Excellent polarization-independent reflector based on guided mode resonance effect*

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A broad band polarization-independent reflector working in the telecommunication C+L band is proposed using the guided mode resonance effect of a periodic surface relief element deposited by a layer of silicon medium. It is shown that this structure can provide high reflection ($R > 99.5\%$) and wide angular bandwidth ($\theta \approx 20^\circ$, $R > 98\%$) for both TE and TM polarizations over a wide spectrum band 1.5 μm∼1.6 μm. Furthermore, it is found by rigorous coupled wave analysis that the polarization-independent reflector proposed here is tolerant of a deviation of grating thickness, which makes it very easy to fabricate in experiments.

Keywords: polarization-independent reflector, guided mode resonance, rigorous coupled wave analysis

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1. Introduction

Highly reflective broad band reflectors (BBRs) are very important elements that are widely used in numerous fields including lasers,[1] detectors,[2] telecommunications[3], and couplers.[4] Metal and dielectric reflectors[5,6] are the most commonly used BBRs in practical applications. A traditional BBR is designed and fabricated in the normal and oblique angle condition with thin film technology. Although a wide reflection band can be obtained with a metal reflector, the peak reflection is largely determined by the absorption loss of metal, which greatly limits the use of these devices in high power laser systems. Dielectric reflectors consisting of stacks of homogenous layers with high and low refractive indices can achieve higher reflection in a relatively wide bandwidth, but it is not easy to precisely control the refractive indices and thickness of material in the deposition process. In addition, problems such as cohesion, stability and thermal expansion mismatches are commonly existent since different material constitutions are involved in the fabrication of such structures.[7]

New types of subwavelength elements based on the guided mode resonance effect of dielectric grating exhibit various spectral properties, with which Ding and Mugnusson[8] presented a broad band reflector with four subpart profile gratings. Owing to the inherent polarization sensitivity, the performance of the above reflector largely depends on the light polarization, which greatly hinders its application in telecommunication systems. In order to overcome the above disadvantage, Wu *et al.* proposed a multilayered configuration grating structure with multiple subpart profiles, in order to obtain a good performance reflector with a broad band spectrum.[9] Unfortunately, structures that consist of grating with multiple subpart profiles are very hard to fabricate in experiments.

In this paper, based on the physical mechanism of guided mode grating (GMR), we introduce a new structure that consists of single layer grating with homogenous silicon layer deposited on the grating ridge and groove. By using the global optimization technique and the rigorously coupled wave analysis (RCWA) method,[10−13] an excellent wide band polarization-independent reflector operating in the telecommunication spectrum band is designed. Moreover, calculations with RCWA show that the reflector

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proposed here is tolerant of deviations of structural parameters, which makes it very easy to be fabricated with current IC technology.

2. Numerical analysis and simulation

The structure proposed here consists of a single layered grating with a silicon medium deposited on the ridge and groove of the grating, as illustrated in Fig. 1. The incident and substrate media are assumed to be air ($n_{\rm inc} = 1$) and silica ($n_{\rm sub} = 1.48$), the material of the grating ridge is HfO_2 with a refractive index 2.2. The homogenous layer on the top of the grating ridge and groove is silicon (Si) with a refractive index 3.48. The structure is illuminated from the top side at a normal incident angle and only zero-order reflection is considered in our design. For simplicity, the material of the device is assumed to be lossless and dispersion free.

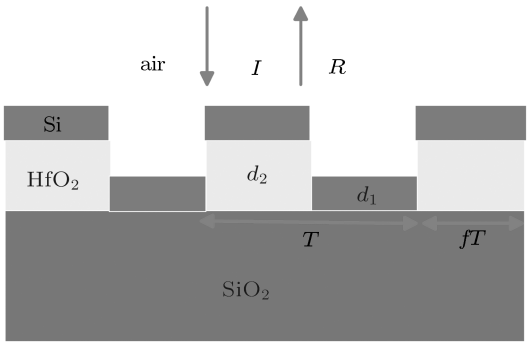


Fig. 1. Schematic diagram of the single-layer guided mode grating structure. T and f are period and fill ratio respectively, d_1 and d_2 represent the depth of silicon layer and grating thickness, respectively. I and R denote the incidence and reflection of light respectively.

In order to design a polarization-independent high reflector over the spectrum band 1.5 μm∼1.6 μm, the RCWA associated with particle swarm optimization (PSO) is adopted to calculate and optimize this device. PSO is a robust and evolutionary strategy used in the optimization design of guided mode resonance grating by Ding and Mugnusson.[8] The most distinctive advantage of this method lies in its powerful global searching ability in handling different multiple parameters design problems. As for our structure, the refractive indexes of the substrate incident layer, grating ridge and homogenous layer are fixed as constants and optimized in our calculation. The period (T), depth of the silicon layer (d_1), grating thickness (d_2), and the fill ratio (f) are chosen as the optimizing parameters. The well-known method RCWA is used to calculate the diffraction efficiency (DE) of this structure over a wide range of spectrum band with the optimized parameters.

The PSO algorithm is employed for the optimization design of the polarization-independent device in our paper. The merit function (MF) $f_{\rm MF}$ is taken to be an rms error function

$$f_{\rm MF} = \left\{ \frac{1}{M} \sum_{\lambda_i} \left[R_{\rm desired}(\lambda) - R_{\rm design}(\lambda) \right]^2 \right\}^{1/2}, \quad (1)$$

where $R_{\rm desired}(\lambda)$ is the desired reflection of zero order in the corresponding wavelength range for the TE and TM polarizations, $R_{\rm design}(\lambda)$ is its designed counterpart by PSO. M is the number of wavelength points. RCWA is used to calculate the DE. All parameters included in this design are arrayed as (T, d_1, d_2, f). The minimum and maximum values of each parameter are set as (200, 10, 10, 0.2) and (2000, 2000, 2000, 0.8), respectively. The units of the first three parameters are nanometers. The optimized wavelength range is from 1500 nm to 1600 nm, and the interval between wavelengths is 2 nm, which means $M = 50$ in Eq. (1). The structural parameters after 2000 iterations is (760, 396, 1471, 0.5), and the design process takes about 60 min with a common PC.

Figure 2 shows the reflection spectra of the reflector for both TE and TM polarizations, as can be seen that the reflections over spectrum band 1.5 μm∼1.6 μm are more than 99.5% for both TE and TM polarizations. Meanwhile, the reflections for TM polarization light are slightly higher than those for TM polarization over the whole wavelength band.

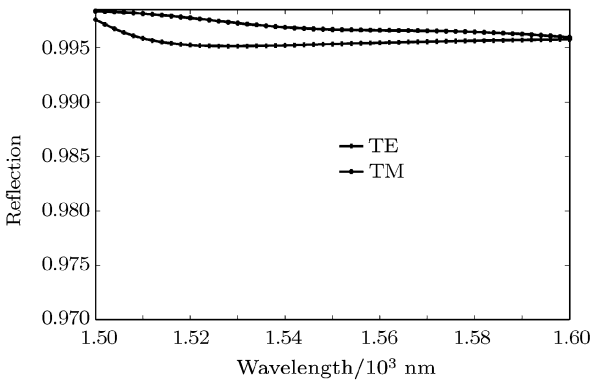


Fig. 2. Reflection spectra of a reflector illuminated at normal incidence for both TE and TM polarizations over spectrum band of 1.5 μm∼1.6 μm. The parameters are denoted as $d_1 = 396$ nm, $d_2 = 1471$ nm, $T = 760$ nm, $f = 0.5$.

According to the guided mode resonance effect of subwavelength grating, the side band of resonant dips can be distinctively lifted up when the strong modulation

guided modes are excited with the high refractive index, such as silicon. Therefore, an extraordinarily wide spectrum band with high reflection can be obtained with this kind of structure.

Figure 3 illustrates the angular spectrum response of the reflector at a wavelength of 1.55 μm for both TE and TM polarizations. For TE polarization, over 98% reflection can be obtained at incident angles ranging from −10° to 10°. For TM polarization, the reflection can achieve over 99% in the corresponding angular range. Compared with the traditional guided mode resonance grating, the incident angle for acquiring a high DE is remarkably larger, which is mainly due to the co-existence and interaction of guided modes.

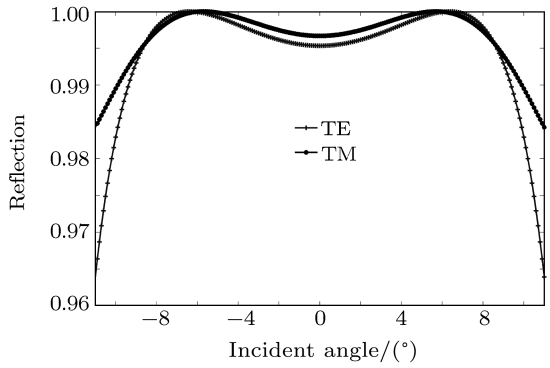


Fig. 3. Angular responses of reflector at wavelength of 1.55 μm for both TE and TM polarizations. Parameters are the same as those in Fig. 2.

The relations between the groove thickness and bandwidth with high reflection for TE and TM polarizations are illustrated in Figs. 4(a) and 4(b), respectively. It can be seen that the reflection is kept above a very high value ($R > 93\%$) over the whole wavelength band even though the groove thickness is increased from 1100 nm to 2000 nm for TE polarization. For the TM polarization, the reflection is still kept over a very high value ($R > 91\%$) in the corresponding wavelength band and grating thickness. The difference between the reflection spectra is that there is a relatively slight modification of spectrum band for TM polarization as compared with that of TE polarization when we vary the grating thickness. In general, there is an extraordinary large fabrication tolerance for grating fabrication no matter whether shallow or deep etching is made. Therefore, excellent polarization-independent reflector can be obtained in the telecommunication wavelength band with the parameters given in our design.

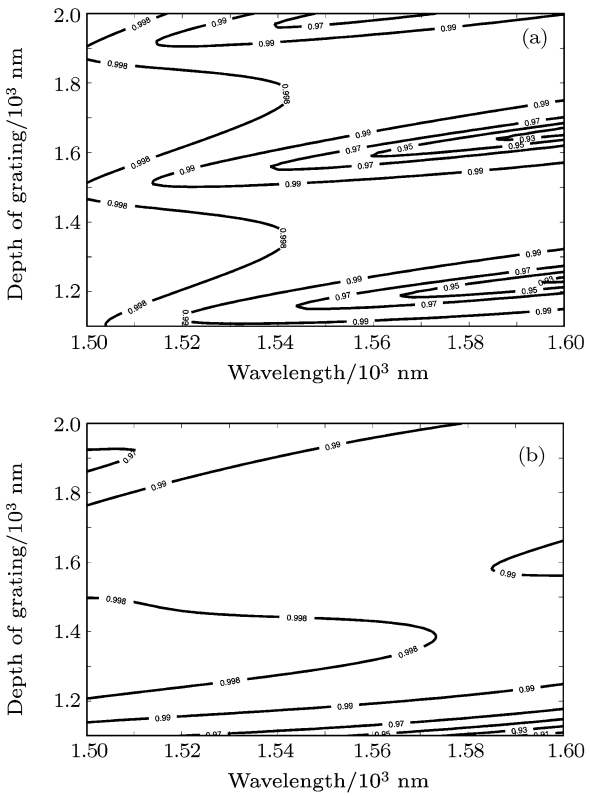


Fig. 4. (a) Diffraction efficiency of the reflector as a function of groove depth and incident wavelength for TE polarization. (b) Diffraction efficiency of the reflector as a function of grating depth and incident wavelength for TM polarization. Other parameters are the same as those in Fig. 2.

Figures 5 (a) and 5 (b) illustrate the diffraction efficiency of the reflector as a function of fill ratio and incident wavelength for TE and TM polarizations, respectively. In general, the variations of the fill ratio play a very minor role in the performance of the grating in the corresponding wavelength range. The DE of the reflector can remain at very high values (above 98%) if the fill ratio is changed from 0.4 to 0.6 (amount to ±20% deviation from the design value).

In addition, we have examined the spectrum responses of the reflector under the variation of the depth of silicon layer. As can be seen from Figs. 6(a) and 6 (b) that the changes in the thickness of silicon layer can shift the spectra slightly for both TE and TM polarizations. Meanwhile, the reflection can be over 99% in the wavelength band if the depth of the silicon layer is in the range between 350 nm and 410 nm for TE polarization, while, for the TM polarization, if the thickness in the range between 340 nm and 410 nm, the reflection can be over 99% in the corresponding wavelength band. In general, a relatively high reflection band can be easily obtained if we make shallow evaporation of the silicon layer on the grating.

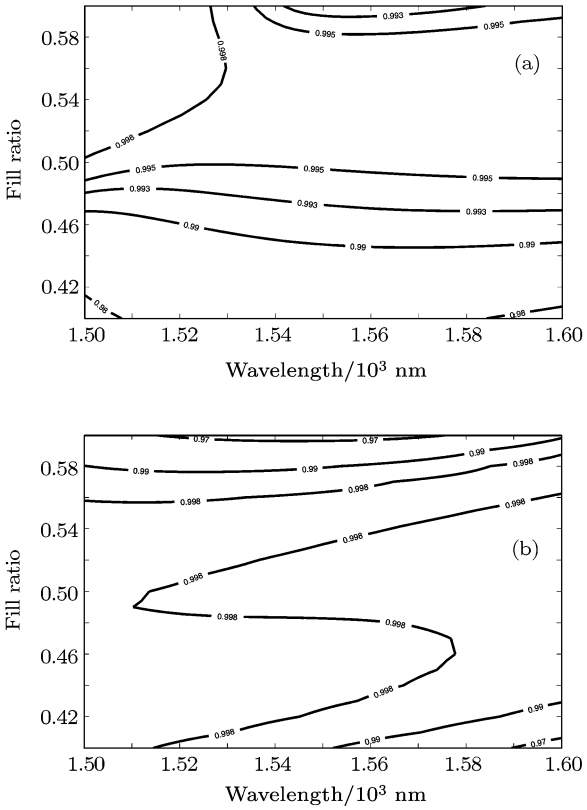


Fig. 5. (a) Diffraction efficiency of the reflector as a function of fill ratio and incident wavelength for TE polarization. (b) Diffraction efficiency of the reflector as a function of fill ratio and incident wavelength for TM polarization. Other parameters are the same as those in Fig. 2.

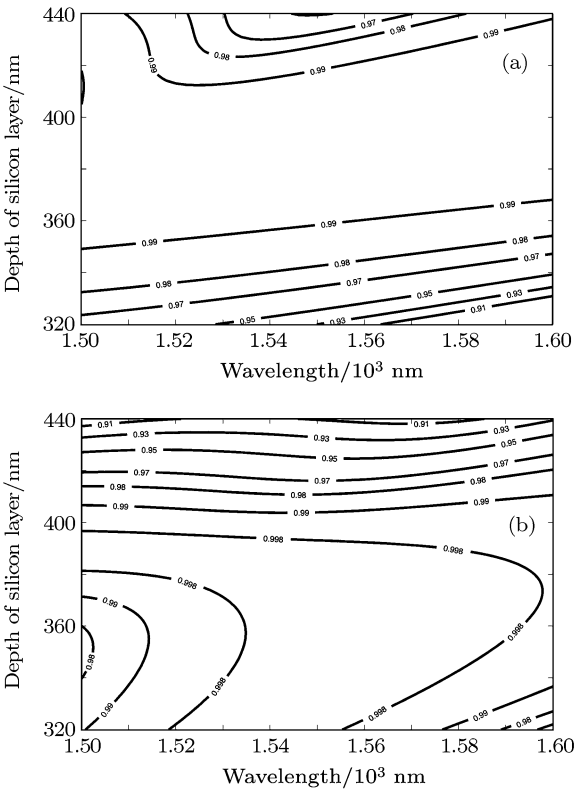


Fig. 6. (a) Diffraction efficiency of the reflector as a function of depth of silicon layer and incident wavelength for TE polarization. (b) Diffraction efficiency of the reflector as a function of depth of silicon layer and incident wavelength for TE polarization. Other parameters are the same as those in Fig. 2.

In conclusion, an excellent polarization-independent reflector over the telecommunication wavelength band is designed using the optimization technique of PSO and RCWA. The reflector given here is based on a very simple structure as compared with other designs. In addition, it demonstrates that the reflector proposed here can offer high reflection, large angular bandwidth as well as large tolerance for fabrication in the spectrum band 1.5 μm∼1.6 μm, which makes it very easy to be fabricated by means of current IC technology.

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