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Hongwen Ren
University of Central Florida

Shin-Tson Wu
University of Central Florida

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Anisotropic liquid crystal gels for switchable polarizers and displays

Hongwen Ren and Shin-Tson Wu^{a)}

School of Optics/CREOL, University of Central Florida, Orlando, Florida 32816

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An anisotropic liquid crystal gel with low operating voltage, high contrast ratio, broad bandwidth, wide viewing angle, and fast response time was demonstrated. In the voltage-off state, the gel is highly transparent. When the gel is activated by an electric field, light scattering occurs for the polarization along the molecular axis. By incorporating a $\lambda/4$ film between the gel and a reflector, this reflective device is useful for modulating unpolarized light. Potential applications of such anisotropic gel as a broadband switchable polarizer, reflective display, and transfective display are emphasized. © 2002 American Institute of Physics. [DOI: 10.1063/1.1502021]

Liquid crystal (LC) gel^{1–3} exhibits a similar light scattering behavior to the polymer-dispersed LC (PDLC)⁴ and polymer-stabilized cholesteric texture (PSCT).⁵ In a LC gel, a small percentage (2%–7%) of diacrylate monomer is mixed in a nematic LC host. The mixture is then injected into a LC cell with the proper surface treatment. In the voltage-off state, the gel is highly transparent due to the ordered molecular alignment. When the voltage exceeds a threshold, the exerted torques from the electric field and polymer networks are working against each other. As a result, microdomains are formed along the polymer chains. If the domain size is near the wavelength, light scattering takes place. Unlike PDLC or PSCT, the light scattering of LC gel is rather anisotropic. The light polarization along the cell rubbing direction is scattered and the perpendicular component is transmitted. Thus, the LC gel can be used as a switchable polarizer for sensor protection, telecom optical switch, and flat panel displays.⁶

Two types of LC gels have been developed depending on whether a homogeneous^{1–3} or homeotropic⁷ alignment is used. The homogeneous-aligned gel is useful for modulating linearly polarized light and the homeotropic gel is intended for unpolarized light. Each type has its own merits and demerits. For instance, the contrast ratio of an 8- μm homogeneous gel could exceed 15:1 except its voltage is high ($V > 20 V_{\text{rms}}$). On the other hand, a homeotropic cell has a lower voltage ($V \sim 15 V_{\text{rms}}$), but its contrast is limited to $\sim 10:1$ (for unpolarized light). Low operating voltage ($< 7 V_{\text{rms}}$) is critical for the silicon thin-film-transistor based flat panel display. Reducing the cell gap would lower the dark-state voltage, nevertheless, the contrast ratio is also reduced.

Both monomer concentration and cell gap have important effects on the operating voltage and contrast ratio of a LC gel. A higher monomer concentration or thicker cell gap definitely leads to a higher operating voltage. However, a higher monomer concentration does not necessarily enhance the contrast ratio. This is because high monomer concentration tends to shrink the domain sizes. Once the domain size is smaller than the wavelength, the light scattering capability is reduced. Thus, monomer concentration and cell gap need

to be properly balanced in order to obtain a low operating voltage and high contrast ratio.

In this letter, we demonstrate a device configuration which enables the homogeneous cell to be used for modulating unpolarized light. By controlling the monomer concentration at $c = 2\text{--}3\text{ wt\%}$ and cell gap $d \sim 5\text{ }\mu\text{m}$, low operating voltage ($\sim 1 V/\mu\text{m}$), high contrast ratio ($\sim 100:1$), and fast response time ($\sim 5\text{ ms}$) are achieved.

To fabricate LC gels, we mixed 1–5 wt % of a rod-like photocurable monomer together with 0.5% photoinitiator in E48 ($n_e - n_o = 0.231$, from Merck) LC host. The monomer used in this study is bisphenol A dimethacrylate (commercial CAS No. 3253-39-2). The cell fabrication process is similar to that reported in Ref. 1. Two cell gaps with $d = 4.5$ and $10.5\text{ }\mu\text{m}$ were prepared. The inner surfaces of the indium–tin–oxide (ITO) glass substrates were overcoated with a thin polyimide layer and buffed in antiparallel directions for achieving homogeneous alignment. The cells were then irradiated with UV light such that the monomers were polymerized along the rubbing direction. To avoid incomplete polymerization, we used a weak UV intensity at 0.03 mW/cm^2 . The exposure time is about 4 h. Weak UV exposure and a slow polymerization process are found crucial to achieve a high contrast ratio and a low dark-state voltage. Slow polymerization would coarsen the polymer network, enlarge the LC domains, and stabilize the polymer network.⁸

A linearly polarized HeNe laser beam was used for characterizing the electro-optic properties of the gels. The laser beam diameter is about 1 mm. A photodiode detector was set at $\sim 30\text{ cm}$ away from the LC sample. A computer controlled LabView data acquisition system was used for driving the LC cell and recording the light transmittance. In the transmittance experiment, the incident laser beam is normal to the cell and its polarization axis is parallel to the LC directors. Results of the $10.5\text{ }\mu\text{m}$ gels with $c = 2\%, 3\%, 4\%$, and 5% are plotted in Fig. 1.

Figure 1 shows the normalized transmittance of the four LC cells we prepared. The maximum transmittance is $\sim 90\%$ if the optical loss from interface reflections is considered. For the 2% LC gel, the transmittance starts to decrease at $\sim 1.8 V_{\text{rms}}$. As the voltage increases, the microdomains scatter light so that the transmittance declines gradually. At $9 V_{\text{rms}}$, the contrast ratio reaches $\sim 300:1$. For the gels with

^{a)}Electronic mail: swu@mail.ucf.edu

FIG. 1. Voltage-dependent transmittance of LC gels. LC=E48, $d = 10.5 \mu\text{m}$, $\lambda = 633 \text{ nm}$, and $T = 23^\circ\text{C}$. The curve marked with X stands for the laser polarization perpendicular to the LC directors.

a higher monomer concentration, the domain sizes are smaller which results in a higher threshold voltage and higher translucent state voltage. The optimal monomer concentration for achieving low voltage and high contrast ratio occurs at $\sim 3\%$.

We also measured the electro-optical properties of the cells with laser polarization perpendicular to the cell rubbing direction. The curve for the 3% gel is included in Fig. 1. The maximum light scattering loss is $\sim 5\%$ at $V \sim 10 V_{\text{rms}}$.

The switching times of the $c = 3\%$, 4%, and 5% gels were measured. Their turn on/off times are (11, 19), (5, 7), and (2, 4) ms for the 3%, 4%, and 5% homogeneous-aligned E48 gels at 8, 15, and $24 V_{\text{rms}}$, respectively. Increasing monomer concentration helps to reduce response time, but the corresponding dark state voltage is increased. A faster response time can be obtained by using a lower viscosity LC mixture.

Similar to PDLC and PSCT, the anisotropic LC gel is a broadband device. To validate this, we used the 3% LC gel as an example. A calcite polarizer was used in this experiment because of its broad transmission range ($0.22\text{--}2.3 \mu\text{m}$). The polarization axis is parallel to the LC directors. Figure 2 shows the measured transmission spectra of the $d = 10.5 \mu\text{m}$ LC gel in the voltage-off (upper trace) and -on (lower trace) states. The on-state voltage is $10 V_{\text{rms}}$. Indeed, the spectral bandwidth covers the whole visible region. Such an anisotropic LC gel can be used as a white light switchable polarizer. In the voltage-off state, the gel is totally transparent. However, in a dark state, the polarization along the buffing direction is scattered so that the transmitted light becomes linearly polarized.

FIG. 2. Spectral bandwidth of a $10.5 \mu\text{m}$ E48 LC gel. Upper trace: voltage-off state; lower trace: $V = 10 V_{\text{rms}}$. A calcite polarizer was used to polarize the incoming light.

FIG. 3. Reflective display containing a homogeneous-aligned LC gel, a quarter-wave film and a reflector. (a) voltage-off state; (b) voltage-on state.

If we stack two anisotropic gels in orthogonal directions, we could control the desired output polarization by voltage. At $V = 0$, the stacked cells transmit the input unpolarized light with high efficiency. When one of the cells is activated, the output light becomes linearly polarized. When both cells are activated, both polarizations are scattered and the device functions like crossed polarizers. An extinction ratio greater than 2000:1 was measured using two 3% LC gels and an unpolarized HeNe laser.

Besides switchable polarizer, the anisotropic gel can also be used for reflective display and variable optical attenuator for telecommunications. Figure 3 shows the device configuration which consists of an anisotropic gel cell, a broadband quarter-wave film, and a reflector. The angle between the optical axis of the wave plate and cell rubbing direction is 45° . In the voltage-off state (top), the cell does not affect the incident polarization. The incident light traverses through the cell and wave plate and is reflected back by the reflector with high efficiency. In a voltage-on state (bottom), the input polarization (say, p wave) which is parallel to the cell rubbing direction is highly scattered at the first pass. The transmitted s wave traverses the $\lambda/4$ film twice and is converted to p wave. During the return path, this p wave is again scattered,

FIG. 4. Voltage-dependent transmittance (gray lines) and reflectance (solid lines) of a LC gel with $d = 4.5 \mu\text{m}$ with 2% (left) and 3% (right) monomer concentration. Transmittance was measured using a linearly polarized HeNe laser beam and reflectance was measured using an unpolarized HeNe laser beam with a $\lambda/4$ film.

FIG. 5. Viewing angle of a LC gel. Filled and open circles represent the measured data at horizontal and vertical viewing directions, respectively. LC=E48, $c=2\%$, $d=4.5\ \mu\text{m}$, and $\lambda=633\ \text{nm}$.

resulting in a translucent state. Ideally, the $\lambda/4$ film should be imbedded in the inner side of the bottom substrate in order to avoid parallax. Such an approach has been attempted in a guest-host display.⁹

Figure 4 shows the voltage-dependent reflectance of the $c=2\%$ and 3% , $d=4.5\ \mu\text{m}$ LC gels. An unpolarized HeNe laser was used in such an experiment. A polymeric $\lambda/4$ film (designed for $\lambda=640\ \text{nm}$) was sandwiched between the cell and a mirror. For convenience, the reflected beam was deviated from the incident beam by $\sim 2^\circ$. Also included in Fig. 4 is the single-pass transmittance (gray lines) of the cells using a linearly polarized HeNe laser. The transmittance and reflectance curves overlap quite well. This is because both p and s waves are scattered only in one path, as illustrated in Fig. 3. This nearly identical gray scale is desirable for transreflective displays where a pixel is divided into reflective and transmissive subpixels.^{10,11} The reflective subpixels are designed for bright ambient and the transmission subpixels (with backlight) are for dark ambient. The major challenge of a transreflective display is to find a LC mode having a similar gray scale for both reflective and transmissive pixels. The LC gels shown in Fig. 4 satisfy this specific requirement. The

turn on/off times for the 2% and 3% gels were measured to be (2, 6) ms and (3, 4) ms at 5 and 7 V_{rms} , respectively.

A wide viewing angle is another important criterion for reflective display. We measured the horizontal and vertical viewing angles of the reflective cell with $d=4.5\ \mu\text{m}$ and $c=3\ \text{wt}\%$. Results are plotted in Fig. 5. The horizontal (or vertical) angles refer to the viewing directions in (or perpendicular to) the incident plane. In both cases, the contrast ratio at $\pm 50^\circ$ viewing angle remains higher than 20:1.

In conclusion, the transmission-type homogeneous-aligned LC gels exhibit a high contrast ratio and fast response time, and can be used as a switchable polarizer and variable optical attenuator. The reflective-type gel in conjunction with a quarter-wave film shows a high reflectance in the voltage-off state, broad bandwidth, low operating voltage, high contrast ratio, fast response time, and wide viewing angle. The nearly identical transmissive and reflective gray scales make this mode particularly attractive for transreflective displays.

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