Transparency window for the absorptive dipole resonance in a symmetry-reduced grating structure

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Abstract: We demonstrate that a transparency window can be obtained within the absorptive dipole resonant regime, by slightly reducing the symmetric arrangement of a dipole-like bar grating covered by a waveguiding layer. The physical understanding is that, under the condition of reducing the grating symmetry, the lossy dipole plasmon resonance can be completely transferred into the waveguide mode in a way of destructive interference. In accompany with the tunable transparency window modulated by the symmetry-reduced displacement, an ultra high group index (slowing down the light) as well as a vortex distribution of the electromagnetic field is found.

OCIS codes: (250.5403) Plasmonics; (160.3918) Metamaterials.

References and links

1. E. Ozbay, "Plasmonics: merging photonics and electronics at nanoscale dimensions," Science **311**(5758), 189–193 (2006).
2. S. Linden, C. Enkrich, M. Wegener, J. Zhou, T. Koschny, and C. M. Soukoulis, "Magnetic response of metamaterials at 100 terahertz," Science **306**(5700), 1351–1353 (2004).
3. S. Zhang, W. Fan, K. J. Malloy, S. R. J. Brueck, N. C. Panoiu, and R. M. Osgood, "Near-infrared double negative metamaterials," Opt. Express **13**(13), 4922–4930 (2005).
4. E. Prodan, C. Radloff, N. J. Halas, and P. Nordlander, "A hybridization model for the plasmon response of complex nanostructures," Science **302**(5644), 419–422 (2003).
5. H. Liu, D. A. Genov, D. M. Wu, Y. M. Liu, Z. W. Liu, C. Sun, S. N. Zhu, and X. Zhang, "Magnetic plasmon hybridization and optical activity at optical frequencies," Phys. Rev. B **76**(7), 073101 (2007).
6. D. J. Bergman and M. I. Stockman, "Surface plasmon amplification by stimulated emission of radiation: quantum generation of coherent surface plasmons in nanosystems," Phys. Rev. Lett. **90**(2), 027402 (2003).
7. M. I. Stockman, "Nanoscience: dark-hot resonances," Nature **467**(7315), 541–542 (2010).
8. R. Singh, C. Rockstuhl, F. Lederer, and W. Zhang, "Coupling between a dark and a bright eigenmode in a terahertz metamaterial," Phys. Rev. B **79**(8), 085111 (2009).
9. S. Zhang, D. A. Genov, Y. Wang, M. Liu, and X. Zhang, "Plasmon-induced transparency in metamaterials," Phys. Rev. Lett. **101**(4), 047401 (2008).
10. N. Papasimakis, V. A. Fedotov, N. I. Zheludev, and S. L. Prosvirnin, "Metamaterial analog of electromagnetically induced transparency," Phys. Rev. Lett. **101**(25), 253903 (2008).
11. N. Liu, L. Langguth, T. Weiss, J. Kastel, M. Fleischhauer, T. Pfau, and H. Giessen, "Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit," Nat. Mater. **8**(9), 758–762 (2009).
12. Y. Sun, H. Jiang, Y. Yang, Y. Zhang, H. Chen, and S. Zhu, "Electromagnetically induced transparency in metamaterials: Influence of intrinsic loss and dynamic evolution," Phys. Rev. B **83**(19), 195140 (2011).
13. V. Yannopapas, E. Paspalakis, and N. V. Vitanov, "Electromagnetically induced transparency and slow light in an array of metallic nanoparticles," Phys. Rev. B **80**(3), 035104 (2009).
14. P. Tassin, L. Zhang, T. Koschny, E. N. Economou, and C. M. Soukoulis, "Low-loss metamaterials based on classical electromagnetically induced transparency," Phys. Rev. Lett. **102**(5), 053901 (2009).
15. P. Tassin, L. Zhang, T. Koschny, E. N. Economou, and C. M. Soukoulis, "Planar designs for electromagnetically induced transparency in metamaterials," Opt. Express **17**(7), 5595–5605 (2009).
16. S.-Y. Chiam, R. Singh, C. Rockstuhl, F. Lederer, W. Zhang, and A. A. Bettiol, "Analogue of electromagnetically induced transparency in a terahertz metamaterial," Phys. Rev. B **80**(15), 153103 (2009).
17. R. D. Kekatpure, E. S. Barnard, W. Cai, and M. L. Brongersma, "Phase-coupled plasmon-induced transparency," Phys. Rev. Lett. **104**(24), 243902 (2010).

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18. S. Linden, J. Kuhl, and H. Giessen, "Controlling the interaction between light and gold nanoparticles: selective suppression of extinction," Phys. Rev. Lett. **86**(20), 4688–4691 (2001).
19. A. Christ, T. Zentgraf, J. Kuhl, S. G. Tikhodeev, N. A. Gippius, and H. Giessen, "Optical properties of planar metallic photonic crystal structures: experiment and theory," Phys. Rev. B **70**(12), 125113 (2004).
20. T. Zentgraf, S. Zhang, R. F. Oulton, and X. Zhang, "Ultranarrow coupling-induced transparency bands in hybrid plasmonic systems," Phys. Rev. B **80**(19), 195415 (2009).
21. A. Christ, O. J. F. Martin, Y. Ekinci, N. A. Gippius, and S. G. Tikhodeev, "Symmetry breaking in a plasmonic metamaterial at optical wavelength," Nano Lett. **8**(8), 2171–2175 (2008).
22. F. Hao, Y. Sonnefraud, P. V. Dorpe, S. A. Maier, N. J. Halas, and P. Nordlander, "Symmetry breaking in plasmonic nanocavities: subradiant LSPR sensing and a tunable Fano resonance," Nano Lett. **8**(11), 3983–3988 (2008).
23. C.-Y. Chen, I.-W. Un, N.-H. Tai, and T.-J. Yen, "Asymmetric coupling between subradiant and superradiant plasmonic resonances and its enhanced sensing performance," Opt. Express **17**(17), 15372–15380 (2009).
24. L. V. Brown, H. Sobhani, J. B. Lassiter, P. Nordlander, and N. J. Halas, "Heterodimers: plasmonic properties of mismatched nanoparticle pairs," ACS Nano **4**(2), 819–832 (2010).
25. V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, "Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry," Phys. Rev. Lett. **99**(14), 147401 (2007).
26. Z.-G. Dong, H. Liu, T. Li, Z.-H. Zhu, S.-M. Wang, J.-X. Cao, S.-N. Zhu, and X. Zhang, "Optical loss compensation in a bulk left-handed metamaterial by the gain in quantum dots," Appl. Phys. Lett. **96**(4), 044104 (2010).
27. F. M. Wang, H. Liu, T. Li, Z. G. Dong, S. N. Zhu, and X. Zhang, "Metamaterial of rod pairs standing on gold plate and its negative refraction property in the far-infrared frequency regime," Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **75**(1), 016604 (2007).
28. Z.-G. Dong, H. Liu, M.-X. Xu, T. Li, S.-M. Wang, J.-X. Cao, S.-N. Zhu, and X. Zhang, "Role of asymmetric environment on the dark mode excitation in metamaterial analogue of electromagnetically-induced transparency," Opt. Express **18**(21), 22412–22417 (2010).

1. Introduction

For decades, plasmon resonances and their hybridization modes have been the popular means to manipulate the electromagnetic propagation in artificial nanostructures, such as the photonic crystals, metamaterials, cavities, and gratings [1–5]. Particular resonant modes by deliberate structural designs, excitable by the incident waves, are sufficient to produce the optical magnetism and left-handed response in split-ring resonators [2] and fishnet metamaterials [3], respectively. However, there is another kind of resonance, called dark or subradiant mode, which cannot be directly excited by far-field impinging waves [6–8]. Nevertheless, near-field coupling effect between two neighboring resonators can significantly modify the resonant behavior, resulting in an electromagnetic field distribution localized in the subradiant resonator due to the constructive or destructive interference, which usually gives a very narrow transmission spectrum and was considered as an analogue to the electromagnetically induced transparency (EIT) [9–17]. However, for these nanostructures whose intriguing properties depend on resonant metallic particles, the intrinsic optical loss in metal is always overwhelming, even for the EIT-like metallic metamaterials.

A good choice to avoid the issue of optical losses in metals is to transfer a localized surface plasmon resonance into a waveguiding mode in a dielectric slab by means of coherent near-field interaction [18–20]. In this coupling scheme, a very narrow transmission spectrum with a high quality factor can be obtained for bio-sensing or slowing down the light (high group index of refraction). Generally, this coupling can be realized from the phase matching approach, with the additional momentum (i.e., reciprocal lattice vector) offered by the periodic lattice [18]. On the other hand, as a matter of fact, the method of breaking the geometric symmetry is also capable to modulate the resonant response, which usually renders an otherwise subradiant mode accessible. Noticeably, the asymmetry-induced resonance generally exhibits a Fano-type narrow spectrum, due to the interference effect between different resonant channels [21–25].

In this paper, we investigate an EIT-like planar structure composed of a gold-bar grating placed in a waveguiding layer. A distinct structural feature for the periodic gold grating proposed in this work is the symmetry-reduced arrangement, which is different to Ref. 20. It will be demonstrated that a pronounced transparency window can be opened within the frequency region of the absorptive dipole resonance by metallic bars, as long as the narrow grating waveguide mode induced by reducing the grating symmetry is coincided in spectrum

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with the dipole resonance such that a destructive interference happens between these two resonant modes.

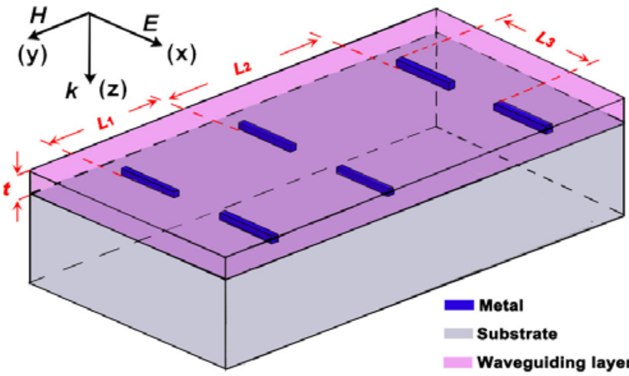

Fig. 1. Structural schematic of the planar grating structure composed of metallic bars.

2. Numerical model

Figure 1 shows a schematic illustration of the proposed planar structure comprising gold bars. The scales for the bar are length a= 300 nm, width b= 50 nm, and thickness c = 50 nm. Two kinds of planar arrangement will be studied: one is the symmetric configuration with equal gaps $L_1 = L_2 = 770$nm , which means a single periodic structure. Another is the symmetry-reduced configuration with different gaps $L_1 = 700$ nm and $L_2 = 840$ nm . The latter case means that, for every bar, the nearest neighboring counterparts on its two sides along the y direction are not placed equidistantly ($L_1 \neq L_2$). This symmetry-reduced arrangement can be obtained from the equal-gap symmetric configuration by alternately shifting the bars along the y direction with a displacement of $\Delta L/2=(L_2-L_1)/2=70$nm (for both cases, $L_2+L_1=1540$nm). The unit interval in the x direction is kept at $L_3 = 400$ nm. The metals are deposited on a quartz substrate with $n_s = 1.55$, and then a layer of waveguiding superstrate is covered with a thickness t = 200 nm and a refractive index $n_w = 1.944$. The electromagnetic wave is incident normally on the grating surface with the electric field polarized along the bar length to induce the dipole plasmon resonance. For our full-wave simulation based the finite element method [26, 27], the metal is numerically treated as gold with Drude-type permittivity ($\omega_p = 1.37 \times 10^{16} s^{-1}$ and $\gamma = 1.2 \times 10^{14} s^{-1}$). In addition, perfect electric and magnetic boundaries are used in compliance with the incident polarization requirement, which can mimic the infinite bar periodicity in the xy plane.

3. Results and discussions

As for the symmetric grating array, only the dipole plasmon resonance of the bar can be excited by incident waves, corresponding to a transmission dip [Fig. 2(a)] and an absorbance peak [Fig. 2(b)] around 136 THz, no matter the *y*-direction periodicity ($L_1 = L_2$) will be 700, 770 nm, or 840 nm. In contrast, it is interesting to find that there will be a transparency window within the absorptive dipole resonant spectrum for the symmetry-reduced grating structure with $L_1 = 700$ nm and $L_2 = 840$ nm. What highlight this transparency window are the nearly complete transmittance and a very narrow shape, this is promising to overcome the Drude damping limit for the EIT-like phenomenon at optical frequencies in pure metallic resonant structures [11]. Nevertheless, it should be mentioning that, when the structure is illuminated by a finite beam or there is only a finite grating area in transversal directions, light coupled to the waveguide mode will propagate out of the structure in transversal directions. Consequently, a lossy EIT effect will be observed due to the radiation loss.

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As is well known, a transparency window can be formed, as an EIT analogue by metamaterials, when the destructive interference happens between a broad resonance (e.g., dipole mode) and a narrow one (usually a subradiant mode). In this work, the subradiant resonance comes from the grating waveguide structure with the resonant frequency modulated by the grating periodicity (offering a y-direction reciprocal lattice vector for momentum matching to the waveguiding propagation constant) as well as the waveguiding layer thickness, dielectric constant, and the surrounding media [18–20]. Note that this mode cannot be excited for a bare waveguiding layer without the bar grating since the normally incident wave has zero momentum parallel to the waveguiding layer (i.e., xy plane). Although this grating waveguide mode is not excited for the symmetric grating configuration ($L_1 = L_2$), the numerical result indicates that a symmetry-reduced displacement (i.e., $L_1 \neq L_2$) introduced in the original symmetric case can make it an excitable mode. This interesting asymmetry-induced resonance is in accordance with recent literatures [21–25].

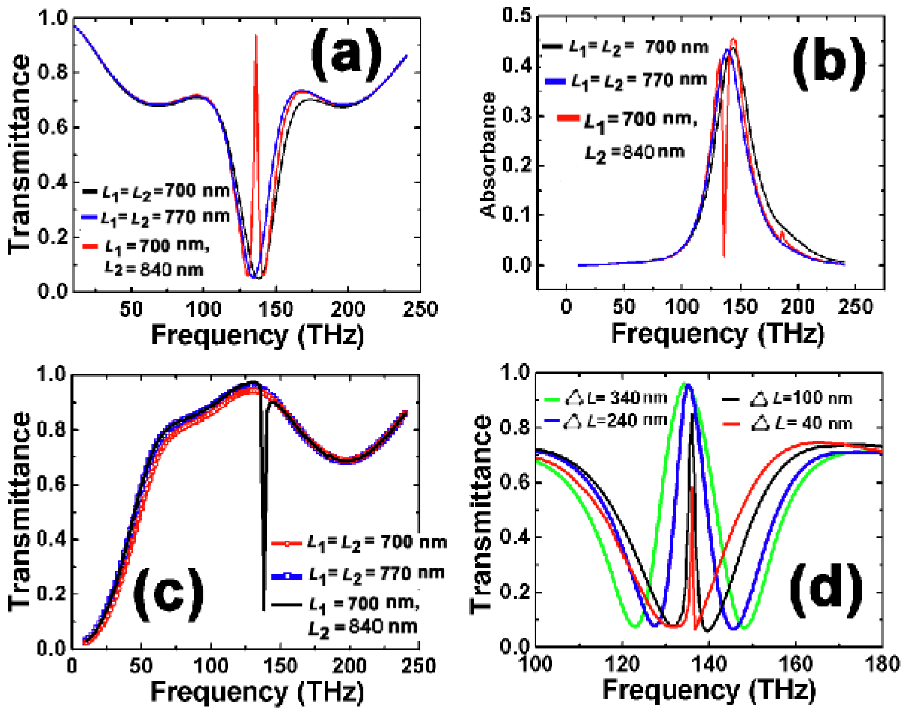

Fig. 2. The transparency window on dependence of structural parameters. Transmission (a) and absorption (b) spectra with symmetric and symmetry-reduced bar arrangements. (c) Transmission spectra for bars with infinite lengths. Note that the subradiant waveguiding mode can only be induced for the symmetry-reduced geometry. (d) The modulated transparency window on different ΔL, while $L_2 + L_1 = 1540$ nm for all ΔL cases.

The excitation independence of the grating waveguide mode on the dipole resonance can be confirmed easily by elongating all the bars to be infinite in length [Fig. 2(c)]. This strategy eliminates the dipole resonance, but the grating waveguide mode can still be excited as long as the same symmetry-reduced scheme is adopted. It should worth of mentioning that this result also implies the feasibility of dark mode excitation by the way of breaking or reducing symmetry, instead of by the plasmon-coupling excitation of a radiant resonant mode [28].

Figure 2(d) shows the dependence of the narrow transparency window on the symmetry-reduced degree $\Delta L = L_2 - L_1$, from where the transparency window is found to get narrower with decreasing ΔL, but at the sacrifice of transmission intensity. In addition, the central frequency for the transparency window does not shift obviously with altering ΔL, since a

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same reciprocal lattice vector $G = 2\pi / [(L_1 + L_2) / 2]$ is kept throughout the modulation of ΔL, matching to a corresponding propagation constant of the waveguiding mode.

To explicitly verify the dipole resonance (transmission dip) as well as the symmetry-reduction induced EIT-like mode (transparency window), the resonant *E*-field distributions are plot in Fig. 3. It is interesting to find that no strong *E*-field is localized around the metals for the symmetry-reduced configuration [Figs. 3(a) and 3(b)] due to the standing wave induced transversally in the waveguiding layer, in contrast to the dipole plasmon resonance for a symmetric grating with equal-gap array [Fig. 3(c)]. Physically, the clear *E*-field distribution shown in Figs. 3(a) and 3(b) implies the destructive interference happens predominantly so that the electromagnetic energy of the dipole resonance is totally transferred to the grating waveguide resonance, which apparently contributes to the transparency window. On the other hand, although such "selective" mode excitation is physically a result of destructive interference, it should be much easier to understand in the following way: when the plane wave is incident normally to the symmetric bar grating with $L_1 = L_2$, the *E*-field distributions in gaps L_1 and L_2 should have the same vector direction (in phase) and hence it does not excite the transversal grating waveguide mode. However, for the symmetry-reduced case the standing wave of the grating waveguide mode is excitable since the asymmetric gaps can break the synchronized phase of the plane wave impinging onto the meta-surface. For this case, all the y-direction gap centers between neighboring bars have a same interval of $(L_1 + L_2)/2$ with respect to each other, forming the nodes of the transversal standing wave.

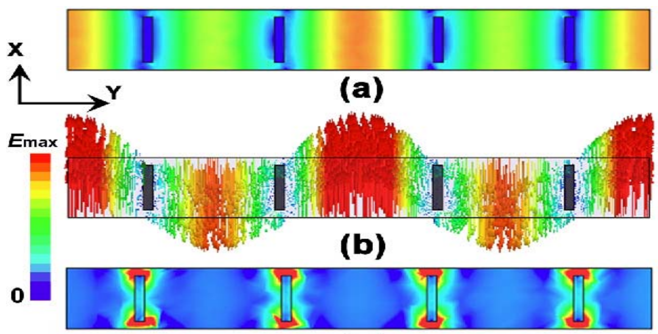

Fig. 3. The comparison of resonant *E*-field distribution at 136 THz. (a) and (b) are the *E*-field magnitude and vector for the symmetry-reduced configuration, respectively. (c) Dipole resonance excited for the equal-gap symmetry configuration. It is clear that the bright dipole mode can be transferred into the subradiant waveguiding mode as long as the grating symmetry is reduced, resulting in a transparency narrow band.

As shown earlier, by breaking the gap equivalence between the nearest neighboring counterparts with respect to an arbitrary bar, a grating-modulated waveguide mode can be excited. This mode interferes destructively with the channel of absorptive dipole resonance of and consequently a transparency window is obtained. The main advantage for the significant transparency window shown in this work comes from the low-loss nature for the grating-modulated waveguiding mode within the dielectric layer, as compared to some other all-metal metamaterial analogues of the EIT phenomenon. As a consequence of the destructive interference, an ultra high group index n_g with the capability of slowing down the light propagation can be expected [Fig. 4(a)], according to the formula $n_g = c_0 \cdot dk / d\omega = c_0 \cdot (d\phi / d\omega)/t$. Here, c_0 is the speed of light in vacuum, ω is the angular frequency, φ is the phase advance across the waveguiding layer, and t is the thickness of the waveguide layer [20]. In addition, it is noticed that a phenomenon of electromagnetic energy vortex is formed at the transparency window, which should be related to the slow light characteristic. In Fig. 4(b), the plot of the real part of the Poynting vector shows that the incident electromagnetic energy only passes through the large gap L_2 (i.e., parallel to the

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incident direction) and a portion of the passed energy will go back through the small gap L_1. Consequently, a vortex of the electromagnetic field is formed around the grating region.

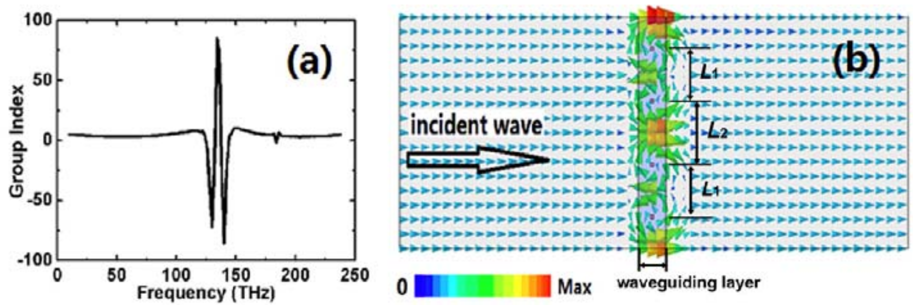

Fig. 4. (a) The ultra high group index at the transparency window. (b) The real part of Poynting vector at the frequency of the transparency resonance, indicating the electromagnetic vortex around the grating structure (Media 1). Note that the quartz substrate was not considered in the plot of (b), in order to show a clear picture of the vortex phenomenon in the symmetric waveguide structure, rather than in the asymmetric waveguide configuration with the quartz substrate and air superstrate.

4. Summary

In summary, a dark grating-modulated waveguide mode for normally incident waves becomes excitable as soon as the grating symmetry is reduced by shifting the bars alternately. If this narrow-band grating waveguide mode is coincided in spectrum with a broad dipole mode of the plasmon resonance so that a destructive interference happens between these two modes, a transparency window will be opened within the absorptive dipole-resonance regime. Accordingly, an ultra high group index, as well as a vortex phenomenon of the electromagnetic field, is confirmed by the simulation results. We believe that the symmetry-reduction induced EIT-like transparency window not only has a possibility for sensor applications due to its low-loss feature and high quality factor, but also has a potential for trapping of small particles due to the vortex characteristic of the electromagnetic field around the grating structure.

Acknowledgments

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