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Fabrication of a focal length variable microlens array based on a nematic liquid crystal

Yoonseuk Choi [a], Jae-Hong Park [a], Jae-Hoon Kim [a,b], Sin-Doo Lee [a,*]

[a] *Molecular Integrated Physics and Devices Laboratory, ENG 032, Seoul National University, Kwanak, P.O. Box 34, Seoul 151-742, South Korea*

[b] *Department of Physics, Hallym University, Chunchon, Kangwon-Do 200-702, South Korea*

Abstract

We fabricated a two-dimensional liquid crystal microlens array using a surface relief structure of ultraviolet (UV) curable polymer. The surface relief structure is produced by the spatially modulated UV exposure of the polymer through a photomask. Application of a voltage to the microlens changes the effective refractive index of the liquid crystal layer, which gives the change of a focal length. A variety of microlens structures and focal length variations could be produced on different surface relief structures by controlling the UV exposure.

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Keywords: Liquid crystal; Microlens array; Focal length tuning; Photopolymer

1. Introduction

With the technological progress in optics, the need of microlenses has been increased for various optical applications such as optical interconnections, photonic devices, integrated optics components and optical communication systems [1–3]. In these applications, both the focal length change and tuning capability in microlens arrays are the key factors for active components. Until now, several attempts have been made to achieve those properties in microlens arrays [4]. However, most of them are based on sophisticated fabrication methods and the small optical modulation properties limit the switching characteristics of the microlenses. Therefore, it is of great importance to achieve sufficient switching capabilities by combining a solid-state planar optical passive component and a liquid (LC) optical modulator as an active part [5,6].

In this work, we report on a novel method of fabricating a LC microlens array using a surface relief structure of the UV curable polymer. Using the UV curable polymer a desirable surface structure is obtained for optical modulation without any complex fabrication processes such as an ion beam etching [7]. Moreover, it should be noted that the large birefringence of the LC provides a wide range of the switching characteristics of the microlens.

* Corresponding author. Tel.: +82-2-880-1823; fax: +82-2-874-9769.

E-mail address: sidlee@plaza.snu.ac.kr (S.-D. Lee).

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2. Experimental

The microlens array cell was made with indium-tin-oxide (ITO) glass substrates. One of the substrates had a specific surface relief structure of the photopolymer and the other had only ITO layer. In order to make a surface relief structure, the UV curable polymer was spin-coated on the substrates at the rate of 4000 rpm during 30 s. The thickness of the spin-coated polymer film was about 3 μm. After making a polymer film on the glass substrate, the spatially modulated UV light was irradiated onto the film through a photomask. The photomask was designed to generate the intensity modulation of the UV light to form a pattern of microlens arrays. Such irradiation process led to the diffusion of monomers in polymer composites from the unexposed to the exposed regions. This results in the formation of the lens-shaped surface relief structure.

The alignment layer was prepared from the polyvinyl alcohol (PVA) solution (1 wt.%). In this case, the average pretilt angle of the LC molecules is almost negligible on the alignment layer. The alignment layer coated over the surface relief structure determines the optical axis of the LC when the rubbing process is involved. Two cases of the LC alignment on the surface relief structure (with and without the alignment layer) were examined. The LC was filled into the sandwiched substrates by capillary action.

Fig. 1 shows a schematic diagram of a LC microlens structure and the two operating states. The materials used in this study were a commercial nematic LC of ZLI-2293 (Merck Chemical Co.) and a photocurable prepolymer NOA 65 (Norland Co.).

3. Result and discussion

The ordinary (n_o) and extraordinary (n_e) refractive indices of the LC used in this study at room temperature are 1.499 and 1.632, respectively. The refractive index (n_p) of the cured NOA 65 is 1.524 which is close to the typical refractive index of glass (1.5). Within a simple model, the focal length of microlens, f, is simply given by $R/[n_{lc} - n_p]$ where n_{lc} is the effective refractive index of the LC layer and R is the curvature of the surface relief structure. This tells us that the microlens acts as either a convex or a concave lens depending on the values of n_p and n_{lc}. In fact, n_{lc} varies with the applied voltage while n_p remains constant under operation. However, in a real system, the convex lens is more applicable for photonic components. As a result, the parameters of microlens should be optimized to enlarge an active region for the convex lens. Fig. 2 shows a focused beam image of the microlens arrays from CCD in the OFF state under no applied voltage.

With increasing the applied voltage, the director of the LC becomes deformed to reduce the effec-

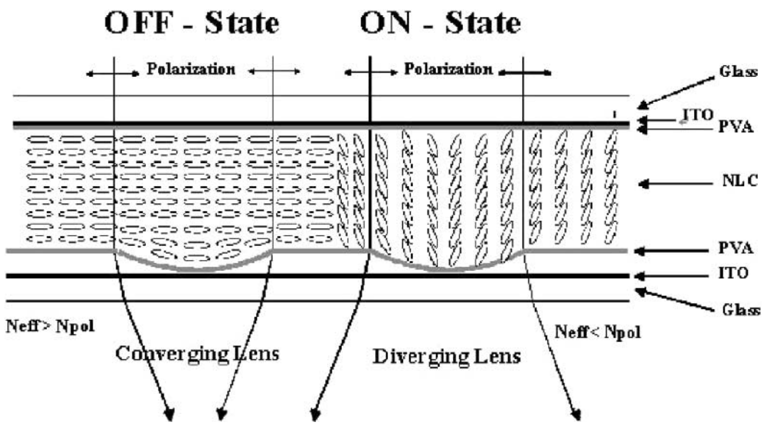

Fig. 1. The schematic diagram of a LC mircolens structure and two operating states. The LC was homogeneously aligned on both surfaces.

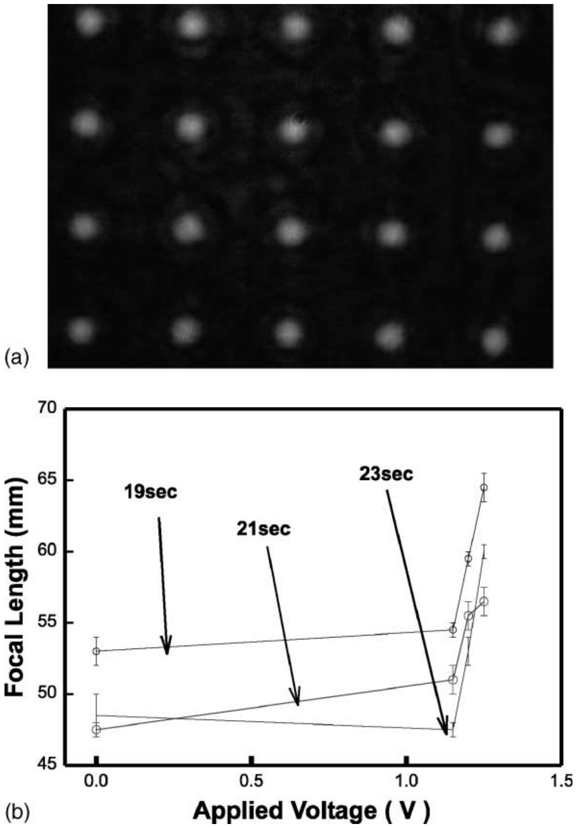

Fig. 2. (a) A focused beam image from CCD and (b) focal length as a function of the applied voltage. Each time denotes the duration of the UV exposure.

tive refractive index of the LC layer, and thus the focal length of microlens increases. The focal length variations as a function of voltage are shown in Fig. 2(b). It was found that the focal length variation increases linearly with the applied voltage. This is important to precisely control the electro-optic (EO) performances of the microlens arrays. In contrast to conventional microlenses, our microlens with 200 μm diameter gives a wide range of tuning (about 10 mm). Such a wide tuning capability would be useful for practical applications in optical communications. As shown in Fig. 2(b), the focal length can be varied by changing the surface relief structure as a function of duration of the UV exposure. Note that the LC microlens array has a certain threshold at which the LC director starts to be distorted.

Instead of using an optically isotropic structure [8], in the surface relief structure, the LC possesses the initial surface alignment along the geometrical curvature. This gives spontaneous distortions of the director in the azimuthal angle around the edge of each microlens. Such effect arises predominantly from the surface morphology and the nature of the alignment layer. Fig. 3 shows the microscopic textures of the microlens array under crossed-polarizers, one of which has the alignment layer over the surface relief structure. In the case of no alignment layer over the surface relief structure, the 2-fold symmetry exists because the LC on the other substrate aligns along the rubbing direction. This results in the leakage of light due to the initial distortion of the LC director along the curved surface as shown in Fig. 3(b). In contrast, Fig. 3(a)

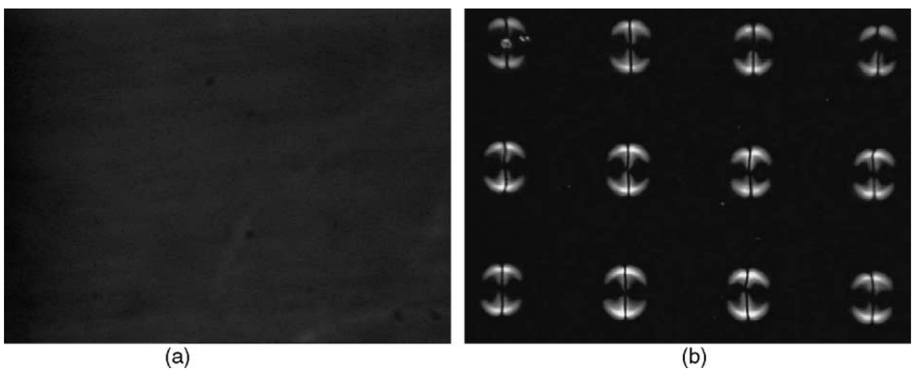

Fig. 3. The textures of the LC microlens cell under crossed polarizers: (a) when the alignment layer was prepared on the surface relief structure and (b) when no alignment layer was present on the surface relief structure.

shows no light leakage when the LC molecules were aligned on both treated substrates. This implies that the uniformly aligned LC behaves as an optically isotropic structure having wide tuning capability.

4. Concluding remarks

We have demonstrated the LC microlens arrays with wide tuning capability of the focal length by the application of a voltage. Using the LC layer as an active medium, the microlens provides a wide tuning range as well as good EO characteristics due to the high optical anisotropy of the LC. Moreover, the surface relief structure of the UV curable photopolymer makes the fabrication process simple. It may be concluded that uniform alignment of the LC reduces the aberration effect. The effect from local variations of the voltage around the microlens remains to be explored. The microlens arrays presented here are expected to play a significant role in photonic systems.

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