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Manipulating single second mode transparency in a corrugated waveguide via the thickness of sputtered gold

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ABSTRACT

We propose a classical analog of electromagnetically induced transparency in a cylindrical waveguide with undulated metallic walls. The transparency, induced by multi-mode interactions in waveguides, not only has a narrow line-width, but also consists of a single second-order transverse mode, which corresponds to the Bessel function distributions investigated extensively due to their unique characteristics. By increasing the thickness of sputtered gold layers of the waveguide, we demonstrate a frequency-agile single mode transparency phenomenon in a terahertz radiation. It is found that the center frequency of the transparency is linearly related to the gold thickness, indicating the achievement of a controllable single mode terahertz device. The field distributions at the cross-sections of outlets verify the single second mode transparency and indicate the mechanism of its frequency manipulation, which will significantly benefit the mode-control engineering in terahertz applications.

1. Introduction

Electromagnetically induced transparency (EIT) has been paid extensive attention [1,2] since it was used by Harris et al. to investigate the nonlinear optical phenomenon [3]. Quantum interference induced by two laser beams results in an opaque medium to be transparent in an extremely narrow spectrum, that cannot only enhance nonlinear effects but also significantly slow the light. Since the transparency is very promising in various applications such as dispersion engineering, quantum or optical information storage, and slow light, the EIT-like behaviors have been considerably demonstrated in classical systems in recent years. Totsuka et al. have employed two micro-spheres with different diameters to induce a EIT-like transparency and have observed slow light [4]. Papasimakis et al. have investigated a metamaterial analog of EIT [5], in which electromagnetic pulses have been delayed by a subwavelength fish-scale planar grating. Later, the plasmon-induced transparency has also been investigated to slow down the light [6]. Moreover, other transparencies induced by Fano-like resonances [7] and by coupling of Tamm and defect states [8] have been studied in a photonic circuit and in a terahertz (THz) plasmonic crystals, respectively. Almost all the high quality EIT-like behaviors have been realized by appending the micro resonators to a straight waveguide, but no high-order modes were discussed.

It is worth noting that the high-order modes will participate in resonances and play a major role when the transverse scale of waveguides gets larger. In 1998, Pogrebnyak has investigated the electromagnetic properties of a corrugated waveguide and found the miniband behavior of the spectrum caused by the resonances of transverse modes [9]. The THz non-Bragg gaps [10] have been investigated in the periodic metallic waveguides, indicating the fundamental role of the high-order modes in wave–structure interactions. Especially, the transverse mode in a cylindrical waveguide always associates with a pure Bessel function distribution. These Bessel beams have found applications in various fields such as optical tweezers, optically bound control, virtual ghost imaging, and nanofabrications [11–14].

On the other hand, THz radiation in a frequency range between the infrared and microwaves has been paid more attention owing to its applications in communications, imaging, non-destructive evaluation, spectroscopy biochemical sensing, security screening, and so on [15]. Besides the low-loss and low-dispersion waveguide structures, the single mode operation in THz frequency range has also been investigated. By introducing microstructured air holes, a directional coupler at 1 THz was optimized with single mode operation last year [16]. Mitrofanov and Harrington have detected

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four different THz modes in a dielectric-lined cylindrical metallic waveguide by their different time delays at the output [17] and Tang et al. have investigated the dependence of mode structure on the ellipticity in a silver coated elliptical hollow fiber [18]. The single THz modes have also been produced and used in superluminal devices [19], quantum cascade lasers [20], nondiffractive beams [21], low propagation loss and low bending loss waveguides [22].

Therefore, it is very intriguing to realize and manipulate a transparency of single high-order modes in a cylindrical THz waveguide. Here, we show that the phenomenon occurs as a result of multi-mode interactions, which can be interpreted by a graph shifting method. When the material for manufacturing the waveguide is considered to be Au, the transparent frequency will shift according to the thickness of sputtered gold layers. Then, we demonstrate the transparency characteristics when the thickness increases, including the band width, the transmittance, the slow down factor, the propagation length, and the transverse distributions of the electromagnetic fields. Finally, a terahertz single mode transparency manipulated by the gold thickness is discussed and its mechanism is revealed.

2. Multi-mode interactions

In order to transmit a single high-order mode in a waveguide, we break the orthogonality of the eigenmodes of a smooth waveguide and manipulate the energy redistribution between them by means of undulating the tube walls. The geometry structure is shown in Fig. 1 (a), where Λ and h are the period and the height of wall undulations, respectively. t, the thickness of gold layers, is chosen as zero in this section for the convenience of multi-mode analysis. It is found that a 10-period long hollow tube can produce the proposed transparency very well. According to the Floquet theorem and dispersion relations [23,24], we can obtain the relationship between the frequency f and the reference propagation constant β for the mth order mode of the nth spatial harmonic:

$$f = \frac{c}{2\pi}\sqrt{\left(\frac{k_r^{(m)}}{r_0}\right)^2 + \left(\frac{2n\pi}{\Lambda} + \beta\right)^2}, \tag{1}$$

where r_0 is the mean radius and $k_r^{(m)}$ is the zeros of the zeroth-order Bessel functions for transverse magnetic (TM) waves. For the first and second modes, $k_r^{(m)}$ is equal to 2.4048 and 5.5201, respectively. Thus, the reference lines defined by Eq. (1) for the first two modes in the Brillouin zone are illustrated in Fig. 1 (b) by the blue and red solid lines, respectively. In a graph shifting method [23], changing the period and mean radius of the waveguide always results in the vertical movements of solid lines in the first Brillouin zone and the relative location of the red and blue lines varies to achieve different spectrum structures. Setting $\Lambda = 334$ μm and $r_0 = 264$ μm, we can obtain a three mode interaction at 1 THz where a red line (the second mode) intersects with two blue lines (the first modes). A single high-order mode transparency could be expected. By using the numerical method in [24], we calculated the dispersion curves of the structure with $\Lambda = 334$ μm, $r_0 = 264$ μm, and $h = 52.8$ μm. The results are depicted in Fig. 1 (b) by the bold dots, indicating that the two lower modes are pushed away and a single second mode is left. It is clear that at 1 THz, there is a narrow pass band in a wide stop band related to the second mode. The solid line in Fig. 1 (c) is the transmission T simulated by COMSOL Multiphysics with the finite element method. The perfect electrical boundary conditions were assigned to the tube wall when the gold thickness $t = 0$ μm. The simulated result confirms the transparency in a stop band.

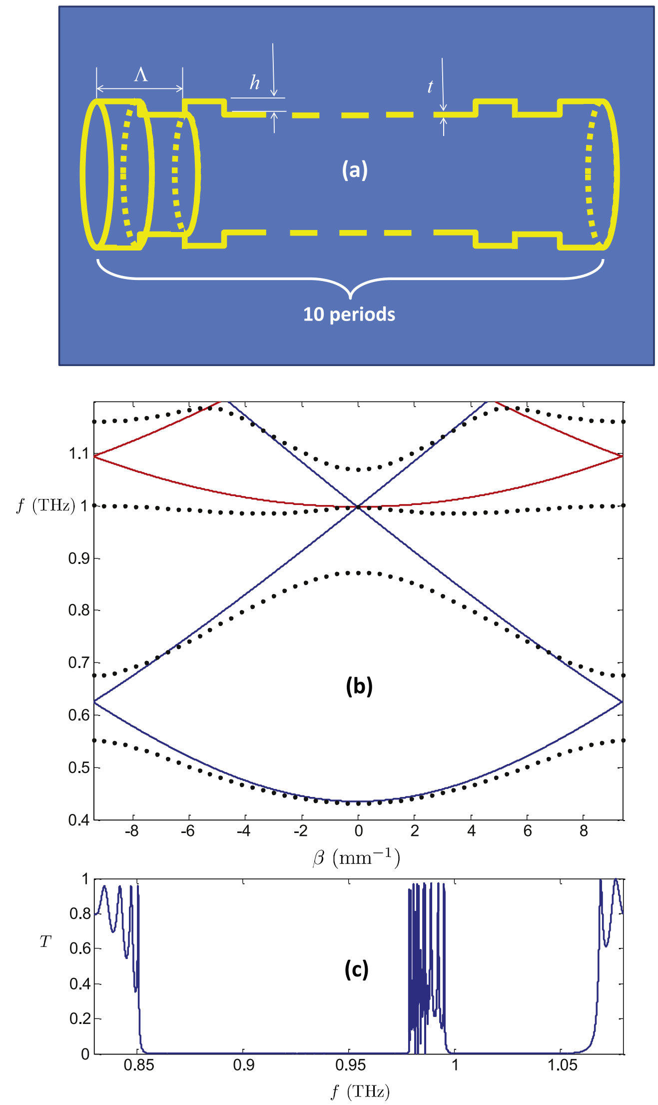

Fig. 1. Geometry parameters and band structures of a gold tube transparent to a single second mode. (a) A 10-period gold tube with corrugated walls is designed to realize the single second mode transparency. The thickness of the sputtered gold layer t is increased to the inside to modulate the frequency of the transparency. (b) The blue and red lines denote the first and second transverse modes, respectively. Mode manipulation using the shifting method of reference lines results in the three mode interactions near 1 THz when the period and the mean radius of the waveguide are selected as 334 μm and 264 μm, respectively. The bold dots constitute dispersion curves confirming the manipulation. (c) The transmission simulated by the finite element method with the perfect electrical boundary conditions when $t = 0$ μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Frequency shifting

To manipulate the frequency of the transparency, we have made the tube wall with different thicknesses of gold layers. With the fixed values of the period Λ, of the height h, and of the mean outer radius r_0, we obtained different waveguides with the gold layers thickened to the inside. Around 1 THz, the Drude model was employed in the simulations for the dielectric function of Au with

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\omega_\tau}, \tag{2}$$

where the circular frequency $\omega = 2\pi f$, the plasma frequency $\omega_p = 1.37 \times 10^4$ THz, and the damping frequency $\omega_\tau = 40.7$ THz [25].

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