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Focus modulation of cylindrical vector beams through negative-index grating lenses

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ABSTRACT

A cylindrically symmetric negative-index grating lens composed of unitary material is proposed as an effective method to modulate the focusing of cylindrical vector beams (CVBs). The grating parameters are designed to obtain an appropriate negative index, and the lens profile is tailored to realize the constructive interference. The plano-concave lens is parameterized to achieve desired focal length and the plano-cone lens is proposed to obtain large depth of focus. An optical needle is generated with radially polarized incidence, and an optical tube is achieved with incidence of azimuthal polarization. Moreover, the presented modulation methods can be applied for any arbitrary polarized CVBs. This work offers a more flexible and effective approach to design negative-index lenses for subwavelength focusing of CVBs, which has potential application value in related areas, such as optical trapping, and other nano-optics fields.

1. Introduction

Subwavelength focusing of cylindrical vector beams (CVBs) exhibits specific characteristics and has widespread applications owing to the unique distribution of intensity and polarization [1]. Researchers have proposed various methods to realize and modulate the focusing of CVBs [2–5]. However, traditional lenses can hardly achieve tighter focusing, and this limits the flexibility of focus modulation [6]. There are many other modulation methods involved in the subwavelength photonic domain [7–9]. Plasmonic lenses can focus radially polarized beams to the subwavelength scale, and the structure is compact with high integration [7,10–13]. However, the plasmonic lens is not suitable when different polarized components need to be focused because the polarization condition of the excitation of surface plasmon polaritons is usually not valid for all polarization states of CVBs [14]. Subwavelength focusing of all polarized components of CVBs has been achieved using cylindrically symmetric structured 1D photonic crystal (PC) lenses [14,15], owing to negative refraction, which is effective for both TE and TM polarization. However, the lenses are composed of two or more kinds of material so that they are not easy to design and fabricate.

Fortunately, subwavelength gratings offer a reliable way of achieving negative refraction for both TE and TM polarizations. If the period of such gratings is appropriately chosen, the negative refraction effect will occur [16,17]. For a concave lens with a negative refraction index, tight focusing is achievable.

Here, we propose a new cylindrically symmetric grating lens concept that can effectively realize subwavelength focusing of CVBs. The physical mechanism and the design principle are thoroughly illuminated. The grating lens can be composed of unitary material, and therefore, it is easy to fabricate. As the negative refraction of the grating lens is effective for orthogonal polarizations, the focal field can be modulated by manipulating the incident polarization components. More importantly, specific focusing effects can be achieved by tailoring the emergent surface of the grating lens.

2. Effective refraction negative index of grating lens

The negative index of the grating lens originates from the -1 order diffraction of the grating, and it has been used in focusing plane waves in various frequency bands [16,17]. As shown in Fig. 1 (a), for a grating composed of material with refraction index n and period d, the effective index n_{eff} of -1 order diffraction is expressed as

$$n_{\mathrm{eff}} = n - \lambda/(d \sin \theta_{\mathrm{i}}). \qquad (1)$$

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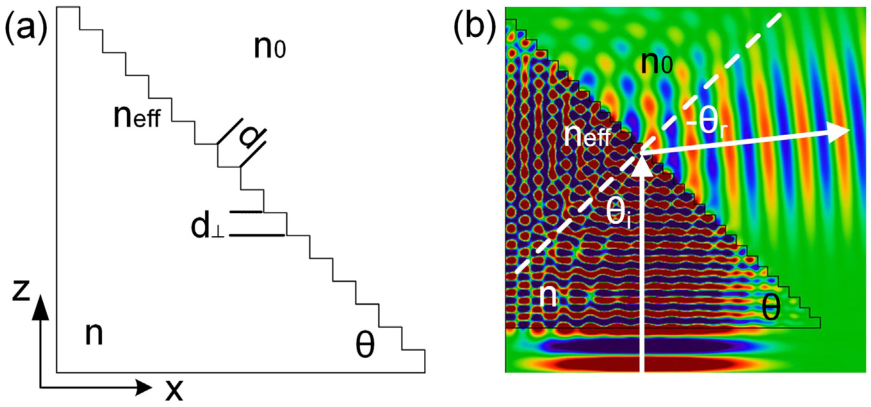

Fig. 1. (a) Schematic diagram of grism. (b) Negative refraction effect of grism.

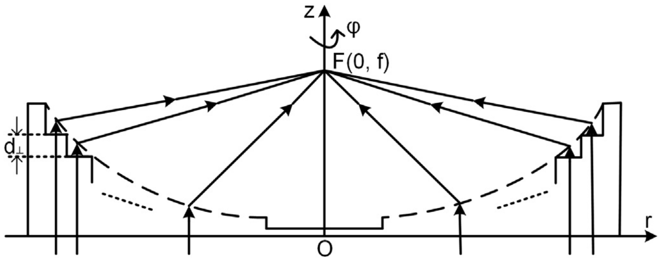

Fig. 2. Cross-section of the plano-concave grating lens in the *r–z* plane.

Here, θ_i represents the incident angle at the exit surface of the incidence from the grating side and λ is the wavelength of the incidence.

To effectively design the negative-index grating lens, it is necessary to choose the parameters properly. First, the wavelength should satisfy the relationship $\lambda > d \sin\theta_i$, in order to get $n_{eff} < 0$. Second, according to Snell's law of refraction $n_{eff} \sin\theta_i = n_0 \sin\theta_r$, here n_0 is the refractive index of the vacuum. Obviously, when $|n_{eff}| \sin\theta_i \le (n_0 \sin\theta_r)_{max} = 1$, total reflection can be avoided for any incident angle, i.e., it is required that $|n_{eff}| \le 1$. In this paper, the range of $-1 \le n_{eff} < 0$ is discussed. Thus, the wavelength of incidence is restricted to the range $d \sin\theta_i < \lambda < d(1 + n \sin\theta_i)$. More importantly, within this range, only the -1 order diffractive wave can radiate from the exit surface. For the incident direction parallel to the *z*-axis, it is convenient to define $d \sin\theta_i = d \sin\theta = d_\perp$, where θ is the angle between the grating surface and the *x*-axis, and $d_\perp$ is the vertical dimension of the grating period along the *z*-axis. Thus, n_{eff} is deduced to be $n_{eff} = n - \lambda/d_\perp$, and the values of n and $\lambda/d_\perp$ should be properly set.

To verify Eq. (1), consider an isosceles right triangular grating prism (grism) as depicted in Fig. 1(a). The parameters are $d_\perp = 150$nm, $n = 2.67$ (GaN), and $\lambda = 532$nm, which satisfy the conditions mentioned above. The negative refraction effect under TE polarization is simulated using a finite element method (FEM), and the result is shown in Fig. 1(b). According to Eq. (1), the effective refraction index of the grism is -0.88. Thus, the refraction angle is 38.48° as calculated by Snell's law, which is in good agreement with the simulated result of 38.7°. Moreover, the negative index of the grism purely composed of isotropic material is invariable with different polarization states.

The negative-index grating lens has been utilized to focus plane waves using a plano-concave structure [16]. In this kind of structure, the exit surface can be seen as a series of slopes with different tilted angles. In this condition, the effective refraction index of each slope is crucially decided by $d_\perp$. In order to get an ideal focal spot, a fixed negative index is expected, which corresponds to the same $d_\perp$ for every slope. For CVBs, it is rational to design an axisymmetric lens. The shape of the exit surface and the index of the material are two critical factors that determine the phase condition of the constructive interference. When parameters of the grating are fixed, the negative index is a constant, and thus, the focal field is determined by tailoring the shape of the lens.

3. Tightly focused field of CVBs

A focal spot with a specific focal length can be realized by tailoring a plano-concave grating lens. Considering the *r–z* plane of the tailored plano-concave grating lens, which is a cylindrically symmetric structure, as the cross-section of the lens depicted in Fig. 2, the focal spot can be regarded as the intersection point of all emergent rays. For emergent light, the interface between incident and refracted light is tailored by gratings with the same vertical dimension $d_\perp$. By connecting the adjacent tips of each grating on the exit surface, an equivalent profile of the exit surface is obtained. To achieve constructive interference, based on Fermat's principle, the relationship between the exit surface and the focal length f in the *r–z* plane is given by the following equation:

$$n_0^2 r^2 + (n_0^2 - n_{eff}^2) z^2 - 2 n_0 f (1 - n_{eff}) z = 0, \tag{2}$$

where r and z are the coordinates of the aplanatic refracting surface. The curve of the coordinates is obtained from Eq. (2).

If a plano-concave grating lens with $d_\perp = 150$nm, $n_{eff} = -0.88$, and focal length $f = 5$ µm is required, Eq. (2) is deduced to $r^2 + 0.2256 z^2 - 18.8 z = 0$. By substituting $z_1 = d_\perp = 150$ nm into the curve equation, the value of r_1 is obtained, and (r_1, z_1) is the coordinate of the lowest tip. The set of coordinates of each tip is calculated by substituting $z_2 = 2 \cdot d_\perp$, $z_3 = 3 \cdot d_\perp$. Based on these coordinates of each grating tip and the vertical dimension $d_\perp$, the profile of the grating is designed. By rotating the profile of the grating 360°, the cylindrically symmetric plano-concave grating composed of unitary material is obtained. The focusing of radial polarization incidence is shown in Fig. 3(a). The focal field, especially for radially polarized beams, tends to be much brighter due to the cylindrically symmetric intensity and polarization distribution of the incident beams [17]. The simulated result shows a focal length of $f = 4.94$ µm as depicted in Fig. 3(b). The FWHM of the focal field is 240 nm (0.45λ).

For comparison, a series of plano-concave lenses is designed to realize focal lengths of 6 µm, 7 µm, 8 µm, and 9 µm under incidence of radially polarized beams. Fig. 3(b) exhibits the focal field distribution in the longitudinal direction along the *z*-axis, and the simulated focal lengths are 6.02 µm, 7.02 µm, 7.99 µm, and 8.95 µm, within 2% absolute error. Therefore, subwavelength gratings composed of unitary material can achieve tight focusing