Fabrication of electro-optic devices using liquid crystals with a single glass substrate

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A recently developed phase separated composite film method has been employed to fabricate a liquid crystal (LC) based electro-optical device using a single glass substrate. The resultant device is made of adjacent parallel layers of LC and polymer created by phase separation. The LC layer is confined between a film of solidified polymer layer on one side and the glass substrate on the other. Electro-optical properties of these devices demonstrate their technological potential in light weight and hand-held electronic products.
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Conventional liquid crystal (LC) electro-optical (EO) devices, such as flat panel displays, are prepared by sandwiching the LC between two glass substrates with a transparent indium tin oxide (ITO) electrode pattern and rubbed polymer alignment layers to facilitate alignment of the LCs optical axis in a predetermined configuration. It is not possible to avoid the use of two substrates because of the fluid nature of LCs. There has been a considerable effort in recent years to replace glass substrates with plastic films for thin profile, light weight, and flexible devices which are essential requirements for hand-held electronic products.[1]

In the past 20 years, techniques to prepare dispersions of microscopic LC droplets in a polymer matrix have been developed.[2–4] These polymer dispersed liquid crystal (PDLC) devices operate in the scattering mode, in which an applied electric field is used not to control the extent of the light scattered by the LC droplets caused by a mismatch of refractive indices at the droplet boundary. PDLC structures are the result of isotropic and relatively fast phase separation. Recently, a method using anisotropic phase separation has been developed to fabricate phase separated composite films (PSCOFs) of LC and polymer.[5] The rate of phase separation is controlled and deliberately kept low to allow the system to undergo a complete phase separation into regions of nearly pure LC and solid polymer. This PSCOF method can, in general, be used to prepare multilayer or other complex geometrical structures. In the simplest case, it yields adjacent, uniform, and parallel layers of the LC and the polymer. The configuration of the optic axis in the LC layer is controlled with an alignment layer on the substrate that is in touch with the LC. The operation of such PSCOF devices exploits the birefringence of the LC and relies on changes in the direction of the LCs optic axis in response to an applied electric field, as in conventional displays. Since the LC is naturally confined between one of the glass substrates and the phase separated polymer layer, the PSCOF method lends itself to building devices with a single glass or plastic substrate.

Here, we report the fabrication of an EO device with the PSCOF method using the nematic liquid crystal and requiring only one supporting substrate imprinted with in-plane electrodes to apply the electric field.

The materials used are commertically available E48 (Merck) nematic LC and UV curable optical adhesive NOA-72 (Norland) for prepolymer. A solution of E48 and NOA-72 was prepared in 1:1 ratio. The in-plane electrodes are prepared by etching 100 μm wide interdigitated ITO strips on the glass substrate with a separation of 100 μm. In order to achieve a wide viewing angle, we patterned the ITO in a chevron shape. The substrate was spin coated with 1 wt% Nylon 6 in trichloroethanol. The Nylon 6 film was unidirectionally rubbed after drying to achieve homogeneous LC alignment. To obtain an optically uniform film of the LC+prepolymer mixture, we used a two step process. First, the mixture was spread on the substrate using a steel blade as shown in Fig. 1. The coating direction was kept parallel (or antiparallel) to the rubbing direction to avoid LC misalignment by shear stress. The thickness of the film was about 10 μm. Then, we spun the glass substrate for 30 s at 1500 rpm to increase its uniformity. Phase separation was initiated by exposing the film directly to a collimated beam of UV light for approximately 60 min to fully cure the prepolymer. The source of UV light was a high pressure mercury vapor lamp operated at 400 W of electrical power.

The mechanism responsible for the formation of PSCOF is similar to the anisotropic polymerization[6] reported previously. Because of the absorption of the UV light by the LC and prepolymer molecules in the solution, an intensity gradient is produced in direction perpendicular to the sample. Consequently, NOA-72 molecules first undergo polymerization near the UV source at the air-film interface and the LC is

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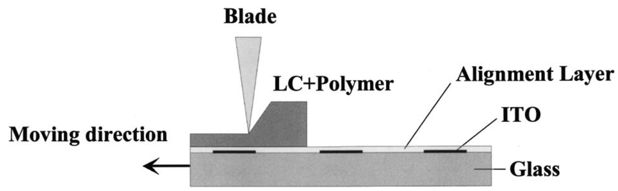

FIG. 1. Schematic illustration of the fabrication process.

expelled from the polymerized volume, forcing them to move away from the source. Droplet formation is inhibited because of the relatively slow rate of phase separation and fast diffusion of the relatively small LC molecules. As a result, the phase separated liquid crystal moves closer to the glass substrate. The LCs tendency to wet the alignment layer on the substrate enhances the formation of a uniform film. 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 phase separation. Oriented LC molecules determine the microscopic structure of the polymer-LC interface which becomes compatible with the LC alignment.

Measurements of PSCOF cells prepared with different concentrations of nematic liquid crystal show that the thickness of the LC layer depends on the amount of LC in the mixture and that $<2\%$ of LC is retained in the polymer film. The light scattered by the trapped LC is found to be negligible.

As shown schematically in Fig. 2, the LC layer is confined between the glass substrate and the solidified polymer layer which replaces the second glass substrate in conventional cells. The LC acquires a homogeneous alignment under the influence of the rubbed alignment layer. Thickness of the LC layer mainly depends on the concentration and the speed of spin coating. The LC and polymer films are uniform except in microscopic regions where the polymer-LC interface bonds to the substrate. These bonding sites are affected by the concentration, chemical nature of the LC, defects, and singularities in the alignment layer, temperature, and the rate of phase separation. The process can be optimized to reduce the lateral cross section of these bounding sites to $\sim 1\ \mu$m and to control their density resulting in an almost perfectly uniform LC film. It is important to note that such PSCOF devices can also be made using flexible plastic substrates.

To determine the internal structure of the devices obtained, one of the cells was viewed under a scanning electron microscope (SEM). As evident from Fig. 3, a 3-μm-thick solidified film of polymer is formed. For this device, since the prepolymer and the LC were mixed in 1:1 ratio, we estimate that the thickness of LC layer also to be $\sim 3\ \mu$m.

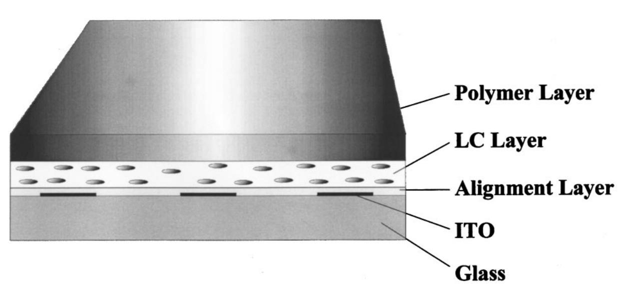

FIG. 2. Schematic diagram of fabricated LC device with a single glass substrate.

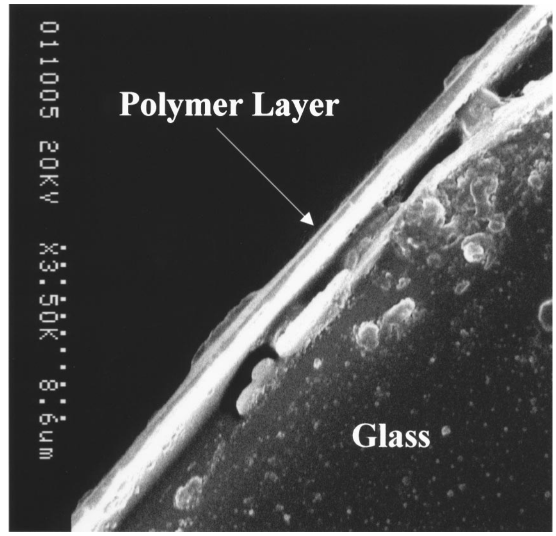

FIG. 3. SEM image showing substrate and polymer film.

Figure 4 shows the microscopic and macroscopic textures under a polarizing microscope with/without applied voltages. With zero applied voltage, the uniform dark state is achieved due to good LC alignment [Fig. 4(a)]. The small number of defects visible as faint spots in the photograph are due to nonuniform mixing of the LC and prepolymer [Fig. 4(b)]. Above a certain field strength (0.2 V/μm), the LC molecules start to reorient and align along the electric field due to their positive dielectric anisotropy. At higher field strengths (>1.5 V/μm), one can obtain the white state in which the LC molecules have turned by 45° with respect to the rubbing direction [Fig. 4(c)]. The results demonstrate that devices so fabricated using single glass substrate are uniform and possess gray scale capability. Figure 4(d) shows a

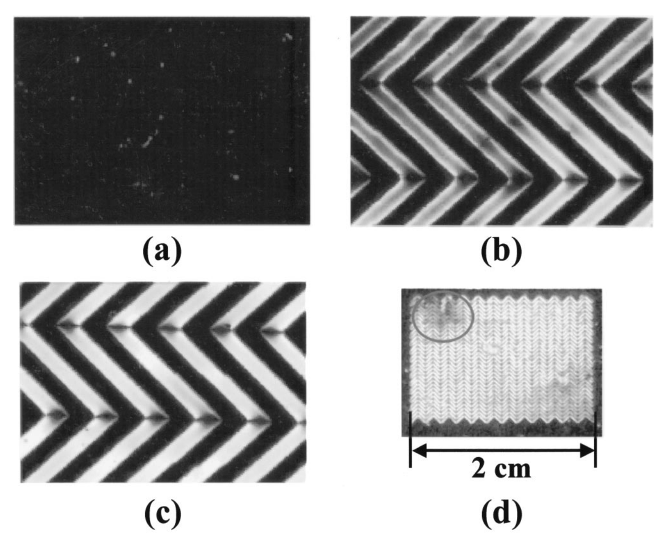

FIG. 4. Microscopic textures under polarizing microscope with/without applied field: (a) 0, (b) 0.7, and (c) 1.5 V/μm

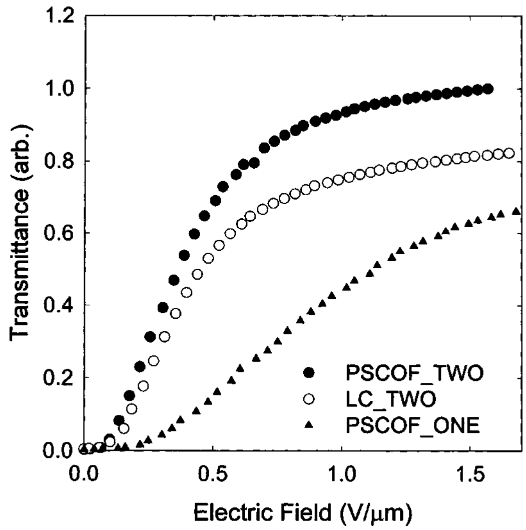

FIG. 5. Transmission vs applied field for the one substrate (PSCOF–ONE), two-substrate (PSCOF–TWO), and normal IPS cell (LC–TWO).

1.5 cm×2 cm cell between crossed polarizers with an applied field of 1.5 V/μm. Except for a small area enclosed by the circle, the whole sample is in the uniform white state. The dark area is caused by nonuniformity of the LC and prepolymer coat.

Figure 5 compares the field dependence of optical transmission of a one substrate device (PSCOF–ONE) with a conventional two substrate (LC–TWO) and a two substrate PSCOF (PSCOF–TWO) cell. All devices were operate in the in-plane switching (IPS) mode. The two-substrate cells show almost the same behavior. Their transmittance begins to increase at a field of about 0.2 V/μm, and reaches its maximum value at 0.8 V/μm. In contrast, transmission through the PSCOF–ONE cell reaches saturation at 1.5 V/μm. It is possible to reduce the driving voltage by optimizing the concentration, dielectric anisotropy of LC, overall cell gap, and the electrode pattern. The maximum contrast of the one-glass sample is about 200:1 which is comparable to a normal IPS sample. The field driven and relaxation times are 7.8 and 20 ms at 1.5 V/μm, respectively. The cell exhibits good switching characteristics at all gray levels.

We have fabricated a LC device using anisotropic phase separation and a single glass substrate. The resultant structures are made of adjacent parallel layers of liquid crystal and solidified polymer. The electro-optical properties of these displays are comparable to the normal displays using two glass substrates. The method demonstrated here opens the doors to a class of devices.

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