Electromagnetically Induced Transparency in All-Dielectric Metamaterial of Bi-layer Asymmetric Bars

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Abstract. The authors demonstrate the all-dielectric-metamaterials-based electromagnetically induced transparency with low loss and high quality (Q) factor. The all-dielectric metamaterial is made up of bi-layer silicon bars. A transparency window is observed by the coupled the bright and dark modes when the asymmetry is introduced. Compared with metallic metamaterials, it avoids of the loss of ohmic damping, so that the Q factor and the window transmittance can reach 1864 and 96\%, respectively.

1. Introduction
Metamaterials with flexible subwavelength designs of geometric shape and size have become an important research field for nano-optical applications attributed to the intriguing electromagnetic phenomena that do not exist in natural materials [1]. For example, the realization of the perfect absorbance, Fano resonances, asymmetric transmissions [2-6]. In addition, “graphene metamaterials” have been proposed with active tunability by changing Fermi levels of graphene [7]. “Digital metamaterials” is a proposal that manipulates the electromagnetic wave in a flexible way as the coded 0 and 1 elements under controlled sequences [8]. Recently, more attentions are focused on the mimic of classical electromagnetically induced transparency (EIT) phenomenon by using metamaterials at the visible [9], terahertz [10], and microwave spectra [11]. EIT is a destructive quantum interference phenomenon between two different excitation pathways of the excited state, which results in a narrow transparency window within an absorption band. It occurs usually in the three-level atomic systems [12], and can lead to the slowing-light effect. Classical EIT in the metamaterials is analogue of EIT in three-level atomic systems. Previous works have demonstrated that the EIT effect, attributed to the coupling between the dark and bright modes, could be modified by varying the distance between the resonant structures or just by breaking the symmetry of the structure [11-16]. In comparison with the EIT effect in atomic systems, the realization of classical EIT in the metamaterials has been demonstrated in many artificially designed structures, such as the split dipolar antennas [13], the ring resonators [14] and the perpendicular bars [11, 12, 15, 16].

The classical-EIT has been demonstrated in the terahertz and microwave regions by two dimensional metamaterials, such as bi-layer metamaterials [14, 17]. It is an important to overcome the difficulty of fabricating bi-layer components in the infrared and visible optical regions [17-19].
Besides, over the past several years, great attentions have been paid to metal-based metamaterials. However, these metallic systems unavoidably suffer large nonradiative losses because of ohmic damping, which is the main disadvantage to achieve high quality (Q) factor and high transmittance of EIT-like window. Fortunately, to provide a possible approach to overcome the loss of metallic metamaterials, researchers have found that high refractive index dielectrics could be a realistic choice [20-22].

In this paper, we proposed a dielectric metamaterial that consists of perpendicularly arranged bi-layer Si nanobars. By analyzing the transparency window as well as the local field and phase shifts of transmitted light, an interference result of bright and dark modes based on symmetric or asymmetric metamaterials, we concluded that only the asymmetric design of our Si metamaterial can realize the high-efficiency EIT-like phenomenon.

2. Proposed Metamaterial Structure

For the numerical calculation, we use the commercial finite integral technique (FIT) method. With the unit-cell boundary conditions, a frequency-domain solver is employed with Floquet ports normal to the z-direction. The perspective view based on a unit cell is shown in figure 1a, which consists of bi-layer of mutually perpendicular nano-scale silicon (ε=11.9) bars embedded in a SiO$_2$ dielectric environment (ε=2.1). Incident plane wave propagates along the z-direction, and its magnetic field H is parallel to the x-direction and electric component E is parallel to the y-direction. The periodicities of unit cell are 1290 nm on x-direction and 1350 nm on y-direction. The size of the SiO$_2$ dielectric environment in z-direction is 1100 nm. The lengths of the upper vertical and lower horizontal bar are $L_1=720$ nm and $L_2=780$ nm respectively.

For the asymmetric bi-layer metamaterials, its lateral displacement ($S$) of the upper vertical silicon strip of is shown in figure 1b. The $t=165$ nm stands for the thickness of the bi-layer silicon bars. In figure 1c, the width of silicon bars is $w=210$ nm. The distance between the horizontal and vertical bars is $d=160$ nm.

![Figure 1. Schematic of bi-layer perpendicular Si-bar metamaterial embedded in a SiO$_2$ dielectric environment. (a) Slanted side view, (b) top view and (c) side view of the unit cell of the investigated EIT metamaterials.](image)

3. Results and Discussion

Under the excitations mentioned earlier, the collective oscillation of the vertical silicon is a bright mode resonance that can be excited directly by the incident light. A clear response can be observed in the transmission spectrum in figure 2. It is easy to find that the transmission dip of the bright mode locates at 150 THz. On the other hand, the horizontal bar can serve as a structure with only dark mode for the incident light, which means it has no resonant response in the transmission spectra shown in figure 2. It shows that when the dark mode works solely approaching to normal incident light, no strong coupling will occur in the external field [15, 23-29]. As a matter of fact, when we have incident
normally polarized in our bi-layer structure, the electric component of the light results in the resonance.

Figure 2. Black, red-circle, green-triangle and blue-square curves refer to the simulation results of transmittance for pure dark mode, pure bright mode, combination of bright and dark modes in symmetric ($S=0$ nm) and asymmetric ($S=60$ nm) arrangements, respectively.

Two configurations are considered for our bi-layer Si bars metamaterials. One is asymmetrically arranged by shifting the vertical nanoscale bars to the left side along the x-direction, this refers to the asymmetric configuration with $S=60$ nm. The other one is symmetric configuration with $S=0$ nm. Due to the fact that the dark mode cannot be induced and only a bright mode occurs in the symmetric case at 148.9 THz. Therefore, it is expected that on the symmetric configuration, such EIT-like transparency window cannot be achieved [11-15]. However, the dark mode can be induced under asymmetric geometry configuration. It was demonstrated in recently reported works that symmetry breaking of the geometry has a key role in realizing classical-EIT effect in metamaterials [14, 23-26]. For the asymmetric configuration $S=60$ nm, it exhibits an EIT-like window at 149.14 THz with a very high transmission coefficient about 96%. In comparison with the resonant dip of the pure bright mode, the narrow EIT-like window peak suffers a frequency shift, attributed to the overlapped middle parts in the bi-layer bars perpendicular to each other [16]. According to the full width at half maximum shown in figure 2, the $Q$ factor of transparency window is calculated to be as high as 1864. Thus, our asymmetric bi-layer Si-bar metamaterial makes it possible for low-loss EIT-based applications, such as slowing lights, ultra-fast switching, and sensing.

The induced surface currents of resonant mode is usually useful to explain the underlying physics. Instead, for our dielectric structure, the localized electric field at 149.14 THz is plotted in figure 3. It is demonstrated that the excitation of the vertical bar is resulted from the incident light, while exerts an electric field following the vertical nanoscale bar in figure 3. Nevertheless, the electric field intensity of the elevation view of the metamaterial is not very strong. For the side view, it is easy to see the stronger electric field lies at one of the ends of vertical nanoscale bar, while the corresponding weaker electric field is localized at another end of the vertical nanoscale bar. These two distinct local electric fields as a result of the damaging interference amongst “bright” and “dark” resonator which lead to the EIT phenomenon [15].

It is known that EIT-like phenomenon can lead to slow light effect. The transmission phase occurs dramatic change in the transmission window, thus giving rise to a strong dispersion, meanwhile the slow-light effect happens. Figure 4 shows that the phase slope is the steepest at the location of the EIT-like peak, denoting the occurrence of an optical delay associated with the EIT-like peak [27, 28].
Figure 3. Electric field distribution of the (a) elevation and (b) side views of the unit cell in the bi-layer asymmetric metamaterial ($S=60$ nm) at 149.14 THz.

Figure 4. Simulated transmission phase shifts with asymmetric ($S=60$ nm) bi-layer structure.

4. Conclusion
In summary, a bi-layer EIT-like metamaterial comprises bi-layer Si bars is designed and numerically investigated. It is demonstrated that the all dielectric metamaterial could support an obvious EIT-like response in the near-infrared region, exhibiting a high-efficiency as well as a low-loss transparency window, as compared with other metal-based (e.g., Ag or Au) EIT-like metamaterials that suffers heavy ohmic damping. Those features presented in this numerical work confirms that the designed all-dielectric metamaterial can be potentially employed for novel devices associated with slowing-light effect, such as efficient sensing and optical switching.

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