



Volumetric light-shaping polymer-dispersed liquid crystal films for mini-LED backlights

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ABSTRACT

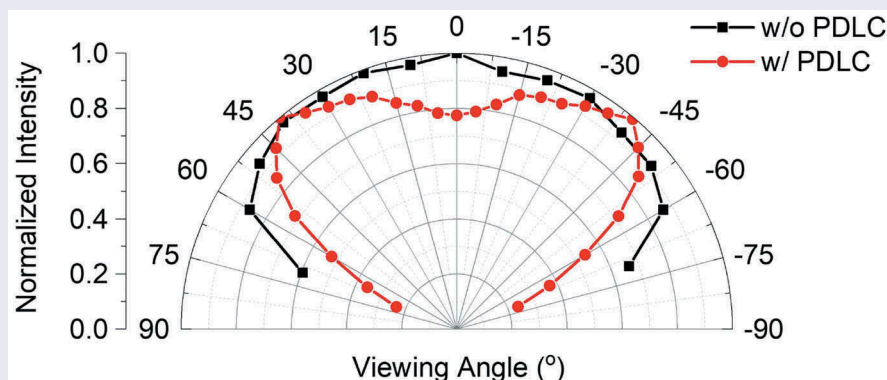
Volumetric light-shaping polymer-dispersed liquid crystal (PDLC) films for mini-LED backlit liquid crystal displays (LCDs) are proposed and experimentally demonstrated. With proper material engineering and good vertical alignment of liquid crystals, passive PDLC films with angle-selective scattering properties can be achieved. Such films only respond to angles rather than spatial locations. By directly adhering the PDLC films onto a LED, angular intensity distribution of light can be tailored from Lambertian-like to batwing-like. Further simulation shows that by engineering the angular distribution, a fewer number of LEDs or equivalently a shorter light-spreading distance should be required to maintain good uniformity. Such a PDLC film would find widespread applications in emerging mini-LED backlit LCDs and shed light on designing other light-shaping films in the future.

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1. Introduction

To fulfil the urgent need on high dynamic range, mini-LED (light emitting diode) backlit liquid crystal displays (LCDs) are emerging [1,2]. With locally dimmable LED zones, a contrast ratio higher than $10^6:1$ and visual performance similar to self-emissive displays such as organic LEDs (OLEDs) can be achieved [3,4]. However, the use of thousands or more of mini LEDs will increase the cost substantially because the mass transfer yield and defect mapping and repair speed of mini-LED chips still need improvement. Moreover, the direct backlight is still too thick for smartphones [5]. Increasing the number of LEDs can effectively reduce the backlight thickness but with an even higher cost. Another method is to tailor the angular distribution of light so that the light emitted from mini-LEDs can

spread out faster in a shorter propagation distance, where sophisticated surface microstructures are usually needed [6,7].

In this paper, we demonstrate a new volumetric light-shaping polymer-dispersed liquid crystal (PDLC) film for mini-LED backlit LCDs. By choosing proper refractive indices of liquid crystals (LC) and polymer, and providing sufficiently strong anchoring to the LC droplets along the vertical direction, a passive PDLC film with angle-selective scattering properties can be realised. Such a PDLC film can effectively scatter the normally incident light and increase the transmittance of light at a range of oblique incident angles, and they only respond to light at different angles but not at different spatial locations. Adhering such films directly onto LEDs, the angular intensity distribution of light can be tailored from

Lambertian-like to batwing-like. Further simulation shows that by engineering the angular distribution of light, a much fewer number of LEDs is required to maintain high uniformity at a fixed propagating distance.

2. Working principles

In a traditional scattering-type PDLC, the LC molecules form micron-sized droplets dispersed in the polymer matrix by phase separation [8]. Within each droplet, the LCs are aligned in a certain direction to minimise the free energy. However, the aligned directions are random among different droplets, which will cause light scattering macroscopically. If the ordinary refractive index of LCs (n_o) matches the refractive index of the polymer (n_p), the PDLC cell can be switched transparent when a sufficient voltage is applied to align all the droplets along the vertical direction (assuming the host LC has a positive dielectric anisotropy) [9–11]. Selective scattering will be observed in such a PDLC in the voltage-on state, where the normal incidence shows high transmittance and the scattering becomes stronger as the incident angle increases [12,13]. This selective-scattering property can be utilised to outcouple the waveguiding mode in OLEDs. Previously, somewhat aligned passive PDLC films were achieved by curing the PDLC precursors with a reactive mesogen and under a high voltage [14].

Aligning LC droplets in vertical direction is highly desirable in our case. However, the refractive index of the polymer is selected to be different from the ordinary refractive index of LCs ($n_p \neq n_o$) but matches the effective refractive index of the employed LC at some oblique incident angle α ($n_p = n_{eff}$), where n_{eff} can be calculated using n_o , n_e (the extraordinary refractive index of the LC), and α as [15]:

$$n_{eff} = \frac{n_o n_e}{\sqrt{n_e^2 \cos^2 \alpha + n_o^2 \sin^2 \alpha}} \quad (1)$$

As shown in Figure 1, due to the refractive index mismatch, the normally incident light (along z direction) is scattered independent of polarisations. At an oblique incidence, the film is polarisation dependent. Ideally, the p -polarised light sees n_p of the polymer and n_{eff} of the LC droplets (Figure 1(a)). As the incident angle increases, the refractive index mismatch and thus scattering decreases first, reaches the minimum value at α , and then increases again. On the other hand, the s -polarised light sees n_p of the polymer and n_o of the LC droplets no matter at what incident angle (Figure 1(b)). Therefore, it is even more scattered at oblique incidence due to the increased optical path length inside the polymer matrix. This principle applies to not only the xz plane but also the yz plane. If the alignment of LC droplets is not good enough, the loss of angular selectivity from s -polarised light will offset the gain from p -polarised light. Consequently, realising good

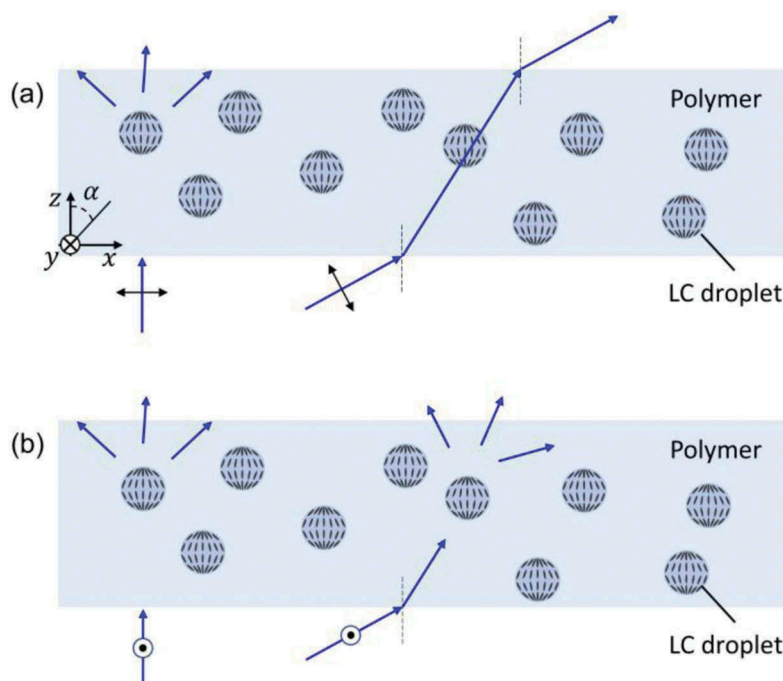


Figure 1. (Colour online) Schematic illustration of the working principles when (a) p -polarised and (b) s -polarised light rays are incident on the proposed PDLC film.

vertical alignment of LC droplets for such passive films is crucial.

It is worth mentioning that 3M has experimentally demonstrated a different angle-dependent birefringent diffuser using polymer beads-in-polymer systems where the polymer beads are isotropic, and the polymer matrix is anisotropic [16]. By stretching the composites at an elevated temperature, the optical axis of the polymer matrix can be aligned along the stretching direction (e.g. x -axis) while the polymer beads remain isotropic. This composite film can achieve angle-selective scattering, but only in the xz plane. Moreover, the angular selectivity realised in the experiment is somewhat weak. Therefore, it still needs improvement in order to be employed in the mini-LED backlight system.

3. Experimental and simulation results

Our initial attempt is to fabricate a thick ($\sim 50 \mu\text{m}$) film similar to that reported in [14]. After sweeping the material composition (weight ratio of LCs, reactive mesogens and prepolymers) and the fabrication condition (applied electric field, UV light irradiance and curing time duration), we successfully fabricated partially aligned PDLC samples. Specifically, a $50\text{-}\mu\text{m}$ LC cell without surface alignment was filled with a precursor mixture containing 49.92% ZLI 1844 (Merck; birefringence $\Delta n = 0.18$), 2.97% RM 257 (reactive mesogen) and 47.11% NOA 60 (prepolymer with $n_p = 1.56$). In the presence of a $4 \text{ V}/\mu\text{m}$ electric field, the cell was exposed under UV light with an irradiance of $5 \text{ mW}/\text{cm}^2$ for 40 min. To characterise its selective scattering properties, the passive PDLC was fixed on a rotation stage and set to the centre of a glass cylindrical container filled with an index matching oil. The incident light (from a 450-nm laser diode) was perpendicular to the PDLC at the initial state, and the incident angle could then be adjusted by rotating the PDLC. The transmittance is normalised to the case where the PDLC is absent and the collection

angle of the detector is 2.4° . Here an angle range of 40° in glass was measured since practically there is an air gap in between the LED and the light-shaping film, and such a range can cover most angles in air. The measured results are plotted in Figure 2, denoted by the black line. The PDLC is partially aligned based on the observed weak angular selectivity for the p -polarised incidence. However, the alignment is not ideal because the transmittance difference between $\alpha = 30^\circ$ is not too significant from that at 0° .

To overcome this imperfect alignment issue, a thin vertical-alignment (VA) cell was applied. The surface anchoring does provide decent alignment to the LC droplets near the surface, reduce the droplet size, and narrow the droplet size distribution [17,18]. In experiment, we modified and optimised the material system to provide moderate angle-selective scattering. Here, a PDLC precursor mixture was developed, consisting of 49.21% ZLI 2144 ($\Delta n = 0.19$), 4.90% RM 82 and 45.89% NOA 60. After being injected into a $5\text{-}\mu\text{m}$ VA cell, the PDLC precursor was exposed by UV light with an irradiance of $2 \text{ mW}/\text{cm}^2$ for 40 min, either with or without $4 \text{ V}/\mu\text{m}$ electric field applied. The angle-dependent scattering properties were then measured, as shown in Figure 2. The $5\text{-}\mu\text{m}$ PDLC cured without voltage (red lines in Figure 2(a)) shows some angle-dependent transmittance, indicating that the surface anchoring has some influence on the LC droplet alignment. However, in comparison with the $5\text{-}\mu\text{m}$ PDLC cell cured at 20 V (green lines in Figure 2(a)), such an angular selectivity is much weaker. That is to say, with the help of both surface anchoring and electric field, an almost perfectly aligned PDLC can be realised.

After achieving PDLC films with good alignment and thus outstanding angular selectivity, we apply them to a commercial blue LED (unpolarised light source) and study how the angular intensity distribution is tailored. In the characterisation, four $5\text{-}\mu\text{m}$ PDLC films cured at 20 V are stacked together and adhered to the blue LED

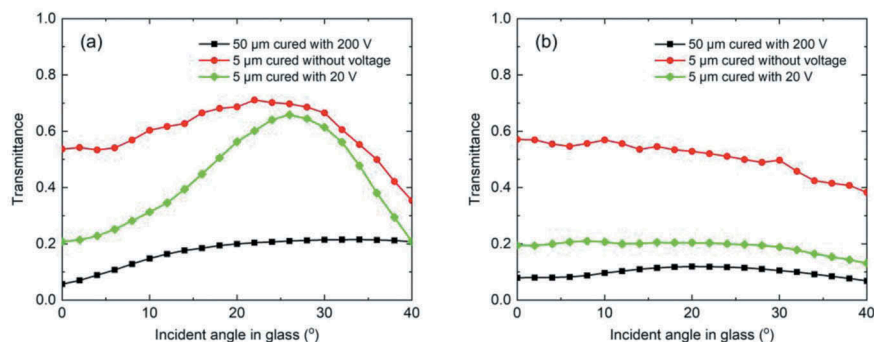


Figure 2. (Colour online) Angle-dependent transmittance measurements for (a) p -polarised and (b) s -polarised input light in glass.

directly. Here, four films are utilised to increase the contrast of angle-selective scattering. As Figure 3 shows, the angular intensity distribution of the LED without PDLC films is already quite broad with a peak at the normal view. After the PDLC films are applied, the angular intensity distribution of the LED becomes batwing-like, with a peak at about 40° in air and the intensity at normal view is about 77% of that at 40° . For mini-LED backlights, a batwing-like angular distribution can spread the light out much faster than a Lambertian-like angular distribution. Therefore, the introduction of the light-shaping films into the backlight system should effectively decrease the backlight thickness or/and reduce the number of mini-LEDs.

To show how this angular distribution change influences the mini-LED backlight system, a simplified ray-tracing simulation model in LightTools is established. As demonstrated in Figure 4(a), mini-LEDs with a size of $200 \times 200 \mu\text{m}^2$ are arranged in a square lattice with a lattice constant (pitch) of d , and a receiver is placed 1 mm away from the mini-LED backplane. By assigning the angular intensity distributions illustrated in Figure 3 to the LEDs, light uniformity at the receiver plane can be obtained, which is calculated by:

$$\text{uniformity} = 1 - \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (2)$$

where I_{\max} and I_{\min} denote the maximum and minimum illuminances at the receiver plane, respectively. The simulated uniformity as a function of d for the two angular intensity distributions is depicted in Figure 4(b). If we set a target uniformity of 90%, then the largest pitches for the LED without PDLC, and the LED with PDLC are about 1.26 mm and 1.53 mm, respectively. These two cases are circled in Figure 4(b), and the corresponding normalised illuminance distributions are plotted in Figure 4(c) (without PDLC) and Figure 4(d) (with PDLC). The illuminance distribution plots have a dimension of $2d \times 2d$, which encloses four mini-LEDs. By utilising the PDLC films, about 32%

($= 1 - (1.26/1.53)^2$) of the mini-LEDs can be saved to achieve the same uniformity.

It should be pointed out that our simulation model is simplified for proving concept. In real cases, brightness enhancement films (BEFs) and/or other films will still be required to narrow the angular distribution of light and depolarise the light before entering the LC module so that the light intensity distribution after passing through the polariser of the LC module remains uniform. Back reflectors are also useful for recycling the reflected light from PDLC [19]. Nevertheless, since the effective thickness of the PDLC films is only about $20 \mu\text{m}$, applying these PDLC films to the existing mini-LED backlight system helps to reduce the number of LEDs and/or the backlight thickness. Another aspect is that for a white backlight, a separate colour-conversion layer is indispensable if only blue LEDs are employed. But fortunately, the PDLC films are intrinsically broadband. Consequently, they are highly promising to be directly applied to white LEDs.

The optical properties of the PDLC films can also be tailored according to different requirements. For example, the angle of maximum transmittance can be tuned by engineering the refractive indices of the employed LC and polymer as long as n_p matches n_{eff} at α . The scattering strength can also be adjusted by controlling the index mismatch between n_p and n_o and/or the total thickness of the PDLC film. The large variability ensures the potential of almost arbitrary tailoring the angular distribution of LEDs. More importantly, with good spatial uniformity, such a PDLC film only responds to different angles rather than spatial locations. Therefore, these films can be placed in close vicinity to the LEDs without registration issue so that the backlight unit can be very compact.

4. Conclusion

In conclusion, volumetric light-shaping PDLC films for mini-LED backlit LCDs are proposed and experimentally demonstrated. By vertically aligning the LC droplets in the polymer matrix and matching the refractive

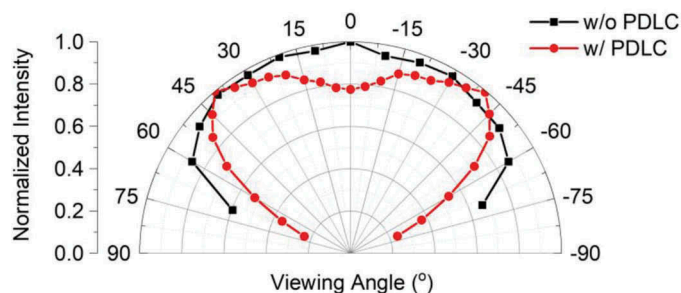


Figure 3. (Colour online) Measured angular intensity distribution of a commercial LED without (black) and with (red) PDLC films.

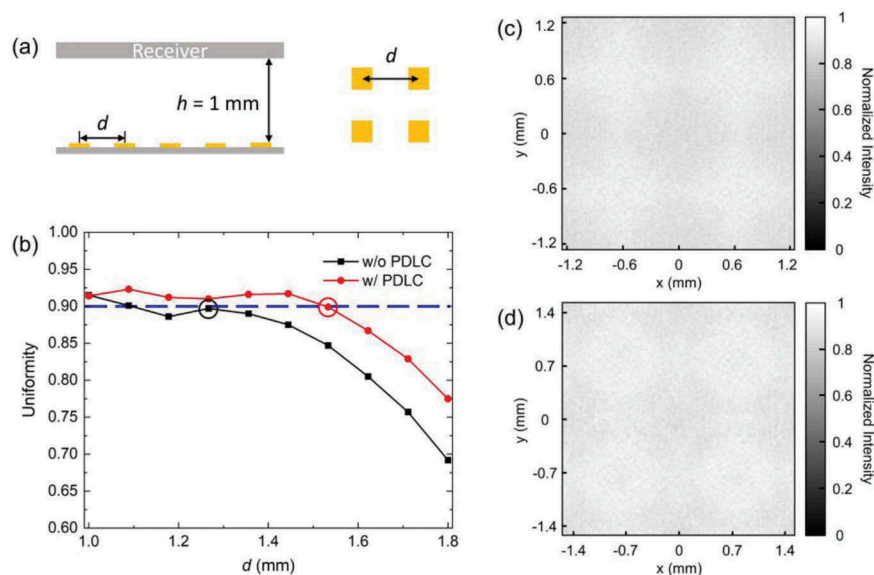


Figure 4. (Colour online) (a) Schematic plot of the simplified ray tracing model; (b) Uniformity of the two mini-LED backlights as a function of LED pitch length d where the normalised light illuminance distributions of the black circle and the red circle are plotted in (c) and (d), respectively.

index of the polymer with the effective refractive index of the LC at a designed angle α , the passive PDLC films are scattering at the normal angle but highly transparent at α . As an example, by adhering a stack of four $5\text{-}\mu\text{m}$ films (resulting in a total effective thickness of $20\text{ }\mu\text{m}$) onto a blue LED, a batwing-like angular intensity distribution with a peak at 40° is obtained. Further simulations show that with the PDLC films, about 32% of LEDs can be saved where maintaining a 90% uniformity. These PDLC films show large design degree of freedom in terms of shaping the angular distribution, respond only to incident angles rather than spatial locations which makes it compact and registration-free, and can potentially work for white LEDs. This work should not only find applications in mini-LED backlit LCDs but also shed light on future light-shaping diffuser designs.

Disclosure statement

No potential conflict of interest was reported by the authors.

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