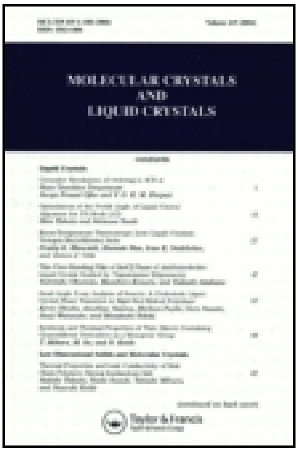

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Polymer/LC Phase Separation Assisted in Fabrication of Self-Assembled Optical Microlens Arrays

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To cite this article: Li-Chen Huang, Tzu-Chieh Lin, Chiu-Chang Huang & Chih-Yu Chao (2011): Polymer/LC Phase Separation Assisted in Fabrication of Self-Assembled Optical Microlens Arrays, Molecular Crystals and Liquid Crystals, 543:1, 136/[902]-142/[908]

To link to this article: http://dx.doi.org/10.1080/15421406.2011.569447

Mol. Cryst. Liq. Cryst., Vol. 543: pp. 136/[902]–142/[908], 2011
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.569447

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Polymer/LC Phase Separation Assisted in Fabrication of Self-Assembled Optical Microlens Arrays

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Here we report on the development of the low-temperature self-assembly microlens arrays via liquid crystal/photopolymer blends phase separation method. In this method, liquid crystal/photopolymer blends phase separate well to form a pioneer structure for the subsequently photopolymerized mircolens arrays. The morphology of the microlens arrays has been observed by SEM, AFM and scanning white light interferometer. The obtained focal length and f-number are 95 μm and 7.6, respectively. The results obtained from our experiments show a comparable light-gathering capability and can be applied in optical systems.

Keywords Liquid crystals; microlens arrays; phase separation; photopolymerization; self-assembly

1. Introduction

The ability to develop micro-optics for use in devices, such as communication performance, display technologies, and photovoltaic devices, has been of considerable interest over past decades [1]. Making the fabrication technique faster and more efficient requires that optical systems can be produced simply and parallel, and as a result the low-cost fabrication of microlenses is becoming necessarily and even plays an important role in many optics-based applications.

Several fabrication techniques for the microlens array have been demonstrated such as the photo-resist reflow method [2], the gray-scale photolithography [3], the micro-jet fabrication [4], the LIGA process [5], and so on. However, the reflow method has many drawbacks. For example, high processing temperature and the need for an etch-transfer process to produce stable optical components are not convenient in microlens production. As for the gray-scale photolithography, it is difficult to fit the desired shape precisely and distinguish the gray levels in a sharp edge so that the lens surface is also rough. In addition, the micro-jet fabrication suffers from limitations in minimum lens size and alignment accuracy. Similarly, the modified LIGA method is also quite complex especially for its time-consuming

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processes using expensive facilities. Although these above-mentioned techniques can produce micro-optics devices, their fabrication requires multiple sophisticated processes and long timescales in mass production.

To date, many techniques have also been developed for making arrayed microlenses in a variety of materials. For example, swellable polymer microlenses upon exposure to solvents create a tunable range of focal lengths [6]. Due to the hydrophobic effect in this technique, the well-defined boundary of microlenses in solvent vapors would either expand or contract, resulting in the variation of focal lengths. In addition, the stimuli-responsive hydrogel aperture undergoes reversible volume change in response to enviromental stimuli by absorbing and releasing water in order to function as adjustable focusing lenses [7]. Herein, this paper describes a novel technique for fabricating polymeric microlens arrays based on liquid crystal (LC)/photopolymer blends phase separation and self-assembled process owning to the surface tension.

2. Experimental Details

A schematic diagram of the fabrication process of this study is shown in Figure 1 which comprises several stpes. In Figure 1(a), a mixture of LC, a photocurable polymer and a photo-initiator was confined within a packing cell which is composed of

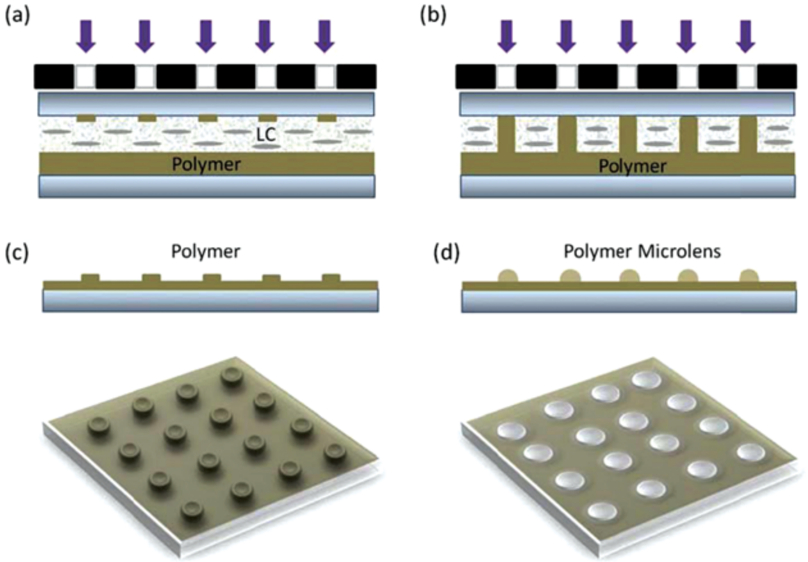

Figure 1. Schematic representation of the formation of self-assembled microlens arrays using photopolymerization based on phase separation. (a) A cross-sectional view of the packing cell that was injected with the mixture of LCs, photo-curable polymer and photo-initiator. (b) The cell was exposed to UV light through the photo mask which is patterned with circular-hole arrays. The polymer is polymerized under the radiation area and the polymer pillar structure is connected to the top and bottom substrates. (c) Peeling off the top substrate induces the broken columns which are affixed to the bottom substrate. (d) The uncured polymer around the short columns gradually accumulates to form the plano-convex lens. The microlens arrays are completely polymerized through another UV treatment. (Figure appears in color online.)

two glass substrates, and its cell gap was controlled by ~13 μm aluminum spacer. In this procedure, UV light was irradiated onto the photopolymer in areas that are not covered with a chrome-on-quartz photomask. The region irradiated by UV light was cured faster compared to the shaded region. This situation leads to the spatial distribution of the thickness of the cured polymer layer, and the polymer pillar arrays were thus formed between the top and bottom substrate. This process is indicated in Figure 1(b). The UV intensity is 5 mW/cm^2 and the irradiation time is 30 min. It is better to use thinner glass substrates (~100 μm) in this procedure to reduce the diffraction effect of incident UV light. The diameter of the pillar is in a range of 10~20 μm. After polymerization was performed with 356 nm UV light, the top substrate was subsequently removed and therefore the pillar arrays adhered to the substrate was broken into short column arrays which are shown in Figure 1(c). The short columns are always surrounded by some uncured polymer because polymers under the shadow of the photomask were not polymerized. Then we placed the substrate patterned with flat columns in a moisture-proof box for few hours, and the uncured polymer would tend to accumulate within the boundaries where the flat columns had originally dwelled. Finally, the accumulating polymer was self-assembled into the plano-convex shape as shown in Figure 1(d). We speculate the formation of a hemisphere shape was driven by the minimization of the surface free energy. After the second UV exposure, the microlens arrays that were made of uncured polymers became fully cured and stable. It is thus demonstrated that the microlens arrays are formed by self-assembled polymer and can be solidified by a photopolymerization.

Commercially available LCs E7 (from Merck), photocurable prepolymers, e.g., Isobornyl-methacrylate (IBOMA), and photoinitiator Irgacure 651 (purchased from Ciba Company) were mixed in our experiments. The experiments were carried out by a nearly 50/50 (wt/wt) mixture of LC E7 and a methacrylate-base polymer-forming material. The chemical structures of the compounds are shown in Figure 2. The methacrylate polymer, i.e., isobornyl methacrylate, was selected because the monomers can uniformly dissolve in LC, but also phase separate well during polymerization. Moreover, isobornyl methacrylate was chosen as the main component because it combines many properties like high solubility and low viscosity before experiment,

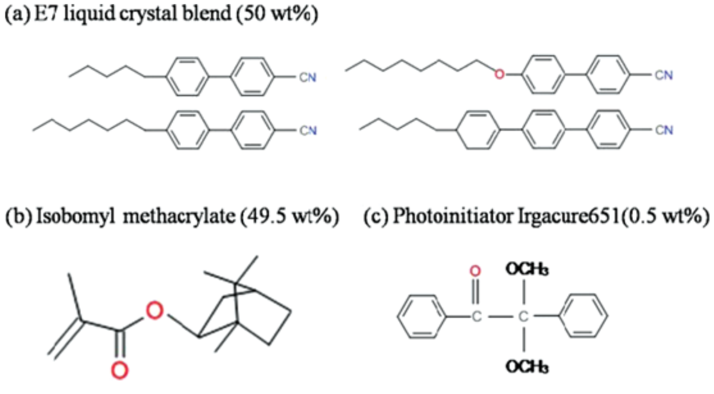

Figure 2. The chemical structure of the LC E7, the reactive monomer isobornyl methacrylate, and the photoinitiator Irgacure 651. The relative amounts of these compounds in the mixture are shown in parentheses. (Figure appears in color online.)

high diffusion rates and controlled phase separation during polymerization and rigidity after process [8]. In order to get a better absorption, photoinitiator Irgacure 651 has been added in the mixture for ultraviolet radiation in the wavelength region around 360 nm. Excellent phase separation is achieved due to strong immiscibility of the acrylates with LC molecules [9]. Due to strong immiscibility of the polymerized monomers, a diffusion of monomers occurs so as to maintain the equilibrium of their relative concentration in the mixed solution [10]. During the UV curing, an oxygen free environment is necessary since oxygen inhibits the radical polymerization of methacrylates. Therefore, the mixture enclosed within the glass cell could be prevented from the attack of oxygen in air. The surface profile of the microlenses was measured using a scanning white light interferometer (BMT WLI). The lens diameter was determined using a SEM (JEOL JSM-6390LV). The sag height of the microlenses was obtained using an atomic force microscope (Veeco CP-R).

3. Results and Discussion

3.1. *Morphologies Observation*

Each process of the formation of the self-assembled microlens arrays was observed under optical microscope. (see Fig. 3) First, the small column arrays were broken into half segments during cell splitting and remained on the substrate after the top substrate was peeled off. The diameter of the small column arrays is around 30 μm and its pitch is 50 μm shown in Figure 3(a). In the beginning, the uncured photopolymer was distributed randomly between the small columns spacing, then slowly flowing into the small column patterns and finally self-accumulating to form plano-convex structures. Figure 3(b) depicts its intermediate process and Figure 3(c) reveals the formation of the plano-convex microlens arrays. During photopolymerization period, the role of the liquid crystal plays a crucial factor to assist the prepolymer in localizing at the exact place where the light irradiated so that the polymer pillars could be formed well. On the contrary, the prepolymer would be polymerized randomly inside this cell.

The surface profile of the structure after the formation of the polymer microlens arrays has been visualized with the aid of interferometric microscope. Shown in Figure 4 is a top and side view of the microlens arrays. The average sag-height of the microlenses arrays is around 400 nm. The top view picture demonstrates that

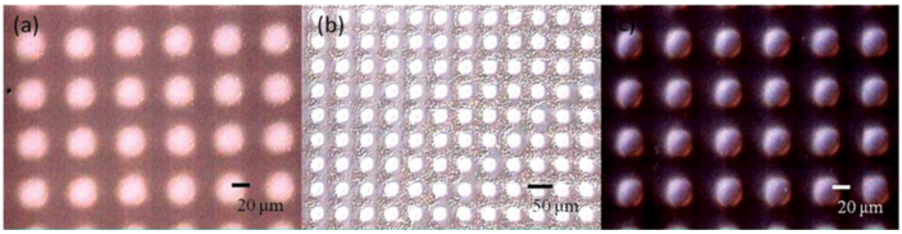

Figure 3. Optical microscopes image of polymer structure in each fabricating process. (a) A small column arrays after splitting the glass cell. (b) The uncured polymer around the column arrays are moving toward the column location. (c) The accumulated polymer gradually forms a hemisphere lens shape after few hours in a moisture-proof environment. (Figure appears in color online.)

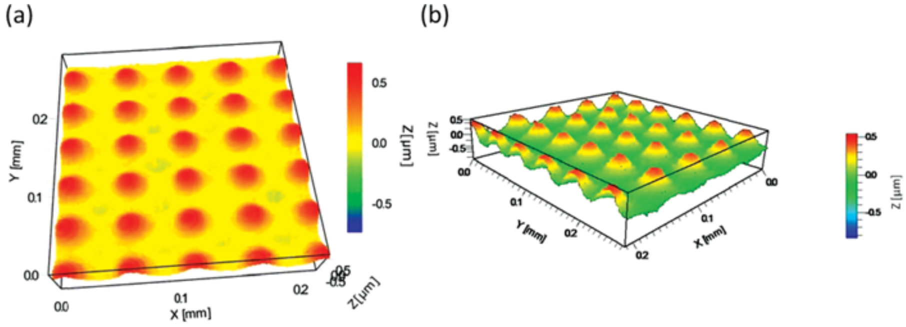

Figure 4. (a) Top view of a microlens array. (b) Side view of a microlens array. The resulting height variations could be observed with the aid of white light interferometer. (Figure appears in color online.)

the profile of the microlens arrays is uniform and each microlens is equally high. Figure 5(a) reveals the top view scanning electron microscopy (SEM) image of a self-assembled microlens with diameter $d = 12\,\mu m$, while that in Figure 5(b) shows a lens profile obtained by an atomic force microscope. The samples for SEM measurement were previously treated as follows. The resultant polymer microlens

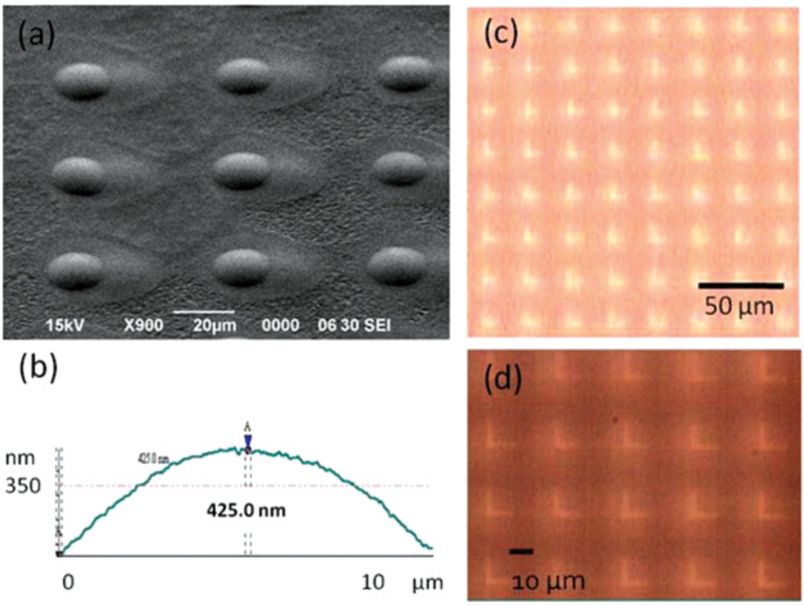

Figure 5. (a) The SEM image of a microlens array that was self-assembled by uncured photopolymer. The lens has a 425-nm height and 12-µm diameter. (b) The lens-profile obtained from an atomic force microscope (AFM). The average sag-height is 425 nm. (c) The image was recorded with a reflective transmission optical microscope by projecting a letter "L" through an array of microlenses. The object "L" was developed on the silicon substrate by electro beam lithography. (d) Enlarged picture of (c) with higher magnification. (Figure appears in color online.)

Table 1. The parameters of the self-assembled microlenses. The lens height h and diameter d are measured values, while the spherical radius R and focal length f are obtained from theoretical equations [11]

h [μm]	d [μm]	R [μm]	f [μm]	$f_{\#}{}^{a}$
0.42	12.42	45.5	95	7.6

[a] The *f-number* ($f_{\#}$), which indicates the light-gathering power of the lens.

arrays were first rinsed with ethanol to remove the LCs. At last, the polymer surface was coated with thin Au film to avoid electron damage.

3.2. *Optical Simulation*

On the basis of geometry and optical theory [11], the radius of curvature (R), focal length (f) and *f-number* ($f_{\#}$) can be calculated using the following formulas:

$$R = \frac{h^2 + r^2}{2h}, \quad f = \frac{R}{n-1}, \quad f_{\#} = \frac{f}{2r} \tag{1}$$

where h is the sag height, r is the radius of the plano-convex lenses, R is the radius of the curvature of the lenses, n is the refractive index, and f is the focal length. In these calculations, the refractive index is 1.477 for methacrylates microlenses. Following the above equation, for example, the $f_{\#}$ of the 12 μm-lens is approximately 7.6. These optical parameters of the 12 μm-lens are listed in Table 1. The smaller $f_{\#}$, which indicates the light-gathering power of the lens, is better. The obtained $f_{\#}$ results in our work are comparable to those of the previous reports using other methods [12,13]. Figure 5(c) demonstrates that the letter "L" was imaged through the microlens array by placing a silicon substrate behind the lens substrate. The "L" object was developed on the silicon substrate by electron beam lithography. Enlarged picture with higher magnification is shown in Figure 5(d). These results indicate that the microlenses have good light gathering ability.

4. Conclusions and Perspectives

In summary, we have explored the simple fabrication of self-assembled microlens arrays by combining the LC/photopolymer phase separation, the subsequent photopolymerization, and polymer self-assembled process. The cured polymer arrays adhere to the top and bottom substrates, and produce a self-sustaining polymer column structure making it possible to be a pioneer base for microlenses structure. After the top glass is peeled off, the uncured polymer around the polymer pillar is self-assembled to form a hemisphere shape covering each polymer pillar at room temperature. Such a sequential process leads to a dense plano-convex microlens arrays on the surface of the substrate. The method presented here is quite unique from several aspects. First, it provides a non-heating and non-pressure way to produce the microlens arrays. Second, the process is not as complex as the conventional photolithography. Furthermore, the methacrylate-based polymer is an index-matching material which could reduce light scattering between the microlens arrays and the glass substrate. Finally, the microlens array developed in this study is a promising candidate for broad applications, for example, as key components in optical parallel-processing systems and large-scale flexible display technology.

Acknowledgment

One of us (CYC) would like to acknowledge the support from the National Science Council and Ministry of Education of the Republic of China.

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