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Non-periodic high-index contrast gratings reflector with large-angle beam forming ability

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A non-periodic high-index contrast gratings (HCGs) reflector on SOI wafer with large-angle beam forming ability has been proposed and fabricated. The proposed reflector was designed using rigorous coupled-wave analysis (RCWA) and finite-element-method (FEM). A deflection angle of 17.35° and high reflectivity of 92.31% are achieved under transverse magnetic (TM) polarized light in numerical simulation. Experimental results show that the reflected power peaked at 17.2° under a 1550 nm incident light, which is in good accordance with the simulation results. Moreover, the reflected power spectrum was also measured. Under different incident wavelengths around 1550 nm, reflected powers all peaked at 17.2°. The results show that the proposed non-periodic HCGs reflector has a good reflection and beam forming ability in a wavelength range as wide as 40 nm around 1550 nm.

1. Introduction

High-index contrast gratings (HCGs) [1–3] have attracted great attention recently due to its high reflectivity over a broad bandwidth and ability to control the phase shift of the reflected or transmitted light. Owning to its simple and compact structure, HCGs have become a promising alternative to replace conventional reflectors in many optical devices, such as vertical-cavity surface-emitting lasers (VCSELs) [4,5] and reflective enhanced photodetectors [6]. In addition, with different designs, HCGs are suitable for numbers of different applications, including high efficiency transmission and reflection filters [7], optical couplers with the excitation of surface plasmons [8], and polarization-insensitive reflectors [9], etc. Another important property of HCGs is that the phase of the reflected or transmitted light can be manipulated while keeping a high reflectivity or transmittance. This property can be applied to non-periodic HCGs [10–13]. Reference [12] has shown focusing reflectors and lenses obtained by changing the phase of reflected and transmitted light from non-periodic HCGs. Reference [13] has demonstrated that reflectors can be designed by controlling the phase of transmitted light to steer the propagation direction of the transmitted light under vertical incidence condition. However, the deflection angle is small and the transmittance property is not satisfactory. So, it's necessary to study reflectors with high reflectivity and large-angle beam forming ability using non-periodic HCGs. These mirrors will be great promises for integrated optical devices due to their simple fabrication and good beam forming property.

In this paper, we study the fundamental properties of the non-periodic HCGs to design the phase front of reflected light and formulate useful design rules for realizing practical structures. Based on these rules, a non-periodic HCGs reflector with a deflection angle of 17.35° and a high reflectivity of 92.31% is designed and simulated using rigorous coupled-wave analysis (RCWA) [14] and finite-element-method (FEM) [15] at the designed wavelength of 1550 nm. The designed non-periodic HCGs structure can be easily fabricated with a combination process of electron beam (EB) lithography [16] and inductively coupled-plasma (ICP) etching. We experimentally demonstrate that the maximum reflected power is obtained at 17.2° at 1550 nm wavelength, which is in good accordance with the simulated value. Moreover, the reflected power spectrum was also measured. Under different wavelength around 1550 nm, the maximum reflected powers were all obtained at 17.2°. The results show a good reflection and beam forming ability at a range of 40 nm around 1550 nm for proposed non-periodic HCGs reflector.

2. Theoretical background

HCGs are sub-wavelength gratings comprised of high index bars fully surrounded by low index media. In sub-wavelength gratings (SWGs), the first-order diffracted mode does not correspond to freely propagating lights, but to a guided wave trapped in dielectric layers. The trapped wave is scattered into the zeroth diffracted order and interferes with the incident light to create a

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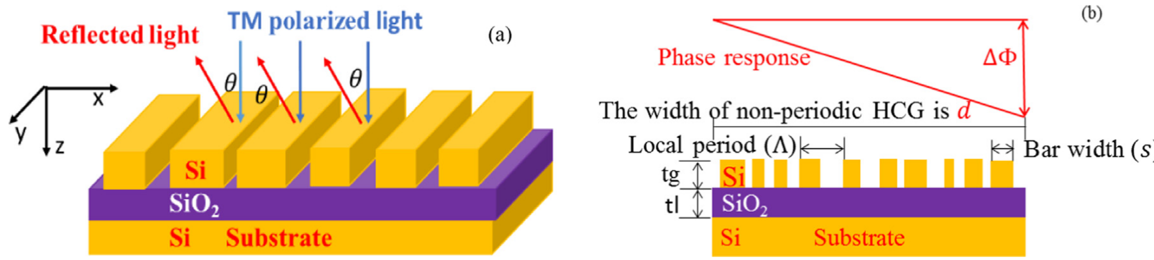

Fig. 1. (a) Schematic diagram of the investigated non-periodic HCGs with linear phase response. (b) Cross-section diagram of the non-periodic HCGs structure.

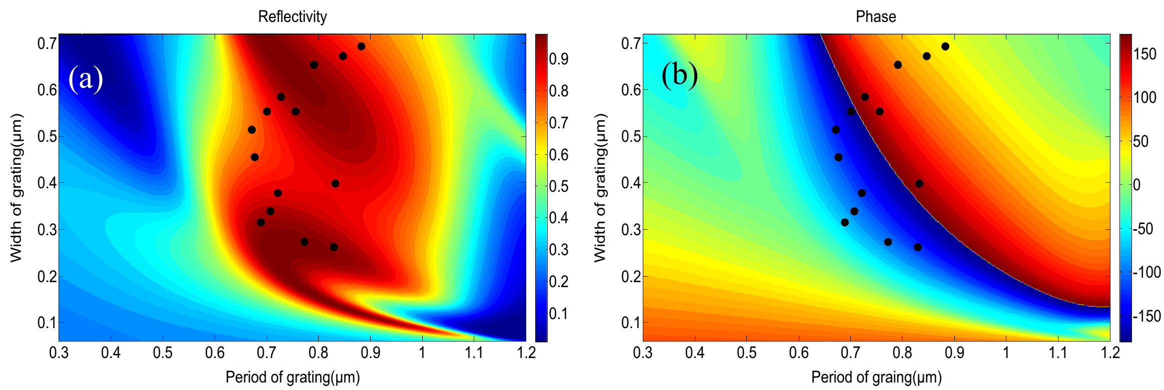

Fig. 2. Contour map of the reflection and phase properties (a) reflectivity and (b) the matching phase shift of periodic HCGs versus grating period (Λ) and bar width (s) for TM-polarized light at 1550 nm wavelength.

pronounced modulation of transmission and reflection. The guided waves in a HCG are rapidly scattered and do not propagate very far laterally. In this case, it is appropriate to think of the grating as a coupled resonator system. High reflection and transmission features can be achieved since the elimination of non-zero diffraction orders increases the coupling efficiency. When a periodic HCG was illuminated by a wave, phase variations will be developed by the varying structural parameters, such as the gratings period (Λ) and bar width (s). The phase is spatially dependent on these grating structural parameters. The beam forming of reflection light can be realized by properly choosing the phase distribution to form a linear phase shift of the reflected light at the reflect plane.

Fig. 1(a) shows the schematic of the investigated non-periodic HCGs. The electric field of the reflected light is a power envelop with the expression of $E(x, z) = E_0(x, z)\exp(jk_0(x \sin\theta + z \sin\theta))$, where $k_0 = 2\pi/\lambda$ is the wave number at the wavelength λ, and θ is the angle between the reflected light wave vector and the negative z-axis. For a fixed z coordinate, the phase of the reflected light can be written as

$$\Phi(x) = k_0 x \sin\theta + c \qquad (1)$$

where c is a constant. Since the phase profile is linear, Eq. (1) can be written as $\Phi(x) = \alpha x$, $\alpha = k_0 \sin\theta$, where α is a proportional factor which depends on the phase difference $\Delta\Phi$ determined by width d of the non-periodic HCGs as shown in Fig. 1(b). The proportional factor is $\alpha = \frac{\Delta\Phi}{d}$, then the deflecting angle θ is obtained by

$$\theta = \arcsin^{-1}\left(\frac{\Delta\Phi}{dk_0}\right) \qquad (2)$$

The deflected angle θ is determined by the designed parameters $\Delta\Phi$, grating width d and wavelength λ. At a certain wavelength and the gratings width, larger deflected angle can be obtained by increasing the total phase shift. Therefore, with the structure size d is determined by the requirements, the only way to achieve a bigger tilting angle is to feature a larger phase difference $\Delta\Phi$.

3. Design and simulations

For design of a non-periodic HCGs with beam forming ability, the most important part is the selection of a set of proper grating period and bar width calculated from Eq. (1) to realize a linear phase profile. The next step is to find out a one–one correspondence between the HCG's reflection and dimensions. In this work, the non-periodic HCGs was designed as a reflector with a deflecting angle of 20°. The structure is implemented on a SOI wafer consisting of a 500 nm silicon layer (t_g) and a 500 nm buried oxide layer (t_l) as depicted in Fig. 1(a). The refractive indexes of Si and buried SiO_2 are 3.47 and 1.47, respectively. For a certain grating layer thickness, the periodic HCGs' reflection properties, as of reflectivity and phase shift, are investigated using RCWA simulation method under TM polarized illumination. In this approach, the structure's periodicity is exploited to solve Maxwell's equations. A linear system of equations is built from the boundary conditions. The system solution yields the field distribution, as well as the reflection characteristics. This result serves as a look-up table to find a set of grating parameters which can provide the targeted phase and reflectivity.

Shown in Fig. 2, the reflectivity and phase shift property of the periodic HCGs are simulated using RCWA method for TM polarization at 1550 nm. The thickness of the grating is kept constant at 500 nm, while the period varies from 0.3 μm to 1.2 μm, and the bar width of grating varies from 0.2 μm to 0.7 μm. Fig. 2(a) shows the reflectivity of periodic HCGs. Fig. 2(b) shows the phase shift of reflected light which cover a full 2π shifting within the high reflectivity region. Realizing a full 2π phase shift in the high reflectivity region is very important due to the need of arbitrary phase front control. According to the look-up tables, a set of useful discrete data, (Λ_n, s_n), corresponding to the maximum reflectivity $R_{max}(\Lambda_n, s_n)$ for phase covering a full 2π shifts, can be chosen to