A Multilayer-Based High-Performance Multisubpart Profile Grating Reflector
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Abstract—In this letter, a multilayer-based high-performance subwavelength multisubpart profile grating reflector (MPGR) is proposed and fabricated. The properties of the reflector are investigated by rigorous coupled-wave analysis for multilayered grating structures. It is shown that with the properly configured profile and strongly modulated grating layer in transverse-electric polarized wave, the MPGR experimentally demonstrates a broadband reflection spectrum from 1.56 to 1.8 μm, very high reflectivity (>97%), and good angular insensitivity of about 27.8°.

Index Terms—Diffraction and grating, guided-mode resonance (GMR), reflector.

I. INTRODUCTION

As a powerful tool for variable reflection and wavelength selection, broadband reflectors with high reflectivity are essential for numerous optical devices such as absorbers [1], couplers [2], lasers [3], [4], and light-matter interfaces [5]. Traditionally, broadband reflectors are realized by both metallic reflectors and dielectric ones. Metal reflectors with larger reflection bandwidths are low in reflectivity because of the absorption loss. Reflectivity dielectric mirrors are generally composed of multilayer films, which are difficult to achieve high reflectivity by deposition methods [6]. Recently, an alternative approach, based on the phenomenon of guided-mode resonance (GMR) in dielectric gratings [7], has attracted increasing interest. Theoretical analysis shows that at resonance a maximum (100%) in the zero order reflectance (R0) spectra [8] can be attained. Based on the principle, Nie et al. [9] had reported the broadband reflectors realized by multilayered grating structures. Using a subwavelength grating with a low-index cladding layer on a silicon substrate, Mateus et al. [6], [10] and Lu et al. [11] had designed and fabricated flattop reflectors that demonstrated very high reflectivity and very broad reflection spectrum. To emphasize the unique characteristics introduced by multisubpart 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 [12]. In this letter, according to the concept, we propose a multilayer configuration reflector, which experimentally demonstrates combined merits of ultrabroadband reflection spectrum, very high reflectivity, and low sensitivity to incident angle. This unique property opens up a variety of applications in nanophotonic integration.

II. STRUCTURE DESIGN AND RESULTS

The multisubpart profile grating reflector (MPGR) has a multilayer configuration with a six subpart surface-relief grating etched onto the top silicon layer, as shown in Fig. 1. The structure is normally illuminated by a monochromatic plane wave and then highly reflected in the zeroth-order. In this letter, rigorous coupled-wave analysis (RCWA) for multilayered grating structures [13]–[15] associated with the particle swarm optimization (PSO) method [16] is adopted to design and optimize the structure. The PSO strategy is a global, readily implemented optimization technique that can handle different optimization problems. As for the MPGR, the parameters to be optimized are grating transition points (x1,x2,x3,x4,x5), thickness (tG), period (T), and thickness of middle layer (tm). The angle of incidence (θ), thickness of silica (tS), and refractive index of each constituent material are set to proper values for the design. And transverse-electric (TE) electric field parallel to the grating grooves polarization is treated in the design. The optimized results are: x1/x2/x3/x4/x5 = 0.37/0.5/0.58/0.8/0.9, T = 1 μm, θ = 0°, tG = 0.64 μm, tm = 0.04 μm, tS = 1 μm.

In this letter, for simplicity, it is assumed that the reflector is transversely infinite and that the dielectric materials are lossless and dispersion free.

The current IC fabrication technology supports a cost-effective and precise fabrication for the MPGR. This multi-
layer-based reflector also facilitates monolithic integration of silicon-based photonic and electronic components at a wide range of wavelengths [11], [17]. To fabricate the MPGR, a silicon dioxide layer and a polysilicon layer were sequentially deposited on bare silicon surface by low-pressure chemical vapor deposition (LPCVD). Then, the pattern of intended grating profile is defined in positive photoresist (ZEP520) by electron beam lithography and following an inductive-coupled plasma (ICP) dry etching process is used to transfer the defined pattern to the poly-silicon. Finally, the MPGR is completed after the removal of residual photoresist. Fig. 2 shows a scanning electron microscope (SEM) picture of a fabricated MPGR. The grating profile closely resembles the designed one. The lateral size of the fabricated grating region is over square of 0.5 mm.

The optical measurement setup is shown in Fig. 3. An unpolarized broadband light source covering the wavelength range from 1 to 2 μm is used. The light output from the single-mode fiber is collimated by an objective lens, and then polarized by a polarizer as TE mode, finally focused onto the sample by a focusing lens (NA = 0.35). The reflected light from the MPGR is collimated again, directed by the beam splitter and coupled into a single-mode fiber connected to an optical spectrum analyzer (OSA). A silver-coated mirror (rated ≥ 98.5% reflectivity from 1.1 to 20 μm) is used as a reference, and the absolute reflectivity of the MPGR is deduced from the silver-coated mirror reflectivity.

Fig. 4 shows the theoretical and experimental reflectivity spectra of the MPGR for TE polarization. From the figure, we can see that $R_0 > 0.99$ for a broad wavelength range from 1.54 to 1.84 μm is obtained theoretically, while $R_0 > 0.97$ from 1.56 to 1.8 μm is achieved experimentally. To clearly illustrate the high reflectance and large bandwidth of the MPGR, we plot the transmissivity on logarithmic scales. As displayed in Fig. 5, there are two transmittance dips inside the high-reflectance band, each of which corresponds to a GMR [18]. This shows that the broad reflection band results from coexistence and interaction of the TE guided modes.

Furthermore, the coexistence and interaction of guided modes are associated with the high refractive index difference among materials and the properly configured top grating profile. The high-index-contrast grating layer can expand resonances and eventually lead to the formation of broadband reflectance spectra [18]. Moreover, the multisubpart profile of the top grating layer can work to remove the guided modes degeneracy of the grating and permit interaction of the resulting guided modes, which opens the possibility of a flat reflection band [12]. Also, the high-index middle layer and grating together function simultaneously as the waveguide, which can increase the mode confinements, therefore providing a broad linewidth [19].

Fig. 6 displays the theoretical and experimental angular response of the MPGR at the wavelength of 1.68 μm. As presented, the theoretical result reveals an over 0.99 reflectivity for incident angle at the range of $-16^\circ < \theta < +16^\circ$. The experimental result demonstrates that about 0.97 reflectivity can be
achieved at the range of $-13.8^\circ < \theta < +14^\circ$. These remarkable large angular tolerances are mainly due to the coexistence and interaction of guided modes [18]. Generally, GMR-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 [20], while the coexistence and interaction of guided modes resulting from the high-index-contrast materials and modulation profile of grating can provide broadband reflection with high reflectivity at wide angular bandwidth, and it is not surprising to see that the structure has a wide angular aperture at the wavelength of 1.68 $\mu$m.

There are several factors that may lead to performance degradation of the reflector. First, the surface of the grating wafer is not so smooth, which would induce scattering and absorption of the incident light. Second, the small variations in effective refraction index of materials may also have influence on the diffraction efficiency. Third, as presented in Fig. 2, the fabricated MPGR is somewhat different from the designed one, which can deteriorate the performance of the device. As displayed, the actual profile of the grating slightly resembles a trapezoid after etching, which may result in changes in modulation profile to deteriorate the reflection performance. Variations in period and grating thickness, along with the thickness of middle and buffer layer, are other factors for the performance degradation. These variations can be improved by careful management in the fabrication processing. Taking all the above factors into consideration, from Figs. 4 and 6, we can see that a strong agreement between simulated and experimental results is achieved.

III. CONCLUSION

In summary, we have proposed and actually fabricated a multilayer-based high-performance subwavelength MPGR, which possesses ultrabroadband reflection spectrum, high reflectivity, and large angular bandwidth. This combined merit mainly results from the properly configured multisubpart profile and strongly modulated grating layer in the device structure. The MPGRs can be potentially used in the areas of tunable devices, vertical-cavity surface-emitting lasers (VCSELs), broadband flattop bandstop filters, and so on.

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