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Modal analysis on resonant excitation of two-dimensional waveguide grating filters

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ABSTRACT

Modal analysis on resonant excitation of two-dimensional (2-D) waveguide grating filters (WGFs) is proposed. It is shown that the 2-D WGFs can support the excitation of a resonant pair, and the locations of the resonant pair arising from the TE and TM guided-mode resonances (GMRs) can be estimated accurately based on the modal analysis. Multichannel filtering using the resonant pair is investigated, and the antireflection (AR) design of the 2-D WGFs is also studied. It is shown that the reflection sideband can be reduced by placing an AR layer on the bottom of the homogeneous layer, and the well-shaped reflection spectrum with near-zero sideband reflection can be achieved by using the double-faced AR design. By merely increasing the thickness of the homogeneous layer with other parameters maintained, the spectrally dense comb-like filters with good unpolarized filtering features can be achieved. The proposed modal analysis can be extended to study the resonant excitation of 2-D periodic nanoarrays with diverse surface profiles.

1. Introduction

With the development of nanophotonics, the waveguide grating structures based on the leaky mode resonance have drawn much attention and shown diverse spectral bands with a rich variety of possible surface-localized photonic states [1]. As the incident light illuminates a periodic surface structure, the leaky waveguide modes can be resonantly excited as the phase-matching condition is satisfied. At resonance, the incident light is totally reflected with highly angular and spectral selectivity. This phenomenon is also known as the guided-mode resonance (GMR) [2,3]. It has been shown that optical elements such as optical filters [4,5], photonic detectors [6], sensors [7], and optical switch devices [8] can be obtained by sculpturing the resonant leaky modes.

In recent years, the two-dimensional (2-D) waveguide grating filters (WGFs) based on the GMR have attracted much attention due to their versatile functionalities for various applications in optoelectronics and integrated optics. In 2006, Boonruang et al. [9] designed multiline WGFs using 2-D grating structures with rectangular and hexagonal grids. In the next year, they [10] investigated the angular response of 2-D WGFs with hexagonal-lattice grating, and achieved resonances with high angular tolerance (~1°) and narrow spectral bandwidth (~0.3 nm). Later, Pung et al. [11] carried out a deep research on a manufactured low-contrast WGF with 60% reflectivity at a wavelength of 1.741 μm that exhibits polarization independence at normal incidence. Sun et al. [12] achieved color generation in all-dielectric resonant nanostructures by combining 2-D WGFs with metasurfaces. These researches are mainly focused on the spectral characteristics of the leaky waveguide modes. However, the underlying physical mechanism for the resonant excitation of 2-D WGFs is less studied. Previously, Ko et al. [13] demonstrated the correlation of the modal processes between the 2-D gratings and their quasi-equivalent one-dimensional (1-D) grating structures. Very naturally, some problems emerge: how to identify the resonant excitation of the 2-D WGFs? How to tailor these resonant leaky modes?

In this paper, a modal analysis method on resonant excitation of 2-D WGFs is proposed. The design of the 2-D WGFs can support the excitation of resonant pairs, the resonant locations and their corresponding modes can be estimated accurately by using the proposed analysis formulas. Furthermore, the low sideband filtering properties of 2-D WGFs can be enhanced by introducing an antireflection (AR) layer, the spectral characteristics by using the double-faced AR design are also investigated. At last, by exciting multiple resonant pairs, the comb-like multichannel filtering can be obtained by merely increasing the thickness of the homogeneous layer with other parameters maintained.

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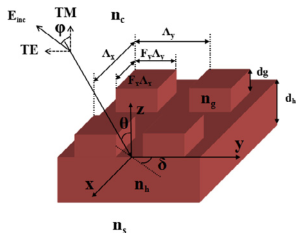

Fig. 1. Schematic diagram of the 2-D WGF under research denoting thickness (d_g) of the 2-D periodic grating, thickness (d_h) of the homogeneous layer and refractive index ($n = n_g = n_h$) of the various regions as well as the period (Λ_x and Λ_y) and fill factor (F_x and F_y) of the grating.

2. Resonant excitation of 2-D WGFs

Fig. 1 shows the schematic diagram of the 2-D WGF consisting of a 2-D grating layer and a homogeneous layer. The refractive indices of the cover and the substrate are equal with $n_c = n_s = 1$. The refractive indices of the grating membrane are $n_g = n_h = 2.35$. The periods of the grating in the x-axis and the y-axis are the same with $\Lambda_x = \Lambda_y = 0.8$ μm, and the filling factors are $F_x = F_y = 0.6$. The thickness of the 2-D periodic grating membrane d_g is 0.253 μm, and the thickness of the homogeneous layer is d_h. θ and φ denote the incident angle and the polarization angle, respectively. δ denotes the azimuth angle. $\varphi = 0°$ and $\varphi = 90°$ denote the TM polarization and the TE polarization, respectively.

For a 2-D periodic surface structure at normal incidence, whether a diffracted order propagates in the cover or substrate region can be expressed as [14]

$$\frac{p^2 + q^2}{N^2} < \frac{\Lambda^2}{\lambda^2} \tag{1}$$

where p is the diffraction order in the x-axis, q is the diffraction order in the y-axis, λ is the free space wavelength. $N^2 = {n_c}^2$ in the cover region, and $N^2 = {n_s}^2$ in the substrate region. The property of unpolarized filtering can be achieved at normal incidence due to the symmetry of the structure in orthogonal directions [15].

Fig. 2 shows the color-coded reflectance map of the 2-D WGF as a function of d_h, where the red color indicates the high reflectivity. As can be seen in Fig. 2, high reflectance occurs in pair and the number of the resonant pair is increased with the increase of d_h. The resonant pair is resulted from the excitations of the resonant leaky mode of the structure. When the modulation strength $\Delta\varepsilon = {n_g}^2 - {n_c}^2$ is relatively small, the spectra correlation of 2-D gratings and their quasi-equivalent 1-D grating can be distinguished [13]. The spectral response, as for others presented in this paper, are based on rigorous coupled-wave analysis [16].

To estimate the locations of the resonant pairs and to improve the understanding of the relationship between the diffraction orders and the waveguide modes of the 2-D waveguide structure, the spectral properties of the 2-D WGFs can be explained in terms of quasi-equivalent 1-D relatives defined by the equivalent medium theory (EMT) [13]. That is, the spectral response of the 2-D WGFs can be interpreted in terms of the mode structure of the quasi-equivalent 1-D gratings with a polarized input light. As shown in Fig. 3(a) and (b), the corresponding quasi-equivalent 1-D gratings of the 2-D WGF can be established by using the second-order EMT. For the TE and TM polarizations, the effective refractive indices of the quasi-equivalent 1-D gratings are given by [17]

$$n_{\mathrm{TE}}^{(2)} = \left[\left(n_{\mathrm{TE}}^{(0)}\right)^2 + c_{\mathrm{TE}}^{(2)}\left(\frac{\Lambda}{\lambda}\right)^2\right]^{1/2} \tag{2}$$

$$n_{\mathrm{TM}}^{(2)} = \left[\left(n_{\mathrm{TM}}^{(0)}\right)^2 + c_{\mathrm{TM}}^{(2)}\left(\frac{\Lambda}{\lambda}\right)^2\right]^{1/2} \tag{3}$$

$$c_{\mathrm{TE}}^{(2)} = \frac{1}{3}\pi^2 F^2 (1-F)^2 \left(n_g^2 - n_c^2\right)^2 \tag{4}$$

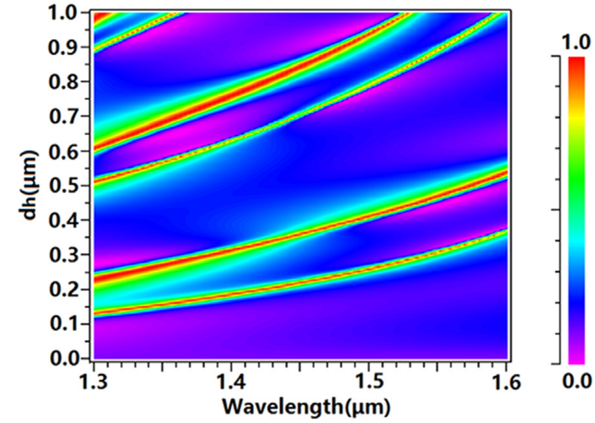

Fig. 2. Color-coded reflectance map of the 2-D WGF as a function of d_h. The parameters are: $n_c = n_s = 1$, $n_g = n_h = 2.35$, $F = F_x = F_y = 0.6$, $\Lambda = \Lambda_x = \Lambda_y = 0.8$ μm, $d_g = 0.253$ μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

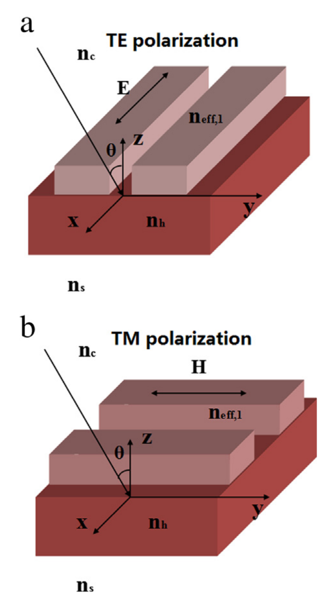

Fig. 3. Quasi-equivalent 1-D gratings of the 2-D unpolarized WGF with the effective refractive index $n_{eff,1}$ of the grating ridges. (a) TE polarization ($n_{eff,1} = n_{\mathrm{TM}}^{(2)}$) with the set of parameters ($\Lambda_y = \Lambda$, $\Lambda_x = 0$, d_g, $F_y = F$, $F_x = 0$, d_h) and (b) TM polarization ($n_{eff,1} = n_{\mathrm{TE}}^{(2)}$) with the set of parameters ($\Lambda_x = \Lambda$, $\Lambda_y = 0$, d_g, $F_x = F$, $F_y = 0$, d_h).

$$c_{\mathrm{TM}}^{(2)} = \frac{1}{3}\pi^2 F^2 (1-F)^2 \left(\frac{1}{n_g^2} - \frac{1}{n_c^2}\right)^2 \left(n_{\mathrm{TM}}^{(0)}\right)^6 \left(n_{\mathrm{TE}}^{(0)}\right)^2 \tag{5}$$

$$n_{\mathrm{TE}}^{(0)} = \left[F n_g^2 + (1-F)\, n_c^2\right]^{1/2} \tag{6}$$

$$n_{\mathrm{TM}}^{(0)} = \left[F n_g^{-2} + (1-F)\, n_c^{-2}\right]^{-1/2}. \tag{7}$$

By using $n_{\mathrm{TE}}^{(2)}$ and $n_{\mathrm{TM}}^{(2)}$, the quasi-equivalent 1-D grating structures can be determined by sets of structural parameters ($\Lambda_y = \Lambda$, $\Lambda_x = 0$, d_g, $F_y = F$, $F_x = 0$, d_h) or ($\Lambda_x = \Lambda$, $\Lambda_y = 0$, d_g, $F_x = F$, $F_y = 0$, d_h).

To excite the GMRs for the quasi-equivalent 1-D gratings shown in Fig. 3, the waveguide modes need to be generated with the incident wave satisfying the phase-matching condition of the periodic structure, which will result in [18]

$$\beta_0 \approx k_0 \left(n_c \sin\theta - |m|\, \lambda/\Lambda\right), m = \pm 1, \pm 2, \ldots \tag{8}$$

where m is the diffraction order, and $k_0 = 2\pi/\lambda$.