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Rigorous electromagnetic analysis of dual-closed-surface microlens arrays

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Abstract

In this paper, we investigated the focal performance of the dual-closed-surface microlens arrays (DCSMAs) based on rigorous electromagnetic theory and boundary element method (BEM) in the case of TE polarization. The DCSMAs are designed with different substrate thickness and different distance between microlenses. DCSMAs designed according to different wavelengths are surveyed. The DCSMAs with different incident angles are also studied. Several focusing performance measures, such as the focal spot size, the focal position on the preset focal plane, the diffraction efficiency and the normalized transmitted power, are presented. Numerical results indicate the DCSMAs with different parameters can implement focusing beams and the focal performance of DCSMAs is easily influenced by the substrate thickness and the incident wavelength. Furthermore, the optimal thickness for the maximal diffraction efficiency of the DCSMAs is given. It is expected that the DCSMAs may be used as a parallel processing device in micro-optics systems.

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Keywords: Boundary element method; Dual-closed-surface microlens arrays; Focal performance

1. Introduction

In the field of micro optics, diffractive optical elements (DOEs) have received considerable attention and have been widely studied recently [1–3]. For instance, DOEs have been extensively applied in laser scanning, optical interconnections, laser-beam focusing, coupling, and beam array generation [4–6]. With the development in fabrication techniques such as microphotolithography and laser-beam writing, various complex surface relief can be fabricated [7,8]. For DOEs with characteristic scale comparable to or smaller than the incident wavelength, the scalar diffraction theory cannot be employed to analyze their performance [9–11], and therefore, requires a fully rigorous solution to the electromagnetic equations [1,2,12–15]. For two dimensional (2D) homogeneous DOEs, the boundary element method (BEM) has enormous advantages [1–3,16,17].

Owing to the ability of parallel processing, the beam array generation and focusing arrays have been widely investigated [18–22]. Although rigorous analysis of open boundary focusing arrays has been intensively studied [19], the closed-surface microlens arrays are still not well explored. In this paper, the focusing performance of the quantization-level dual-closed-surface microlens array (DCSMA) are studied by rigorous electromagnetic theory and BEM. Considering the scattering and diffraction effects in the closed region and interference between microlenses, the focal performance of DCSMAs is quite different from that of the open-boundary dual microlens arrays. A number of performance quantities, such as the focal spot size, the focal position on the preset focal plane, the diffraction

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efficiency and the normalized transmitted power are calculated.

This paper is organized as follows. We describe the fundamental formulas of the BEM for 2D DCSMAs in Section 2. In Section 3, DCSMAs are designed and the numerical results are given, together with detailed analysis. Section 4 follows with a brief conclusion.

2. Rigorous electromagnetic theory for DOEs

2.1. Boundary integral equations

The 2D DCSMA is shown in Fig. 1. The whole space is divided into two regions by the closed-surface Γ: region S_1, which contains the array of the DOE, and region S_2, which is free space. Each of the regions S_i $(i = 1,2)$ is filled by a homogeneous material with refractive index n_i $(i = 1,2)$. The xy-plane denotes the incident plane. The unit vector $\hat{n}$ is normal to the surface Γ and points to region S_2. We assume that the incident plane wave with the free-space wave number k_0 is incident from the upper region of S_2. After passing through the DCSMA, it is finally focused in the lower region of S_2. Applying Green's theorem to Maxwell's equations and incorporating the Sommerfeld radiation condition, the boundary integral equations are obtained as [16,17]

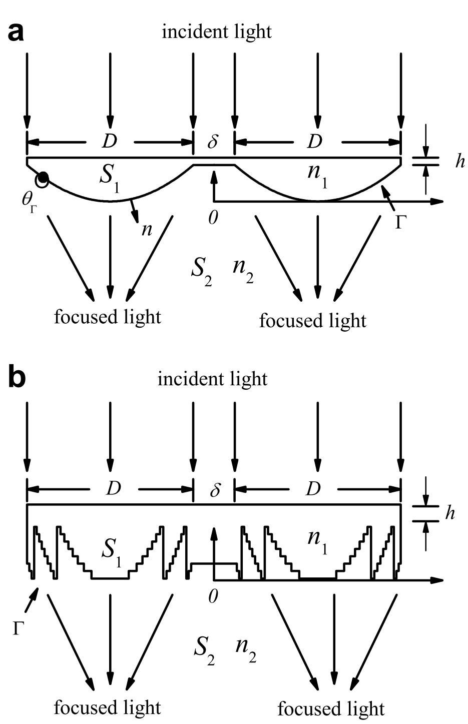

Fig. 1. A schematic diagram of the two dimensional dual-closed-surface microlens array (DCSMA) with different surface-relief profiles. (a) The continuously refractive DCSMA and (b) the multilevel diffractive DCSMA.

$$0 = \boldsymbol{\phi}_\Gamma^{\rm sc}(\mathbf{r}_\Gamma)\left(1-\frac{\theta}{2\pi}\right) + \boldsymbol{\phi}_\Gamma^{\rm inc}(\mathbf{r}_\Gamma)\left(1-\frac{\theta}{2\pi}\right) + \fint_\Gamma\left[\boldsymbol{\phi}_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)\frac{\partial G_1(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}} - p_1G_1(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)\frac{\partial\phi_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}}\right]{\rm d}l' + \fint_\Gamma\left[\boldsymbol{\phi}_\Gamma^{\rm inc}(\mathbf{r}'_\Gamma)\frac{\partial G_1(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}} - p_1G_1(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)\frac{\partial\phi_\Gamma^{\rm inc}(\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}}\right]{\rm d}l', \tag{1a}$$

$$0 = \left(\frac{\theta}{2\pi}\right)\boldsymbol{\phi}_\Gamma^{\rm sc}(\mathbf{r}_\Gamma) + \fint_\Gamma\left[p_2G_2(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)\frac{\partial\boldsymbol{\phi}_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}} - \boldsymbol{\phi}_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)\frac{\partial G_2(\mathbf{r}_\Gamma,\mathbf{r}'_\Gamma)}{\partial\hat{\mathbf{n}}}\right]{\rm d}l', \tag{1b}$$

where $\phi = E_z$ and $p_i = 1$ for TE polarization and $\phi = H_z$ and $p_i = n_i^2$ for TM polarization $(i = 1,2)$; $\fint$ indicates Cauchy's principal value of integration. θ represents the integral angle of Γ at the point r_Γ. $\phi_\Gamma^{\rm sc}$ and $\phi_\Gamma^{\rm inc}$ are scattered field and incident field, respectively. Subscripts 1, 2, and Γ represent the quantities in region S_1, region S_2, and on surface Γ of the DCSMA, respectively. The 2D Green's function is $G_i(r_i, r') = (-j/4)H_0^{(2)}(k_i|r_i - r'_\Gamma|)$ $(i = 1,2)$, where $H_0^{(2)}(k_i|r_i - r'_\Gamma|)$ is the zeroth order Hankel function of the second kind. The wave number in region S_i is $k_i =$ - $n_ik_0 = n_i(2\pi/\lambda_0)$, where λ_0 is the wavelength of the incident light in free space. The vector r_1, r_2, and r'_Γ correspond to the positions vectors of points in region S_1, region S_2, and on surface Γ, respectively.

Eqs. (1a) and (1b) can be cast into the form of a set of linear equations by discretizing $\phi_\Gamma^{\rm sc}(r_\Gamma)$ and $\frac{\partial\phi_\Gamma^{\rm sc}(r_\Gamma)}{\partial\hat{n}}$ over the quadratic element. Once the fields and their normal derivatives on the boundary are specified, the scattered fields in region S_2 can be calculated by [16]

$$\phi_2^{\rm sc}(\mathbf{r}_2) = \int_\Gamma\left[\phi_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)\frac{\partial G_2(\mathbf{r}_2,\mathbf{r}'_\Gamma)}{\partial\hat{n}} - p_2G_2(\mathbf{r}_2,\mathbf{r}'_\Gamma)\frac{\partial\phi_\Gamma^{\rm sc}(\mathbf{r}'_\Gamma)}{\partial\hat{n}}\right]{\rm d}l'. \tag{2}$$

However, the total field in region S_2 is the sum of the incident field and the scattered field, i.e., $\phi_2^{\rm tot}(\mathbf{r}_2) = \phi_2^{\rm inc}(\mathbf{r}_2) + \phi_2^{\rm sc}(\mathbf{r}_2)$. For evaluating the incident field on the near-field observation plane, the first Rayleigh–Sommerfeld diffractive integral method is used in our analysis. The dielectric BEM is validated by comparing numerical results for the dielectric cylinder [16].

2.2. Power and diffraction efficiency

In order to examine the focal performance of the DCSMA, the diffraction efficiency and the normalized transmitted power are calculated. The total field at $y = y_i$ can be expressed in the angular spectrum form. For the TE polarization, the total field $E_z(x, y_i)$ can be expressed as [2]