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High reflectivity broadband infrared mirrors with all dielectric subwavelength gratings

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ABSTRACT

A high reflectivity (> 99%) subwavelength grating mirror (SWGM), yields a very broad reflection spectrum (1.3–2.1 μm), has been designed for parallel polarized (*p*-polarized) incident light and evaluated by rigorous electromagnetic simulations. Design-sensitive analysis was made by varying one parameter at one time while keeping the other constant. The operating region of the grating mirror can be adjusted by varying the parameters of grating. The results show that the broadband reflection is unaffected by the refractive index and the thickness of the low index material, which is different from the previous conclusions. Because of its ease of fabrication, the mirror can be integrated with any photonic component with a flat surface, which has potential applications for active and passive photonic devices.

1. Introduction

High reflection broadband mirrors (BBMs) have a wide range of applications in optoelectronics, including laser cavities, sensors, imaging, and other tunable optical devices [1,2]. Traditionally, BBMs can be realized by both highly conductive metallic mirrors and dielectric Bragg mirrors. Metallic mirrors have very wide reflection bands, but due to the high absorption loss, most metal mirrors cannot achieve reflectivity larger than 99%. They are also not suitable for mirrors which require transmission applications. The distributed Bragg reflector (DBR), which consists of multiple layers of alternating dielectric materials with periodic variation of refractive indices, has been widely used as high reflectance mirrors in most surface emitting lasers. However, due to the relatively small available index contrast in a lattice matching system, a large number of DBR pairs is required which makes such mirrors difficult to be integrated [3].

A grating with a period smaller than the wavelength is called a subwavelength grating (SWG) [4–7]. If light is incident normal onto a subwavelength grating surface, only the zeroth order diffraction exists as a propagation mode, all the higher diffraction orders are evanescent modes, thus the grating will basically serve as a simple mirror [8–10]. SWGs have been used as cavity mirrors in vertical cavity light-emitting diodes. Recently, the fully dielectric SWGs based on guided-mode resonance (GMR) have been designed to replace thick DBR mirrors [11,12]. The main idea of a GMR mirror is to create standing waves in a periodic waveguide layer. The resonances arise when a normally incident wave is coupled with the leaky waveguide modes supported by the slab. The leaky standing waves interact with the waveguide grating and reradiate back the incident wave [13]. The main challenge with pushing the operation regime of GMR mirrors into the IR range is in finding suitable material systems.

In this paper, we report theoretical calculations of a novel design of a SWG that yields a very broad reflection spectrum (1.3–2.1 μm) with very high reflectivity (> 99%). The design requires a single layer of high index material sandwiched in between low index materials. Rigorous coupled wave analysis (RCWA) method is used for rigorous electromagnetic computations to evaluate the performance of the designed SWGs. The results show that the broadband reflection seems unaffected by the refractive index and the thickness of the low index material, which is different from the previous conclusion that the extraordinarily broadband and the high reflectivity from the high contrast gratings (HCGs) are the results of the unique arrangement of high-index gratings that are completely surrounded by low-index media [14,15].

2. Calculation model and results

Fig. 1 shows a schematic of such subwavelength HCG mirror. The HCG structure consists of a single layer of periodic grating structure with a highly refractive index material that is surrounded by two low index layers. The design parameters for the structure include the index of refraction of high-index material (n_h) and low-index material (n_l), grating thickness (h), thickness of low index layer (d), grating period (Λ), and ratio of the grating width to Λ (fill factor f).

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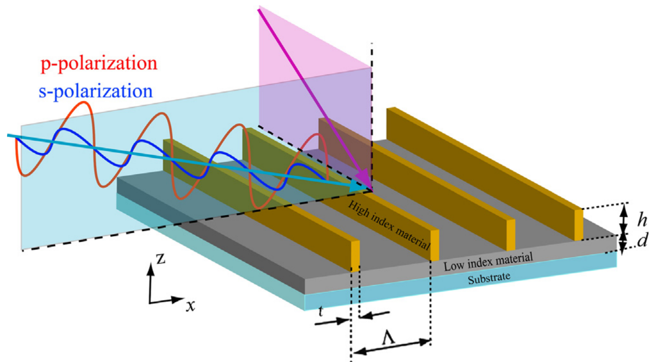

Fig. 1. Scheme of the SWG reflector combined with two layers to achieve high reflectivity. The low index material under the grating is essential for the broad-band mirror effect.

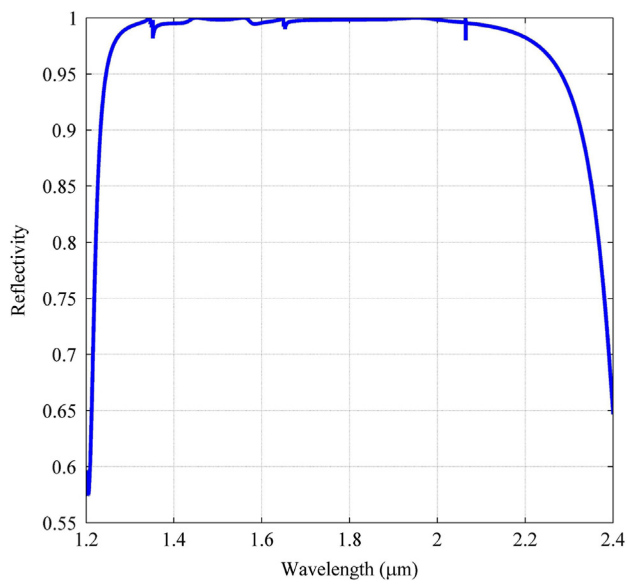

Fig. 2. Calculated reflectivity spectrum of HCG for *p*-polarized light with normal incidence.

We started from the calculated reflectivity spectrum for a *p*-polarized incident light (with field components E_x, E_z and H_y) from surface normal direction. The parameters used in the simulation were: Si substrate ($n=3.48$), $\Lambda=700$ nm, $n_h=3.5$, low index material in and above the grating (air), $n_L=1.47$ (SiO_2), $h=400$ nm, $d=200$ nm, and $f=0.7$. The result was shown in Fig. 2, a very broadband mirror $\Delta\lambda/\lambda>45\%$ with $R>0.99$ was obtained around 1.7 μm over the range 1.3–2.1 μm.

In this section, we will study how the HCG reflectivity spectrum varies when we change the parameters of the grating. We will show design-sensitive analysis by varying one parameter at one time while keeping the others constant.

The grating period determines the location of the center wavelength of the reflection band, and this effect is shown in Fig. 3(a). The band shifts to longer wavelengths proportionally to Λ, and for $\Lambda=660$ nm, the band is the broadest. The period can be controlled very accurately by lithographic methods, and thus, the reflection band can be precisely fabricated. Fig. 3(b) shows the effect of fill factor. In this study, we fix HCG parameters as $\Lambda=660$ nm and $d=200$ nm and scan the fill factor from 0.1 to 0.99. Broadband is achieved for a duty cycle of 0.7. The reflection band is still broad outside this range but with slightly smaller reflectivity. Given the grating is one dimensional, the broad-band mirror effect is obtained only for *p*-polarized light. This can be advantageous to control the polarization on a VCSEL, e.g., if the grating design is used for the mirrors. If a two-dimensional grating is chosen instead, reflectivity would be polarization independent. The fill factor is the most critical parameter in the fabrication process since small variations during the lithographic exposure, resist development, or dry etching processes can perturb the final geometries significantly. By comparison, the reflectivity of 1-D HCGs is much less sensitive to variations than 2-D structures, and therefore, 1-D structures are more tolerant to fabrication errors [16].

Fig. 4(a) shows the contour plot of reflectivity as a function of the wavelength and n_H for $\Lambda=660$ nm, $f=0.7$, and $n_L=1.47$. The simulations are based on RCWA calculation. The high index material layer in the grating is essential to obtain the high broadband reflection. Keeping all the other parameters the same, the reflection becomes low when $n_H>4$. The low index sensitivity study is shown in Fig. 4(b) for $\Lambda=660$ nm, $f=0.7$, and $n_H=3.45$. The calculated reflectivity spectra as a function of n_L is presented. The structure has low sensitivity to the low index layer, but this parameter can be used to optimize the reflection band.

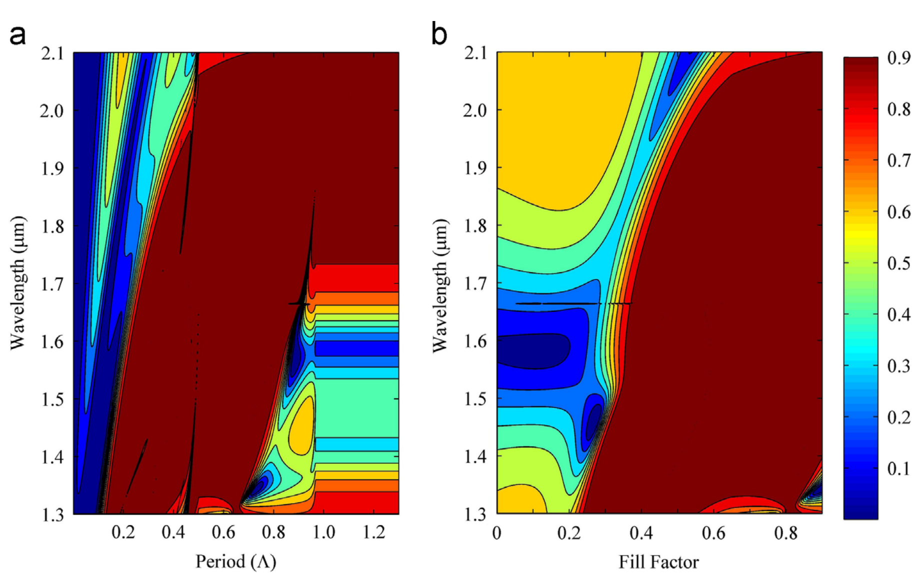

Fig. 3. (a) Calculated contour plot showing reflectivity as function of wavelength and period. The broad-band effect is achieved for a period of 0.46–0.68 μm. (b) Calculated contour plot showing reflectivity as function of wavelength and fill factor.