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Bandwidth tunable guided-mode resonance filter using contact coupled gratings at oblique incidence

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ABSTRACT

A novel bandwidth tunable guided-mode resonance filter (GMRF) is proposed based on the contact coupled gratings (CCGs) with the absentee layers at oblique incidence. The design principle of the CCGs with double absentee layers is presented. The lateral shift of the CCGs changes the magnetic field distributions of the waveguide mode in the grating cavity and the surface-confined mode at the cover/grating interface thus facilitates the dynamic control of both the spectral and angular bandwidth of the GMRF. The resonance locations are almost immune to the variation of the lateral shift of the CCGs. The sideband level of the GMRF is almost unaffected by the lateral shift due to the Brewster AR effect. The resonance peak red-shifts quasi-linearly as the incident angle is increased, and the resonance wavelength can be selected by merely tuning the incident angle. The tunable ranges of both the spectral and angular bandwidth can be significantly enhanced by increasing the refractive-index contrast. Low-sideband reflection with controllable bandwidth at 650 nm is designed to demonstrate this concept.

1. Introduction

Guided-mode resonance filters (GMRFs) have attracted considerable interest due to their simple structures with versatile spectral characteristics, such as high peak efficiency, wide sideband rejection, and the narrow bandwidth [1]. Numerous functional optical devices can be obtained by combining the GMR effect with the thin film interference effect. It has been proposed that optical elements such as light modulators [2], wavelength selectors [3], tunable filters [4], and sensors [5] can be obtained based on the GMR structures.

The filter bandwidth is an important characteristic parameter for the GMRFs. To control the bandwidth of the GMRFs, the conventional way is to control the structure parameters such as modulation index [1,6], filling factor [7,8], and grating thickness [9–11]. Comparing with the conventional way, other effective approaches to control the spectral bandwidth include such as using the buffer layer structures [12,13] and the compound waveguide grating structures [14]. Unfortunately, the buffer layer structures controls the filter bandwidth at the price of increased layer thickness, and the compound waveguide grating structures require complicated grating profiles and precisely controlling of the filling factor in the etching process. Recently, Qian et al. [15] proposed the bandwidth-tunable device based on the nonpolarizing GMR effects, and the spectral bandwidth can be enhanced 3.73 times by controlling the applied voltage. Later, they showed that the bandwidth-tunable device can be obtained by using the superposition spectra response of two GMRFs, the superposition spectrum shows a bandwidth-tuning feature without efficiency changing at the design wavelength [16]. These bandwidth-tunable filters provide a new approach for the design and application of the filtering properties based on the GMR effect. However, the bandwidth-tuning range of these devices is limited because it is confined between the bandwidth of the TE and TM mode waves.

In this paper, the bandwidth tunable GMRF is proposed based on the contact coupled gratings (CCGs) at oblique incidence, and the design principle of the CCGs with the antireflection (AR) features is presented. Double gratings with the $\lambda/2$ absentee layers are used to extend the low reflection sidebands by using the Brewster AR effect. The resonance wavelength can be selected by merely tuning the incident angle. The lateral shift of the CCGs alters the magnetic field distributions of the waveguide mode and the surface-confined mode thus facilitates the dynamic control of the spectral and angular bandwidth. Both the spectral and angular bandwidth of the GMRF can be enhanced greater than 26.55 times without changing the structure parameters such as the modulation index, filling factor, and grating thickness. By increasing the

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refractive-index contrast of the CCGs, the range of tunable bandwidth can be improved with symmetrical bandshapes and low sideband levels maintained.

2. Design principles

Fig. 1 is the schematic diagram of the CCGs structure under TM polarization light (magnetic-field vector lies along the *y*-axis) at oblique incidence. The CCGs structure consists two grating layers with alternating high/low-index dielectric bars. The refractive indices of the high- and low-index bars are denoted as $n_{1,H}/n_{2,H}$ and $n_{1,L}/n_{2,L}$. n_c and n_s are the refractive indices of the cover and the substrate, respectively. The lateral alignment shift is denoted by *S*, which is defined by the ratio between the horizontal shift and the grating period within a period, and it is the dimensionless coefficient.

According to the effective media theory (EMT) [17], the principle ordinary and extraordinary refractive indices of the *m*th grating layer are given by

$$n_{m,o} = [n_{m,H}^2 f + n_{m,L}^2(1-f)]^{1/2}, \tag{1}$$

$$n_{m,e} = [f/n_{m,H}^2 + (1-f)/n_{m,L}^2]^{-1/2}. \tag{2}$$

When the TM mode wave is incident from the cover to the grating layer, the refractive index of the *m*th grating layer seen by the extraordinary wave can be expressed as [18,19]

$$n_m = n_{m,o}n_{m,e}/\sqrt{n_{m,e}^2\sin^2\theta_m + n_{m,o}^2\cos^2\theta_m}, \tag{3}$$

where the angle of refraction inside the *m*th grating layer is

$$\theta_m = \tan^{-1}(n_{m,o}n_c\sin\theta_c/\sqrt{n_{m,o}^2 n_{m,e}^2 - n_{m,e}^2 n_c^2\sin^2\theta_c}). \tag{4}$$

For the zero-order diffraction, the angles of refraction inside the *m*th grating layer and the substrate yields Snell's law

$$n_c\sin\theta_c = n_m\sin\theta_m = n_s\sin\theta_s. \tag{5}$$

The equation of the characteristic matrix of the equivalent double homogenous films is given as [20]

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & (i\sin\delta_1)/\eta_1 \\ i\eta_1\sin\delta_1 & \cos\delta_1 \end{bmatrix}\begin{bmatrix} \cos\delta_2 & (i\sin\delta_2)/\eta_2 \\ i\eta_2\sin\delta_2 & \cos\delta_2 \end{bmatrix}\begin{bmatrix} 1 \\ \eta_s \end{bmatrix}, \tag{6}$$

where δ_m is the phase for the *m*th layer, $\delta_1 = 2\pi d_1\eta_1/\lambda$, and $\delta_2 = 2\pi d_2\eta_2/\lambda$. η_m is the optical admittance for the *m*th layer, $\eta_1 = n_{1,e}^2/(n_1\cos\theta_1)$, and $\eta_2 = n_{2,e}^2/(n_2\cos\theta_2)$. η_s is the optical admittance of the substrate, and $\eta_s = n_s/\cos\theta_s$.

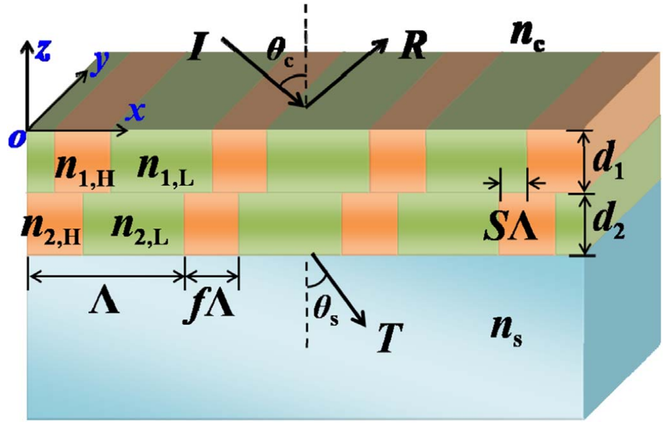

Fig. 1. Schematic diagram of the CCGs structure under TM polarization light at oblique incidence with period Λ, fill factor f, grating thickness d_1 and d_2. The lateral alignment shift is denoted by S.

The effective admittance can be written as $Y = C/B$, and the reflectivity of the equivalent double homogenous films can be written as

$$R = \left(\frac{\eta_c - Y}{\eta_c + Y}\right)\left(\frac{\eta_c - Y}{\eta_c + Y}\right)^*. \tag{7}$$

In order to obtain zero reflectivity, the AR condition of the CCGs structure can be simplified to $\eta_c = n_c/\cos\theta_c = Y$. For the CCGs structure with the $\lambda/2$ optical thickness of the *m*th grating layer, i.e.

$$d_m = \frac{M\lambda}{2n_m\cos\theta_m} = \frac{M\lambda}{2\sqrt{n_{m,e}^2 - n_{m,e}^2 n_c^2\sin^2\theta_c/n_{m,o}^2}}, \quad M = 1, 3, 5, \cdots \tag{8}$$

By using (Eqs. (1)–8), the AR condition of the CCGs can be reduced to

$$\theta_c = \tan^{-1}(n_s/n_c). \tag{9}$$

Therefore, the CCGs structure with double $\lambda/2$ optical thickness acts as an absentee layer, which means the AR condition of the

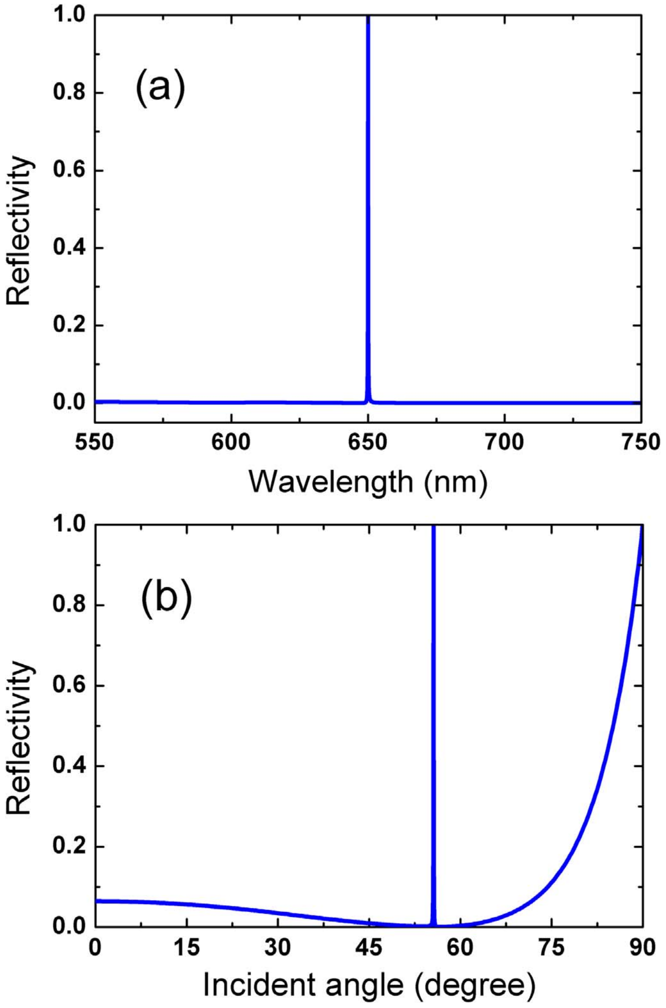

Fig. 2. Response of the CCGs structure shown in Fig. 1. (a) Spectral response at $\theta_c = 55.59°$. (b) Angular response. The parameters are $n_c = 1$, $n_{1,H} = n_{2,H} = 1.98$ (HfO$_2$), $n_{1,L} = n_{2,L} = 1.46$ (SiO$_2$), $n_s = 1.46$ (fused silica), $f_1 = f_2 = 0.3$, $d_1 = d_2 = 239.62$ nm, $\Lambda = 276.04$ nm, and $S = 0$.