Investigation of optical performance of gradient index microlens by mode matching method

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Abstract

Microlens arrays are widely used in 3D display, optical communication, etc. Microlens fabricated by ion-exchange method have a gradient refraction index distribution, whose performance could hardly be simulated by means of light ray tracing since optical rays follow a sinusoidal propagation path within a gradient index (GRIN) microlens. Here we use mode matching method (MMM) to investigate light propagation through a GRIN microlens. Since MMM is usually used in simulation of light propagation in waveguides, to check its validity for microlens, we first used MMM to study a cylindrical microlens with homogeneous refraction index distribution. From obtained results of the total light field for different wavelengths, we can see clearly how a cylindrical microlens focuses a parallel light beam, which agreed well with that by light ray tracing. Then we calculated exact 2D light field distribution over the entire light path for a GRIN microlens. The derived focal length also agreed well with preset value.

***Key words*:** *Optical information, 3D display, GRIN Microlens, Mode Matching Method.*

1. INTRODUCTION

Microlens arrays have wide applications in 3D display, optical communication, biomedical inspection, information processing, mobile phone camera, etc. They could be fabricated using glass, polymer, liquid crystal, etc., by means of lithography, ion exchange, chemical vapor deposition, neutron irradiation and so on[1-6]. Among them microlens fabricated by means of ion exchange have a gradient refraction index distribution, whose performance could hardly be simulated by means of light ray tracing since optical rays follow a sinusoidal propagation path within a gradient index (GRIN) microlens. Many researchers simulate GRIN microlens using FDTD and FE method [7-8]. In this paper we attempt Mode Matching Method (MMM). The paper is organized as follows. In section 2 we give an outline of MMM. Since MMM is usually used to calculate light field distribution in a waveguide structure [9-10], in section 3 we first checked its validity for simulation of macro-optical devices. For the purpose we simulated a convex cylindrical microlens and compared the results with that obtained using ray tracing method. Then we extended the simulation to GRIN microlens. Finally a brief conclusion was given in section 4.

2. Mode matching method

In MMM a device is sliced into a number of stacks in which the index profile doesn't change in the propagation direction Z. The light field within each stack could be described by a linear combination of its eigenmodes[11-12]

$$\mathbf{E}(x,z)=\sum_{i=1}^{i=N}\alpha_i \bullet \mathbf{E}_{ti}(x)\bullet \exp(-j\gamma_i z) \tag{1}$$

where α_i is the expansion coefficient, $\mathbf{E}_{ti}(x)$ the transverse mode profile, γ_i the propagation constant of *i*-th eigenmode.

By imposing the continuity for the tangential component of the total field at the interface of two stacks the forward and backward fields, represented in the form of column vectors of expansion coefficients, could be related to each other by a scattering matrix $\mathbf{S}_{1,2}$,

$$\begin{pmatrix} \mathbf{F}_2 \\ \mathbf{B}_1 \end{pmatrix} = \mathbf{S}_{1,2} \cdot \begin{pmatrix} \mathbf{F}_1 \\ \mathbf{B}_2 \end{pmatrix} \tag{2}$$

Combining the scattering matrixes of all the stacks, the total scattering matrix $\mathbf{S}_{Total}$ of the device could be determined. Then the input and out fields at both ends of a device could be related to each other by

$$\begin{pmatrix} \mathbf{F}_{R-out} \\ \mathbf{B}_{L-out} \end{pmatrix} = \mathbf{S}_{Total} \cdot \begin{pmatrix} \mathbf{F}_{L-in} \\ \mathbf{B}_{R-in} \end{pmatrix} \tag{3}$$

Once the input fields at both ends of a device are known, the coefficients vector of each stack could derived from Eq.(2)-(3). Then the light field within each stack could be calculated using Eq.(1).

3. Simulation results and discussion

3.1 Convex microlens

To check the validity of mode matching method for the simulation of macro optical elements, we first calculated the field distribution in a convex cylindrical microlens with homogeneous refraction index distribution and compared the results with that by traditional light ray tracing as shown in Fig.1-2. In Fig.1a the microlens has a radius of R=20μm, a thickness of ω=10μm and a refraction index of n=1.5. In the calculation the microlens was cut into 40 stacks along its optical axis. The height of the first stack is 17.32μm. Then the heights of following stacks decrease with a constant increment of -0.433μm. In the calculation the total number of eigenmodes was N=800. A parallel TE mode plane wave with wavelengths of λ=0.630μm, λ=0.530 μm, λ=0.470 μm incident normally at the microlens from left. The calculated 2D field distribution $|E_y|$ for electrical field component along y-direction of the total light field for different wavelengths were plotted in Fig.1 (b)-(d).

From these results, one can see clearly that the incident parallel light beam was focused by the cylindrical microlens at a distance of about 40μm from the microlens, which was in good agreement with the focal length estimated by R/(n-1)=40μm.

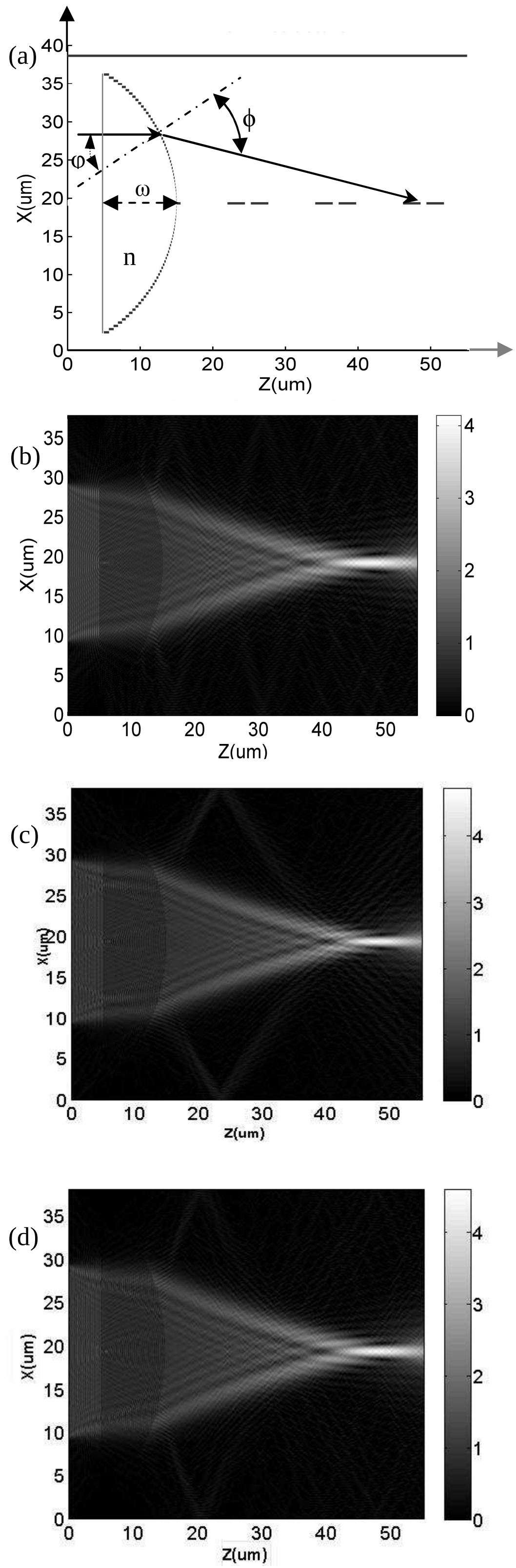

Fig.1 2D field distribution in case of a convex microlens. (a) Structure; (b) λ=0.630 μm, (c) λ=0.530 μm, and (d) λ=0.470 μm.

Reflections which one can see in top and bottom on Fig.1 (c) and (d), are due to the low value of perfect matched layers (PML) as boundary conditions. It implies that in MMM, like in other numerical methods for electromagnetism, the boundary conditions problem should be rigorously treated.

Fig.2 plotted 2D field distribution calculated under the same condition as in Fig.1b except that the wavelength changed to λ=0.45μm. It looked the same. For comparison, the optical ray tracing was performed. The results were also plotted on Fig.2. The directions of refracted light rays were determined by Snell-Descartes law:

$$n\sin\varphi = \sin\phi \qquad (4)$$

It could be seen that the light was also focused near Z=40μm. In a word the simulation results by MMM were in good agreement with that by light ray tracing.

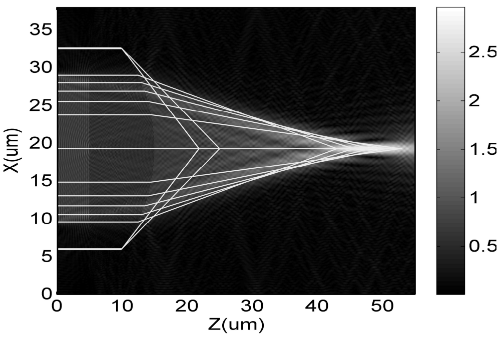

Fig.2 2D field distribution in case of a convex microlens with λ= 0.45μm. Solid lines are for light ray tracing.

3.2 GRIN microlens

With above success we turned to simulate GRIN microlens. For a thin flat GRIN microlens the parallel light ray passing through a GRIN microlens at different height should have same optical path length when they arrive at the focus. So we can write,

$$n(x)e+\sqrt{(x^2-x_0)+f^2}=n_0e+f \qquad (5)$$

Where e is the thickness of the GRIN microlens, $n(x)$ being the refraction index at height x, n_0 being the refraction index at the center(x_0=12 μm), f being the focal length.From Eq.(5) we can determine $n(x)$ once y, n_0, x_0 are given.

Fig.3 simulated a GRIN microlens with e=10μm, f=50μm and n_0=1.599. In the calculation the GRIN microlens is sliced vertically into 20 layers as indicated in Fig.3(a).

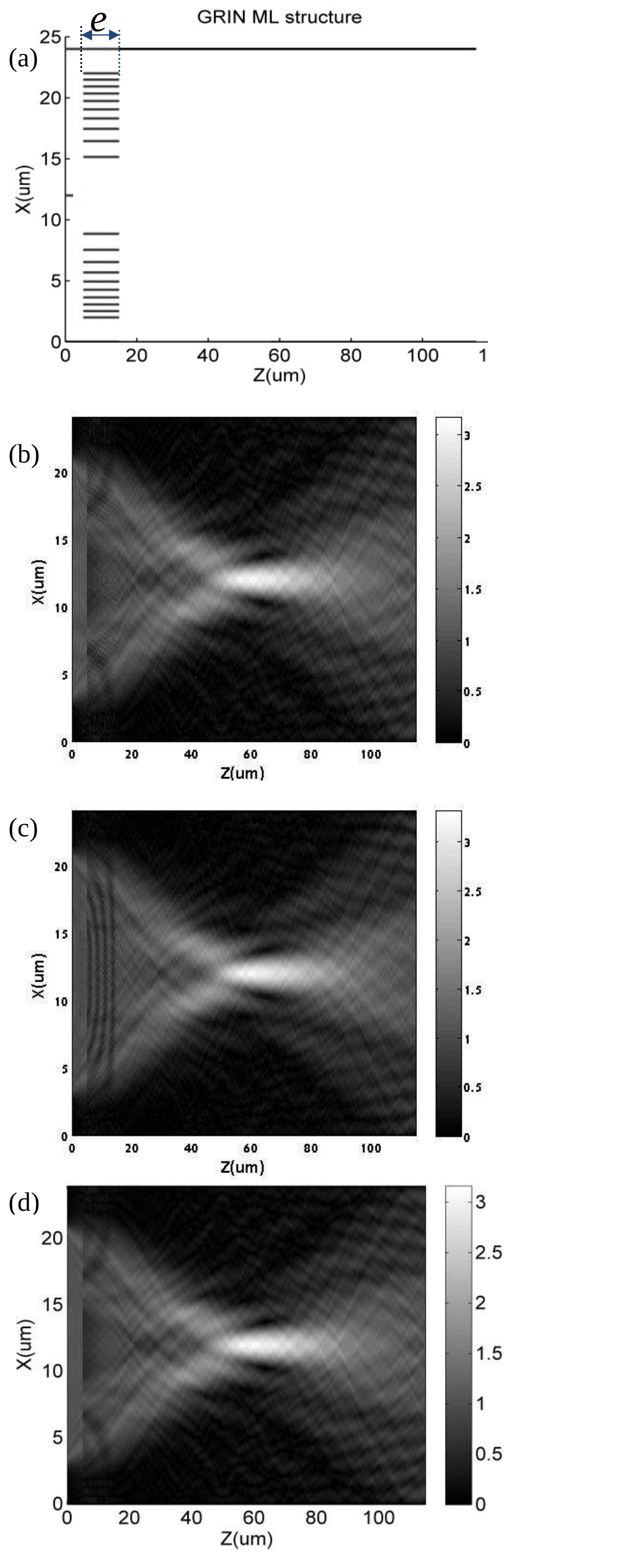

Fig.3 2D field distribution in case of a GRIN microlens (a) Structure; (b), λ=0.630 μm, (c) λ= 0.590 μm and (d) λ=0.450 μm.

The refraction index difference between adjacent layers is 0.0099. The total light field for λ=0.630 μm, λ= 0.590 μm and λ=0.450 μm were plotted in Fig.3(b)-(d) respectively. From the results we can see that the focal length was about 50μm as we expected.

4. Conclusion

We simulated microlenses with homogeneous refraction index distribution and gradient refraction index distribution using mode matching method. In the former case light rays go straight in the microlens, while in the latter case light rays do not go straight. However in both cases MMM provided good results.

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