Increasing the angular tolerance of resonant grating filters with doubly periodic structures

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One can increase the angular tolerance of resonant grating filters without modifying the spectral bandwidth by adding a second grating component parallel to the first one. The angular tolerance and the filter linewidth can be controlled by the designer in an independent way. Numerical results show that this property permits the use of waveguide-grating filters with standard collimated beams. © 1998 Optical Society of America

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Narrow-band filters have proved to be crucial components in some applications such as in astronomy and telecommunications. These components can be made with classic thin-film Fabry–Perot stacks. However, such structures require a large number of layers. Problems of stress, monitoring, and absorption make these components difficult to manufacture. Resonant grating filters represent an alternative solution to making narrow-band filters. The guided-mode resonance phenomena in grating diffraction have drawn much attention for the past ten years. Vincent and Neviere[1] showed that these structures yield filters with 100% peak reflectance under certain conditions of symmetry at a desired wavelength. Experimental results obtained in the optical region by Peng and Morris[2] and in the microwave domain by Magnusson *et al.*[3] have confirmed the theoretical predictions. An appropriate design of these components provides narrow-band reflection filters with symmetric line shapes and low sidebands.[4] However, one should place considerable emphasis on the fact that, in general, the narrower the spectral response, the narrower the angular response. In practice, the divergence of the incident optical beam leads to a significant reduction in the reflectance peak.[5] In this Letter we present a method to increase the angular tolerance of resonant grating filters without modifying the spectral bandwidth.

To investigate the angular behavior of single resonant grating (SRG) filters [Fig. 1(a)] we study the dispersion curves of the guided modes in the homogenized structure, and we focus on the modifications induced by the periodic perturbation.[6,7] For convenience's sake we consider only the TE fundamental mode and disregard the possible presence of higher-order modes. The field expression of a guided mode in the periodic system of period Λ_s can be expressed as

$$E(x, y) = \exp(i\beta x) f(x, y)\,, \tag{1}$$

with $f(x + \Lambda_s, y) = f(x, y) = \sum f_n(y)\exp(inK_s x)$ and $K_s = 2\pi/\Lambda_s$. Equation (1) satisfies the Helmholtz equation

$$\Delta E + \langle\epsilon\rangle(y)(\omega/c)^2 E = -\delta\epsilon(x, y)(\omega/c)^2 E\,, \tag{2}$$

where $\langle\epsilon\rangle$ is the average dielectric constant, $\langle\epsilon\rangle(y) = a\epsilon_1/\Lambda_s + (1 - a/\Lambda_s)\epsilon_2$ for $0 < y < d_s$, $\langle\epsilon\rangle(y) = \epsilon_{\text{subs}}$ for $y < 0$, and $\langle\epsilon\rangle = \epsilon_{\text{inc}}$ for $y > d_s$. The periodic perturbation $\delta\epsilon$ is defined by $\delta\epsilon(x, y) = \epsilon(x, y) - \langle\epsilon\rangle$, where $\epsilon(x + \Lambda_s, y) = \epsilon(x, y)$ is the permittivity of the system as described in Fig. 1(a). We obtain the dispersion curves either by fixing ω real in Eq. (1) and searching the wave vector β complex that satisfies Eq. (2) or by fixing β real and searching the frequency ω complex [Fig. 2(a)]. The second technique, unlike the first, allows us to delimit the forbidden frequency gaps accurately[2] and permits an easier interpretation of the reflectivity behavior in the vicinity of the stop-band regions. The angular dependence of the system is deduced from the dispersion curves through the relation

$$\beta = k \sin\theta + mK_s\,, \tag{3}$$

where $k = \text{Re}(\omega)/c = 2\pi/\lambda$, m is an integer, and θ is the angle of the incident plane wave.

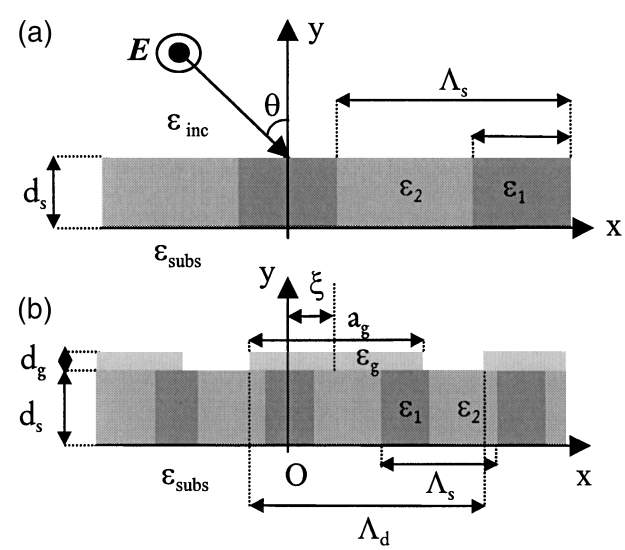

Fig. 1. (a) Geometry of a one-dimensional SRG under TE illumination. (b) Geometry of the double grating structure.

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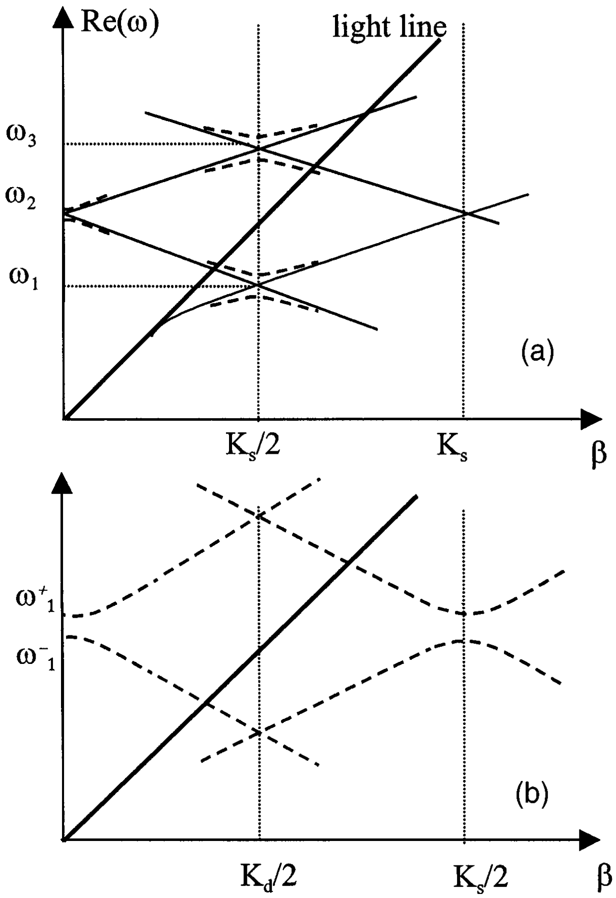

Fig. 2. (a) Dispersion curves of the homogenized structure (solid curves). Changes induced by the periodic modulation of the dielectric constant (dashed curves). (b) Dispersion curves for a doubly periodic structure.

In a first approximation the dispersion curves of the periodically perturbed structure differ from the homogenized system essentially when both backward and forward guided modes are excited [Fig. 2(a)] through the grating. Forbidden gaps (or stop-band regions) appear when β lies on Bragg planes, $\beta = mK_s/2$. The lower branch corresponds to a symmetric mode with respect to the y axis, and the upper one to an antisymmetric mode.[1] In these regions the resonant frequency ω varies weakly with β. Hence one expects to improve the angular tolerance by using the resonant grating in the vicinity of a gap. The wider the gap, the better the angular behavior.

In general, resonant grating filters are used under normal incidence, and the period is chosen such that a guided mode with wave vector β is excited at a particular frequency ω, $\Lambda_s = 2\pi/\beta(\omega)$. This configuration corresponds to the second-order stop band [$\omega = \omega_2$ in Fig. 2(a)]. In this configuration the grating controls the coupling (and leaking) of the incident wave into the guided mode and is also responsible for the flattening of the dispersion curves. In general, a small dielectric contrast is required for a narrow-bandwidth filter. As a result, the forbidden gap is small and the angular tolerance is tight. Increasing the dielectric contrast widens the gap and improves the angular tolerance, but it also enhances the leakage of the guided mode and dramatically enlarges the spectral linewidth.[8] In the first-order stop band, $\omega = \omega_1$, $\Lambda_s = \pi/\beta(\omega_1)$, the dispersion curve lies outside the light line, so in a first approximation the guided mode cannot be coupled to photons even after scattering by the grating.[9] In this case the mode propagating along the modulated layer is not leaky, whatever the dielectric contrast. Hence we can modify the shape of the dispersion curves (by increasing the dielectric contrast) without acting on the spectral response. Under normal incidence, to couple the impinging beam into the guided mode we introduce another periodic perturbation, with period $\Lambda_d = 2\Lambda_s$ on the top grating (TG) of the layer grating (LG). [See Fig. 1(b).] Indeed, this additional periodicity (in the limit of weak perturbation) leads to a $K_d = K_s/2 = 2\pi/\Lambda_d$ translation along the β axis of the dispersion curves as seen in Fig. 2(b).[7,9] The former first-order stop-band region now lies inside the light cone, and the guided mode can be excited by photons. The parameters that control the coupling (leaking) of the mode, that is, the linewidth of the filter, are essentially the height d_g, the permittivity ϵ_g, and the width a_g of the TG. The position ξ of the TG also plays a role in the reflectance behavior of the structure. When the system is not symmetrical with respect to the y axis, the modes of both the lower and the upper branches can be excited under normal incidence.[1] Hence the spectral response will exhibit two reflectance peaks, at ${\omega_1}^+$ and ${\omega_1}^-$. In the particular case $\xi = 0$ or $\xi = \Lambda_s/2$, only one mode can be excited and the other reflectance peaks disappear. This phenomenon is clearly shown in Fig. 3, where we display contour plots of the reflectivity of a doubly periodic structure (DPS), calculated with a rigorous differential method, as a function

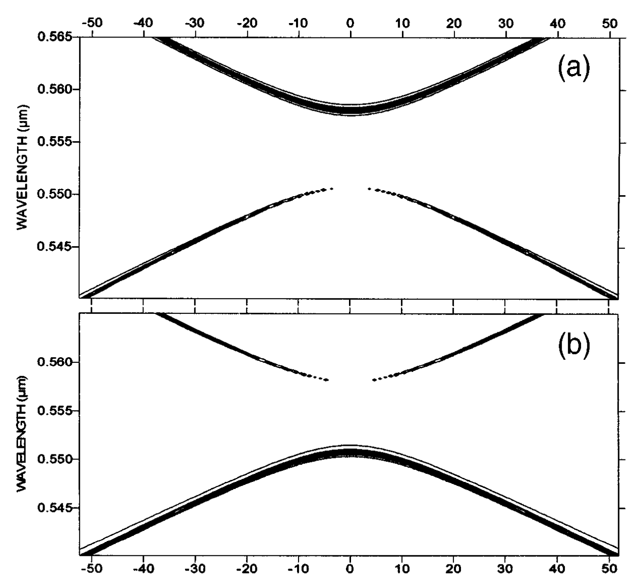

Fig. 3. Reflectance versus angle of incidence and wavelength for two DPS's. Higher values of reflectance correspond to darker zones. $\epsilon_{\rm inc} = 1$, $\epsilon_{\rm subs} = (1.52)^2$, $\epsilon_1 = (2.085)^2$, $\epsilon_2 = (2.035)^2$, $\epsilon_g = (1.97)^2$, $\Lambda_d = 0.314\ \mu$m, $a_g = \Lambda_d/2$, $a = \Lambda_s/2$, $d_g = 0.006\ \mu$m, $d_s = 0.134\ \mu$m. (a) $\xi = 0$, (b) $\xi = \Lambda_s/2$.

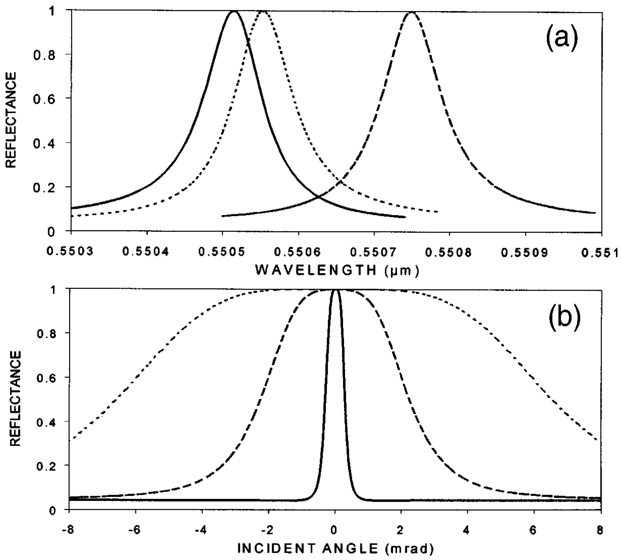

Fig. 4. Spectral and angular response of the DPS's and the SRG. Solid curves, SRG $\epsilon_{\text{inc}} = 1$, $\epsilon_{\text{subs}} = (1.52)^2$, $\epsilon_1 = (2.075)^2$, $\epsilon_2 = (2.025)^2$, $\Lambda_s = 0.314\ \mu\text{m}$, $d_s = 0.134\ \mu\text{m}$, $a = \Lambda_s/2$, $\lambda_0 = 0.550515\ \mu\text{m}$, $(\epsilon_2 - \epsilon_1)/\langle\epsilon\rangle = 0.1$. Long-dashed curves, same as in Fig. 3 but with $\lambda_0 = 0.550750\ \mu\text{m}$, $\xi = \Lambda_s/2$, $(\epsilon_2 - \epsilon_1)/\langle\epsilon\rangle = 0.1$. Short-dashed curves, same as in Fig. 3 but with $\epsilon_1 = (2.5)^2$, $\epsilon_2 = (1.5)^2$, $\epsilon_g = (2.07)^2$, $\Lambda_d = 0.356\ \mu\text{m}$, $a_g = \Lambda_d/2$, $a = \Lambda_s/2$, $\lambda_0 = 0.550554\ \mu\text{m}$, $\xi = \Lambda_s/2$, $(\epsilon_2 - \epsilon_1)/\langle\epsilon\rangle = 0.94$.

of both the wavelength and the angle of incidence for two symmetric structures. As with SRG structures, one obtains 100% maximum reflectance at the resonance wavelengths and low sidebands. The reflectivity contours follows the shape of the dispersion curves drawn in Fig. 2(b). The gap width $(\omega_1{}^-, \omega_1{}^+)$ is related to the coupling force, provided essentially by the LG, between the backward- and forward-propagating guided modes, i.e., the coefficients $\tilde{\delta}\epsilon[2\beta(\omega) = K_s]$, $\tilde{\delta}\epsilon[2\beta(\omega) = K_s]$, and $\tilde{\delta}\epsilon(-K_s)$ of the Fourier series of the dielectric contrast. As the gap widens, the angular tolerance of the doubly periodic structure increases. Note that, in the case of the SRG, the filling factor a/Λ_s is in general equal to 0.5 and $\tilde{\delta}\epsilon(2\beta = 2K_s) = \tilde{\delta}\epsilon(-2\beta = -2K_s) = 0$.

To illustrate the capabilities of DPS's we first consider a SRG whose reflectivity exhibits a spectral resonance peak at $\lambda_0 \approx 0.55\ \mu\text{m}$ with a FWHM of $\Delta\lambda \approx 0.1\ \text{nm}$. The angular FWHM is $\Delta\theta = 0.6$ mrad. Now we consider several DPS's that have similar spectral bandwidths [Fig. 4(a)]. In Fig. 4(b) we compare the reflectance at the resonant wavelength and the incident angle for the SRG and two DPS's. It can be seen that, even when the dielectric contrast of the LG is unchanged, the angular tolerance of the DPS is seven times larger than that of the SRG. Increasing the dielectric contrast of the LG of the DPS ameliorates this performance. The angular tolerance exceeds $\Delta\theta = 12$ mrad for a DPS with a dielectric contrast $(\epsilon_2 - \epsilon_1)/\langle\epsilon\rangle = 0.94$.

Hence, with the doubly periodic structures, all the incident energy coming from standard collimated beams (typical angular divergence, $\Delta\theta = 1$ mrad) should be reflected at the resonance wavelength, even for very narrow spectral linewidths ($\Delta\lambda < 0.1$ nm in the visible range). Finally, it is worth noting that the TG can be placed anywhere in the doubly periodic structure. In particular, it can be etched in the substrate. Because the relative positions of the superposed gratings are of secondary importance, making such structures with a double etching process is conceivable.

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