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Polarization-independent beam focusing by high-contrast grating reflectors

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ABSTRACT

A kind of high-contrast grating (HCG) reflector for beam focusing has been proposed. We design a planar grating structure with a parabolic surface and numerical simulations using a finite different time domain (FDTD) method to verify that the structure has the capability of focusing both transverse-magnetic (TM) and transverse-electric (TE) polarized lights. Finally, we expand the design structure into a three-dimensional (3D) case. Numerical results demonstrate that the power intensities at the focal point are all greater than 8.5 dB compared with incident intensity, which means the structure has a better focusing effect. Further analysis of incident wavelength sensitivity (1.55, 1.79 and 2 μm) reveals that the proposed structure has a wide range of working wavelength.

1. Introduction

Beam focusing is currently a hot research topic in the field of nanophotonics, especially the optical integration, such as communication, sensing, imaging, solar cells, and photolithography [1–3]. The focusing structure can be generally divided into two kinds according to different applications: transmission-type and reflection-type. In recent years, especially when people's interest in investigations about surface plasmon polaritons (SPPs)-based photonic devices has been increased, lots of papers about designing transmission-type focusing structures [4–7], such as a single subwavelength metal slit surrounded by chirped surface gratings [8], and so on, have been published. Not much attention has been paid in researches related to reflection-type focusing structure [9,10]. Focusing reflector, like a concave mirror, can create a focal point on the illumination side, which can be widely used in communications, sensing, solar cells and CD/DVD read/write heads.

In this paper, we propose a kind of focusing reflector using high-contrast gratings (HCGs). HCG is a grating structure which comprises high index bars (e.g. Si) surrounded by low index media (e.g. Air) [11]. If the structural parameters of HCG are designed reasonably, due to its good reflection effect within a wide range of wave band, it can be very suitable for designing focusing reflectors [12]. And because of its advantages of small size and high efficiency, compared with the lens structure, it is more appropriate for integrated photonic devices.

Here we design a planar grating structure with a parabolic surface and numerical simulations using a finite different time domain (FDTD) method to verify that the structure behaves as a good focusing reflector. Such focusing phenomena are obvious for both transverse-magnetic (TM) and transverse-electric (TE) polarized lights which means that the structure has a polarization-independent focusing capability. And then we expand the design structure into a three-dimensional (3D) case. Calculations on full width at half-maximum (FWHM) of the focal width and the power intensity at the focal point show that it has a better focusing effect. Furthermore, analysis of incident wavelength sensitivity (1.55, 1.79 and 2 μm) revealed that the proposed structure has a wide range of working wavelength.

2. Theory

As we mentioned above, HCG is a grating structure which comprises high index material fully surrounded by a low index medium, and the high/low index media corresponding to Si/Air, as shown in Fig. 1(a). When the normal incident light illuminates the HCG, multiple modes would get excited , but only the first two modes are the most important. If the parameters of the HCG are designed reasonably, the destructive interference between the two

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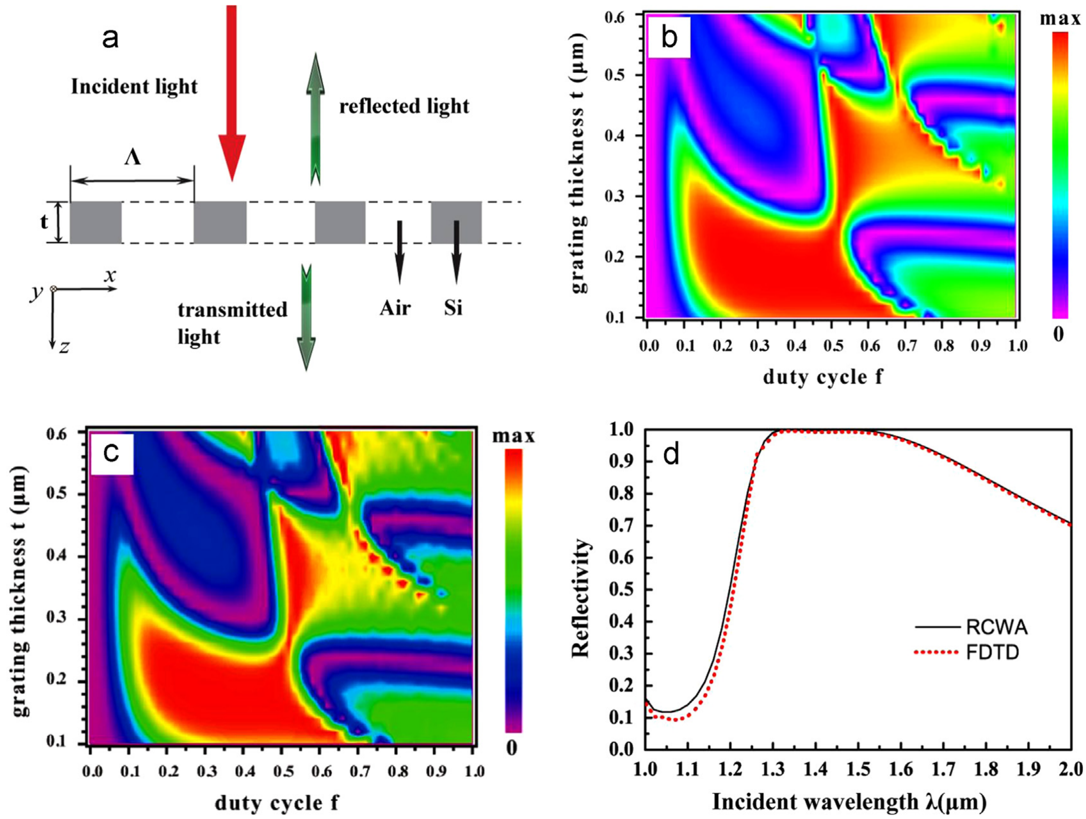

Fig. 1. (a) Schematic of a planar HCG structure. The reflectivity distributions calculated by (b) RCWA and (c) FDTD methods for the grating thickness t from 0.1 μm to 0.6 μm and the duty cycle f from 0 to 1. (d) Results from RCWA/FDTD methods when $\Lambda=1$ μm, $t=0.25$ μm and $f=0.2$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

modes can make the HCG a very high reflective structure [13,14]. So if we fix the period Λ of HCG, the complex reflectivity of the grating structure can be changed by two parameters: the duty cycle f (defined as the ratio of the bar width to the period) and the spacing grating thickness t.

For most of the related designs, the calculation results are almost based on either FDTD or rigorous coupled wave analysis (RCWA) [15] method. Here we design a planar HCG structure (as shown in Fig. 1(a)), and calculate the reflectivity using both methods. Fig. 1(b) and (c) shows the effect of grating thickness t and duty cycle f on reflectivity when we fix $\Lambda=1$ μm, they respectively represent the simulation results by RCWA and FDTD methods. The red/purple parts respectively represent the areas of high/low reflectivities. By comparing the two pictures, we can find that the reflectivity distributions are almost the same corresponding to the two kinds of algorithms. Then we choose $t=0.25$ μm and $f=0.2$ as the parameters of the planar HCG structure. Results from RCWA/FDTD methods are shown in Fig. 1(d). It is observed that the reflectivity is greater than 90% in a wide incident wavelength range from 1.3 μm to 1.6 μm. Moreover, the two results are in good agreement.

Here we not only proved that the structure can have a wide reflection bandwidth by adjusting the parameters reasonably, but also illustrated that the results from the two algorithms are consistent (in this paper, the main algorithm used for designing is the FDTD method).

3. Design, results and discussion

3.1. Two-dimensional focusing reflector

According to the discussion in the above section, if we adjust the structural parameters reasonably, we can obtain a high reflection effect. And as we know about geometrical optics, if a beam of parallel rays is incident upon a reflector whose surface shape is a parabola, the radiation will converge on a spot which is called the focal point [16]. Combining these two points, we proposed a scheme of a planar HCG focusing reflector at an incident wavelength of 1.55 μm as shown in Fig. 2(a). Here, the geometrical shape of the outer surface is expressed as

$$z=\sqrt{4L^2-4Lx} \tag{1}$$

where L is the focal length and the origin of coordinates is the location of focus. We set the shortest thickness of HCG to be 0.3 μm, so the longest is about 1.7 μm. During the design, the period of HCG Λ is fixed at 1 μm, and then we can obtain the best focusing effect when the duty cycle f is 0.6 by optimization. The field distributions are calculated using the FDTD method with perfect matching layer (PML) absorbing boundary conditions. As shown in Fig. 2(b) and (c), the focusing phenomena are obvious for both TE and TM -polarized lights. The focal lengths are 10.57 μm and 9.34 μm, respectively. And the power intensity at the focal point is almost the same as the incident light. Over the focal plane, FWHMs at each focal length are 1.17λ for both TE and TM -polarized lights, which means that the focusing performance of the proposed focusing reflector is consistent with the diffraction limit. So the structure has a polarization-independent focusing capability.

3.2. Three-dimensional focusing reflector

Based on the above discussion about the focusing effect of the two-dimensional (2D) structure, we expand the design structure in the 3D case as shown in Fig. 3(a). The 3D structure is made up of nested hollow cylinders. The cross section σ at $y=0$ of the