Phase Separated Composite Film based LC Devices With and Without Alignment Layers

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The phenomena of *spatially isotropic* phase separation of liquid crystal from its solution with a polymer has long been used for polymer stabilized and polymer dispersed LC structures. A new regime of phase separation, in which the phase separation proceeds *spatially anisotropically*, have recently been discovered. In one of the regimes, the rate of polymerization proceeds relatively slowly resulting in adjacent parallel layers of liquid crystal and solidified polymer known as *Phase Separated Composite Films* (PSCOF). PSCOF devices with only one alignment layer have been made using nematic (π-cell, TN, and STN), ferroelectric (FLC), and antiferroelectric (AFLC) liquid crystals. FLC devices possess grey scale and switch 100 times faster at low fields than SSFLC cells. Electrically controllable 1- and 2-dimensional diffraction grating and microlens array with focal lengths adjustable from 1.8 mm to infinity have also been demonstrated. With the use of plastic substrates, the PSCOF method lends itself to easy and low cost fabrication of very flexible cells.

I. Introduction

Traditionally, liquid crystals (LC) devices are prepared by sandwiching a nematic LC between two glass substrates with transparent electrodes and alignment layers to obtain specific configuration of the optic axis. An electric field is applied across the cell to change the direction of the optic axis and to alter the optical path length in different regions of the devices. They operate in what is known as the birefringence mode. In the past 20 years, polymer dispersed liquid crystals (PDLC) have been developed [1-4]. PDLC devices operate in the scattering mode, where an electric field is used to change the amount of the light scattered by LC droplets due to a mismatch of refractive indices at the droplet boundary. PDLC structures are a result of isotropic and relatively fast phase separation at concentrations above ~ 15wt % of polymer.

Here, we report methods of preparing LC devices using *anisotropic phase separation* [5]. The rate of phase separation is controlled and deliberately kept low to allow the system to undergo a complete phase separation in to separate regions of nearly pure LC and pure polymer. This phase separated composite films (PSCOF) method, in the simplest case, yields adjacent uniform layers of the LC and polymer parallel to substrates. A recent phenomenological model [6] has been successful in providing an insight in to the process of phase separation leading to the

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formation of PSCOF structures. The configuration of the optic axis in the LC layer can be controlled with an alignment layer on the substrate that is in contact with the LC film. Evidently, these devices operate in the birefringence mode just like the conventional devices.

II. Preparation of PSCOF Structures

The method used to prepare PSCOF structures is essentially the same as used for building PDLC and PSCT devices. One starts with a pair of substrates coated with transparent electrodes of indium-tin-oxide (ITO). One of the substrates is spin-coated with an alignment layer of commonly used polymers, such polyimide (PI) or poly-vinyl alcohol (PVA), which is rubbed. The second substrate is left untreated. They are separated by commonly used glass rod or bead spacers of diameter d. We used commercially available photocurable prepolymers [NOA-65, NOA-68, and NOA-72] from Norland and liquid crystals from well known vendors. The prepolymer and the LC are mixed in a ratio ranging from 15:85 to as high 60:40 and introduced in to the cell by capillary action at a temperature well above the clearing point of the LC. Cells made with flexible substrates are filled by spreading the mixture using a roller. Phase separation is initiated by exposing the cell to UV light through the substrate without the alignment layer. The source of UV light is a high pressure mercury vapor lamp operated at 200 W of electrical power. The cell is exposed to a collimated beam of UV for approximately 2-10 minutes for different devices.

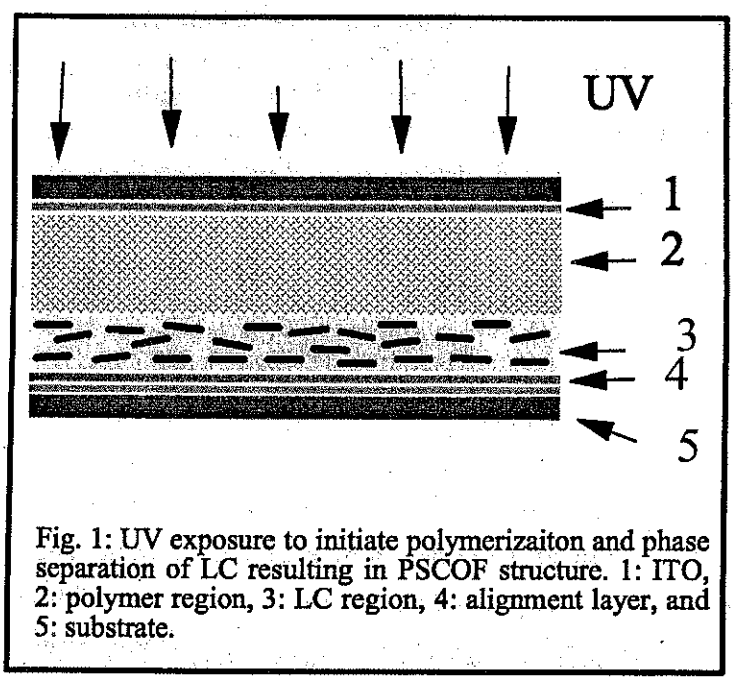

Fig. 1: UV exposure to initiate polymerizaiton and phase separation of LC resulting in PSCOF structure. 1: ITO, 2: polymer region, 3: LC region, 4: alignment layer, and 5: substrate.

The mechanism responsible for the formation of PSCOF is similar to anisotropic polymerization[7]. Because the absorption of the UV light is predominantly by the LC molecules in the solution, an intensity gradient is produced in the sample. Consequently, NOA-65 molecules first undergo polymerization near the substrate closest to the UV source and LC molecules are expelled from the polymerized volume forcing them to move away from the source. Droplet formation is inhibited because of relatively slow rate of phase separation and fast diffusion of the relatively small LC molecules. Consequently, the phase separated liquid crystal moves closer to the second substrate towards the region of lower UV intensity. As schemetically shown in Fig. 1, phase separation results in a

solidified film of polymer on the substrate close to the UV source and a liquid crystal film between the polymer film and the second substrate.

The resulting structure depends on a number of parameters including concentration, temperature of phase separation, spatial gradient in the rate of polymerization, diffusion coefficients of the LC, prepolymer, and polymer substrate wetting properties of various components. A generalized representation of the structures that can be obtained is shown in Fig. 2. At low polymer concentrations PSCT or cellular [8] structures are obtained. At higher polymer contents the results depend on the phase separation rate. For fast phase separation, PDLC/PDFLC are obtained. As the polymerization is slowed down (by, say, reducing the intensity of UV light), the droplets become larger and are formed closer to the substrate away from the UV source. At the slowest rates, the relative diffusion rate of LC and prepolymer dictate whether columnar or film structure are obtained.

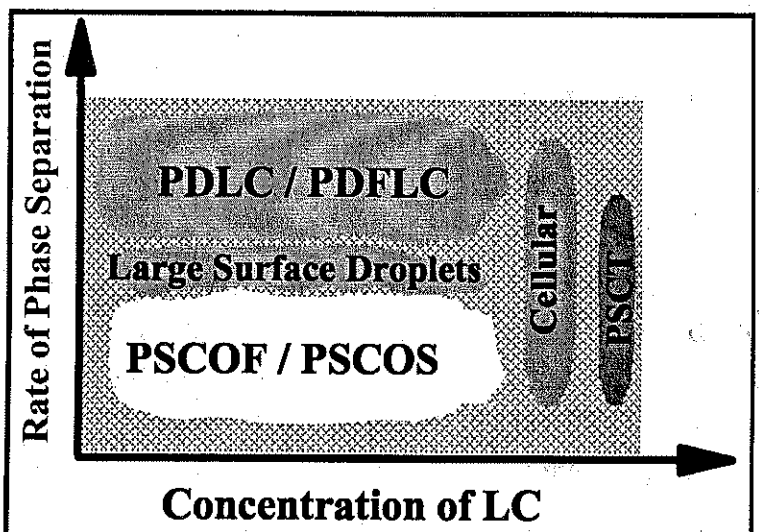

Fig. 2: Phase separation yields different results depending on the concentration, rate of phase separation, relative viscosities of the components, and substrate wetting properties.

Measurements on PSCOF cells, prepared with different concentrations of nematic liquid crystal E7 and prepolymer NOA-65, show that the thickness of the LC layer depends on the amount of LC in the mixture and that only a small amount (< 5%) of LC is trapped in the polymer film. Light scattered by the trapped LC is found to be negligible.

The presence of a PVA alignment layer on the substrate in contact with LC enhances the formation of uniform layers. In its presence, a PSCOF structure (parallel layer morphology) is obtainable at higher UV intensities (i.e., faster phase separation) for the range (1-5 μm) of cell thicknesses that we have studied. This is because the LC material likes to wet the PVA layer and easily spreads over it. The LC molecules near the alignment layer respond to its anchoring potential and align parallel to the rubbing direction. The volume of aligned LC grows during the phase separation process. Oriented LC molecules determine the microscopic structure of the polymer-LC interface which becomes compatible with their alignment. Although it appears that the use of one alignment layer can produce only homogeneously aligned cells, we have

successfully prepared twisted nematic devices [4] by adding a chiral dopant to induce a twist ranging from 90 to 270°.

III. Applications of the PSCOF Method

The PSCOF technology, because of its simple fabrication process and unique internal structure, provides a number of advantages such as ability to prepare LC cells of practically any thickness just by changing the concentration of the LC+prepolymer mixture, mechanical stability leading to the easy fabrication of flexible devices, and important and advantageous modification of the electro-optical effect of FLC and AFLC. Furthermore, the highly insulating polymer film inside the cell eliminates the probability of electrical short circuiting in thin devices and/or active matrix devices. TN, STN, FLC, and AFLC devices constructed with the PSCOF method require only one alignment layer. The following illustrate a number of applications of the PSCOF method to prepare various types of devices.

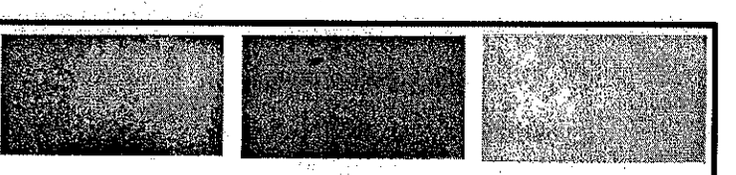

Fig. 3: Homogeneous E7 cells prepared with 2 μm spacres and with 0%, 40%, and 60% polymerresulting in uniform 2, 1.2 and 0.8 μm thick LC film of 1"x2" size.

A. Electrically Controllable Birefringence (ECB) Devices

Thin LC cells of any thickness can be prepared using inexpensive spacers of larger size which are easily available and have smaller size distribution. The mixture concentration can be varied to obtain the desired thickness. This enables one to precisely fine tune the optical path length of the device. Furthermore, cells prepared with the PSCOF method tend to be very uniform. Fig. 3 shows devices prepared using 2μm spacers but different LC concentration with homogeneously aligned nematic of thickness as small as 0.8 μm (~200 molecules)! Still thinner films are possible. Measurements of the response time of such nematic devices reaveal very fast switching, Fig. 4, less than

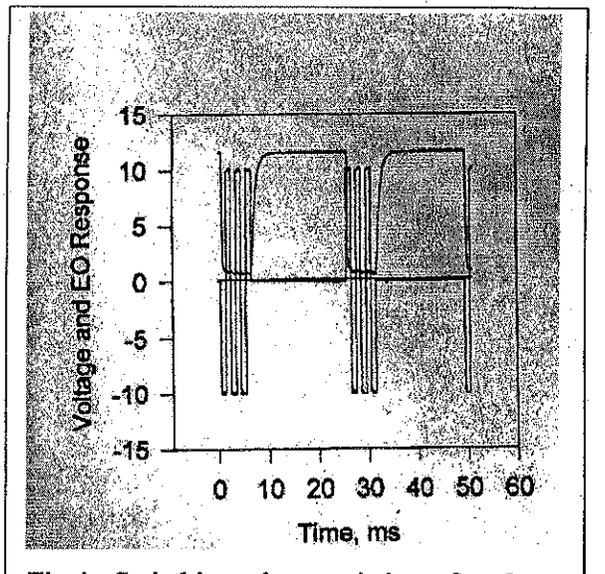

Fig.4: Switching characteristics of a 3μm thick homogene-ously aligned E7 cell. The measured switching speed with ±10V is ~1 - 2 ms.

2 *ms* with a driving voltage of 10V. In thinner cells the speed became as small as 250 μs for approximately 20V across 2μm cell.

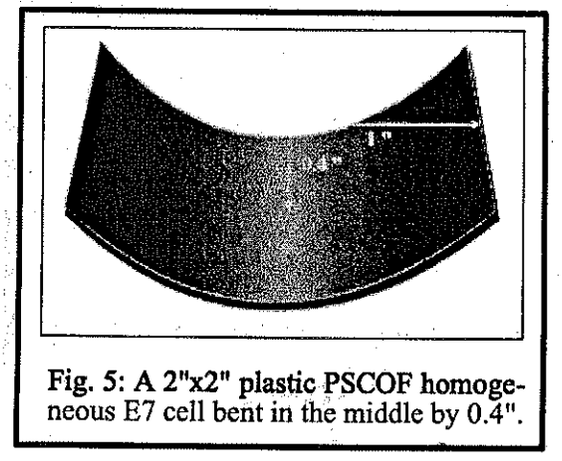

Fig. 5: A 2"x2" plastic PSCOF homogeneous E7 cell bent in the middle by 0.4".

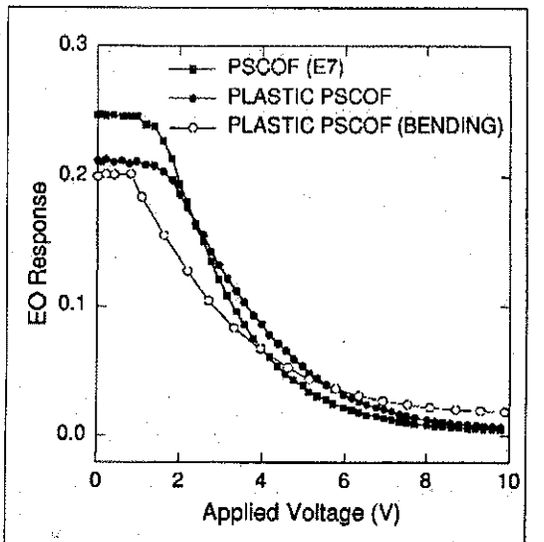

Fig. 6: Transmission characteristics of PSCOF-ECB cell filled with E7 and measured in glass cell, plastic cell without any bending and plastic cell with bending as shown in Fig.5.

The polymer-LC interface in PSCOFs binds to the substrate adjacent to the LC at a large number of randomly distributed but microscopic points providing it rigidity and strength and thereby decreasing the sensitivity to external mechanical deformations without compromising performance. Such mechanical deformations are known to render the SSFLC devices [9] impractical and have been one of the major obstacles to their commercialization. Under a large local pressure, such cells exhibit temporary changes in thickness. Their thickness reverts back to the original value within 5-15 seconds after the pressure is released. This can be illustrated in devices made with flexible plastic substrates. Under severe bending demonstrated in Fig. 5, the transmission characteristics of such a device remains unaffected as shown in Fig. 6. The slight measured change in the dark and bringht levels arises not from any internal changes but due to the fact the director now lies on a curved surface. Apparently, PSCOF devices are ideally suited for flexible displays [10].

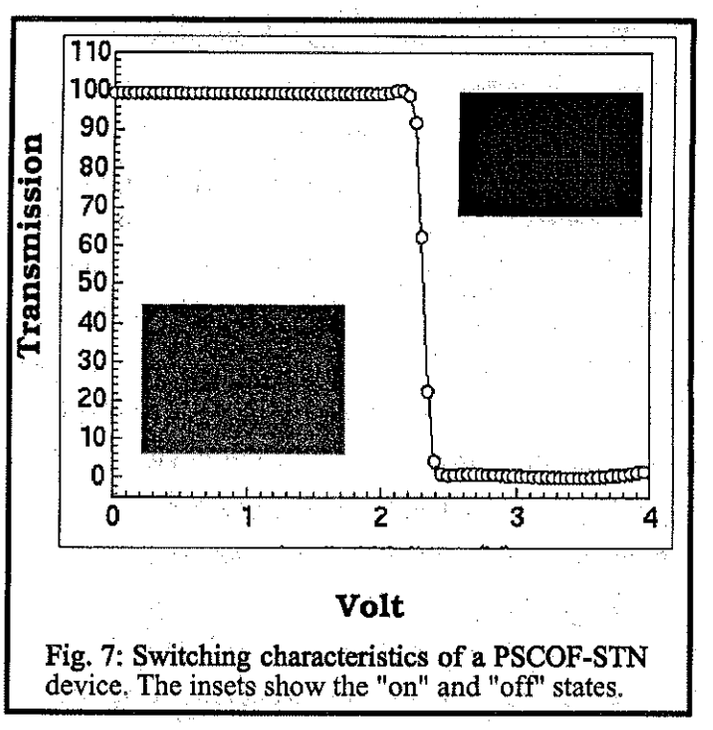

Fig. 7: Switching characteristics of a PSCOF-STN device. The insets show the "on" and "off" states.

B. STN Devices

TN and STN devices have been fabricated by adding a small amount of cholesteric material to induce the desired twist. With only one alignment layer, the LC imprints its own anchoring conditions compatible with the alignment dictated by the rubbed surface during the phase separation process. This creates strong anchoring on one side and weak anchoring conditions at the LC-polymer interface which is conducive to giving sharper threshold curves than with two rubbed surfaces. The results of our initial attempts to fabricate STN devices with ZLI-5400 and NOA-77 are shown in Fig. 7. The LC to prepolymer ratio was approximately 85:15 and total cell gap was 5.3 μm. A small amount of chiral dopant was added to induce a twist of ~180°. The phase separation was carried out at 40°C at a temperature corresponding to the nematic phase in pure material. The ratio V_{on}/V_{off} was 1.07 suggesting a multiplexability of up to 200 lines.

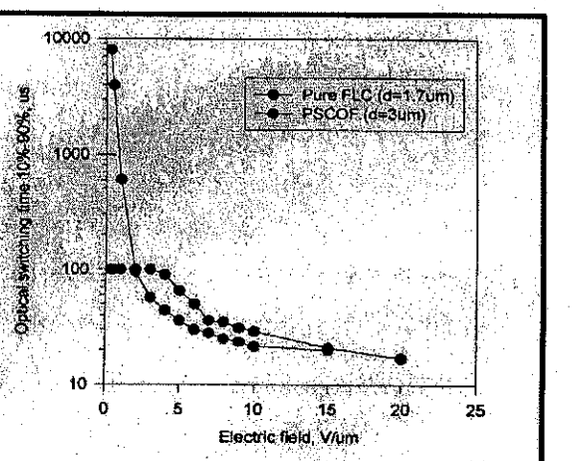

Fig. 8: Electric field dependence of FLC time response. At grey levels, the PSCOF device is nearly 100 times faster than the SSFLC cell.

C. Ferroelectric LC Devices

The SSFLC cells exhibit bistability [9] and electric field dependent switching times (Fig. 8). In a PSCOF device containing the liquid crystal Felix-15-100 (Hoechst, Germany), switching at low fields is two orders of magnitude faster than in SSFLC. Also, the switching angle, which is the difference in molecular orientations in the "on" and "off" states which is a direct measure of the optical transmission is found to continuously depend on the applied field. The suitability of FLC-PSCOF devices for the active matrix (AM) addressing mode is examined in simulated AM mode using an external MOSFET. One side of the cell was kept at 10V, while the other was connected to the source of the MOSFET. The drain voltage was square wave modulated between 0 and 20V, thereby producing a square wave signal between -10 and 10V across the

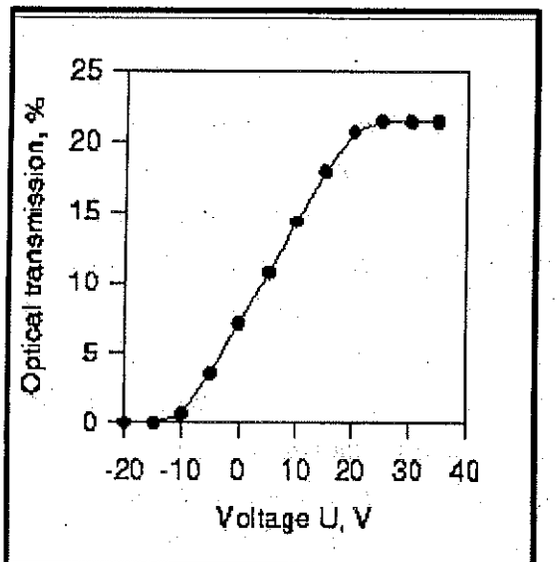

Fig. 9: Linear grey scale in PSCOF-FLC cell in simulated active matrix addressing mode.

cell. The gate was opened for a short period to effectively connect the drain to the cell, after the drain voltage changed polarity. The transmission as a percentage of incident intensity was measured for different drain voltages and is shown in Fig. 9. Clearly, they *possess a continuous and natural gray scale* which is necessary in most applications. Overall light throughput in PSCOFs is ~80 %, much higher than ferroelectric PDLCs [11,12] because the light scattering from the small number of LC droplets embedded in the polymer film is negligible. The switching voltages are also much lower than those of the PDFLC. The shortest usable gate pulse period was determined to be 1μs indicating that these devices are capable of addressing 8000 lines at a refresh rate of 120Hz! With further optimization of LC material and the PSCOF process it should be possible to further reduce the value of shortest gate pulse.

It should also be pointed out that owing to higher resistivity of the internal polymer layer in cells prepared with PSCOF process, the charge retention time in increased. The cell maintains its transmission higher that 99% of the maximum for a long period of 3.5 seconds!

The electro-optical response of an AFLC-PSCOF is found to be very different from that of the pure (or surface stabilized) AFLC. In the latter, the antiferroelectric order is deformed [5] at small field strengths. At high fields, a sharp transition from the antiferroelectric to the field induced ferroelectric state is observed [13]. After the field has been switched off, the system returns to the same antiferroelectric state. In the PSCOF structure, AFLCs exhibit threshold-less response without a transition to the field-induced ferroelectric phase. AFLC order in PSCOFs are able to withstand much higher deformation and provide a grey scale. Furthermore, they exhibit optical memory (bistability) as the optical transmission levels in which these devices remain after the application of positive and negative pulses are different.

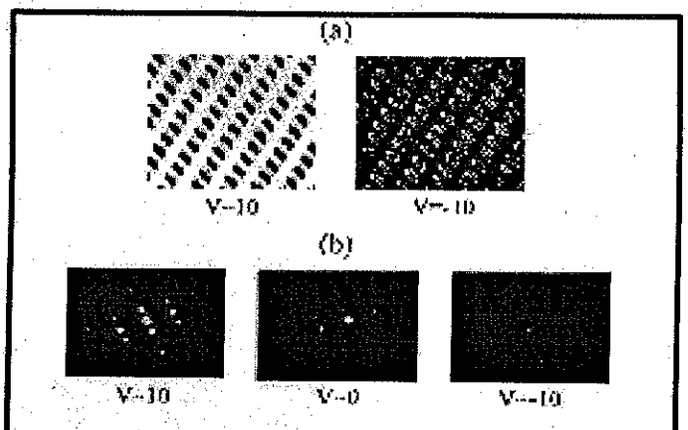

Fig. 10: (a) 2-dimensional diffraction grating with FLC, between cross polars under the effect of opposite electric fields. (b) Changes in the diffraction pattern with different applied voltages.

D. Field Controlled PSCOF Diffraction Gratings

PSCOF structures can be fabricated by affecting phase separation in two and three dimensions with the help of photo-masks. For example, the use of a mask with parallel lines results in alternate lines of pure polymer and lines of LC + polymer, permitting their use as tunable optical gratings for diffractive optics and beam steering applications. Other very interesting and useful

structures form when phase separation occurs in 3-dimensions (3-D). For example, when a cell is exposed through a 2-dimensional grid pattern, the LC molecules diffuse in the two in-plane directions towards shaded regions and away from the UV source. Regions of pure polymer and regions with sub-structures of pure LC and pure polymer are obtained. The alignment layer orients LC molecules homogeneously. An applied electric field reorients the molecules changing the effective relative index of refraction for the incident beam of light. This permits a control of 2-dimensional (2-D) diffraction pattern with the application of positive and negative voltages to an FLC grating, as shown in Fig. 10. With matrix addressing, such a device can be used as 2-D diffraction grating for reprogrammable interconnects to couple an incoming light beam to a number of outgoing optical fibers.

E. Microlens Array with Field Controlled Focal Length

Most importantly, the PSCOF method permits construction of microlens array with great ease. It requires a mask with circular dot pattern to block the UV light. LC diffuses to the shaded areas, i.e., under the circular dots, upon UV induced phase separation forming a plano-convex volume of homogeneously aligned LC, Fig. 11. This shape of LC volume offers a gradient refractive index (GRI) profile and acts as a converging lens. Lenses have been made with natural focal length (*f*) ranging from 50 *mm* down to less than 2 *mm* with both the nematic and FLCs. One such FLC microlens array is

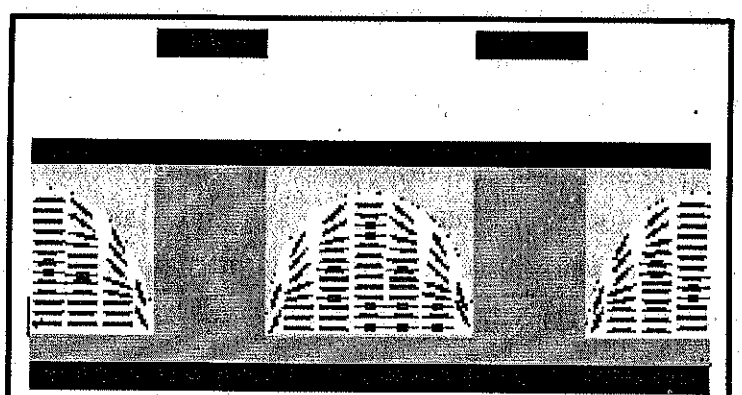

Fig. 11: Schematic representation of the fabri-cation, internal structure, and director configuraiton inside microlens array.

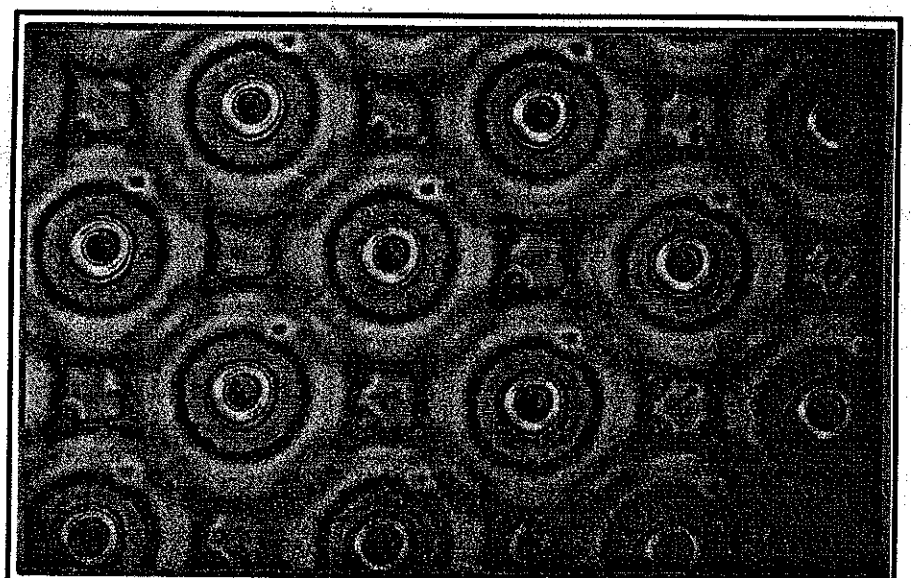

Fig. 12: Microlens array with focal length of 1 cm.

shown in Fig. 12. For this microlens array, lens diameter is ~400 μm, color fringes show varying optical pathlength within each lens, and focused laser beam through one of the lenses are shown on an expanded scale in Fig. 13. The natural focal length of this lens is 1*cm*.

The microlens arrays can be matrix addressed just like the display devices permitting one to perform wavefront shaping. These have a great potential in robotic navigation and optical

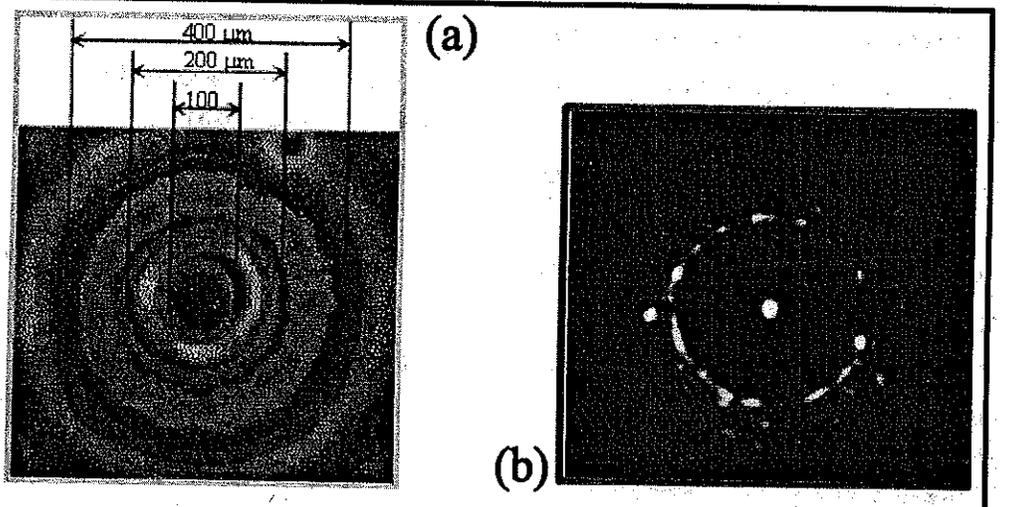

Fig. 12:(a) Dimensions of one of the microlenses in the array shown in Fig. 11 on expanded scale, and (b) Focussing of a laser beam by one of these lenses.

interconnects. Using *fly's eye* effect, devices can be fabricated to aid fighter pilot detect moving objects in much shorter times. Additional uses involve integral photography, and in writing optical disks in multi-layers to increase their capacity.

IV. Summary

Here, we have reported the basics of a new phase separation with great potential for use in fabricating various electro-optical devices using LCs at low cost and simplified process. The results show that it can be used essentialy any type of device that is possible with other methods. The PSCOF is also capable of producing microlens array.

V. Acknowledgments

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