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Multiband guided-mode resonance filter in bilayer asymmetric metallic gratings

Yanhui Wang, Xiangjun Li, Tingting Lang, Xufeng Jing, Zhi Hong *

Centre for THz Research, China Jiliang University, Hangzhou 310018, China

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ABSTRACT

In this paper, a guided-mode resonances (GMRs) based multiband filter in bilayer asymmetric metallic gratings is presented. Four sharp dips are generated in the frequency range of 1.4–2.0 THz, which are induced by the split of two GMR modes (TE_0 and TM_0) due to the break of the structure's symmetry. This symmetry of the structure depends on the relative position between the upper layer and lower layer gratings. Therefore, by choosing proper lateral displacement, the split of TE_0 or/and TM_0 modes can be eliminated. Two-, three-, and four- GMRs based polarization insensitive or sensitive filters are demonstrated numerically.

1. Introduction

Guided-mode resonance (GMR) is a typical diffraction phenomenon of waveguide gratings with periodic structures [1,2]. In recent years, GMRs have attracted much attention because of their superior spectral properties: symmetrical peak shape, low nonoscillatory sidebands, and high Q (quality factor), etc. [3–5]. In view of these notable features, GMR based filters and sensors have been widely investigated [6–16]. The GMR filters are usually composed of a sub-wavelength grating associated with one or several dielectric layers. When the thickness of the waveguide layer is small, only the lowest order GMR (TM_0 or TE_0 mode) exists in terms of phase matching condition. Thus only one GMR of TE/TM mode can be excited under TE/TM polarization incidence for single layer one-dimensional (1D) grating structure [17–20]. In order to design multiband filter excluding high order GMR modes [21–23], two or more fundamental GMRs need to be excited simultaneously. One way is to separate 1D grating arrays with different period. This configuration allows receiving a series of resonance peaks in the reflection spectrum [15]. Another way is using two-dimensional (2D) waveguide gratings or metamaterials, thus polarization sensitive or insensitive two GMRs (one TE_0 and one TM_0) are excited simultaneously in different grating structures [24–28]. These resonances are the result of the multiple orthogonal planes of diffraction in 2D structure, and multiband filter is easy to be designed by changing the physical dimensions of the structure (grating period, geometry, depth, and waveguide thickness) [29]. Moreover, Fundamental resonances could be excited in symmetry-reduced 1D dielectric gratings or double layer metallic gratings for a dual-wavelength filter [30–32], in which the two GMRs are attributed to the split of one GMR (TE_0 or TM_0 mode). To the best of our knowledge, a filter with three or more GMRs due to the split of TE and TM modes is not reported.

In this paper, a multiband GMR based filter which works in the terahertz (THz) range is proposed. The designed filter is composed of a 2D array of square metallic disks deposited on each side of dielectric waveguide. The split of TE and/or TM GMRs is observed by changing the relative position between the upper layer and lower layer gratings. Two-, three-, or four- GMRs based polarization insensitive or sensitive filters are demonstrated.

2. Configuration of the multiband GMR filter

The proposed structure of the multiband GMR filter is schematically shown in Fig. 1. The filter consists of two 2D metallic gratings deposited on top and bottom of a polymer film as dielectric slab waveguide. Compared with the dielectric grating waveguides, the metallic counterparts are much easier to be fabricated, especially in terahertz frequencies. The period of the structure is P, t_d is the thickness of the slab waveguide, t_m and a are the thickness and side length of the metallic square disk. The arrangement of the upper layer grating for the filter can be obtained from a pair of symmetric 2D metallic gratings by alternately shifting the metal squares along x-direction by $Lx = P/4$ (shown in Fig. 1(b)), while the lower layer grating shifting in the same way along y-direction by $Ly = P/4$ (shown in Fig. 1(c)). Thus, the period dimension of the upper grating are P in x-direction and $P/2$ in y-direction, while it is $P/2$ in

* Corresponding author.
E-mail address: hongzhi@cjlu.edu.cn (Z. Hong).

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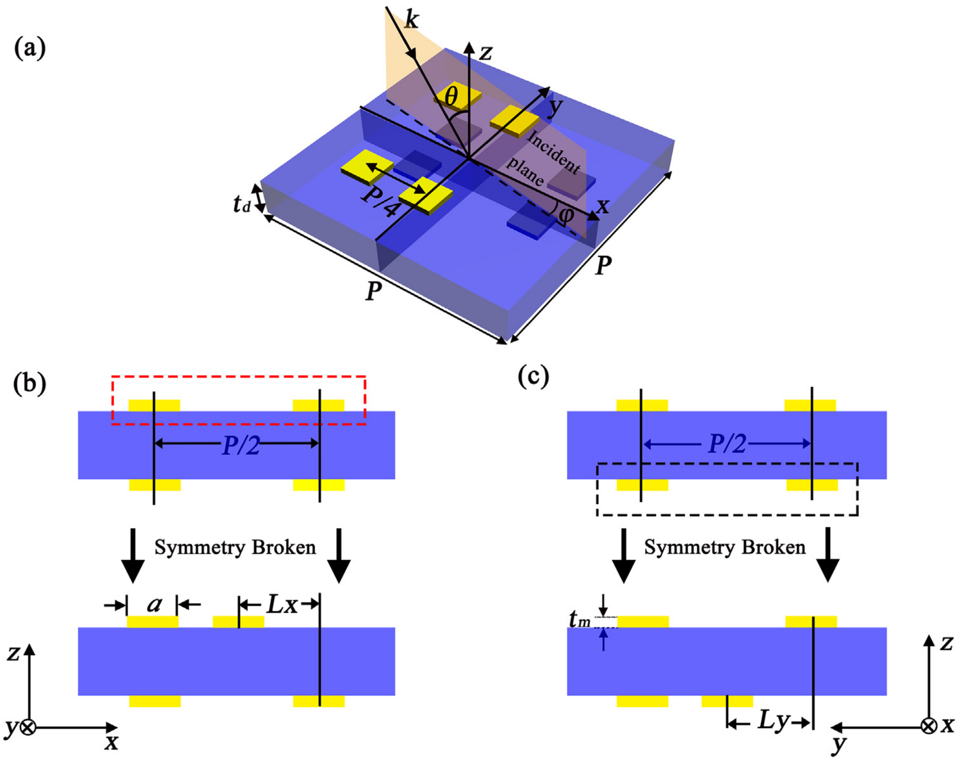

Fig. 1. (a) Schematic diagram of the bilayer asymmetric metallic grating filter. (b) Cross-section of the filter in the x-z plane. (c) Cross-section of the filter in the y-z plane. The upper and lower metallic gratings are marked with red and black rectangle, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

x-direction and P in y-direction for the lower grating. This device can be fabricated based on laser-induced site-selective silver seeding on polymer film for electroless copper plating [33]. The transparent lavender incident plane illustrates the angle between incident light and coordinate axis by a given incidence angle θ and an azimuth angle φ.

The transmission of the GMR filter was numerically calculated using simulation software CST Microwave Studio in the frequency domain. Periodic boundary conditions were used in both x- and y-directions while open boundary condition was used in ±z direction. In simulation, the thickness of the substrate (the dielectric constant is 3.5) is t_d = 40 μm, the side length of the metallic square disk is a = 20 μm and its electrical conductivity is set to be 5.8 × 10^7 S/m, and the period of the structure is P = 120 μm. The normally incident THz wave (the wave vector k is along the z direction) polarized in x-direction illuminates on the filter under the condition of $\theta = 0°$, $\varphi = 0°$.

3. Theory and simulation results

GMRs are based on the coupling of the incident light to a dielectric waveguide via ±1st order diffraction by a periodic grating [25]. The resonance wavelength is determined by the phase matching condition, requiring that the magnitude of the grating vector $k_p = 2\pi/P_g$ (P_g is the period of grating) should equal to the propagation constant β for transverse electric (TE) or transverse magnetic (TM) guided modes. At first, the dispersion and propagation properties of the waveguide are investigated. The dispersion relation can be derived as [26]:

$$m\pi = t_d\sqrt{n_d^2k_0^2 - \beta^2} - 2 \times \tan^{-1}\left[(n_d/n_0)^{2\rho}\sqrt{\left(\beta^2 - n_0^2k_0^2\right)/\left(n_d^2k_0^2 - \beta^2\right)}\right] \quad (1)$$

where m is the mode number (only the fundamental mode considered here due to the small thickness of the waveguide t_d), k_0 is the wave number of the incident light in free space, and n_0 is the refractive index of air, n_d is the refractive index of the slab waveguide. The TE and TM guided modes are represented by ρ = 0 and 1, respectively. The calculated dispersion relation with ignored additional phases of all reflection at upper and lower face of the waveguide for TE or TM mode is shown in Fig. 2(a). A metallic grating with a period of $P_g = P$ = 120 μm corresponds to a grating vector k_p = 0.0524 μm^{-1} as depicted by the black line. The blue line and red line denote the dispersion relationship of TE_0 and TM_0, respectively. The intersections of the black line with the blue and red lines are at 1.67 THz and 1.95 THz, which indicate the frequencies of the GMRs. For a metallic grating with a period of $P_g = P/2$ = 60 μm, the corresponding grating vector k_p equals to 0.1047 μm^{-1}, thus the frequencies of the GMRs are larger than 2.0 THz, which is beyond our interest. Considering our bilayer grating waveguide structure in Fig. 1, it is concluded that the GMR of TE_0 at 1.67 THz is excited by lower layer grating in the y-direction, whereas the GMR of TM_0 at 1.95 THz is attributed to the upper layer grating in the x-direction.

Then, the transmission of GMR based filter was numerically calculated for the bilayer asymmetric grating structure when the electric field of normally incident THz wave is polarized along the x-direction, which is shown in Fig. 2(b). Different from the above theory, there are four resonance dips, which are located at f_1 = 1.62 THz, f_2 = 1.67 THz, f_3 = 1.87 THz and f_4 = 1.91 THz. In order to reveal the properties of these four dips, the electric field and magnetic field distributions were calculated and depicted in Fig. 3. Note that the magnetic field at 1.62, 1.67 THz and the electric field at 1.87, 1.91 THz do not provide more information of the waveguide modes [7,27], they are not shown in the figure.

As discussed above, when the electric of normally incident THz wave is polarized along the x-direction, the GMR of TE mode is excited by the lower layer grating in the y-direction, and it