Observation of electromagnetically induced transparency-like transmission in terahertz asymmetric waveguide-cavities systems

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Electromagnetically induced transparency (EIT)-like transmission was demonstrated in terahertz asymmetric parallel plate waveguides with two identical cavities. By shifting the position of the bottom cavity from the symmetric position in the propagation direction, both the phases of the propagating wave at resonances and the coupling strengths between two cavities are changed, resulting in exciting the additional asymmetric resonance and manipulating the detuning of two different resonant frequencies. The transparent peak between two resonances comes from the cancelation of symmetric and asymmetric resonances. We also use the physical picture of excitation of quasi-dark mode to explain this EIT-like transmission, which is similar to the metamaterial systems. © 2013 Optical Society of America

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Electromagnetically induced transparency (EIT) at the atomic level can be observed by the coherently quantum interference between atoms and external optical fields [1]. The realization of this EIT in atomic systems is a tough task since some restrictions must be strictly fulfilled. So mimicking EIT in classical systems has been continuously done. In the field of optics, waveguide-based EIT-like resonances have been proposed numerically in resonant cavity systems [2, 3]. Importantly, the phase coupling between the resonators has been proved to be a key factor for EIT-like response [3]. Such an EIT effect can be used to design superluminescent light emitting diodes [4–6]. In the terahertz (THz) region, a plasmon-induced transparency (PIT) that relies on the strength of near-field coupling of metallic cavities has been observed in asymmetric metamaterial systems [7–9]. However, tuning the physical parameters of THz metamaterials after fabrication is a huge challenge [8].

A metal parallel plate waveguide (PPWG) in the THz regime is intensively studied due to its superior confining effect for the propagating THz waves [10, 11]. The PPWG with a single cavity has also been found to be a strong and high Q resonant system in which a transverse electric (TE_1) mode can be excited [12, 13]. These unique properties of the PPWG-cavity system probably offer a way for achieving waveguide-based EIT. In this Letter, we report an observation of an EIT-like phenomenon in THz PPWG-cavities systems and analyzed the relation between the off-position of the cavities and the transmission properties. The proposed system has the following features: first, since the most popular metals are seen as perfect conductors due to extremely large conductivity in the THz region, the realization of THz EIT-like response in PPWG-cavities systems is not plasmonically induced. Second, the two cavities have identical geometry; therefore, the detuning of resonant frequencies does not arise from the different geometrical parameters of two cavities [2, 3]. We find the EIT-like transmission presented here results from the resonance hybridization induced by the change of coupling strength of top and bottom cavities. We also find that two detuned resonances (the symmetric and asymmetric resonances) can be varied by choosing different shifting length between two cavities. This means that phase shift of the propagating wave between two resonances may be another important factor for the realization of EIT. The physical picture of an analogy to the coupling of bright and dark modes in THz metamaterials is also presented.

The PPWG-cavities system consists of two aluminum plates, each with a micromachined rectangular groove (cavity), as shown in Fig. 1. All cavities have the identical geometry with a width $w = 470$ μm (± 5 μm) and a depth $h = 420$ μm (± 5 μm). We fabricated four sets of PPWG-cavities configurations: a perfect symmetric one with the top and the bottom cavities exactly at the center of the waveguide and asymmetric configurations made by keeping the top cavity fixed and displacing the bottom cavity from the center position with $L = 100$, 200, 300 μm, respectively, where L represents the bottom cavity shifting length from the center in the propagation direction. S represents the length of the plates. Combined fast and slow scan-based THz time domain spectroscopy (THz-TDS) was used for evaluating the transmission properties of the PPWG system [14]. A femtosecond fiber

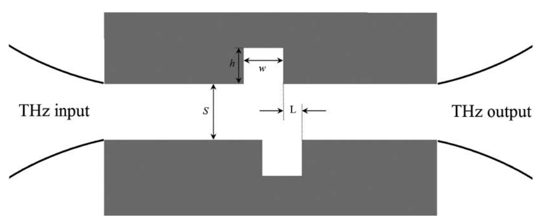

Fig. 1. Schematic of PPWG with two cavities. w, the width of the groove; h, the depth of the groove; S, the length of the plates; L, the shifting length between two grooves.

laser was applied to pump and detect the THz wave, with the central wavelength at 780 nm, output power 150 mW, pulse duration around 90 fs, and repeat frequency at 80 MHz. Both the emitter and the detector are the LTG-GaAs-based photoconductive antenna. The radiated THz beam with waist radius ~5 mm was focused to the PPWG-cavities system by two off-axis parabolic mirrors. The fast optical delay line with 110 ps range can be obtained. If we combine it with slow scan, the overall delay line can be expanded to 218.4 ps. This means the experimental spectra resolution can be achieved to 4.58 GHz. The electric field of the incident beam was oriented parallelly to the plates in order to excite the TE_1 mode [12].

Next, we discuss the influence of the shifting length L on the transmission response. For this discussion, the length of the top and bottom plates was fixed at $S = 650$ μm. The PPWG without any cavity acts as the reference. Figure 2 shows the power transmission of the PPWG-cavities system with different L. For the structure with symmetry ($L = 0$), only one broad symmetric resonant dip at 0.417 THz was observed. For the PPWG cavities structure with $L = 100$ μm, asymmetry is introduced, resulting in a new resonant dip at lower frequency (0.354 THz). When the bottom cavity is further shifted up to $L = 200$ μm, the lower resonant frequency shows blue shift and the high resonant frequency shows red shift. A transparent band between two resonant dips becomes narrow as well as the decrease of the transmittance. Here, we observed an EIT-like transmission that is similar to previous investigations for metamaterial and plasmon analogues of EIT [2, 9]. For the asymmetric structure with $L = 300$ μm, two resonance dips come closer and the transmission peak reduces further. The experimental results agree well with numerical results in Fig. 2 and the deviation is probably caused by the fabrication imperfections of the sample, which introduce further asymmetry and rearrangement of some resonant frequencies. For a complete picture of resonant frequencies change, several calculations were performed with the variation of the shifting length from 0 to 450 μm, as plotted in Fig. 3. The detuning $|\omega_1 - \omega_2|$ (ω_1 and ω_2 are low and high resonant frequencies, respectively) decreases and the transparency window narrows down with the increase of the shifting length L. The transparent peak centered at about 0.384 THz can also be observed in Fig. 3.

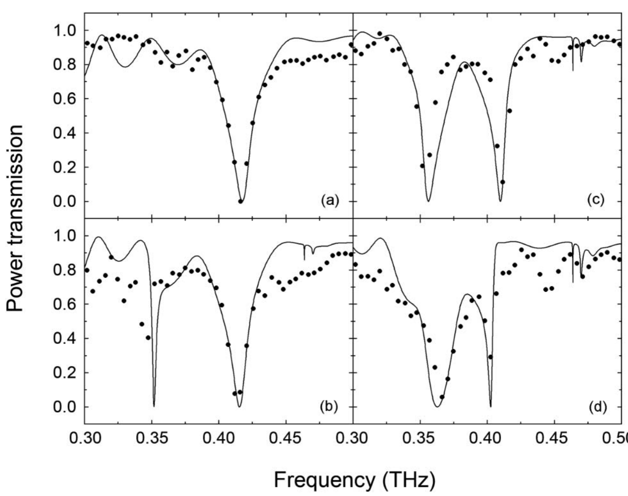

Fig. 2. Power transmission spectra for (a) $L = 0$ μm, (b) $L = 100$ μm, (c) $L = 200$ μm, and (d) $L = 300$ μm. The solid lines are the numerical results based on the finite element method. The dots represent the power transmission spectra (the frequency resolution ~4.58 GHz) derived by Fourier-transforming the 218.4 ps time-domain waveforms and compared to a PPWG without cavities.

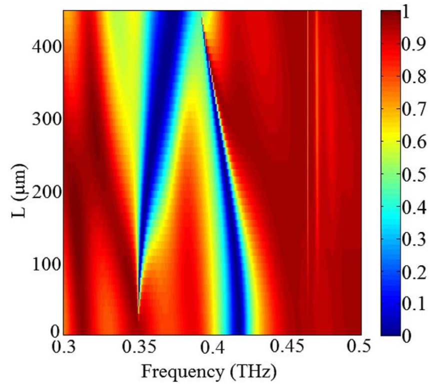

Fig. 3. Simulated transmission amplitude of PPWG-cavities systems as a function of the asymmetric shifting length L.

To obtain understanding of the resonances and transparent properties, we simulate the electric field distributions inside the PPWG at the resonances and transparency peaks for $L = 0$ and $L = 200$ μm, respectively (Fig. 4). At the symmetric situation ($L = 0$), as shown in Fig. 4(a), the excited electric fields have the same magnitudes and phases on both sides of the cavities, displaying the symmetric mode property. Once the symmetric situation is broken, the resonance coupling strength between the two cavities depends greatly on the shifting length L; the longer the length, the weaker the coupling strength. Since two cavities with the same geometry both have resonant frequency ω, the change of coupling strength emerges the resonance hybridization [15]. Then the symmetric and asymmetric resonant modes can be observed in the asymmetric PPWG-cavities structure. For example, at $L = 200$ μm, the symmetric mode splits into two distinct resonances at 0.359 and 0.41 THz, respectively. In Fig. 4(b), the electric field in the top cavity shows opposite phase to the field in the bottom cavity. The higher frequency resonance [0.41 THz, Fig. 4(d)] reveals that in two cavities the fields have the same phases.

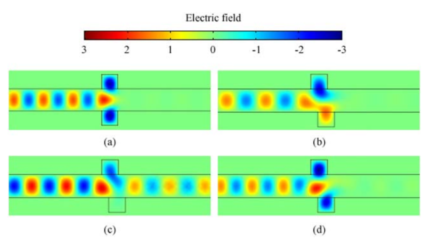

Fig. 4. Electric field distribution of PPWG-cavities systems inside the waveguide at the resonant and transparency peak frequencies with $S = 650$ μm: (a) $L = 0$ μm at 0.419 THz, (b) $L = 200$ μm at 0.359 THz (the lower frequency resonance dip), (c) $L = 200$ μm at 0.383 THz (the transparency peak), and (d) $L = 200$ μm at 0.41 THz (the higher frequency resonance dip).

In waveguide-cavity systems, the phase shift of the propagating wave between two resonances is calculated as $\Delta\varphi = |\omega_1 - \omega_2| n_{\mathrm{eff}} L/c$, where n_{eff} is the effective index of TE_1 mode [3]. From Figs. 4(b) and 4(d), the phase shift in the bottom cavity is π, indicating that the interference between two resonances is destructive. At destructive interference condition ($\Delta\varphi = \pi$), the detuning of resonant frequencies $|\omega_1 - \omega_2|$ decreases with the increase of shifting length L. As the two cavities separate far away from each other, the coupling strength is very weak, and the resonant frequency ω caused by single cavity is just between ω_1 (asymmetric resonance) and ω_2 (symmetric resonance). That is to say, both the lower resonant frequency and higher resonant frequency incline to ω with the increase of L. In this process, the lower resonant frequency shows blue shift and the high resonant frequency shows red shift. At the transparency peak [Fig. 4(c)], the magnitude of electric field in bottom cavity is near zero. Since the total field in two cavities can be regarded as the superposition of symmetric and asymmetric modes by interference when the frequency of incident wave is between high and low resonant frequencies (analogy of processing in quantum optics [1]), both cavities are partially resonant with symmetric and asymmetric reflectivities less than their maximum. At the transparency peak, the two modes are canceled with each other and the superposition of symmetric and asymmetric reflectivities reaches to minimum. The transparent peak between two resonances comes from the cancelation of symmetric and asymmetric resonances. As a result, to our PPWG-cavities design, the EIT-like transmission arises from both the phase shift of two resonances and the coupling strength between two cavities. This is different with results in [2, 3, 7–9].

This EIT-like transmission can also be explained by analogy to the coupling of bright and dark modes. When the bottom cavity is set symmetrically to the top one, only one resonant dip, which corresponds to the two bright modes (each of them has the same resonant frequency), can be excited in both cavities simultaneously. In this condition, the dark mode cannot be excited. When the bottom cavity is shifted backward from the symmetric position, due to the identical geometry of the two cavities, the incident wave first arrives at the top cavity and couples with it. The shifted bottom cavity can hardly be interacted directly with the incident wave anymore but can couple with the top cavity. In other words, the top cavity acts as the "radiative" resonator (a bright mode) that is coupled to a "bus" waveguide; the bottom cavity acts as the "subradiant" resonator (a quasi-dark mode, induced by the shifting length of two cavities) that cannot be coupled to the "bus" waveguide. This physical picture is similar to the unit cell (consists of an upper gold strip as a bright mode, a pair of lower gold strips as a dark mode, and a dielectric spacer) described in [7]. Then this EIT-like transmission can also be seen as the coupling between bright and quasi-dark modes when the symmetry is broken [7, 8].

In conclusion, we have demonstrated an EIT-like transmission in PPWG-cavities system. Experimental and theoretical results show that the origin of EIT-like transmission comes from the coupling strength between two cavities and the phase shift of two resonances. Both of them are related to the asymmetric location of the two cavities. We also use the bright and quasi-dark modes to explain this EIT-like effect, which is similar but different from the PIT effect. The shifting length of the bottom cavity plays an important role in the transmission properties and can be tuned easily, which can be further utilized to adjust the two resonant frequencies. Our results provide a further understanding of the waveguide-based EIT-like transmission in THz range and are helpful for the development of THz photonics and devices.

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