Physics Letters A 379 (2015) 3008–3012

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Design and analyses of an ultra-thin flat lens for wave front shaping in the visible

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 1 August 2015
Accepted 2 August 2015
Available online 21 August 2015
Communicated by R. Wu

Keywords:
Moment method
Focal plane
Nanoantenna
Phase discontinuities
Snell's law

ABSTRACT

An ultra-thin flat lens is proposed for focusing circularly polarized light in the visible range. Anisotropic C-shaped nanoantennas with phase discontinuities are used to form the metasurface of the lens. The phase response of the C-shaped nanoantennas can be manipulated by simply rotating the angle of the unit nanoantenna. A 600 nm incident circularly polarized light is focused by the proposed techniques. Good agreements are observed by using our MoM and a commercial FDTD software package. The computation time spent by using MoM is approximately 10–100 times smaller than using FDTD. All the results show the proposed nanoantenna array has a great potential for nanoscale optical microscopy, solar cell energy conversion enhancement, as well as integrated optical circuits.

1. Introduction

Differently from the gradual phase changes along the optical path in traditional bulk lenses, prisms and gratings, nanoantenna-based metasurfaces can create abrupt phase shifts in the wavelength scale [1]. The greatest benefit of using this technique is in making highly customizable and scalable lenses with large aperture and short focal length [1]. The potential applications are numerous, for example, embedded light-on-a-chip system [2], super-resolution imaging [3], nanolithography [4] and broadband chromatic optical systems [5]. Recently, different topologies of the non-uniform metamaterial units have been investigated, such as V-shaped anisotropic dipoles [1–4,6], phase-conjugated dipole rod [6] and variant widths (or depths) nano-slits [7]. Additionally, traditional log-periodic antennas have been redesigned in nanoscale to obtain broadband resonance in terahertz incident levels [8].

An alternative topology proposed here is a C-shaped nanoantenna [9] for focusing the light in the visible range. C-shaped nanoantennas have several advantages in phase manipulation over other nanoantenna topologies. The phase discontinuity manipulation of the C-shaped nanoantenna can simply be implemented by rotating the angle of the body which improves the cross-polarization ratio by using this geometry. A 2-D phased array of the C-shaped nanoantennas are designed and numerically analyzed in this study.

To customize the parameters such as the focal length, beam width and phase distribution of the C-shaped nanoantenna based metasurfaces, numerical simulations such as finite-difference time-domain (FDTD) and moment method (MoM) are conducted to provide guidance for the future nano-fabrication. Due to the increasing scale of the nanoantenna array, the simulation usually takes a couple of days or even several weeks using FDTD [10]. The MoM particularly designed for the proposed nanoantenna array in this study effectively shortens the simulation time without losing significant resolution. Anomalous refraction and focus properties are investigated by our MoM and FDTD in both time and frequency domain. Results show good agreements between our MoM and a FDTD software package.

2. Materials and methods

Fig. 1 shows the nanoantenna array designed in this study. A C-shaped nanoantenna is used as the unit cell for the array. The C-shaped nanoantenna with a rotation angle of θ is shown in Fig. 1. The rotation angle θ is the angle between the localized optical axis of the unit C-shaped nanoantenna and the horizontal axis in the clockwise direction (Fig. 2(b)). The dimension of the nanoantenna is designed as $\lambda = 2.21a$, $b = 0.6a$, $c = 0.2a$ [9]. Wavelength

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http://dx.doi.org/10.1016/j.physleta.2015.08.022
0375-9601/

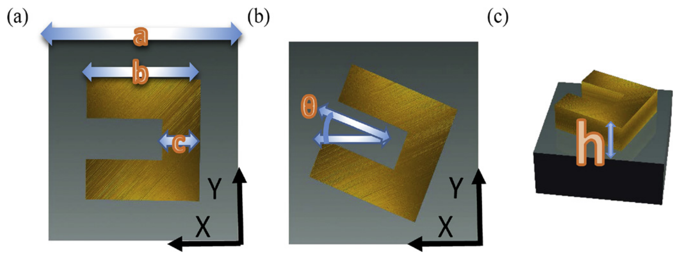

Fig. 1. The geometric parameters of the unit C-shaped nanoantenna. ‘a’ is the width of the unit cell. ‘b’, ‘c’ and ‘h’ are the length, width and height of each nanoantenna. ‘θ’ is the rotation angle of the C-shaped nanoantenna.

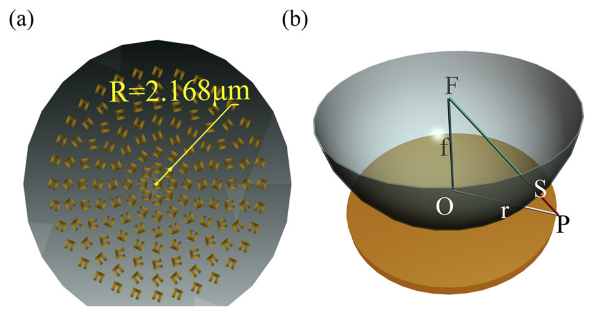

Fig. 2. (a) The schematic of the two-dimensional circular array. (b) The parabolic phase profile of the scattering light. ‘P’ is a point on the metasurface. ‘S’ is the projection of point ‘P’ onto the parabolic surface. ‘O’ is the center of the circular lens. The length of PS is proportional to the length of PO.

λ is 600 nm. $a = 271$ nm, $b = 163$ nm, $c = 54$ nm. The incident light is left circularly polarized.

The relationship between the phase profile of the nanoantennas Φ and its location center coordinate x is shown in Eq. (1) [9,11,12]:

$$n_t \sin\alpha_t - n_i \sin\alpha_i = \frac{\lambda}{2\pi}\frac{d\Phi}{dx} \tag{1}$$

where n_t is the refractive index of the medium where the light is leaving, n_i is the refractive index of the medium where the light is entering. α_t and α_i are the angle between the corresponding light and the normal to the medium interface. If $\alpha_t = 0$ and substituting $\Phi = 2\theta = 2k\pi x = \frac{2k_g\pi}{a}x$ into Eq. (2), the angle of refraction for the scattering cross-polarized beam is obtained as:

$$\alpha_t = \arcsin\left(-\frac{\lambda}{2\pi}\times\frac{d\Phi}{dx}\right) = \arcsin(-2.21k_g) \tag{2}$$

where k_g is the gradient of the phase variation. Then we get:

$$\Phi(x) = 2\theta = 2k\pi x = -\frac{2\pi\sin(\alpha_t)}{2.21a} \tag{3}$$

In order to provide a parabolic wave front, the phase shift in every unit is described by Eq. (4) [9,13]. In Eq. (4), f_d is the given focal length, λ is wavelength, x and y is the coordination of the nanoantenna unit. Φ is the phase shift in every unit nanoantenna. The phase profile is plotted in Fig. 2(b). With fixed focus length f_d and incident wavelength λ, the scattering phase is distributed concentrically along the radius of the plate:

$$\Phi(x, y) = \frac{2\pi f_d}{\lambda} - \frac{2\pi\sqrt{f_d^2 + x^2 + y^2}}{\lambda} \tag{4}$$

The lens is divided into ‘m’ annular areas concentrically. The nanoantenna units in each annular area have the same geometry, orientation angle and phase shifts to the incident light [14]. For a given focus length f_d, the coordinate and the phase shift φ of each unit must satisfy Eq. (5) [14]:

$$\begin{cases} x_{i,j} = i\times a\times\cos\left(\frac{2\pi}{n}\times j\right) \\ y_{i,j} = i\times a\times\cos\left(\frac{2\pi}{n}\times j\right) \\ \varphi_{i,j} = \frac{2\pi f_d}{\lambda} - \frac{2\pi\sqrt{f_d^2 + (i\times a)^2}}{\lambda} \end{cases} \tag{5}$$

$i = 0, \ldots, m$, $j = 1, \ldots, n$, where ‘i’ means the i-th annulus ($i = 0$ corresponds to the center nanoantenna). ‘j’ means the j-th nanoantenna in the i-th annulus. ‘a’ is the width of every annulus. Fig. 2(a) shows the schematic of the 2-D circularly arranged lens.

The MoM uses the triangular-type “rooftop” vector basis functions to represent the surface-induced current. The PDE tools of MATLAB were used to create the triangle meshes. In the MoM, surface-induced current must be solved by linear equations (Eq. (6)) [15], where V is the voltage matrix, Z is the impedance matrix, and I is the unknown current matrix:

$$V = Z\cdot I \tag{6}$$

The voltage elements V_m and the impedance elements Z_{mn} are given by Eq. (7) and Eq. (8):

$$V_m = l_m\left(E_m^+\cdot\frac{\rho_m^{c+}}{2} + E_m^-\cdot\frac{\rho_m^{c-}}{2}\right) \tag{7}$$

$$Z_{mn} = l_m j\omega\left(A_{mn}^+\cdot\frac{\rho_m^{c+}}{2} + A_{mn}^-\cdot\frac{\rho_m^{c-}}{2} + \Phi_{mn}^- - \Phi_{mn}^+\right) \tag{8}$$

where

$$A_{mn}^{\pm} = \frac{\mu}{4\pi}\int_S \boldsymbol{f_n}(\mathbf{r}')\frac{e^{-jkR_m^{\pm}}}{R_m^{\pm}}dS' \tag{9}$$

$$\Phi_{mn}^{\pm} = -\frac{1}{4\pi j\omega\varepsilon}\int_S \nabla_s'\cdot\boldsymbol{f_n}(\mathbf{r}')\frac{e^{-jkR_m^{\pm}}}{R_m^{\pm}}dS' \tag{10}$$

$$\boldsymbol{E_m^{\pm}} = \boldsymbol{E^i}(\boldsymbol{r_m^{c\pm}}) \tag{11}$$

$$R_m^{\pm} = \left|\boldsymbol{r_m^{c\pm}} - \mathbf{r}'\right| \tag{12}$$

$\boldsymbol{f_n}(\mathbf{r})$ is the basis function for MoM, $R_m^{\pm}$ represents the distance from any point $\boldsymbol{r}$ to the midpoint of edge $\boldsymbol{m}$. $\boldsymbol{E^i}(\boldsymbol{r_m^{c\pm}})$ represents the incident electric field at a point $\boldsymbol{r_m^{c\pm}}$:

$$\boldsymbol{f_n}(\mathbf{r}) = \begin{cases} \frac{l_n}{2A_n^+}\rho_n^+, & \mathbf{r} \text{ in } T_n^+ \\ \frac{l_n}{2A_n^-}\rho_n^-, & \mathbf{r} \text{ in } T_n^- \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

l_n is the length of the edge of the triangle pair $T_n^{\pm}$. $A_n^{\pm}$ is the area of the triangle pair $T_n^{\pm}$.

The results obtained from our MoM are completed to a FDTD solution software package (FDTD Solutions, Lumerical Solutions Inc., Vancouver, Canada). ‘Total field scattering field source’ was used as the incident light. FDTD is a direct solution of Maxwell’s time dependent curl equations. FDTD uses central-difference to approximate the space and time derivatives to avoid solving huge matrices for frequency-domain integral-equations and requires no calculation of structure-dependent Green functions [16]. The FDTD simulation dimension in this study is 4.2 μm in the X direction, 0.4 μm in the Y direction and 0.2 μm in the Z direction. A Perfectly matched layer absorbing boundary condition, containing 64 layers, is adopted in all directions. The condition of convergence is less than 10^{-5}. The mesh length in X and Y directions are set as 5 nm. Length in the Z direction is varying.