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Design and fabrication of microlens based on laser writing technology

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Abstract: *The design and preparation of microlens has shown obvious potential in practical applications in areas like microscale optical and optical-electrical devices, especially for integration of tiny structures, which are of great significance for study and application. Traditionally, the optical lenses are mainly prepared by grinding or melting materials, which often suffers from oversized volume, difficulty to integrate, and low degree of freedom for designed functions, which therefore limits the area of usage as we expected. In this work, by using the principles of micro-nano optics, we designed nano-structured artificial lenses that meet the focusing ability of lenses. This method utilizes the basic principles of diffractive optics and allows for the free design of any lens structure as needed. At the same time, the use of direct laser writing successfully helped fabricate the lens of microscale to achieve the function of simulated designed lens in the experiment. This overall process, including the simulation of optical design as well as the experimental preparation and testing of micro lens proves the effectiveness of the design and preparation of this micro-nano optical lens for freely designed functions which would be potential for integration of optical electrical platform with precise scales as tiny as micrometers. Objectively, this design provides a powerful method and technology for the design and preparation of microelectronic and micro-optical devices.*

Keywords: *Microlens, diffractive optics, laser writing, beam focusing*

1. Introduction

Lens and mirrors are typical optical components in design of instruments and devices mostly fabricated by polishing the glasses with large sizes, which however would be difficult for integration in precision equipment like chips, cameras or detectors. By introducing the diffractive concept, the imaging of light with lens and mirrors can be considered as a combination of diffractions from image pixel matrix, i.e. the object and optical components. [1-2] So, we can consider a design of series of diffractive atoms to realize any desirable imaging performance, including beam focusing, steering, or other imaging, based on optical simulation and design beforehand. Based on this idea, the microlens have been proved a novel design in manufacture of optic lenses, especially for devices as tiny as tens of micrometers. [2-4] Using careful design and calculation of light field based on diffractive models, we can accurately manipulate focusing performance of lens with only a sheet of thin optical diffractive layer, and furthermore, we can realize kinds of novel beam control functions beyond traditional designs, e.g. multi-focal imaging, wide-broad imaging and achromatic imaging etc., which shows a leap of lens design over traditional technology. [4 - 7]

In physics, the function of lens, e.g. focusing and beam steering, is realized by reconstruction of light field when the light is diffracted from the components of devices, and interfered in far field. [8] Compared to traditional lenses, microlenses based on the design of interference patterns have the advantages of being small, flexible, and easy to integrate into a two-dimensional precise device. As seen in Figure 1, when the light is incident into the device, the beams will be focused if they are constructively superposed at the point in far field. Based on the microscopic interference of light beams, the components on the lens device surface can be carefully designed to obtain modulation of light amplitude and phase, as the result, achieve equivalent function of lens. [9-10] For example, when lights are focused from positions O and A on the surface of lens, the phase difference between diffractions from the two positions should satisfy the constructive interference condition, i.e. the path from A (rA) and focal length f follows that $\Delta r = rA - f = m\lambda$, in which m is the order of superposition while λ is the wavelength of incidence. As the result, the light field can be enhanced at the same point, i.e. the focal point. For our numerical calculation, the phase difference is

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$$\phi = \frac{2\pi}{\lambda}\Delta \qquad (1)$$

and Δ= nd is the difference of optical path when travelling a distance of d in a medium with refractive index n. [11] When designing the microlens, we need to find sufficient order groups of diffractive components to satisfy efficient beam imaging. In out numerical design, the phase distribution is expected to obtain by tracing back the results from the final targeted image, including focal distance and the spot size.

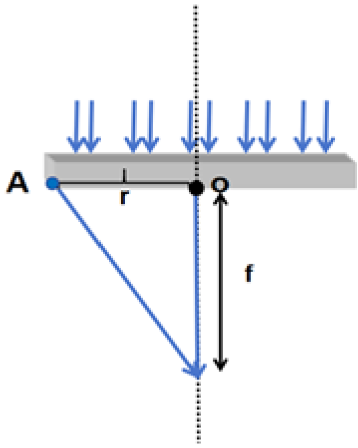

Figure 1. Sketch for principle of the microlens focusing based on diffraction from different positions of object.

Based on this method of microlens' design, we can obtain different kinds of optical lens. Since the key to light modulation is the reconstruction of light wavefronts, we can calculate the targeted wavefront distribution and trace back to the light propagation, hence obtain the phase and amplitude modulation need to be produced in the diffractive component. The following equation defines the phase of light when propagating from a position r = (x, y) from the center of lens with a focal position f:

$$\psi(x,y) = -\frac{2\pi}{\lambda}\left(f - \sqrt{x^2 + y^2 + f^2}\right) \qquad (2)$$

Then we can fabricate the components with the sizes following the diffractive phase difference $\phi = \frac{2\pi}{\lambda}\Delta$ as discussed above. [12] This helps us to realize fabrication of different kinds of lens and even diffractive devices.

Another issue to obtain the microlens is the technique for fabrication. The wavelength of light is on a micro-scale or even shorter, thus we need precise and accurate methods and technology to manufacture the diffractive components. Traditionally, industries use electric beam lithography, but this technology is expensive and complicated, and the cost of producing microlens is inacceptable. Here, we use laser writing technology to conduct micro-lens. Laser writing is using lasers to directly react with the materials on the lens. Therefore, we can crave different patterns on the surface of the lens. [13, 14]

In this paper, micro-lens to realize focusing function were designed by numerical analysis software MATLAB and photonic simulation software Lumerical FDTD before fabrication by laser writing technology. The sample is simulated and then patterned on a photo-resistive polymer material. Sample characterization and optical test were also carried out to make sure the designed optical performance. The design and laser-writing fabrication of microlens is successfully verified.

2. Method

Simulation/numerical design of microlens.

According to the principle of diffraction and imaging reconstruction as introduced above, the beam's focusing can be simulated by software of MATLAB. We setup a beam focusing model that demonstrates how we can modify the focus and wavelength by altering variables such as the size of the lens (more

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specifically height, width, and length of the lens), and the material (index of refraction), following the phase shift relation as introduced above. The layout of components is pre-set based on the incident wavelength λ = 632 nm red light and focal length of f = 18 cm. We modulate those variable numbers in ways to reach the optimal result. As given in Figure 2(a), the focusing performance based on microlens calculated by MATLAB is successfully obtained. The micro-pixel for light diffraction is arranged based on the physics in Equation (2).

After the model is set and calculated by MATLAB, we use Lumerical FDTD for the actual simulation of beam focusing before fabrication of the lens device. There will be phase shift when the light is incident into the Si antennas, which is determined by the geometry of the structure. For λ = 632 nm incidence, we obtained an optimized geometry of IP-dip resist antennas (refractive index n = 1.5): length L = 0.7 ~ 1.1 μm, width W=1.3 μm and height H=0.6 μm to realize proper phase shift range of 2π, which is necessary to realize full modulation of light wavefront (see Figure 2(b)). By calculating the relation between phase of each diffractive components and their combination of length, height, and width, we can further reconstruct the process of how light focuses based on the layout of lens atoms as calculated in MATLAB results with the help of FDTD. The model of simulation by FDTD is given in Figure 2(c), including the lens area of simulation and incidence direction.

(a)

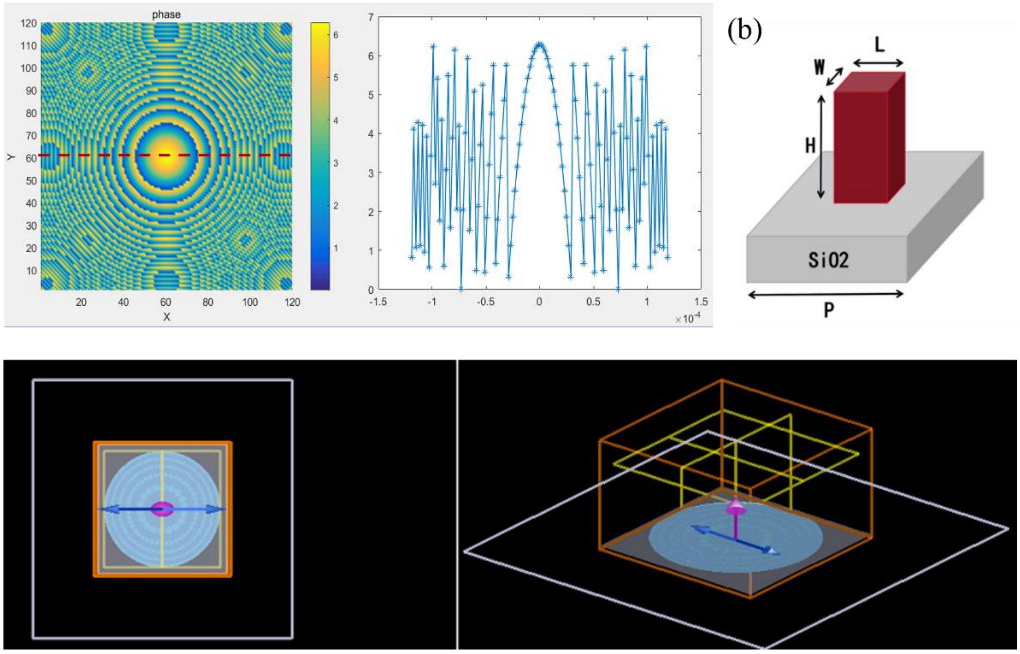

Figure 2. simulation of microlens of (a) MATLAB phase calculation and (b) model of IP - dip resist antennas' simulation, as well as the FDTD simulation model.

3. Fabrication of microlens by laser writing

The microlens were patterned on a thin layer of photo-resist on a piece of soda lime glass by laser writing. Similar technology has been widely applied in micro/nano scale structure fabrication. [15, 16] The photo-resist is a commercial 2p-dip from the Nanoscribe company. The writing laser is a 780 nm red light ultrafast beam at 80 MHz. The output power of the beam is measured to be 90 mW by power meter. A droplet of 10 microliter Ip-dip is dropped on the glass and stuck to the holder. The pattern designed by simulation of the microlens was input into the software beforehand and formed an STL (Stereo Lithography) file. Hence the laser will be exposed according to the layout of the designed pattern when running. Before exposure, the sample holder will be lowered to approach the objective lens, such that interface between glass and 2p-dip photo-resist can be found for laser writing at the focal plane.

The microlens can be fabricated as much as a size with about 4 mm side length. which can be directly observed by an optical microscope. After that, the sample will be developed in iso-Propyl alcohol (IPA) for 15 min and dried under hot air for 10 min at 70 oC. The imagining of microlens can be experimentally indicated by our hand-made optical imaging system. In which the sample will be illuminated by a 632 nm laser tube as we designed by MATLAB. A 4F optical system is setup to reduce the beam size less than 2 mm to make sure that all the light can be focused on the array of microlens. Finally, a charge

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coupled device (CCD) camera is used to detect the focusing image.

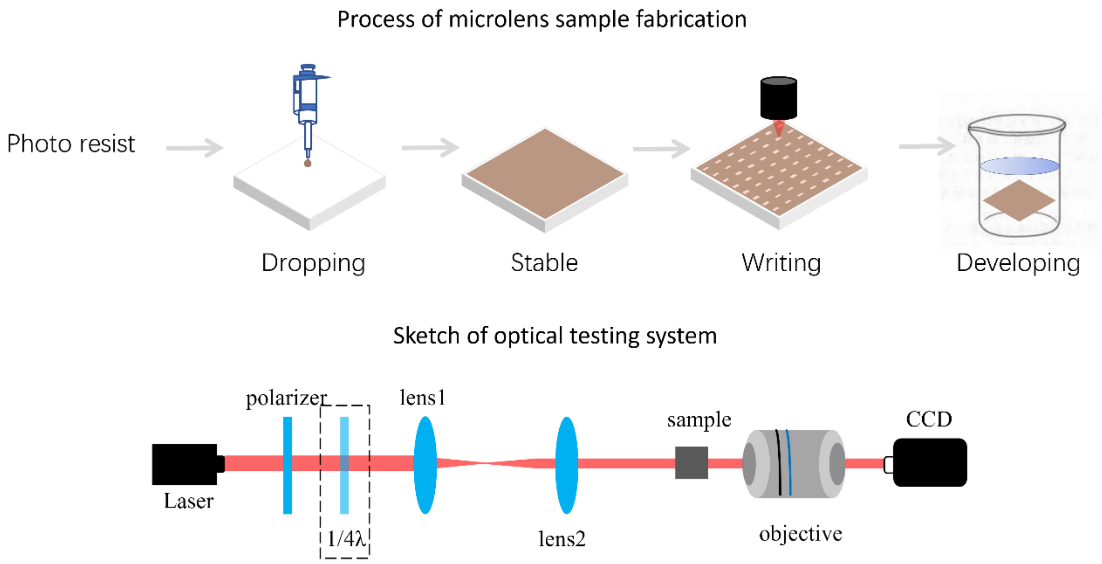

Figure 3. Sketch of process of sample fabrication (up): direct laser writing on the IP – dip photoresist as well as structure development, and optical testing system (down): beam focusing and capture by CCD

4. Results and discussion

As introduced in the Method section, we have established the FDTD simulation model of microlens. The phase dependence can be directly calculated based on the propagation phase principle in Equation (1). The geometry of IP – dip resist antennas can be thus arranged following the phase map as calculated by MATLAB. According the simulation by FDTD, the beam can be correctly focused under the lamination of λ = 632 nm incidence (see Figure 4). As shown in Figure 4 (a), the focal spot can be correctly expected at the designed position z = 18 cm, confirming an effective method of microlens optical design. In the meantime, the narrow beam of focus also proves a good focusing performance with a tiny size of about 1.6 mm (FWHM) with a long focal length lens as given in Figure 4 (b).

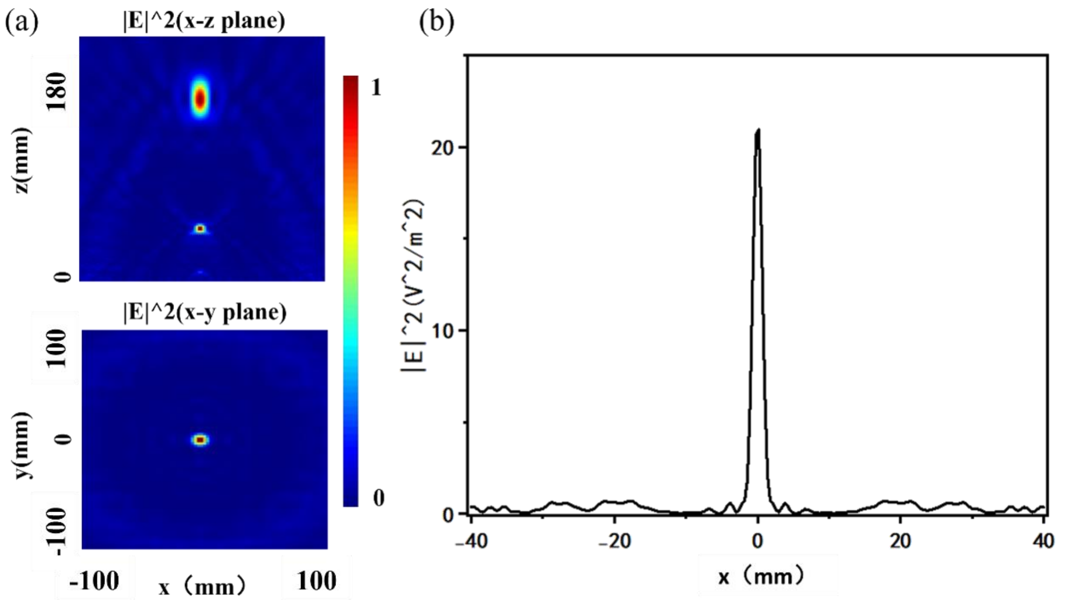

Figure 4. (a) Simulation results of designed microlens by FDTD software with an expected focal length of about f = 18 cm under λ = 632 nm incidence. (b) the distribution of light field across the focal point.

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Based on the simulation, we clearly obtain the designed geometry of diffractive components by commercial Nanoscribe direct laser writing. As introduced in method section, the pattern is laser written in the commercial IP - Dip photoresist from Nanoscribe Co. Ltd., cured at the laser focal point due to two-photon absorption when the focused laser is irradiated. Geometry of fabrication were generated based on the phase file following the propagation phase equation as in Equation 1 from simulation. It's immobilized on the substrate by immersion in propylene glycol for 30 minutes and then dried at room temperature. For the laser writing process, several parameters should be considered to make sure of the fabrication. Among these control parameters, the average power, pulse repetition rate, and beam scanning speed are the key parameters which determines whether the photothermal or photochemical process dominates. Higher power, slower scanning speed, and lower repetition rate could bring up photochemical process more; this is because the higher power can exceed the power threshold for the photochemical process and lower repetition rate allows the heat to be dissipated to the surrounding area so as to have less photothermal process. A high repetition rate leads to the heat accumulation which results in the photocuring reduction of IP-dip photoresist as illustrated above. As given in Figure 5, we use a SEM (scanning electronic microscope) to observe the fabricated microlens structure. The size of the antennas is about the range of 20 μm, and the general structure of the whole lens is about 4 mm, which almost satisfies the designed sample structure.

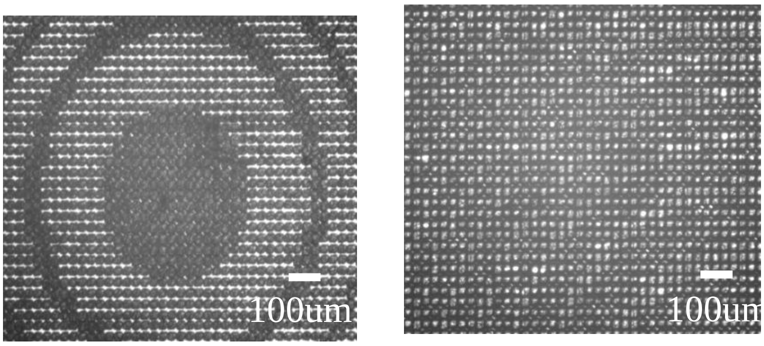

Figure 5 Microlens sample fabricated and characterized by SEM microscope including the center and side areas

By using the laser writing fabricated microlens sample, we further do the optical test, i.e. the focusing performance under λ = 632 nm incidence. The beam propagation after passing through the laser writing prepared microlens were captured and analyzed along the propagation axis as shown in Fig. 6. The collimated 632 nm CW laser beam was used as the input and the beam was converged to the focal point, which is designed about 18 cm away from the sample. The laser beam of output is about 6.4 mm, and skunk by the 4F system with two pieces of lens sheets: the focal lengths of each lens are: F1 = 300 mm and F2 = 150 mm. The intensity distribution at each cross-sectional area was captured with a range of about 20 cm as shown Fig. 6. The images are captured by CCD camera at different positions marked from the sample. The Figure 6 images show that, when the sample is close to CCD camera (d < 10 cm), the focal point light spot is hard to be observed, which corresponds to a position deviated from the designed focal point about f = 18 cm. When captured at d = 11.5 cm, an irregular spot is obtained.

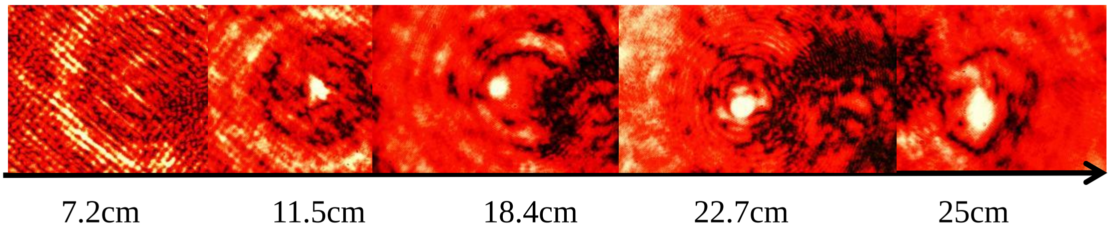

Figure 6. Beam focusing tested of the microlens by CCD camera. The length is defined from the lens sample to the position of camera.

An optimized spot is observed when captured at a distance d = 18.4 cm, confirming a correct experimental performance of the designed microlens. The spot size of the optimized position is about 2.4 mm. The spot at the focal point is slightly larger than the designed focal size. This can be the reason of light diffraction from the focusing lens, which would be diffused to a wider area. Anyway, the spot of focusing is still obvious to observe.

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While such thin layer diffractive micro-optics have been successfully demonstrated by such laser writing fabricated structure in this study, there are still remaining challenges for practical uses. For example, the optical properties should be controlled to be uniform over the surface with a high reproducibility. As in our test, the beam of focusing is very difficult to control with uniform cross-sectional size. The diffractive microlens were fabricated with the fixed laser spot over the whole lens area. Based on such method, more flexible design and patterning could be realized for wider application area with better optical performances. To achieve a smooth transition of optical properties, e.g. transmittance and phase delay, many control parameters can be spatially controlled in real time. Higher reproducibility can be achieved by carrying out the patterning in an environmental chamber with inert gases, temperature, humidity, and contaminant controls.

In general, the experimental test shows that the method and fabrication of the microlens as we introduced in this work is successful. For extension, the method can be effective to design all kinds of micro size optical components, e.g. mirrors, lens, gratings etc., which shows obvious potential in future development of micro-electronic and optical devices. Furthermore, the direct laser writing is also a powerful technology for microscopic and precise fabrication with low cost.

5. Summary

In this paper, we have systematically studied the method of micro scale lens' design and fabrication. By using the numerical software MATLAB and FDTD simulation, we designed a structure of lens as much as 4 mm with the advantage of being small, flexible, and easy to integrate into a two-dimensional precise device. The lens comprises small structures at the micrometer scale, arranged according to the optical focusing effect based on diffractive optics, which can successfully achieve a focusing ability of 18 cm focal length. At the same time, using the direct laser writing method, we achieved sample processing and preparation on photoresist, characterized and tested the samples using SEM and optical testing systems. The focusing is tested with a focal length of 18.4 cm. This result shows that our design has been successfully proved based on the focusing performance. The direct laser writing is an effective method for less expensive and massive fabrication of micro-optical devices. These results indicated that the development of micro-lens has great potential. It can be applied to and beneficial to multiple industries. The usage of laser writing has also proved to be an efficient and precise method that can be helpful to the sector of microscopic.

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