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Ultra-narrow bandwidth resonant reflection grating filters using the second diffracted orders

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ABSTRACT

In this paper, we design resonant reflection grating filters employing the second diffracted orders as the leaky modes, then analyze the bandwidth of the reflection peak and the electric field distributions inside the waveguide under resonance. The numeric calculation confirms that ultra-narrow resonant reflection peaks can be observed in these structures. At the same time, strong electric field enhancement appears under resonance. It provides a new approach to diversify the resonant reflection filters and may open a new way to the realization of ultra-narrow bandwidth filters.

1. Introduction

Resonant grating filters, also known as guided-mode resonance (GMR) filters, are integrated optical structures consisting of a waveguide in the presence of a periodic perturbation of the structure's geometric and material properties [1,2]. Typical device configurations include single-layer grating embedded structures and double-layer surface-relief grating structures. When a diffracted wave from the grating couples to a leaky mode supported by the waveguide layer, it excites a guided-mode resonance that causes sharp variations in the wavelength or angular spectra of the externally propagating fields, thus applying the guided-mode resonance effect a variety of passive optical elements are realized. By incorporating a grating whose periodicity is such that only the 0th diffraction order propagates in the input and output regions, with all other diffracted orders in these regions being evanescent, efficient narrowband optical filters have been designed in both reflection and transmission regimes [3,4]. A desirable response from a resonant grating filter normally includes a minimal broadband reflection (transmission), a nearly 100% narrowband resonant spectral reflection (transmission), and a broad angular acceptance at either normal incidence [5] or an oblique angle of incidence [6]. A variety of novel resonant grating filters have been proposed and realized in experiment. Magnusson et al. [7] fabricated a high-efficiency guided-mode resonance Brewster filter using the Brewster effect to produce low-reflectance sidebands. Lemarchand et al. [8] used the doubly periodic structures to increase the angular tolerance without modifying the spectral bandwidth. Fehrembach et al. [9] obtained a 0.5 nm bandpass polarization independent reflection filter for telecom wavelength using a two direction periodic resonant grating filter to remove the polarization dependence. Liu and Magmusson [10] gave the concept of implementing optical filters by coupling evanescent waves from several diffracted orders into multiple leaky waveguide modes. Yurista et al. [11] put a low refractive index buffer layer, between the grating and waveguide layers, to get significant reduction of losses and weaker coupling and achieved very narrow spectral bandwidths and high contrast ratios. In realizing narrow bandwidth resonant grating filters experimentally, many restrictions have to be overcome in order to achieve desirable performance. Imperfections in fabrication, absorption losses, limited angular tolerance, finite size effects [12]

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and so on are all fatal to the performance of the resonant grating filters. To achieve ultra-narrow bandwidth, the most common meaning is to use the weakly modulated grating [13]. But to align two different materials with small index difference to form a grating is often difficult in realization. In this letter, we use the second diffracted orders to achieve ultra-narrow bandwidth resonant reflection grating filters and the properties of the second diffracted order resonant grating filters are explored. In the model we analyze in this paper, although the modulation is quite strong, the bandwidth is still very narrow. In the following, we first describe the design principle and then investigate their spectral properties and electric field distributions under resonance. At the end we give some reviews about the second order diffraction resonant filters, especially about the advantage to other narrow bandwidth methods and the realizing problem. All the filters designed in this paper work under normal TE wave incidence.

2. Analytical and design methods

A schematic diagram of a resonant grating filter is illustrated in Fig. 1. We use h_g, h_w to present the depth of the grating and the thickness of the waveguide layer; n_h, n_l, n_w, n_s, n_c to present the refractive indices of the ridge of the grating, the groove of the grating, the waveguide layer, the substrate and the cover respectively; f to the fill factor (the width of the ridge to the period of the grating) and Λ to the period of the grating. If we use the effective medium theory to present the grating layer with the effective index n_e, the structure may be viewed as a equivalent four-layer waveguide. To achieve a highly efficient resonance, the waveguide condition (i.e. the index of the waveguide layer being higher than the effective index of the grating layer and the index of the substrate) and the subwavelength grating condition (i.e. $\Lambda < \lambda$) has to be satisfied. If we want to have the resonance peak achieved using the mth diffracted orders, these conditions give out that

$$m\frac{2\pi/\Lambda}{2\pi/\lambda} = m\frac{\lambda}{\Lambda} < n_w \tag{1}$$

$$\frac{2\pi/\Lambda}{2\pi/\lambda} = \frac{\lambda}{\Lambda} > \max(n_e, n_s) \tag{2}$$

To determine the modal properties and spatial distribution of TE modes within the waveguides considered, the effective medium theory [14,15] (EMT) and the transfer matrix theory of planar multilayer waveguides [16] are utilized. According to the EMT, a periodic structure may be represented by an anisotropic homogeneous medium if only the zero-order diffraction propagates and higher diffraction orders are evanescent. For the grating layer shown in Fig. 1, the effective index can be written as

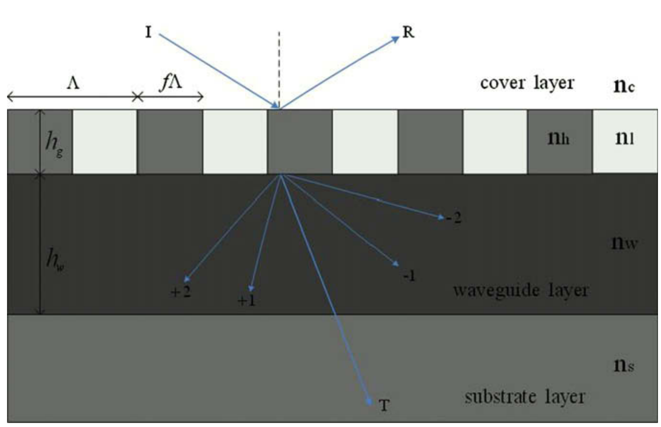

Fig. 1. Schematic diagram of the resonant grating filter considered in this paper.

$$n_e = \left(\bar{\varepsilon} + \frac{\pi^2}{3}f^2(1-f)^2\left(n_h^2 - n_l^2\right)^2\left(\frac{\Lambda}{\lambda}\right)^2\right)^{1/2} \tag{3}$$

under TE wave incidence, where $\bar{\varepsilon} = n_h^2 f + n_l^2(1-f)$ and λ is the free-space wavelength. For TE polarization, using the transfer matrix theory away from resonance, the waveguide eigenvalue can be found from the root of the modal-dispersion function [16]

$$\chi_M(\beta) = \gamma_c m_{11} + \gamma_c\gamma_s m_{12} + m_{21} + \gamma_s m_{22} = 0 \tag{4}$$

where β is the propagation constant of the certain diffracted waves, m_{11},m_{12}, m_{21}, m_{22} are the elements of the transfer matrix for the stack, γ_c, γ_s are the tilted optical admittance of the cover and the substrate. Using Eqs. (3) and (4), the dispersion relation of any waveguide mode (for example TE_0 mode) of the equivalent waveguide can be plotted. If we want to let the first diffracted wave to be resonant as the TE_0 mode, the resonant wavelength can be found from the crossing of the dispersion curves between TE_0 mode and the first diffracted order [17]. In this way, we may get the resonant wavelength approximately and in principle the resonance may be placed at any wavelength after carefully optimizing. Fig. 2 gives an example to determine the resonance wavelength. All the param-

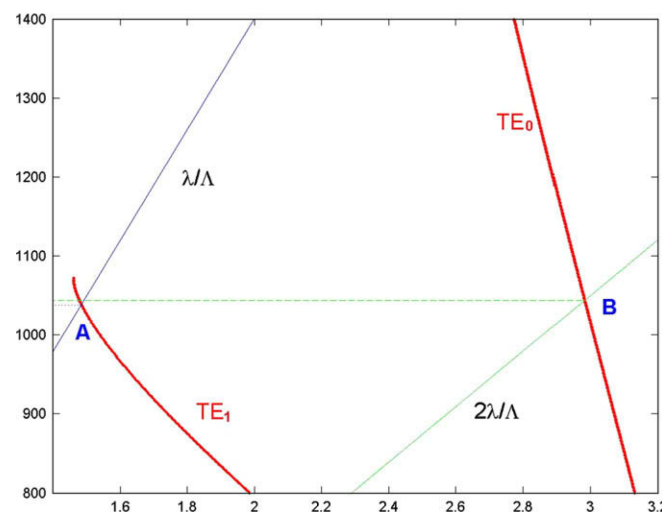

Fig. 2. Determination of the resonant wavelength from the dispersion curves of the waveguide mode and the diffracted wave. The parameters used here are n_h = 1.46, n_l = 1.0, n_s = 1.46, n_c = 1.0, n_w = 3.48, Λ = 700 nm, f = 0.75, h_g = 200 nm, h_w = 180 nm.

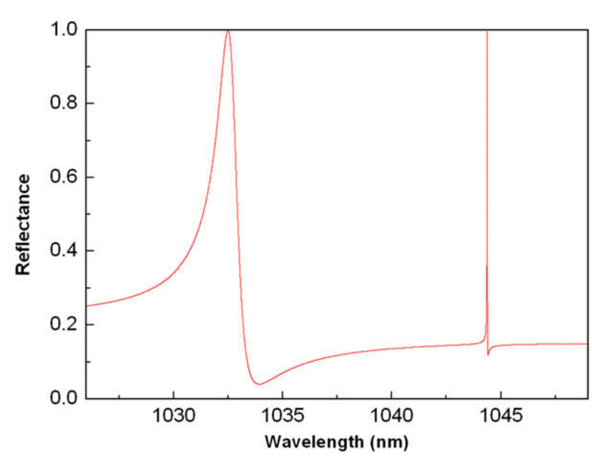

Fig. 3. Zero-order reflectance spectra under normal TE incidence. The geometry parameters are specified as n_h = 1.46, n_l = 1.0, n_s = 1.46, n_c = 1.0, n_w = 3.48, Λ = 700 nm, f = 0.75, h_g = 200 nm, h_w = 180 nm.

eters used are specified in the caption. The modal index is obtained from the propagation constant of the guided mode by normalizing with respect to the free-space wavenumber [17]. The crossing point A is the approximate position at which the first diffracted order serves as the TE_1 leaky mode and form one resonance peak. The crossing point B is the approximate position at which the second diffracted order serves as the TE_0 leaky mode and forms the other resonance peak.

The 0th diffracted order reflection response from the system is determined through a rigorous coupled-wave analysis (RCWA) [18] formulation. The electric field distributions under resonance are solved based on rigorous calculations by use of the Fourier modal method [19].

3. Numerical analysis and simulation

We select the poly-silicon ($n = 3.48$) and silica ($n = 1.46$) as the building materials to construct the resonant grating filter. The parameters of the refractive indices are specified as $n_w = 3.48$, $n_s = 1.46$, $n_h = 1.46$, $n_l = 1.0$, $n_c = 1.0$. According to Eqs. (1) and (2), if we let $\Lambda = 700$ nm, the wavelength range of our interest (i.e. the second diffracted orders satisfying the waveguide condition and the sub-wavelength grating condition and hence forming the resonance) is

$$1022 < \lambda < 1218 \tag{5}$$

The other geometry parameters (f, h_g, h_w) can be varied according to the central wavelength of the filter.

For the first structure we consider here, one reflection peak originates from the second diffracted order and the other from the first one. We let $f = 0.75$, $h_g = 200$ nm, $h_w = 180$ nm, and the 0th order reflection spectra are shown in Fig. 3. From Fig. 3 we know that, the second order diffracted order resonates at 1044.36 nm and the full-width half-maximum (FWHM) linewidth is very narrow, almost 0.01 nm. The other peak originating from the first diffracted order resonates at 1032.49 nm with the FWHM linewidth 1.59 nm. In order to investigate the origin of the narrow peak, we analyze their electric field distribution under resonance which is shown in Fig. 4, where the amplitude magnitude $|E|$ of the electric field normalized with respect to the incident over two grating periods is shown.

Fig. 4a shows the electric field enhancement associated with the TE_0 leaky mode originating form the second diffracted order. The characters of no nodes along the vertical direction and four maximums along the waveguide direction in one period manifest the origin of the peak evidently. The standing wave along the lateral direction comes from the superposition of the two coupled identical but counter propagating second diffracted orders (i.e. +2 and −2 orders). If we regard the electric field enhancement as coming from the multiple interference of the energy coupled to the waveguide from every grating period, longer decay distance results in stronger electric field enhancement inevitably. Narrow reflection peak may be resulted from the little loss during the TE_0 leaky mode propagation. From this point, narrow peaks are accompanied by strong electric field enhancement. In Fig. 4b, the electric field distribution associated with the TE_1 leaky mode from the first diffracted order shows weak enhancement, so the bandwidth is quite wide inevitably.

According to the slab waveguide theory, if we change the grating period into half, the TE_0 leaky mode from the second diffracted order originally switches from the first diffracted order with almost the same propagation constant. But the FWHM linewidth becomes almost seven times bigger, that is 0.10 nm centered at 1043.18 nm. We may use Jacob's theory about resonant grating filters incorporating antireflective layers to explain this phenomenon

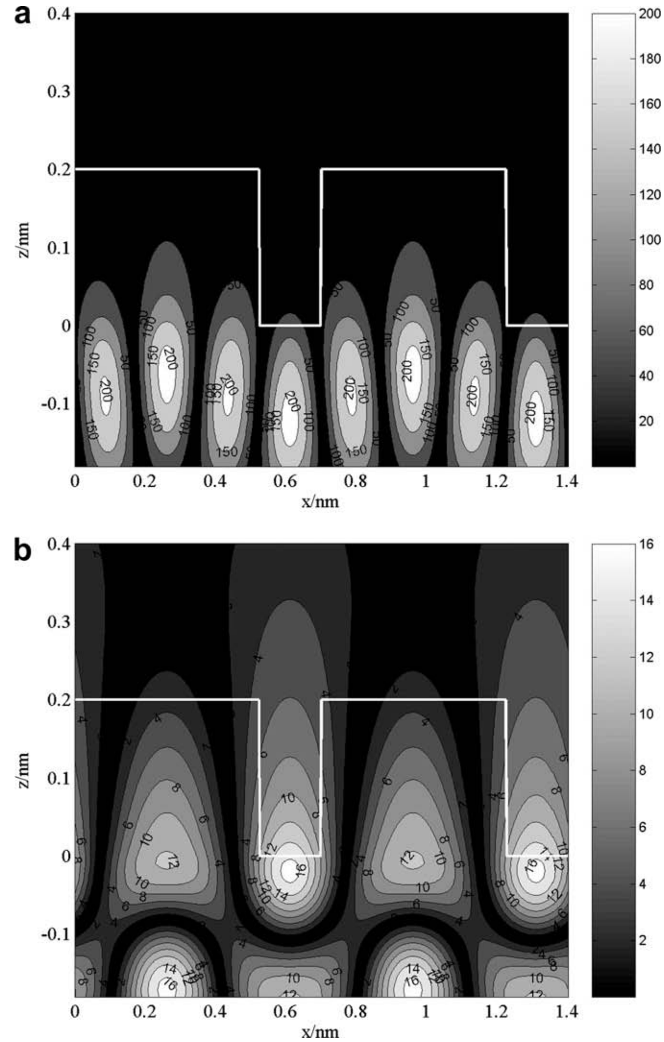

Fig. 4. Normalized amplitude of the electric field in two periods of the resonant grating filter under resonance at $\lambda = 1044.36$ nm as TE_0 leaky mode (a) and $\lambda = 1032.49$ nm as TE_1 leaky mode (b) with the parameters of the structure specified in Fig. 3.

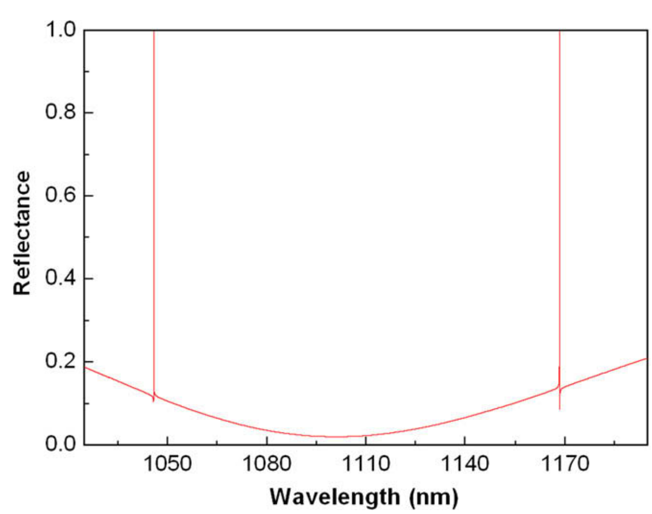

Fig. 5. Zero-order reflectance spectra under normal TE incidence. The geometry parameters are specified as $n_h = 1.46$, $n_l = 1.0$, $n_s = 1.46$, $n_c = 1.0$, $n_w = 3.48$, $\Lambda = 700$ nm, $f = 0.80$, $h_g = 200$ nm, $h_w = 475$ nm.

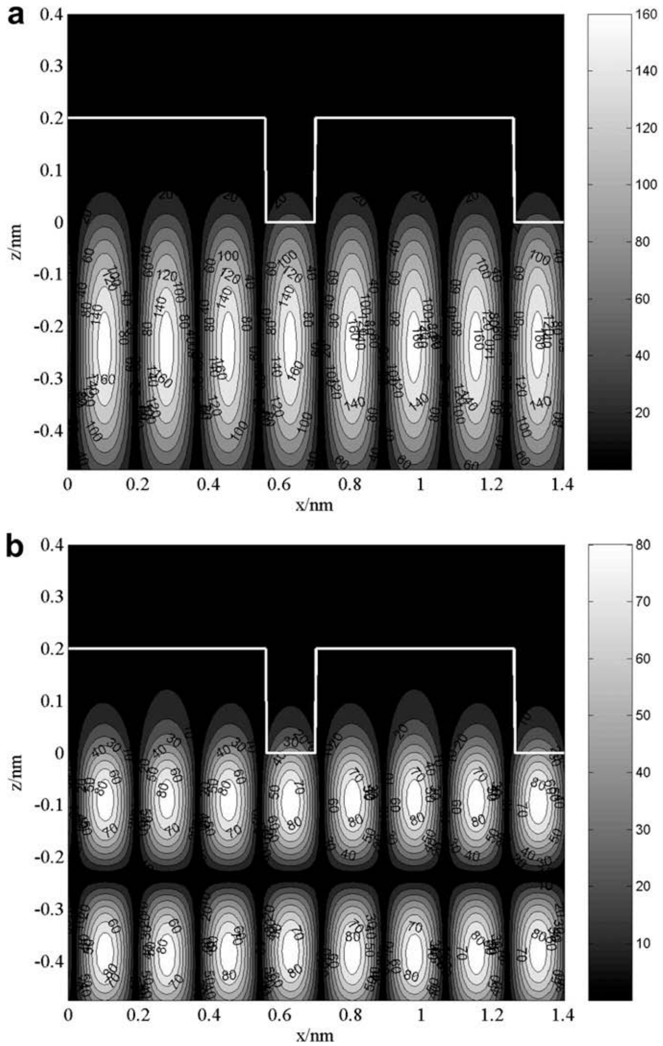

Fig. 6. Normalized amplitude of the electric field in two periods of the resonant grating filter under resonance at $\lambda = 1168.33$ nm as TE_0 leaky mode (a) and $\lambda = 1045.77$ nm as TE_1 leaky mode (b) with the parameters of the structure specified in Fig. 5.

[12]. By Jacob's theory, if we neglect the leakage of the equivalent waveguide, the FWHM linewidth $\Delta\lambda$ may be expressed as

$$\frac{\Delta\lambda}{\lambda} \simeq \frac{4\sin^{-1}\left(\frac{\eta}{2\sqrt{1-\eta}}\right)}{\left(\frac{\lambda}{\Lambda}k_0\left|\frac{d\phi}{d\beta}\right| + 2h_w\sqrt{n_w^2k_0^2 - \beta^2}\right)} \tag{6}$$

where η is equal to the power coefficient diffracted into the leaky mode, $|d\phi/d\beta|$ is only related to the propagation constant β once the structure fixed. When the leaky mode from the second diffracted order switches from the first one, η becomes bigger evidently. The bigger power coefficient makes the bandwidth wider although the period Λ decreases which results in the denominator becoming bigger also.

If we increase the waveguide thickness, there are more modes supported by the equivalent waveguide. As any second diffracted orders produced by the grating have the potential to be coupled to a leaky mode at a proper wavelength, there may be more resonant reflection peaks produced. The second structure we considered here has the structure parameters as $f = 0.80$, $h_g = 200$ nm, $h_w = 475$ nm. Within the wavelength range of our interest, the cutoff mode of the equivalent waveguide is three and the smallest modal index is bigger than two, so all of the possible leaky modes are produced by the second diffracted waves. The 0th order reflection spectra are shown in Fig. 5. From Fig. 5 we know that, the second order diffracted wave resonance peaks centered at 1168.33 nm from the TE_0 leaky mode and at 1045.77 nm from the TE_1 leaky mode are all very narrow and the their FWHM linewidths are 0.013 nm and 0.016 nm respectively. Their electric field distributions under resonance are shown in Fig. 6. Strong electric field enhancement appears evidently. Changing the period into half, we find the same phenomenon with the above. The leaky modes from the second diffracted orders originally switch from the first diffracted orders with almost the same propagation constants but with almost two times wider bandwidths.

4. Conclusions

Resonant reflection grating filters employing the second diffracted orders as the leaky modes are designed and analyzed. With the same modulation, the resonant peaks are much narrower using the second diffracted orders than using the first ones. It is calculated that the reflection peaks as narrow as 0.01 nm may be achieved in these structures. In experiment, the structure we propose is much easier to realize because the grating is all the time an air ($n_l = 1.0$) modulated grating. The narrower the peaks become, the stronger the electric field enhancement under resonance is. Although we can change the period into half to achieve the same resonance wavelength from the first diffracted orders, but the bandwidth increase evidently. Increasing the thickness of the waveguide, we can get more resonance peaks from the second diffracted orders. Likewise we may use the waveguide theory to fashion the guided mode to diversify the resonant reflection filters.

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