavior is almost similar in spectral responses simulated for Silver, Gold and Copper metals. The highest transmission intensity and the largest Q-factor (about 350) is observed in Silver and the lowest transmission intensity is seen in Copper. A comparison between Gold and Copper shows that Gold possesses the highest transmission intensity and the greatest Q-factor (about 205.16); moreover, Silver and Copper resonance frequencies are equal to one another (about 246.23 THz), but in case of Gold, a small frequency shift towards the smaller frequencies (the so-called blue shift) is observed (about 246.11 THz). Since, the transition band and the frequency resonance of these three metals are located in infrared limit the proposed nanostructure can be applied for IR-transparency applications.

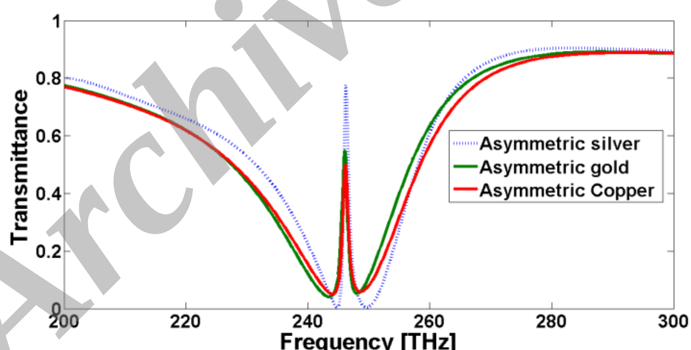
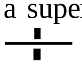


Fig. 6. The curve of Transmittance versus Frequency for Asymmetric proposed nanostructure with different metals: Silver (blue dashed lines), Gold (green line) and Copper (red line).

6. Results and Discussions

In the present work we achieved the electromagnetically induced transparency via breaking the geometrical symmetry through moving the L3 and L2 antennas in an inverse and horizontal direction in a super substance comprised of metal antennas configuration with the shape  .Transmission spectrums were evaluated and simulated based on the bright and dark modes interactions. By displacing L3 metal strip towards left by g=10 nm and the L2 metal strips is towards right by the same displacement distance the symmetry of the structure is broken. According to the Transmission versus frequency cures depicted in Fig. 6 a good transmission intensity and a sharp transition band with a Q-factors about 350, around the central frequency of 246.23 THz is achieved. This indicates that this structure possesses a larger and a very well Q-factor in this region of the wavelength respective to the other 2D structures. Since the resonance frequency of the entire modes is located in Infrared scope, the suggested nanostructure can be applied for the detection of the molecules, the resonance mode of which is also located in IR region and also this structure can be used for light and optic enhancements in nanostructure applications [9-10]. Also, because the sharp transition band and the large Q-factor in EIT phenomenon results in speed reduction and light slowdown, this structure can be applied for the construction of quantum memories and optical communications.

7. References

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