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Concentric circular focusing reflector realized using high index contrast gratings

Wenjing Fang, Yongqing Huang *, Jiarui Fei, Xiaofeng Duan, Kai Liu, Xiaomin Ren

Institute of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), State Key Laboratory of Information Photonics and Optical Communications, Beijing 100876, China

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ABSTRACT

A non-periodic concentric circular high index contrast grating (CC-HCG) focusing reflector on 500 nm silicon-on-insulator (SOI) platform is fabricated and experimentally demonstrated. The proposed mirror is realized with phase modulation of wave front in a high reflectivity region. The circular structure based HCG focusing reflector has a spot of high concentration at the 10.87 mm with normal incidence for radially polarization, along with the center wavelength set at 1550 nm. The FWHM spot size of the focusing beam decreases to 260 μm, and the intensity increases to 1.26 compared with the incident beam. The focusing efficiency of about 80% is observed at 1550 nm in the experimental measurement.

1. Introduction

High reflectivity mirrors play important roles in numerous applications in waveguides, reflectance-enhance photodetectors [1] and vertical-cavity surface-emitting lasers (VCSELs) [2]. The classic example of these reflectors is distributed Bragg reflectors (DBRs) [3,4] that formed from multiple layers of alternating materials with varying refractive index, which can be enhanced quantum efficiency of photodetector and compensate for a VCSEL's short cavity. However, the higher reflectivity can be achieved by DBRs, the more the number of layers will be needed. This requires a great challenge in the fabrication process. High index contrast grating (HCG) [5,6] used as a reflector is one very appealing answer to address the issue of optoelectronic devices miniaturization [7–9]. These kinds of mirrors can offer high reflectivity or high transmitivity over a broad bandwidth and polarization selectivity due to large refractive index difference and sub-wavelength dimensions. This is an excellent optical property for periodic HCGs, which can be used to design for broadband reflectors [10–13], high-Q resonators [14], filters [15], polarizing beam splitter [16], etc. Since its superior optical properties and compact structure, the HCG used as reflector is an alternative to DBRs.

On the other hand, the HCG structures provide new optical features from a novel approach referred to as wave front control which was originally achieved by rendering one-dimensional grating aperiodic by gradually modifying the local period and duty cycle of the grating [17,18]. The novel characteristics include focusing ability and steering ability with non-periodic patterns by wave front control, which is an important development in the application of HCGs. Recently, several kinds of non-periodic HCGs have been studied, aiming at focusing reflectors high reflectivity, vortex beam and Bessel beam [19–27]. They include non-periodic strip patterns, non-periodic ring patterns and two-dimensional non-periodic block patterns. For the HCGs reflector with non-periodic ring patterns, numerical studies have shown that focusing reflector with high reflectivity is achievable and there has been no experimental study yet.

The proposed non-periodic concentric circular high index contrast gratings (CC-HCGs) is based the one-dimensional HCGs in the design process, the structure is simpler than two-dimensional, but the focusing effect is similar to the two-dimensional focusing structure. They realized that most of the reflected light is focused on a dot in space rather than focused on a line by one-dimensional HCGs. We present design, fabrication, and characterization results of CC-HCGs based on silicon-on-insulator (SOI) platform. A CC-HCGs reflector with a focal length of 15 mm is fabricated and measured. Experimental results show that a spot of highest concentration is obtained at $d = 10.87$ mm in front of the grating, and the full-width half maximum (FWHM) is decreased from the 400 to 260 μm, the intensity increases by a factor of 1.26 compared with the incident beam. The focusing efficiency of approximately 80% is get at the wavelength of 1550 nm.

* Corresponding author.
E-mail address: yqhuang@bupt.edu.cn (Y. Huang).

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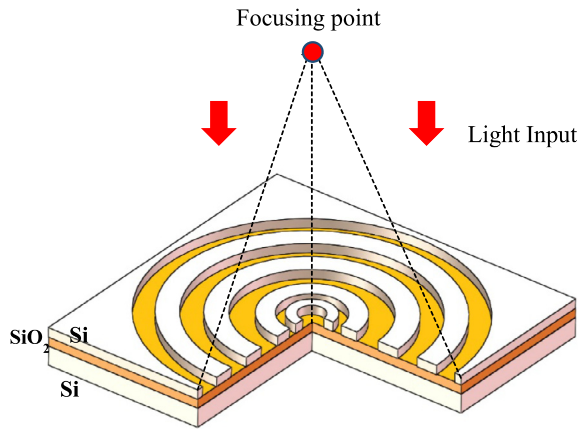

Fig. 1. Schematic representation of the CC-HCG reflector.

2. Design method

The schematic representation of the non-periodic CC-HCG which consists of concentric circles of Si ($n \approx 3.48$) that are surrounded by air ($n \approx 1$) and SiO_2 ($n \approx 1.46$) as the low-index cladding layers on the top and bottom as shown in Fig. 1. The SOI wafer consists of a 500 nm silicon layer and a 500 nm buried oxide layer. There are three physical parameters that control the reflectivity and phase: grating period (Λ), duty cycle (η) grating width (w), and grating thickness (h). Changing schematic representation of the non-periodic CC-HCG which consists of concentric circles of Si ($n \approx 3.48$) that are surrounded by air ($n \approx 1$) and SiO_2 ($n \approx 1.46$) as the low-index cladding layers on the top and bottom as shown in Fig. 1. The SOI wafer consists of a 500 nm silicon layer and a 500 nm buried oxide layer. There are three physical parameters that control the reflectivity and phase: grating period (Λ), grating width (w), and grating thickness (h). Changing the grating thickness is not feasible due to the multiple etching steps it would imply, so only variations of period and width of the grating bar are considered. When the grating period and grating width locally changed, the properties of reflected beam, such as phase and reflectivity, will gradually adapt to this variation. The reflected light will be focused on a spot if the phase shift distribution of the reflected light meets Eq. (1).

$$\Phi(r) = -\frac{2\pi}{\lambda}\left(\sqrt{r^2+f^2}-f\right)+\Phi_0 \tag{1}$$

where f is the focal length, λ is the incident wavelength, and Φ_0 is the phase shift of the reflected light at the position of center.

Our design of the investigated CC-HCG reflector is for a radially polarization at a wavelength of 1550 nm. If we divide the concentric circular grating into a few copies share equally, radially polarization for CC-HCGs is similar to TM polarization for the strip HCGs, its electric field vector is perpendicular to the grating bar direction, as shown in Fig. 2. For the design of CC-HCG reflector, the goal is to find the local period and grating bar that give a particular spatial phase profile along the r direction. The design rulers are also shown in the literature [15]. Firstly, numerical simulations of the periodic strip HCGs based on the rigorous coupled-wave analysis (RCWA) [28,29] are obtained at a wavelength of 1550 nm with TM polarization. Fig. 3 shows reflectivity and phase profile, for a grating thickness h = 500 nm. The next step is to find out optimum structural parameters parameter sets, which can meet the expected parabolic phase profile given by Eq. (1) with a high reflectivity region shown in Fig. 3(a), and the corresponding phase of the reflected light should cover a full 2π range of variation within the high reflectivity region shown in Fig. 3(b). So by carefully selecting grating structure parameters, we can get a focusing reflector where the introducing phase profile adapts to Eq. (1). The literature [17] has proved that the reflected property and phase shift of a concentric circular grating can be obtained from the corresponding periodic strip grating.

The COMSOL implementing finite-element method (FEM) [30] numerical simulation is used to evaluate the focusing performance of the CC-HCG. But a 3D simulation of the real sample would be too computationally costly, according to the design process, we take a CC-HCG structure with a focal length of 12 μm for example. As illustrated in Fig. 4(a), the red line is the ideal phase distribution along r direction for the CC-HCG focusing reflector calculated by Eq. (1), and the blue points are the each designed phase that corresponds to each concentric circular grating unit. The simulation result with radially polarization at a wavelength of 1.55 μm is plotted in Fig. 4(b), and it is obvious that the reflection beam can be focused on a spot of 11.5 μm, this small deviation is caused by discrete phase distribution. The focusing efficiency of 92.1% is obtained by simulation.

The wavelength dependence of the reflectivity of the CC-HCG is presented in Fig. 4(c). The reflectivity of the focused reflected beam in the range of 1530–1580 nm shows higher than 80% by calculation. The results show that the designed grating has a good focusing ability with a high reflectivity at a relatively wide bandwidth.

3. Fabrication

In order to facilitate the measurement of the reflection beam profile, a non-periodic CC-HCG structure with a diameter of 500 μm and a relatively long focal length of 15 mm was fabricated on SOI wafer (500 nm device layer and 500 nm BOX layer). The reflector was patterned with e-beam lithography (EBL) by using diluted ZEP520A as a resist. Then, using the EB resist as a mask, the silicon grooves were formed by inductively coupled-plasma (ICP) etching using C_4F_8 and SF_6. Finally, the residual EB resist was removed with a 1:1 solution of H_2SO_4 and H_2O_2. The gratings were etched 500 nm into the top silicon layer. An optical microscope image of a fabricated CC-HCG reflector is shown in Fig. 5, together with scanning microscope images of the silicon grooves at various locations. The changes in color in the optical microscope picture indicate the changes in the grating period and width due to the phase shift.

4. Measurement and discussion

Focusing properties of the CC-HCG reflector were experimentally studied. The surface of the SOI wafer reflector was illuminated from the patterned side with a collimated 1550 nm laser beam, shown in Fig. 6. The goal of this experiment was to monitor the spatial structure of the beam spot after the light had been reflected through the reflector. An Anritsu Tunics SCL tunable laser with a single-mode fiber pigtail was used as the light source. A fiber collimator connected to the single-mode fiber was used to output beam. The radially polarization converter was used to set polarization state of the input beam to radially polarization. The CC-HCG reflector was illuminated by a transmitted beam though a cube beamsplitter with 50:50 split ratio at normal incidence. When the reflection beam was separated from the incoming beam using the cube beamsplitter again, different beam cross sections of the reflected beam were imaged using a CCD camera. The position of the imaged cross-sections was varied with changing the distance in the front of the grating.

Fig. 7 illustrates the dynamics of the focal spot evolution along the z-axis and presents the distribution of the focal spot at the different position with different distance. Here, the wafer was illuminated by a large beam matching the size of the CC-HCG at normal incidence as shown in Fig. 7(a). The normalized measured intensity profile at the plane of focus for the reflector with the focusing distance of d = 10.87 mm is shown in Fig. 7(d). We can see that the light is focused to a spot of highest concentration at d = 10.87 mm. As plotted in Fig. 7(b)–(f), when increasing the distance in front of the grating, the spot size decreases, and then the spot size increases. It can be seen that the CC-HCG focusing reflector reduces the beam spot size by nearly a factor