Direct write of microlens array using digital projection photopolymerization

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Microlens array is a key element in the field of information processing, optoelectronics, and integrated optics. Many existing fabrication processes remain expensive and complicated even though relatively low-cost replication processes have been developed. Here, we demonstrate the fabrication of microlens arrays through projection photopolymerization using a digital micromirror device (DMD) as a dynamic photomask. The DMD projects grayscale images, which are designed in a computer, onto a photocurable resin. The resin is then solidified with its thickness determined by a grayscale ultraviolet light and exposure time. Therefore, various geometries can be formed in a single-step, massively parallel fashion. We present microlens arrays made of acrylate-based polymer precursor. The physical and optical characteristics of the resulting lenses suggest that this fabrication technique is potentially suitable for applications in integrated optics. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2838751]

Among all the micro-optical elements, microlens arrays are widely used in optical and optoelectronic systems and devices, such as fiber bundle couplers in optical communication systems, charge-coupled devices (CCDs), vertical-cavity surface-emitting lasers, and other related optical applications.[1–3] At present, there are already various methods to fabricate microlenses, including microjet printing,[4] thermal reflow,[5] local melting of doped borosilicate glass using focused laser beam.[6] The underlying physical principle is the natural tendency of liquid droplets to form quasispherical shapes on the surface. However, an ideal spherical shape can only be formed for specific ratios between the lens diameter and photoresist thickness. Significant deviations may occur if the resist is too thin. Moreover, these techniques are only capable of creating near-spherical lenses while nonspherical lenses are often demanded for advanced imaging or lithographic applications.

Direct writing techniques, employing a focused laser beam or an electron beam with a quasicontinuous intensity modulation, can generate arbitrary surface profile in an "analog" fashion, although fabricated microlenses are limited to low numerical apertures.[7,8] Further hindered by its serial nature, the main application of this approach is the generation of masters for replication at the current stage of development. The replication methods have shown their economical advantages in manufacturing plastic micro-optics in the same way compact disks are made. Typically, replicas are produced by embossing, injection molding, or cast and curing of polymeric materials against electroformed metal masters, which are often expensive and prone to wear and contamination.[9] Grayscale mask, often made by aforementioned direct writing methods, has been adopted as a tool for large scale manufacturing.[10–12] The exposure through the grayscale mask results in a continuous intensity distribution in the photoresist coating. The dynamic range of the grayscale masks determines the achievable profiling depth.

In this report, a fabrication technique, digital projection photopolymerization (DPP), for microlens array is presented. DPP uses a digital micromirror device (DMD) as a dynamic grayscale mask. The microlens array made of a photocurable resin is characterized by scanning electron microscopy and optical microscopy. The optical focal length of the microlens is also investigated using a HeNe laser.

The DMD-based projection system was developed based on a commercial projector (PB 2120, BenQ, Taiwan), as illustrated in Fig. 1. We used a high intensity ultraviolet (UV) spot curing system (Green Spot) as the light source. The illumination light was homogenized by a holographic diffuser before striking the DMD chip. A UV lens ($f=25$ mm) was used to project the image to the photopolymer. Grayscale images, which correspond to the optics to be fabricated, were drawn in PowerPoint. These images were then executed on the DMD chip to generate a dynamic mask. The illumination light was modulated according to the pattern on the DMD chip and then projected onto the image plane.

A vat containing photocurable resin was mounted on a translational platform, which moves along image plane. A glass cover slide sit on top of the vat and was in contact with the resin, with its bottom side coincide with the image plane. Since the resin was an absorbing and photobleaching medium, light penetrated into the resin following Beer's law. Consequently, the grayscale image and exposure time determined the shape of the solidified resin.

1,6-hexanediol diacrylate (HDDA) (Sigma-Aldrich, refractive index=1.456), a tetrafunctional monomer was used

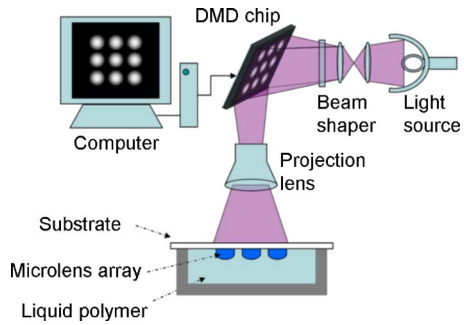

FIG. 1. (Color online) Schematic diagram of the DMD-based projection photopolymerization system.

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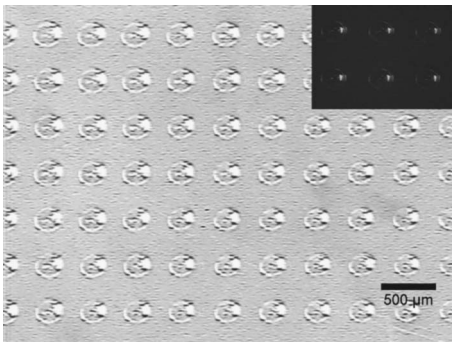

FIG. 2. Optical micrographs of a microlens array. Microlens diameter was 230 μm and pitch was 510 μm. Image taken in the transmission mode at 10× magnification. Scale bar indicates 500 μm. Insert: image taken in the reflection mode.

as received without further purification. 2,2-dimethoxy-1,2-diphenylethan-1-one (Irgacure™ 651, Ciba) was dissolved in HDDA to form 0.5% to 3% wt solution. The solution is sonicated, nitrogen-purged overnight, and kept in dark before use. Glass cover slides were cleaned in acetone and isopropanol.

An array of hemispherelike speckles in a dark background shown in Fig. 1 was projected. The intensity at the center of each speckle was 370 mW/cm^2 and the circumference was 333 mW/cm^2. The time of exposure was 1.3 s. After exposure, the residual liquid was removed using compressed air. Because the resin near the bottom of the microlens receives more energy than that near the sag, which is buried deeper into the surface, inhomogeneous rate of polymerization may impair mechanical and optical properties. For this reason, as-solidified microlens array was flood exposed by a UV lamp for 5 min at 20 mW/cm^2 in order to augment the optical and mechanical performance.

Optical micrographs were taken in both reflective and transmission modes, as shown in Fig. 2. In the reflective mode, the back surface of the glass substrate was covered by black paint. In the transmission mode, a diffusive light source was placed on another side of the array relative to the objective lens. The diameter of each microlens was measured at 230 μm and the pitch at 510 μm. The reflection mode shown that each microlens condensed incident light from the microscope onto the painted back surface and then recollected the diffusive reflection back to the microscope. A sharp focusing spot was observed in the center of each microlens.

The focal length of each microlens was measured using a set up schematically shown in Fig. 3. The microlens array was mounted on a linear stage. The entire array was illuminated with a collimated He–Ne laser beam at 632.8 nm. It

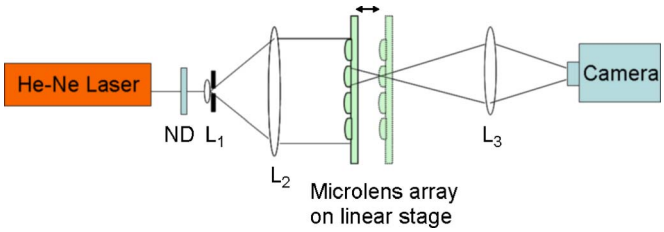

FIG. 3. (Color online) Schematic setup of the optical measurement system. The laser intensity was modulated by a neutral density filter. It was then expanded by lenses L_1 and L_2. L_3 is the objective lens in the microscope.

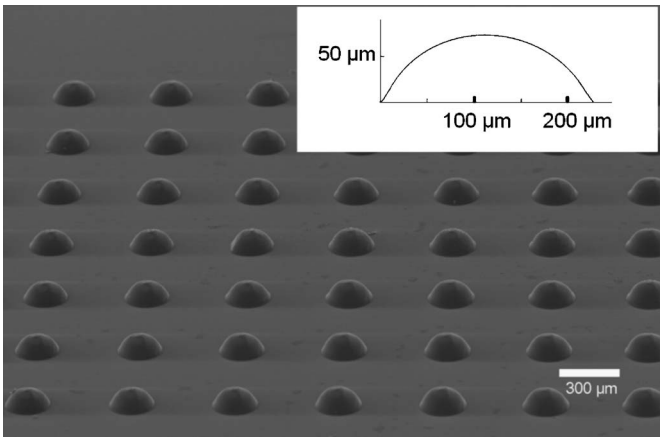

FIG. 4. A SEM micrograph of the microlens array. Insert: surface profile of a microlens.

was then imaged by objective lens L_3 (10× magnification) and a CCD camera. First, we moved the linear stage until a clear image of the microlens array was observed. We then moved the stage away from the objective lens until the microlenses and the objective lens were in conjugation, where an array of tightly focused spots was captured. The focal length of microlenses, equivalent to the distance moved, was 300 μm at 632.8 nm. Airy disks were observed around the zeroth-order peak (full width at half maximum=10 μm).

The scanning electron microscopy (SEM) micrograph shows the bird view of the microlens array (Fig. 4). The identical shape and size of each element indicated uniform illumination from the UV light source. The surface profile was obtained by a stylus profiler. The lens sag was 72 μm. The microlens profile was approximately spherical with a radius of approximately 130 μm. The edge of the microlens deviated slightly from the spherical curvature and flattened out, which may be caused by the residual resin.

The surface roughness was measured by scanning several randomly chosen areas (5×5 μm) using an atomic force microscope. The average surface roughness was 3.0 ± 0.2 nm. Apparently, the surface roughness far exceeds the theoretical possible resolution of 4 μm (image pixel size). We attribute this result to two possible reasons. Firstly, the image was slightly out of focus toward the sag of the microlens and was blurred as opposed to a pixilated pattern. Secondly, a thin film of the residual resin may have been left over the surface of the microlenses. The surface tension smoothens out the rough surface. After postexposure, the thin resin film covers the new surface of the microlens.

Further improvement in the fabrication fidelity requires semiempirical models assisted by thorough depth of curing calibration. It is also necessary to correct errors induced by the cross-talking effect, especially for high resolution or close packed microoptics. Process scale-up is viable through step and repeat or an array comprised of multiple DMDs.

In conclusion, the DPP method offers a considerable degree of flexibility in microfabrication. A wide variety of micro-optics can be fabricated using this technique, including aspheric lens, cylindrical lens, tapered gratings, not only on rigid substrates but also on flexible transparent substrates as well. Changing geometries can be done "on the fly," without requiring to make or to switch photomasks. DPP also has very little or no tool contamination and wear compared to a typical replication process. Furthermore, the DPP method of-

fers low-cost, fast turn-around, and flexible design.

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