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A silicon-based wideband multisubpart profile grating reflector

L. Huang [a,b], D. Liang [a,*], J. Zeng [a,*], Y. Xiao [b], H. Wu [c], W. Xiao [c]

[a] *State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[b] *School of Information Engineering, Nanchang Hangkong University, Nanchang 330063, China*
[c] *Key Laboratory of Nondestructive Test (Ministry of Education), School of Measuring and Optical Engineering, Nanchang Hangkong University, Nanchang 330063, China*

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ABSTRACT

In this paper, a multilayer configuration high-performance reflector utilizing a multisubpart profile grating structure is presented. Rigorous coupled-wave analysis (RCWA) for multilayered grating is adopted to design and optimize the structure. And experimental verification of theoretical design is accomplished. It is shown that, for transverse magnetic (TM) polarization, over a broadband spectrum from 1.65 to 1.72 μm, the reflector experimentally demonstrates combined merits of high reflectivity (> 97%) and good angular insensitivity of about 24.6°. Moreover, it is found by RCWA that the reflector proposed here has a reasonably good tolerance of fabrication error, which provides a favorable advantage in the fabrication process.

1. Introduction

Efficiently reflect light across wide spectra is essential for numerous optical devices such as polarizing beam splitter [1], vertical cavity surface emitting laser (VCSEL) [2] and wideband flattop bandstop filter [3]. Most of the devices require that the reflectors should present high reflectivity, broad wavelength range, wide angular bandwidth, and compact size. Recently, a new kind of wideband reflector based on the phenomenon of leaky mode resonance (LMR) in dielectric gratings [4], has received considerable attention. Theoretical analysis shows that, at resonance, nearly 100% reflection can be attained in the zero order reflectance spectra [5]. Based on the grating related reflectors' simple structures and superior properties of high reflectivity, Wu [6], Tanzina and Magnusson [7] had presented a wideband reflector realized by a single layer subwavelength grating. To emphasize the unique characteristics introduced by multi-subpart profiles, Ding and Magnusson theoretically presented that versatile optical functionalities, such as broadband reflection, can be implemented by using a grating profile with a four-subpart period [8]. On the other hand, owing to the advantages of high refractive index contrast between the silicon core and oxide cladding and the compatibility with the complementary metal–oxide–semiconductor (CMOS) fabrication technology [9,10], silicon nanophotonic devices are now being regarded as promising candidates for low cost high density integration. In this study, with the combined merits of high index contrast and resonant gratings, a silicon-based wideband reflector utilizing a multilayer-based grating structure with multi-subpart profile operating in the telecommunication band is proposed and demonstrated. It is shown that in TM (magnetic field vector parallel to the grating lines) polarized wave the proposed reflector can experimentally offer combined merits of high reflectivity over a wideband spectrum and good angular bandwidth.

2. Structure design and results

The multisubpart profile grating reflector has a multilayer configuration with a six subpart grating etched onto the top silicon layer, as shown in Fig. 1. The structure is normally illuminated by a monochromatic plane wave and is highly reflecting in the zeroth order. In this study, for simplicity, it is assumed that the reflector is transversely infinite and that the dielectric materials are lossless and dispersion free. Rigorous coupled-wave analysis (RCWA) for multilayered grating structures [11–13] associated with particle swarm optimization (PSO) method is adopted to design and optimize the structure. The PSO is a robust and readily implemented strategy presented in the optimization design of leaky mode resonance gratings by Shokooh-Saremi and Magnusson [14]. As for the structure, the parameters to be optimized are grating transition points (x_1, x_2, x_3, x_4, x_5), thickness (t_g), period (Λ), and thickness of middle layer (t_m). The angle of incidence (θ is measured with respect to the grating normal), thickness of silica (t_b), and refractive index of each constituent material are set to proper values for the design. The optimized parameters are: $x_1/x_2/x_3/x_4/x_5 = 0.37/0.5/0.58/0.8/0.9$ μm,

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[*] Corresponding author.
E-mail addresses: liangdk@nuaa.edu.cn (D. Liang), zj2007@nuaa.edu.cn (J. Zeng).

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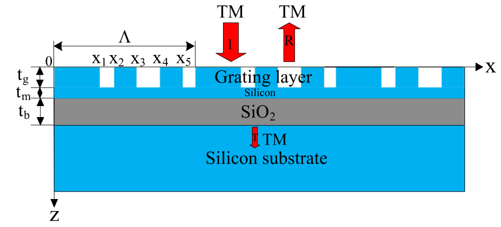

Fig. 1. A schematic view of a multilayer-based reflector under normal incidence. A multilayer grating structure with grating period Λ, thickness t_g, transition points x_1–x_5, thickness of middle layer t_m and buffer layer t_b is treated. I, R, and T denote the incident wave, reflectance, and transmittance, respectively. The incidence medium is air, and the substrate is silicon.

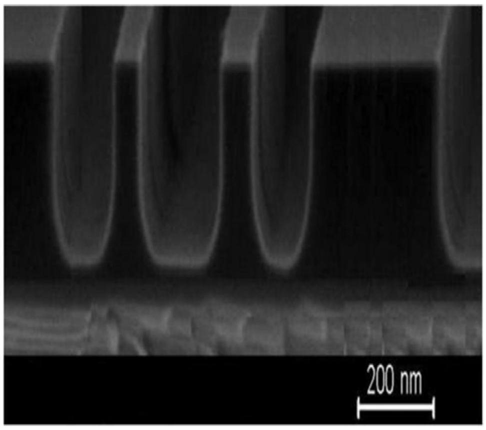

Fig. 2. SEM image of a fabricated reflector.

$\Lambda=1$ μm, $\theta=0°$, $t_g=0.64$ μm, $t_m=0.04$ μm, $t_b=1$ μm.

The current IC fabrication technology supports a cost-effective and precise fabrication for the device. This multilayer-based reflector also facilitates monolithic integration of silicon-based photonic and electronic components at a wide range of wavelengths [15,16]. Fig. 2 shows a scanning electron microscope (SEM) picture of a fabricated reflector. As presented, the grating profile closely resembles the designed one. Experimental verification of theoretical design is carried out by measuring the reflectance spectra and angular response of the reflector.

Fig. 3(a) shows the theoretical and experimental reflectance spectra of the reflector for TM polarization. From the figure, reflectance $R>0.99$ at a broad wavelength range from 1.62 to 1.76 μm is obtained theoretically, while the reflector experimentally presents high reflectivity ($R>97\%$) at the range of 1.65–1.72 μm. To clearly illustrate the high reflectance and large bandwidth of the reflector, we plot the transmittance on logarithmic scales. As displayed in Fig. 3(b), there are two transmittance dips in the range of 1.6–1.8 μm, each of which corresponds to a leaky mode resonance [7,17]. This shows that the broad reflection band results from co-existence and interaction of the TM leaky modes.

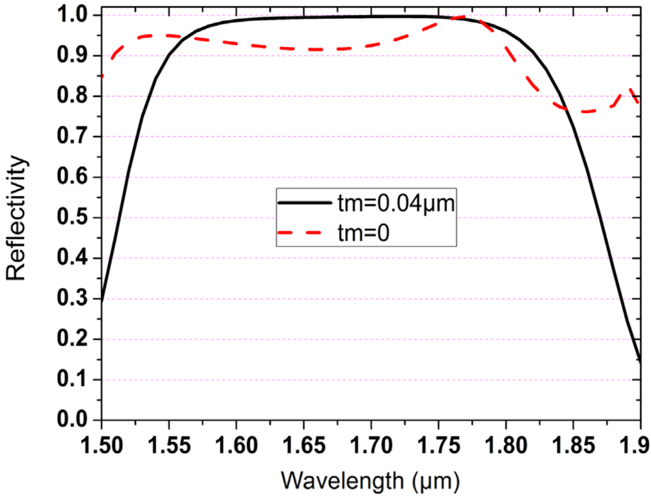

Fig. 4. Reflectivity spectra of the reflector with ($t_m=0.04$ μm) and without ($t_m=0$) the middle layer.

Furthermore, the co-existence and interaction of leaky modes are associated with the high refractive index difference among materials and profile modulation of the top grating layer. The high-index-contrast grating layer can expand resonances and eventually lead to the formation of broadband reflectance spectra [4]. Moreover, the multi-subpart profile of the top grating layer can work to remove the leaky modes degeneracy of the grating and permit interaction of the resulting leaky modes [8], which opens the possibility of a flat reflection band. Also, the high-index middle layer and grating together function simultaneously as the waveguide, which can strengthen the mode confinements and provide a broad line width [18]. As shown in Fig. 4, a 40 nm thick middle layer can improve the properties of high reflectivity.

We also theoretically and experimentally examine the angular response of the reflector at the wavelength of 1.68 μm, as shown in Fig. 5. As displayed, the theoretical prediction is that the reflectivity can be over 0.99 for incident angle at the range of −14.8° to 14.8°, and experimentally obtain high reflectivity ($R>97\%$) from −12.2° to 12.4°. These remarkable large angular tolerances are mainly due to the co-existence and interaction of leaky modes [17]. Generally, LMR-based devices with a single resonant peak usually have small angular apertures due to their inherent rapid variation intensity with respect to the incident angle [19], while

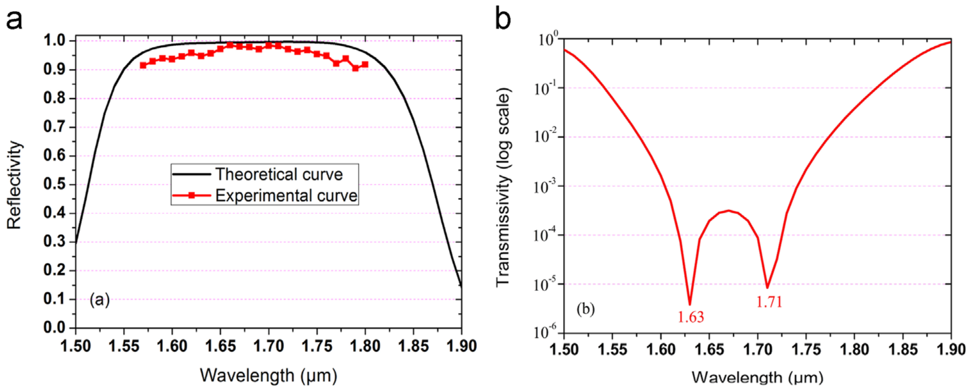

Fig. 3. Reflectance and transmittance spectra of the reflector normally illuminated by TM polarized wave. (a) Theoretical and experimental reflectivity spectra response. (b) Transmittance on log scales. The resonance wavelengths are 1.63 and 1.71 μm, respectively.