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Performance comparison of the electromagnetic induction transparency effects for two U-shaped resonators having different opening directions

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Abstract

This paper gives the design of electromagnetically induced transparency effect using two U-shaped resonators with different opening directions (same direction and opposite direction). It is revealed that extremely similar transparency effect can be found for the two cases. The reason is that the two structures have the same sizes. However, the change in position of the two U-shaped resonators in the opposite opening has a significant effect on the transparent peak which is mainly reflected in the broadening of the broadband and the frequency shift of the working frequency, while there is almost no change in resonance performance for the same opening. We provide the field distributions for analyzing the causes of these different results. We believe these performance can guide future research.

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1. Introduction

The concept of electromagnetic induction transparency (EIT) has attracted a lot attention because of their potential applications in optical buffers, controllable delay lines, sensing, slow-light devices, nonlinear effects, switching and sensing [1, 2, 3, 4, 5, 6, 7, 8]. EIT is derived from destructive interference between different excitation paths in a three-level atomic system, making the initial opaque medium transparent to the detection laser beam, which is a quantum phenomenon [9, 10]. Two different methods of bright-bright mode coupling and bright-dark mode coupling can be used to generate the EIT in metamaterials. The first approach is based on two bright coupling modes. It is the coupling between the low-quality factor with super radiation resonators and the high-quality factor with low radiation resonators. The incident radiation can directly excite these two resonators [11, 12, 13, 14, 15]. As for bright-dark mode, the bright mode resonator couple to the incident wave directly. However, the characteristic of the dark mode resonator is high Q-factor, and the dark mode resonator could not be excited directly by the wave. But, the bright mode resonator can activate this dark mode with near-field coupling. It is the necessary condition for achieving EIT to couple the bright and dark resonances in this systems [16, 17, 18, 19, 20, 21].

Metal split-ring is the simple metamaterial (MM) structure that can achieve many functions, such as filtering, sensing, and so on [22, 23, 24, 25, 26,26,27]. Recent studies have found that combinations of multiple split-rings can achieve EIT effects. For example, Yahiaoui et al. [28] designed a structure composed of L-shaped resonators and U-shaped resonators. The results show a typical EIT effect in a MM structure at terahertz frequencies. This hybrid metamaterial has great application potential in optical switching. Gupta et al. [29] proposed a structure which consists of a double split gap square shaped metallic strip (i.e., the double U-shaped resonators). They demonstrated sensing with toroidal resonance in a two-dimensional terahertz metamaterial in which a pair of mirrored asymmetric Fano resonators possesses anti-aligned magnetic moments at an electromagnetic resonance that gives rise to a toroidal dipole. Tian et al. [30] presented a structure consisting of three U-shaped resonators. When the power of the laser is increased, the transmission peak shows a downward trend and is accompanied by a blueshift phenomenon. The structure in Ref. [31] demonstrated two different U-shaped resonators with the same opening direction. Low-loss and high transmission electromagnetically induced transparency like resonance can be obtained in this structure design. Two identical U-shaped resonators with the opposite opening direction were proposed by Al-Naib [32]. Coating half of this resonator can excite Fano resonant. Unknown analytes can be identified by distinguishing their thickness and refractive index. Chen et al. [7] designed symmetric and asymmetric structures within a set of U-shaped resonators with opposite openings. The symmetric resonator shows a single transmittance dip, and this is the

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expected result, while the latter resonator obtained two transmission peaks by breaking the symmetry. This article is benefit to chemical and biological detection.

Although two U-shaped resonators having same opening and opposite opening can provide the ability to achieve the EIT effect, do these two kinds of openings have the same or similar EIT effect? And how the relative positions of the two U-shaped resonators under different openings affect the EIT effect? This is an interesting but often overlooked issue. In this paper, we systematically compare and study the EIT effect of two U-shaped resonators with different opening directions (the same opening and the opposite opening). It is found that the suggested structures with the two different opening directions have extremely similar (or almost the same) EIT effect, which is derived from the bright-bright mode coupling of the two U-shaped resonators. However, very obvious and different resonance effects can be obtained when the relative positions of the two U-shaped resonators under different opening directions are changed. Specifically, the EIT effect of the structure with opposite opening direction is sensitive to the change of the relative positions of the two U-shaped resonators, while the resonance feature of EIT effect for the same opening direction is nearly unchanged. The reason for the difference in resonance performance is discussed by the distribution of electromagnetic field. We believe that these results obtained here have a guiding role for the design of EIT effect in the future.

2. Design

In order to achieve the purpose of this paper, we present a set of structures in contrast. Both structures consist of a big U and a small U. The opposite opening structure is marked as case I, and we mark the same opening structure as case II (see Fig. 1). These two structures are symmetry about y-axis and described by horizontal and vertical periodicities of Px = 90 μm and Py = 140 μm, respectively. The

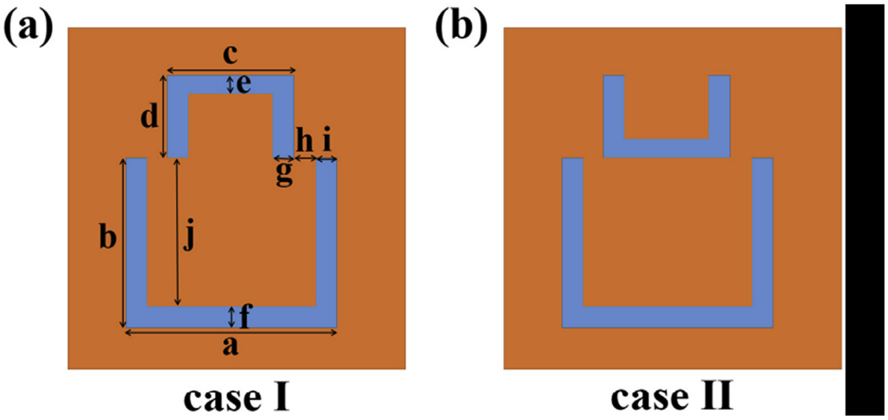

Fig. 1. (a) and (b) consisting of double U-shaped structure with opposite opening direction and same opening direction. The relevant dimensions are: a = 80 μm, b = 70 μm, c = 60 μm, d = 50 μm, $e = f = g = h = i$ = 5 μm.

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incident wave of the electric field is polarized in the x direction. The pattern structures are made of Ag with a conductivity of 6.1×10^7 S/m having the thickness of 0.5 μm. These two metal structures are placed on a dielectric substrate with refraction index of 1.82. Finite difference time domain method is utilized to investigate these two structure. Both x and y directions are periodic boundary conditions and the z direction is a perfectly matched layer.

3. Results and discussion

First we verify the characteristics of the proposed structures. Fig. 2(a) is the transmission spectrum of the case I. From the blue line, we can clearly see that there are two dips and one transmission peak. The transmission peak appears at about 0.59 THz and the two resonance dips at about 0.46 THz and 0.70 THz, respectively. To prove this phenomenon, single small U and single big U are respectively investigated, see Fig. 2(a). As reveled, the dip of the black curve and the dip of the case I almost coincide at around 0.70 THz. Similarly, the dip of the red curve and the other dip of the case I almost coincide at around 0.46 THz. So the appearance of the transmission peak is the result of the interaction of the two U-shaped structures. In regard to Fig. 2(b), there are also two dips and one transmission peak, and the transmission peak is about 0.56 THz and the dips are respectively 0.46 THz and 0.71 THz. Compared with Fig. 2(a), there is a small difference in transmission peak and the second dip, and the trends of the two curves are roughly the same. As a result, the opening directions of the two U-shaped resonators does not affect the transmission peak.

In fact, the two U-shaped resonators can be regard as two bright modes. The appearance of a transparent peak is the result of the interaction between two bright modes, and it can be clearly explained from the electric fields ($|E|$) in Fig. 3. Fig. 3(a) and (c) are respectively the electric field distributions of the two dips of case I in Fig. 2(a), and Fig. 3(b) is the electric field distribution of the transmission peak of case I in

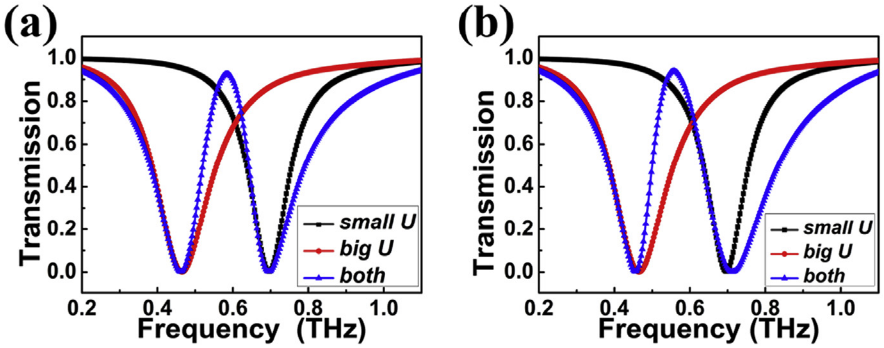

Fig. 2. (a) and (b) respectively gives the resonance curves of case I and case II. The black and red lines indicate the transmission spectra of single small U and single big U, respectively. The blue line represents the transmission spectrum of a double U-shaped structure.

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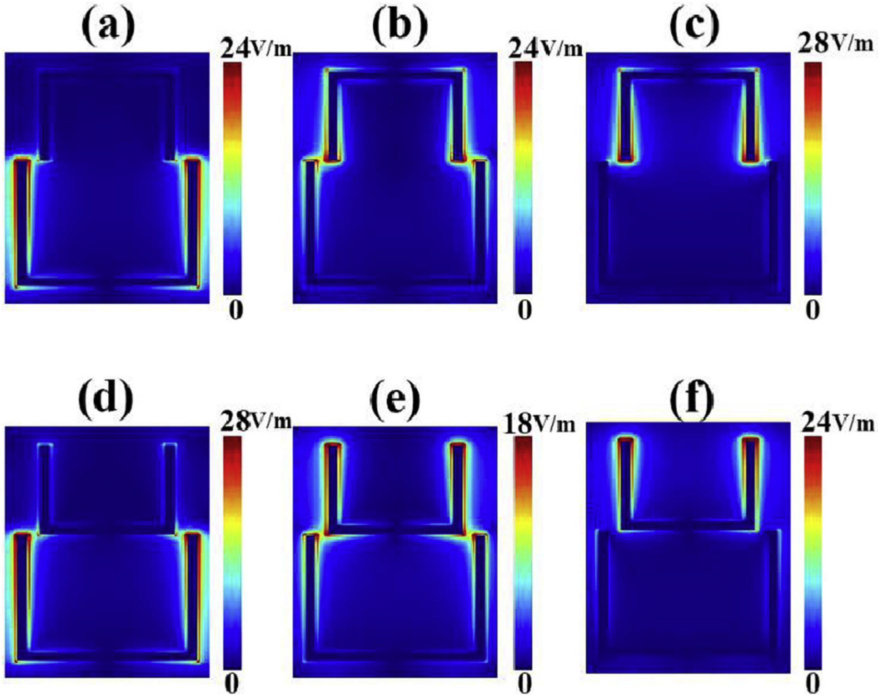

Fig. 3. (a)−(c) give the electric field distribution and correspond to the blue line in Fig. 2(a) at 0.46 THz, 0.59 THz and 0.70 THz. (d)−(f) give the electric field distribution and correspond to the blue line in Fig. 2(b) at 0.46 THz, 0.56 THz and 0.71 THz.

Fig. 2(a). When the frequency is at 0.46 THz, the electric field in Fig. 3(a) is only distributed in the big U, and is mainly concentrated on both sides of the big U. In Fig. 3(c), the similar field distribution can be found in small U with the frequency of 0.70 THz. According to these distribution features, we can conclude that both big U and small U are act as bright modes. Strong electric fields (see Fig. 3(b)) are found in the place where big U and small U are close with the frequency of 0.59 THz. It can be intuitively seen from Figs. 2 and 3 that there is a strong coupling at the peak. Consequently, the EIT effect in case I is verified by bright-bright mode coupling.

For case II, we find similar field distributions. For example, the first dip is mainly concentrated on the big U, as shown in Fig. 3(d), while the field distribution of the second dip is distributed on the small U, see Fig. 3(f). The field distribution of the transparent peak of the case II in Fig. 3(e) is mainly due to the interaction of two U-shaped resonator. Therefore, the EIT effect for case II is also based on the bright-bright mode coupling. We can conclude that the transparency effects of case I and case II are both derived from the bright-bright mode coupling. Because the sizes of small U and big U are invariant, extremely similar EIT effects are found. In other words, the choice of opening direction for the two U-shaped resonators does not affect the resonance performance of EIT effect.

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Although the EIT effect is insensitive to the opening direction of the two U-shaped resonators, is there a very similar EIT effect when the relative positions of the two U rings change? The following studies show that their corresponding EIT effects show the completely different trend. These different change trends and results will be very helpful and can guide future device designs.

This paragraph mainly studies the influence of relative position changes on the EIT effect for two cases. We first study the effect of small U moved down on the EIT effect, and the distance is marked by j. With decreasing j, the frequency of transmission peak of case I in Fig. 4(a) has a significant change. Blue shift and red shift occurred in two dips, respectively. The change in the two dips leads to the widening of the resonance bandwidth of the transparent peak. The bandwidth of the EIT effect in $j = 15$ μm is 0.205 THz, which is about 1.6 times that of $j = 65$ μm. In other words, the bandwidth is increased by 1.6 times. So we can apply it to broadband bandpass devices. However, for the case II, we get completely different effects and phenomena. Its resonance spectrum line is shown in Fig. 4(b). There is almost no change in the transmission peak and there is also no blue shift and red shift in two dips with decreasing j. As the distance decreases, the transparent peak of the two cases have significant differences. Apparently, the opening orientation of the two U-shaped resonators has a great influence on the transmission spectrum.

In order to study the reasons for this phenomenon, we give the field distributions when the resonance spectrum change obviously ($j = 15$ μm). Fig. 5(a), (b) and (c) respectively indicate the fields of case I of the first dip, transparent peak and the second dip. It is obvious that the electric fields of Fig. 5(a) and (c) are respectively distributed on both sides of big U and small U, and the electric field in Fig. 5(b) is concentrated between them. We can see that the EIT effect ($j = 15$ μm) is excited by bright-bright mode coupling. Fig. 5(d)−(f) respectively give the fields of case II, of which Fig. 5(d) and (f) respectively indicate the fields of the first dip and the

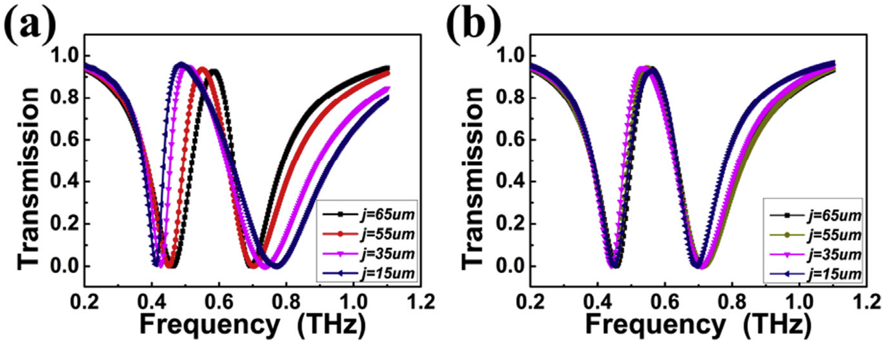

Fig. 4. (a) gives the dependence of the resonance curves of the case I on the change of j. (b) presents the dependence of the resonance curves of the case II on the change of j. The distance indicated by j is shown in Fig. 1.

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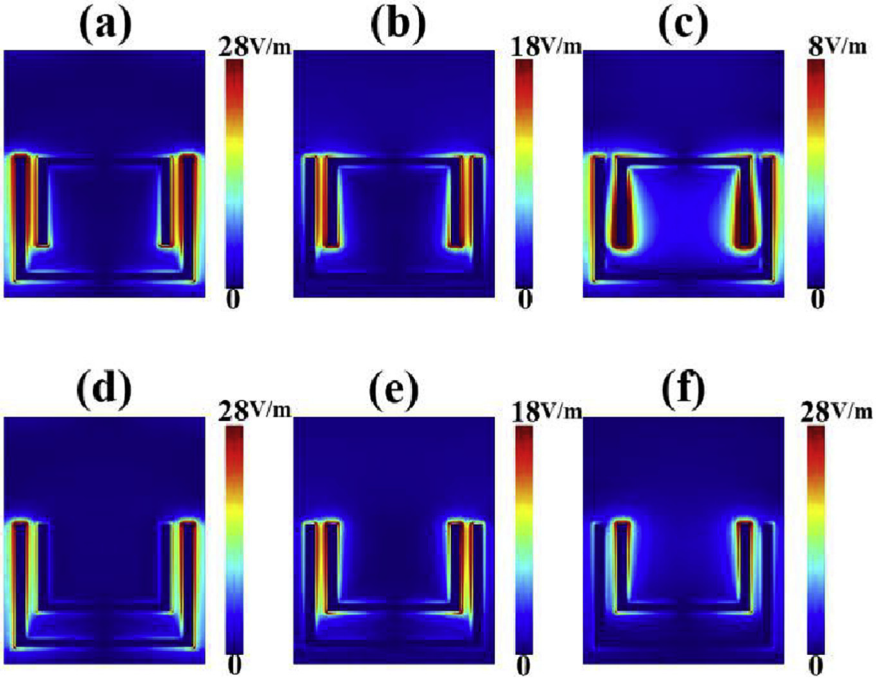

Fig. 5. (a)−(c) respectively indicate the fields of case I of the first dip, transparent peak and the second dip, and (d)−(f) respectively indicate the fields of case II of the first dip, transparent peak and the second dip.

second dip, and Fig. 5(e) represents the fields of transparent peak. Compared with case I, the electric field distribution of case II is almost the same, and the field strength is weaker than case II. This indicates that the coupling strength under case II is significantly stronger than case II. We think that the difference in coupling strength is the cause of the difference in the transmission spectrum between the two cases. So the position of the small U has a significant effect on the performance of the opposite opening structure.

We next study the influence of the small U left and right movement on the EIT effect. In fact, due to the left and right shifts have the same result, we only give the right shift here. The right distance is defined as h. For case I, the transmission spectrum (see Fig. 6(a)) has a large change when $h = 3$ μm, which is reflected in the frequency shift of the two dips and transparent peak. In addition, the bandwidth of the transparent peak becomes smaller. As h continues to decrease, the spectrum has a slight change. The reason may be that the coupling between the two U-shaped resonators is saturated. However, the resonance performance of case II in Fig. 6(b) has almost no change in spectrum. Through the above comparison we found that case I is more sensitive to structure parameters than case II. In other words, changing the relative position of the two metal split-rings has a greater impact on case I, but has little effect on case II.

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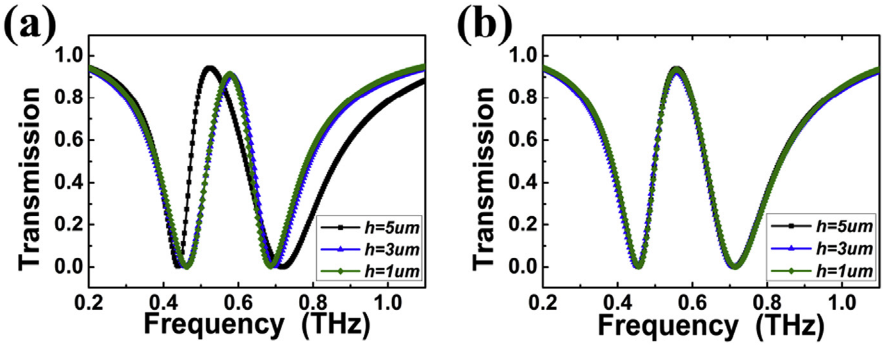

Fig. 6. (a) gives the dependence of the resonance curves of the case I on the change of *h*. (b) presents the dependence of the resonance curves of the case II on the change of *h*. The distance indicated by *h* is shown in Fig. 1.

4. Conclusion

In conclusion, two different sizes of U-shaped split-ring having the opposite opening (case I) and the same opening direction (case II) are demonstrated in this paper. The two cases possess extremely similar transparency effects, which are both proved to be excited by bright-bright mode coupling in the two cases. Although they have similar transparency effects, the relative positions of the two U-shaped resonators under the same and opposite opening directions possess different influence on the transparency effects. More concretely, the change in position of the two U-shaped resonators in the case I has a significant effect on the transparent peak which is mainly reflected in the broadening of the broadband (the broadening factor is 1.6 times) and the frequency shift of the working frequency, while the change of case II is nearly unchanged. This paper has certain reference value for later scientific workers. We can apply in broadband bandpass devices, biosensing, filtering and slow light equipment, etc.

Declarations

Author contribution statement

Qingshan Niu: Performed the experiments; Wrote the paper.

Chao Tang: Analyzed and interpreted the data; Wrote the paper.

Yuanhao He, Wei-Qing Huang, Lifa Hu: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ben-Xin Wang: Conceived and designed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] N. Liu, T. Weiss, M. Mesch, L. Langguth, U. Eigenthaler, M. Hirscher, C. Sonnichsen, H. Giessen, Planar metamaterial analogue of electromagnetically induced transparency for plasmonic sensing, Nano Lett. 10 (2010) 1103–1107.

[2] J.J. Longdell, E. Fraval, M.J. Sellars, N.B. Manson, Stopped light with storage times greater than one second using electromagnetically induced transparency in a solid, Phys. Rev. Lett. 95 (2005) 063601.

[3] K. Totsuka, N. Kobayashi, M. Tomita, Slow light in coupled-resonator-induced transparency, Phys. Rev. Lett. 98 (2007) 213904.

[4] M.F. Yanik, W. Suh, Z. Wang, S. Fan, Stopping light in a waveguide with an all-optical analog of electromagnetically induced transparency, Phys. Rev. Lett. 93 (2004) 233903.

[5] C. Sun, Z. Dong, J. Si, X. Deng, Independently tunable dual-band plasmonically induced transparency based on hybrid metal-graphene metamaterials at mid-infrared frequencies, Optic Express 25 (2017) 1242–1250.

[6] J. Chen, P. Wang, C. Chen, Y. Lu, H. Ming, Q. Zhan, Plasmonic Eit-like Switching in Bright-Dark-Bright Plasmon Resonators, Optic Express 19 (2011) 5970–5978.

[7] C.Y. Chen, I.W. Un, N.H. Tai, T.J. Yen, Asymmetric coupling between subradiant and superradiant plasmonic resonances and its enhanced sensing performance, Optic Express 17 (2009) 15372–15380.

[8] Z. Vafapour, Near infrared biosensor based on classical electromagnetically induced reflectance (cl-eir) in a planar complementary metamaterial, Optic Commun. 387 (2017) 1–11.

[9] S.E. Harris, J.E. Field, A. Imamoglu, J.J. Macklin, Lasers without inversion, Phys. Rev. Lett. 64 (1989) 1107.

https://doi.org/10.1016/j.heliyon.2019.e01442

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[10] M. Fleischhauer, A. Imamoglu, J.P. Marangos, Electromagnetically induced transparency: optics in coherent media, Rev. Mod. Phys. 77 (2005) 633−673.

[11] S. Zhang, D.A. Genov, Y. Wang, M. Liu, X. Zhang, Plasmon-induced transparency in metamaterials, Phys. Rev. Lett. 101 (2008) 047401.

[12] N. Papasimakis, V.A. Fedotov, N.I. Zheludev, Metamaterial analog of electromagnetically induced transparency, Phys. Rev. Lett. 101 (2008) 253903.

[13] R. Singh, C. Rockstuh, F. Lederer, W. Zhang, Coupling between a dark and a bright eigenmode in a terahertz metamaterial, Phys. Rev. B 79 (2009) 085111.

[14] P. Tassin, L. Zhang, T. Koschny, E.N. Economou, C.M. Souboulis, Low-loss metamaterials based on classical electromagnetically induced transparency, Phys. Rev. Lett. 102 (2009) 053901.

[15] N. Liu, L. Langguth, T. Weiss, J. Kästel, M. Fleischhauer, T. Pfau, H. Giessen, Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit, Nat. Mater. 8 (2009) 758−762.

[16] S.J.M. Rao, D. Kumar, G. Kumar, D.R. Chowdhury, Modulating the near field coupling through resonator displacement in planar terahertz metamaterials, J. Infrared, Millim. Terahertz Waves 38 (2017) 124−134.

[17] M. Manjappa, S.P. Turaga, Y.K. Srivastava, A.A. Bettiol, R. Singh, Magnetic annihilation of the dark mode in a strongly coupled bright-dark terahertz metamaterial, Optic Lett. 42 (2017) 2106−2109.

[18] K.M. Devi, A.K. Sarma, D.R. Chowdhury, G. Kumar, Plasmon induced transparency effect through alternately coupled resonators in terahertz metamaterial, Optic Express 25 (2017) 10484.

[19] R. Yahiaoui, M. Manjappa, Y.K. Srivastava, R. Singh, Active control and switching of broadband electromagnetically induced transparency in symmetric metadevices, Appl. Phys. Lett. 111 (2017) 1103−2109.

[20] Q. Xu, X. Su, C. Ouyang, N. Xu, W. Cao, Y. Zhang, Q. Li, C. Hu, J. Gu, Z. Tian, A.K. Azad, J. Han, W. Zhang, Frequency-agile electromagnetically induced transparency analogue in terahertz metamaterials, Optic Lett. 41 (2016) 4562.

[21] J. Gu, R. Singh, X. Liu, X. Zhang, Y. Ma, S. Zhang, S.A. Maier, Z. Tian, A.K. Azad, H.T. Chen, A.J. Taylor, J. Han, W. Zhang, Active control of electromagnetically induced transparency analogue in terahertz metamaterials, Nat. Commun. 3 (2012) 1151.

[22] Z. Song, Q. Chu, Q.H. Liu, Isotropic wide-angle analog of electromagnetically induced transparency in a terahertz metasurface, Mater. Lett. 223 (2018) 90−92.

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[23] F. Bagci, B. Akaoglu, Single and multi-band electromagnetic induced transparency-like metamaterials with coupled split ring resonators, J. Appl. Phys. 122 (2017) 073103.

[24] S. Hu, D. Liu, H. Lin, J. Chen, Y. Yi, H. Yang, Analogue of ultra-broadband and polarization-independent electromagnetically induced transparency using planar metamaterial, J. Appl. Phys. 121 (2017) 123103.

[25] H. Li, F. Xue, Comparing Q-factor of electromagnetically induced transparency based on different space distribution quasi-dark mode resonator, J. Appl. Phys. 122 (2017) 044501.

[26] K.M. Devi, D.R. Chowdhury, G. Kumar, A.K. Sarma, Dual-band electromagnetically induced transparency effect in a concentrically coupled asymmetric terahertz metamaterial, J. Appl. Phys. 124 (2018) 063106.

[27] K.M. Devi, M. Islam, D.R. Chowdhury, A.K. Sarma, G. Kumar, Plasmon-induced transparency in graphene-based terahertz metamaterials, Europhys. Lett. 120 (2017) 27005.

[28] R. Yahiaoui, J.A. Burrow, S.M. Mekonen, A. Sarangan, J. Mathews, I. Agha, et al., Electromagnetically induced transparency control in terahertz metasurfaces based on bright-bright mode coupling, Phys. Rev. B 97 (2018) 155403.

[29] M. Gupta, Y.K. Srivastava, M. Manjappa, R. Singh, Sensing with toroidal metamaterial, Appl. Phys. Lett. 110 (2017) 121108.

[30] Y. Tian, J. Ji, S. Zhou, H. Wang, Z. Ma, F. Ling, J. Yao, Active optical modulator based on a metasurface in the terahertz region, Appl. Optic. 57 (2018) 7778–7781.

[31] Y. Tian, S. Hu, X. Huang, Z. Yu, H. Lin, H. Yang, Low-loss planar metamaterials electromagnetically induced transparency for sensitive refractive index sensing, J. Phys. D 50 (2017) 405105.

[32] I. Al-Naib, Thin-film sensing via fano resonance excitation in symmetric terahertz metamaterials, J. Infrared, Millim. Terahertz Waves 39 (2018) 1–5.

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