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Electromagnetically induced transparency in planar metamaterials based on guided mode resonance

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ABSTRACT

We present and numerically demonstrate a novel, electromagnetically induced transparency (EIT) in planar metamaterials (MMs) based on guided mode resonance (GMR). The unit cell of the MM consists of two metallic ring resonators. The GMR with high quality factor (Q) is achieved by changing the distance between the two rings of the MM. Narrow EIT-like spectral response is realized by coupling between a high Q GMR and a low Q dipolar resonance of the MM. Our work could provide another efficient way towards the realization of EIT with large group index using very simple structures.

1. Introduction

Electromagnetically induced transparency (EIT) is an important phenomenon in multi-level atomic system which gives rise to narrow transparency window in the spectral region [1,2]. The feature of strong dispersion is promising to be used in slow light, optical storage and other devices [3–5]. However, the condition about realizing the EIT effect in the atomic system is relatively restricted. Recent years, much attention has turned to analogy of EIT in various classical oscillator systems [6–8], especially in metamaterials (MMs) [9–15] because their resonances can be easily designed at will such that they can operate at any frequencies in microwave, terahertz, or optical range.

The EIT behavior in MMs can be interpreted by “bright-dark (superadiant-subradiant) mode”, in which two resonances are of high- and low- quality factor (Q), respectively. Generally speaking, the bandwidth of the EIT spectral response, or the group index in transparency window is determined by the high-Q value of the resonance. However, the Ohmic loss in the metal and radiative loss of surface modes of MMs [16–18] limited the resonance performance and high Q resonance is hardly obtained, especially in optical regime. Therefore, the group index for MM based EIT response is also limited to only a few hundreds [19–21].

Recently, guided mode resonances (GMRs) with high Q value in dielectric or metallic grating waveguides were investigated both in optical and terahertz bands [22–25]. The EIT-like response with distinct properties of strong dispersion and calculated group index over 10,000 was realized by coupling between localized surface-plasmon polaritons and the GMR in one dimensional (1D) metallic grating waveguide [26], and it was later experimentally verified with the group index around 80 [27]. The EIT-like effect was also achieved by coupling between the two GMRs with low- and high- Q modes in 1D dielectric grating waveguides with group index over 2200 [28]. Move over, the destructive interference between a GMR and a dipolar resonance allows for an EIT-like response in a simple structure of 2D metallic bar grating waveguide [29]. In order to excite the dipolar resonance, the polarization of normal incident light must be oriented along bar direction, thus, only TE guided mode can be coupled, resulting in low group index of about 80 in transparency window.

As the periodic metallic structure of MMs can behave partly like metallic gratings, the GMRs can also be excited in planar MMs or so called MM grating waveguides. The realization of the EIT phenomenon based on GMR effect in MMs is an interesting research topic because it could provide a new way to manipulate light propagation. However, to the best of our knowledge, there is no research reported on this topic so far. In this paper, we proposed a two closed ring resonators composed planar MM and demonstrated that the quality of EIT-like response can be enhanced greatly by coupling between a high Q GMR of TM mode and a low Q dipolar resonance in this very simple structure. The simulation results show that narrow transparency window can be reached around 3.5 μm resonance wavelength, and the maximal value of the group index in transparency window is as high as 3721.

2. Planar MM for guided mode resonance based EIT

The unit cell of the planar MM we used in this paper is illustrated in Fig. 1(a), which consists of two metallic closed ring resonators (CRRs) in same size deposited on a planar thin SiN_x waveguide. The structure can be fabricated by using a combination of electron beam lithography

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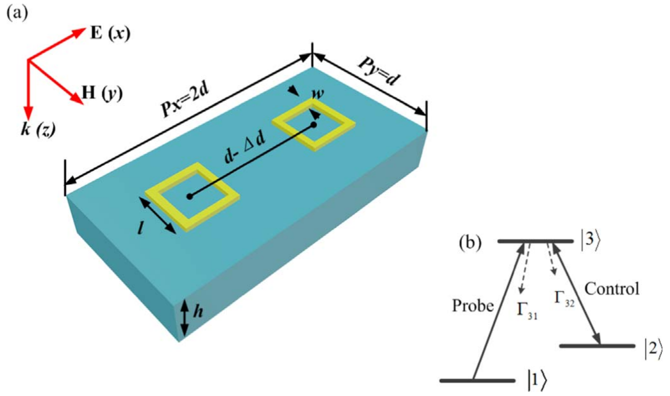

Fig. 1. Sample figure. (a) Schematic of unit cell of planar metamaterial composed of two closed ring resonators. The structure parameters are as follows: Px=2d=3.2 μm, Py=d=1.6 μm, w=100 nm, h=0.54 μm. (b) Generic three-level system for EIT. With strong control field applied in probe beams, atoms in the $|1\rangle$ can be excited by two routes: directly via $|1\rangle \rightarrow |3\rangle$, or via circular path $|1\rangle \rightarrow |3\rangle \rightarrow |2\rangle \rightarrow |3\rangle$. The different pathways interfere with each other leading to the occurrence of EIT effect. The Γ_{ik} denotes radiative decay rate from state $|i\rangle$ to $|k\rangle$.

and a subsequent lift-off process [24]. Because the periodic metallic CRRs can behave partly like 2D metallic gratings, GMRs can be excited by the first order diffracted beams coupling to the waveguide, just as those in conventional waveguide grating structures [23,24]. To obtain high Q of the GMR, a symmetry-reduced structure of MM (shown in Fig. 1) is designed, which is somewhat like those used in bar grating waveguides [25,29]. The central distance between the two rings is defined as $d - \Delta d$. Here, Δd represents the grating modulation depth which is key for the realization of high Q GMRs. Px and Py are periods of the unit cell in the direction of x and y, respectively.

Obviously, there exists a dipolar resonance of the MM with low Q due to the radiative loss and Ohmic loss, and its central resonance frequency is mainly determined by the ring's length l. It is well known that analog of EIT in artificial photonic structures can be realized by employing the coupling between two resonances with strongly contrasting resonance Q value and sufficiently small frequency detuning. The low Q (high Q) mode may serve as the state $|3\rangle$($|2\rangle$) in a typical three-level atomic system as the one depicted in Fig. 1(b), because the decay rate of the state $|2\rangle$ is comparatively small than that of $|3\rangle$ [12,30]. For instance low Q dipolar resonance and high Q GMR are simultaneously excited and coupled, a narrow transparency window is expected to be generated inside the broad background transmission dip produced by the dipolar resonance. Therefore, the design of a high Q GMR and its coupling with a dipolar resonance are essential to realize the EIT in our structure.

3. High Q GMRs in MM cladding waveguides

We analyze the transmission characteristics of the planar MM by employing the finite-element method (COMSOL Multiphysics software). Periodic boundary condition is used both in x and y directions. In simulations, the refractive index of the waveguide n is assumed to be 1.97. Au is chosen for the metallic rings with thickness of 100 nm, and its permittivity in mid-IR wavelength is described by the Drude model $\varepsilon(\lambda) = 1 - [(\lambda_p/\lambda + i\gamma)\lambda_p/\lambda]^{-1}$, where $\lambda_p = 1.5895 \times 10^{-7}$ and $\gamma = 0.0077$ [24]. The light is normally incident onto the MMs with polarization along x direction. Two different structures with Δd=0, and Δd=0.1 μm are considered, which represent whether the metallic rings are uniformly distributed in x direction or not. The simulated transmission spectra in our interested wavelength range of 2.6–4.5 μm are shown in Fig. 2(a) for ring's length l=0.6 μm. It is easy to see that a broad dipolar resonance of the MM appears centered around 3.05 μm wavelengths with Q factor of only ~6. In the case of Δd=0.1 μm, an extremely sharp resonance appears at the wavelength around 3.53 μm, which doesn't exist when Δd=0. The resonance bandwidth is as narrow as 3.30 nm (FWHM) or Q value of 1076, and its strength(from resonant baseline to its peak in transmission) is 0.68. Such high Q resonance doesn't exist if the waveguide thickness is considered to be infinite. In other words, it is not a surface resonance of the MMs. it is a resonance concerned with the reflection between the substrate and air. Furthermore, it can be easily explained by the GMR [22,23] as MMs can also be considered as metallic gratings, involving two equations in this context [31]. The first equation is related with the grating diffraction:

$$P\sin\theta = m\lambda/n \tag{1}$$

in which P is the grating period (Px and Py in the direction of x and y, respectively), θ is diffraction angle, m is diffraction order, λ is wavelength in free space, and n is refractive index of the substrate.

The second equation is concerned with the waveguide phase matching:

$$\frac{4\pi}{\lambda} nh\cos\theta - \varphi_s - \varphi_c = 2N\pi \tag{2}$$

where h is the thickness of the substrate, φ_s and φ_c are additional phases of all reflection at upper and lower face of the waveguide for TM or TE mode, respectively, and N is the mode order of the waveguide.

In terms of Eq. (1) and all reflection condition between the substrate and air, it is easy to calculate that the GMRs in our interested spectral range can only be excited through the first order diffraction by a grating with $2d$ period. In the case of Δd=0, the periods of gratings along x and y direction are all d. In terms of Eqs. (1) and (2), the wavelength of the corresponding GMR falls in the range of 1.6–3.15 μm. An EIT-like effect can also occur by coupling between the GMR and dipolar resonance. However, the Q values of these two GMRs are usually much lower than those of GMRs induced by $2d$-grating, resulting in low group index for the corresponding EIT-like effect. Therefore, the GMRs induced by d-grating and thereafter the EIT-like effect are not in our interests. If $\Delta d \neq 0$, obviously there exists a grating with $2d$ period along x direction besides a grating with d period. Thus, GMRs in Fig. 2(a) will be excited as long as the waveguide phase matching condition is satisfied. To further identify the nature of this sharp resonance in Fig. 2(a), the magnetic field distribution along the waveguide at the resonance wavelength of 3.53 μm was calculated and shown in Fig. 2(b), which clearly indicates that it is a GMR of TM_0 mode.

Moreover, the transmission spectra for the normally incident wave with polarization along y-axis are also given in the Fig. 2(a), showing that another GMR occurs around 4.28 μm wavelength with Q value of 390. And the electric field distribution in x-z plane shown in Fig. 2(c) indicates that it is a GMR of TE_0 mode. We will focus on the characteristics of the GMRs of TM modes in the following due to its much larger Q value than that of TE modes.

The impact of the parameter Δd on the Q value and transmittance of the GMR are calculated and shown in Fig. 3. In conventional waveguide gratings, the linewidth of the GMR can be manipulated flexibly by changing the grating modulation depth. The weak modulation depth means that less diffracted light energy will be coupled to the waveguide, resulting in high Q value of the GMR [25,32]. This is also true for our proposed MM cladding waveguides. If the parameter Δd =0, there exists no grating with $2d$ period, therefore no GMRs are excited in our concerned wavelength range. As Δd increases, the grating component with period $2d$ also increases (the grating component with period d decreases at the same time), so that the Q factor of the GMR decreases rapidly. In meanwhile, the strength of the GMR increases first, then saturated (the transmittance is close to zero). From Fig. 3, the Q value of the GMR decreases from 7270 to only 92 when Δd changes from 0.02 to 0.4 μm. Therefore, the parameter Δd can be regarded as the modulation depth of the grating with period $2d$, through which the Q value and strength of the corresponding GMR can be effectively controlled. Because the grating diffraction efficiency