Broadband near-infrared reflector based on double-layer subwavelength gratings

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Abstract
A broadband reflector with a reflectance up to 97.8% over a 144 nm spectral range from 1476 to 1620 nm is proposed by comprising double-layer subwavelength gratings with one grating layer embedded in SiO2 layer. An analysis of the resonance leaky modes with overlapping gratings shows the physical mechanism of the wide broad high-reflectivity band. The tolerance of structural parameter is analyzed and the variation of bandwidth is explained by combining the behaviors of the two guided mode resonances. The guided mode resonance and high refractive index contrast properties lead to a good angular tolerance that exhibited an angular insensitivity (~ 11°) at 1550 nm. Overall, the broadband reflector may benefit the monolithic integration of optoelectronic devices.

Keywords Broadband reflector · Guided mode resonance · Double-layer grating

1 Introduction

Broadband reflectors with a high reflectance are used extensively in many applications, such as lasers (Chung 2015), sensors (Learkthanakhachon et al. 2016), and polarizers (Mutlu et al. 2012). Usually, based on one-dimensional photonic crystals (PCs) with many layers (MacDougal et al. 1994; Nouman et al. 2020), high-reflection mirrors can be obtained. It is not easy to achieve broadband high reflection at infrared wavelengths, because the coating layers need to be more compared to those in the visible range (Amotchkin et al. 2017). To reduce layer count, many methods that vary the structure of the waveguide grating have been used to design the broadband reflector. For example, in 2004, a broadband reflector at 1550 nm (Δλ/λ > 35%, R > 98.5%) was designed and verified by using the subwavelength grating (SWG) with a low-index sublayer (Mateus et al. 2004a, b; Mateus et al. 2004a, b). In 2008, Magnusson revealed the physical mechanism that yields...
a wide reflection band with a high reflectivity by using the resonant bandwidth overlap of multiple GMRs (Magnusson et al. 2008), which is the important design idea of broadband reflector. A large-refractive-index grating that was suspended in air, namely, high-contrast-grating (HCG) can provide a wideband reflection (Chang-Hasnain et al. 2010). However, it is not easy to fabricate the suspended grating because of the lack of substrate.

Perfect reflectors that have a wideband with polarization independent and omnidirectional are requested for expected in photonics and optical communications. However, the structure of a single-layer grating was not easy to be designed with these multiple properties. Comparatively, it is easier to be realized by using multilayer gratings. For example, two orthogonal gratings were demonstrated experimentally, and achieved a broad independent polarized bandwidth with high reflectance (Niraula et al. 2016; Ko et al. 2017). Nevertheless, it is difficult to combine separate SWGs compactly. More recently, a structure that consists of double-layer SWGs with different periods and fill factors based on GMR was proposed as broadband reflector (Zhang et al. 2020), where an ultra-broadband reflection with reflectance that exceeds 97% over a wavelength range of 955 nm in the near-infrared region was achieved. However, grating with a large fill factor increased the fabrication difficulty.

In this work, we designed double-layer subwavelength gratings with one grating layer embedded in an SiO₂ layer. In Sect. 2, the overlapped resonance pair extends the reflection bandwidth. In Sect. 3, by varying the structural parameters, such as the homogeneous layer thickness and grating fill factor, the important effect of the two corresponding GMRs for the broad reflection band was discussed in detail. An incident angle tolerance of ~ 11° at a central wavelength of 1550 nm was also analyzed.

2 Design and theory

The investigated broadband reflector was designed by double-layer subwavelength gratings based on applying a rigorous coupled-wave analysis method (Peng et al. 1995). The structure diagram is shown in Fig. 1a. The optimized structure consists of four layers, including a fused silica substrate \( n_1 = 1.45 \), a 1000 nm fused silica spacer layer \( n_1 = 1.45 \), and

![Fig. 1](image)

(a) Schematic view of the designed structure. The upper and lower Si gratings are separated by SiO₂ film layer, and the lower grating is embedded in the SiO₂ layer. The structural parameters are \( n_2 = 3.48 \), \( b = 190 \) nm, \( \Lambda = 800 \) nm, \( f = 0.625 \), \( n_3 = 1.45 \), and \( a = 1000 \) nm. I represents the incident plane wave, and R denotes reflected light. (b) Reflectance spectra on linear scale and transmittance spectra on logarithmic scale of the reflector normally illuminated by TE polarized wave. And the resonance wavelengths are 1481.84 and 1561.13 nm, respectively.
two silicon grating layers that include that the top silicon/air grating \((n_H = 3.48, n_L = 1, b = 190 \text{ nm})\) and the bottom silicon/ fused silica grating \((n_H = 3.48, n_L = 1.45, b = 190 \text{ nm})\). The grating period has \(\Lambda = 800 \text{ nm}\), and the filling factor was \(f = 0.625\). The incident wave is a transverse electric (TE) polarized wave (electric-field vector lies along the y-axis) at normal incidence.

In the simulation by finite-difference time-domain software (FDTD Solutions), boundary conditions of the domain along the x-axis and y-axis were periodic, and the distance from the left to the right boundary was accurately equal to one grating period. Perfect match layers were used as boundaries at the top and bottom of the domain.

Under subwavelength conditions, high-order diffracted waves apart from the zeroth diffracted wave become evanescent waves. They propagate in the waveguide layer because they satisfy the phase-matching conditions with a guided mode. Due to the existence of a grating layer, they leak and interact with the zeroth diffracted wave to excite the resonance peak (Fan et al. 2019).

When the incident wave couples to a leaky waveguide mode by phase matching with the grating (Ding et al. 2007), the reflector works under a GMR. The subwavelength and phase-matching conditions under the general incident conditions are given by: (Ding et al. 2004)

\[
\Lambda < \frac{\lambda}{n_s \sin \theta + \max(n_c, n_s)} \tag{1}
\]

\[
\beta_m = k_0 \left( n_c \sin \theta - \frac{m \lambda}{\Lambda} \right), m = \pm 1, \pm 2, \tag{2}
\]

where \(\beta_m\) denotes the propagation constant of the \(m\)th guided mode, which relates the diffraction order \((m)\), the wave vector \((k_0)\) in free space, and \(k_0 = 2\pi/\lambda\). The incident angle \((\theta)\) is critical in the formation of resonant behavior. In the designed model, \(n_s\) is the refractive index of the fused silica substrate \((n_f = n_i = 1.45)\), and \(n_c\) is the refractive index of the cover \((n_{air} = 1)\). By using the effective medium theory (EMT), the grating layer can be equivalent to a uniform waveguide layer with a certain effective refractive index (Brundrett et al. 1994). For the TE wave, the effective refractive index \((n_g)\) can be expressed as Eq. (3).

\[
n_g = \left[ \varepsilon_{0,TE} + \frac{\pi^2}{3} f^2 (1-f)^2 (\varepsilon_H - \varepsilon_L)^2 \left( \frac{\Lambda}{\lambda} \right) \right]^{\frac{1}{2}}, \tag{3}
\]

where \(\varepsilon_H = n_H^2 \varepsilon_L = n_L^2 = n_c^2\), and \(\varepsilon_{0,TE}\) is the zero-order permittivity of the TE modes with \(\varepsilon_{0,TE} = n_H^2 f + n_L^2 (1-f)\).

In the subwavelength region, because the structure is equivalent to the thin-film structure, the double-layer subwavelength gratings structure can be equivalent to a double-channel waveguide.

To clearly understand that a broadband reflection spectrum results from the appropriate coupling of two gratings and indicates the physical mechanism of a wideband, Fig. 1b shows the reflection spectrum (linear scale) and transmittance spectra (logarithmic scale) of the designed structure under TE polarization. A band-pass reflector with reflectance >97.8% over a 144 nm spectral range from 1476 to 1620 nm can be obtained at 1550 nm. Two transmittance dips exist inside the high reflectance band, which are located at 1481.84 and 1561.13 nm, respectively, and each of which corresponds to a GMR (Maghessson et al. 2008). The dips in the transmittance spectrum verify the presence of
leaky-mode resonances, which is the physical basis of wideband reflectors (Shokooh-Saremi et al. 2010). The strong evanescent coupling between the two gratings splits the resonance, which leads to two strong transmission peaks near $\lambda = 1500$ nm (Sang et al. 2011). A reflection band at $\lambda = 1500$ nm is provided due to the overlapping of the GMRs. This result implies that the co-existence of the two TE leaky modes occurred because of the high refractive index difference between the materials and the profile modulation of the grating layer, and their interaction led to the formation of a broadband reflection spectrum (Sang et al. 2011). Overall, this high-reflection band is supported by a blend of two leaky modes (He et al. 2019; Shokooh-Saremi et al. 2008). However, the relative distance of the two GMRs is larger (Khaleque et al. 2014) and results in that a slight dip of high reflectivity near 1520 nm in the operating wavelength band, so the broadband is not flat enough (Sang et al. 2009). Nevertheless, a large relative separation between the two GMRs also contributes to the high extended reflectance band.

To gain insights into the broadband properties that arise from the coupling between the two GMRs, the normalized electric field intensity distribution at the resonant wavelengths of 1485.76 and 1515.65 nm is investigated in Fig. 2a and b, respectively. The electric field distributions were localized on the grating ridge of the top grating and were highly enhanced. The narrower GMR spectral bandwidth is, yielded a higher normalized amplitude of the electric field enhancement effect (Wei et al. 2006). Because the peak at 1485.76 nm had a narrower linewidth than that at 1515.65 nm, the normalized amplitude of the electric field for the former was higher than that of the latter.

### 3 Tolerance discussions

A prefabrication analysis of performance that is associated with parametric tolerance is required. In the following discussion, we show a design tolerance by varying the structure parameters, while keeping the other parameters constant. The reflectivity spectra for structure with different fused silica spacer thickness was calculated and is shown in Fig. 3a. The sideband reflection at the longer wavelength varies more significantly than that at the shorter wavelength. Therefore, the reflection band at a longer wavelength side depends mostly on the middle spacer thickness (Yamada et al. 2017). When fused silica spacer thickness increases form 960 nm to 1040 nm, the bandwidth (R > 90%) increases.
from 141.62 nm to 171.95 nm. To illustrate the physical mechanism, Fig. 3b compares the reflection spectra and transmittance dips for two spacer thicknesses (1000 and 1040 nm). The reflectivity bandwidth decreases when the fused silica spacer thickness is decreased. It can partially arise from the transmittance on logarithmic scale decreased (Sang et al. 2019). Therefore, an effective way of controlling the bandwidth of the reflection band can be obtained by changing the middle spacer thickness. Furthermore, in Fig. 3c, the map $R(\lambda)$ drawn wavelength versus spacer thickness directly illustrates the broadband extended relative to the increasing spacer thickness.

Figure 3d shows the spectra of the wideband reflection as a function of the grating fill factor. The change in grating fill factor shifts the reflection band to a shorter wavelength but has a negligible effect on the reflection band at a longer wavelength.
reflection band at a shorter wavelength produces a red-shift because the effective refractive index of the grating layer from the grating fill factor of the increases (Liu et al. 2010). When grating fill factor increases from 0.62 to 0.64, the bandwidth (R > 90%) decreases from 159.8 nm to 143.5 nm. The physical mechanism of the broadband reflector from the overlapping of the leaky mode resonance of two GMRs shows that, as the fill factor increases, the effective refractive index of the top silicon/air grating and the bottom silicon/ fused silica grating are increased based on Eq. (3), the location of the two GMRs is red-shifted as shown in Fig. 3e, which contributes to the wideband red-shift. Figure 3f provides a reflection map of the wavelength versus fill factor, which shows that the broadband extended with a decreased in fill factor.

Figure 4a shows the angular robustness of the reflector. When the incident angle was increased with a 5° step interval, the high reflectance bandwidth narrows and shifts to a short wavelength with a deeper interceding reflection dip. Particularly, when the incident angle increases to 20°, an obvious reflection dip at ~ 1420 nm arises from a breakdown in the degeneracy of the guided mode resonances (Sang et al. 2009; Han et al. 2020), which reduces the GMRs’ interaction and overlap. Therefore, when the incident angle deviates from normal incidence, the resonances split (Wang et al. 1993), which results in the decrease in reflectivity in the reflection band.

We examine the tolerance of the broadband spectra to a variation in incident angle, θ at 1550 nm is quantified in Fig. 4b. A high reflectivity (R > 99%) broadband exists from −11° to 11°, which means that the variation in incident angle within this range has an almost negligible effect on the reflection spectra in the wavelength range of interest, which is useful in the application of the device. These large angular tolerances at a central wavelength of 1550 nm occur mainly because of the blend of the two GMRs (Huang et al. 2016), which can be assembled in resonant cavity enhanced photodetector as the reflector. Moreover, the comparison of the proposed reflector with the previously reported reflectors is shown in Table 1. The results show that the proposed structure achieves better reflector performance with less layers and low cost.
Conclusions

We demonstrated a broadband reflector based on double-layer subwavelength gratings with an identical period and fill factor, which exhibited a reflection spectrum (above 144 nm) and centered at 1550 nm with a high reflectance (R > 97.8%) and a good angular insensitivity (~ 11°) at 1550 nm. The physical mechanism can be explained by the interactions of two GMRs. The tolerance analysis implied that the demonstrated reflector had a reasonably good fabrication tolerance. The broadband reflector with a high reflectance has potential application and the double-layer resonance structure increases in degrees of design freedom, which facilitates monolithic integration of optoelectronic devices for a wide range of wavelengths.

Declarations

Conflict of interest The authors declare no conflicts of interest.

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