Received: 13 February 2020 | Revised: 11 March 2020 | Accepted: 6 April 2020
DOI: 10.1002/jsid.908

SPECIAL SECTION PAPER

WILEY

Birefringent light-shaping films for mini-LED backlights

Ziqian He SID Student Member[1] | Kun Yin SID Student Member[1] | En-Lin Hsiang SID Student Member[1] | Ming-Chun Li[2] | Seok-Lyul Lee SID Fellow[2] | Kun-Cheng Tien[2] | Shin-Tson Wu SID Fellow[1]

[1]College of Optics and Photonics, University of Central Florida, Orlando, Florida, USA

[2]AU Optronics Corporation, Hsinchu, Taiwan

Correspondence
Shin-Tson Wu, College of Optics and Photonics, University of Central Florida, Orlando, FL, USA.
Email: swu@creol.ucf.edu

Funding information
a. u. Vista, Inc.

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

KEYWORDS
angle-selective scattering, birefringent light-shaping films, mini-LED backlights, polymer-dispersed liquid crystals

1 | INTRODUCTION

Comparing with self-emissive displays such as organic light-emitting diode (OLED) displays and micro-light-emitting diode (micro-LED) displays, traditional liquid crystal displays (LCDs) fall short in delivering true black state and thus have limited dynamic range. To compete with those emissive displays and fulfill the urgent need on high dynamic range, mini-LED backlit LCDs are emerging.[1,2] Through dividing the backlight into many individually dimmable mini-LED zones, mega contrast ratio and over 10-bits of colors can be achieved.[3] However, in such approach, a large number of mini-LEDs are required, resulting in substantially increased costs because of the imperfect mass transfer yield and limited defect mapping and repair speed of mini-LED chips. Moreover, the direct-lit backlight is still too thick for smartphones.[4] Further increasing the number of mini-LEDs can effectively reduce the backlight thickness but will lead to even higher costs. Alternatively, tailoring the angular distribution of light emitted from mini-LEDs such that the light can spread out faster in a shorter propagation distance is preferred, where sophisticated surface microstructures are usually needed.[5,6]

Herein, we propose and demonstrate a birefringent light-shaping film (BLSF) for mini-LED backlit LCDs. The proposed BLSF is volumetric type and thus sophisticated surface microstructures can be avoided. In experiments, this BLSF is realized by polymer-dispersed liquid crystals (PDLCs). Through choosing proper refractive indices of liquid crystals (LCs) and polymers, and providing sufficiently strong vertical anchoring to the LC droplets, a passive PDLC film with angle-selective scattering properties can be fabricated. Such a PDLC film can effectively scatter the normally incident light and increase the transparency at a range of oblique incident angles, functioning as a BLSF. Such a BLSF only responds to the incident light at different angles but not at different spatial locations. By laminating the BLSF directly onto LEDs, the angular intensity distribution of the outgoing light can be engineered from Lambertian-like to batwing-like. Further simulation shows that with the help of BLSF, a much fewer number of LEDs are required to maintain high uniformity at a fixed propagating distance.

2 | WORKING MECHANISMS

In order to spread out the light emitted from mini-LEDs faster, the BLSF should redistribute light at the normal angle into large angles. The angle-dependent light-scattering properties can be achieved by a composite material system which includes at least one birefringent material. Here, PDLC is taken as an example.

In traditional scattering-type PDLCs, the LC molecules form micron-sized droplets dispersed in the polymer matrix by phase separation.[7] Within each droplet, the LCs are aligned in a certain direction to minimize the free energy. However, the alignment directions are random among different droplets, which will cause light scattering macroscopically. Matching the ordinary refractive index of LCs (n_o) with the refractive index of the polymer (n_p), an active PDLC film 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).[8] In the voltage-on state, selective light scattering can be observed, where the normal incidence shows high transmittance and the scattering becomes stronger at larger oblique incident angles.[9,10] The selective-scattering property has been utilized to outcouple the waveguiding mode in OLEDs and somewhat vertically aligned passive PDLC films can be achieved by curing the PDLC precursors with a reactive mesogen and under a strong electric field.[11]

In our case, the required angular scattering property is reversed, where the normal incidence shows low transmittance and the scattering becomes weaker at a range of oblique incident angles. Here, aligning LC droplets in the vertical direction is still desired. 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[12]

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

As schematically shown in Figure 1, due to the refractive index mismatch, the normally incident light (along z direction) is scattered independent of polarizations. At an oblique incidence, the film shows polarization dependency. Ideally, the p-polarized light sees n_p of the polymer and n_{eff} of the LC droplets (Figure 1A). As the incident angle increases, the refractive index mismatch and thus scattering decreases first, reaches the minimum at α, and then increases again. On the other hand, the s-polarized light sees n_p of the polymer and n_o of the LC droplets no matter at what incident angle (Figure 1B). 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-polarization can offset the gain from p-polarization. Consequently, realizing good 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.[13] By stretching the composites at an elevated temperature, the optical axis of the polymer matrix can be aligned along the stretching direction (e.g., y-axis) whereas the polymer beads remain isotropic. This composite film can achieve angle-selective scattering but only

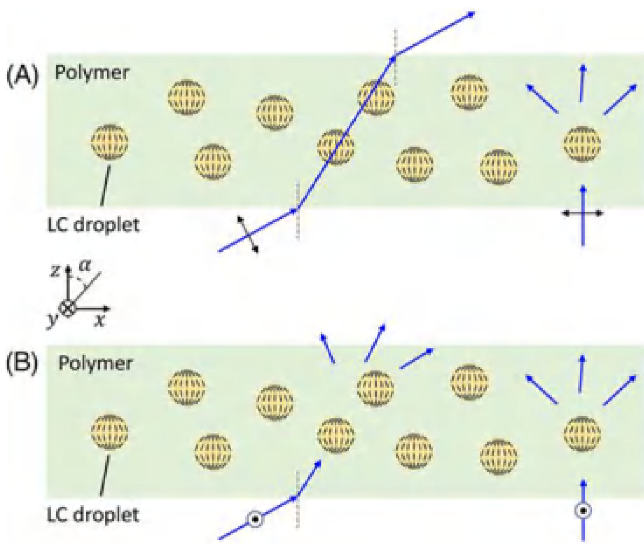


FIGURE 1 Schematic illustration of the working principles when (A) p-polarized and (B) s-polarized beams are incident on the proposed BLSF

in the yz plane. The asymmetric angular properties in the xz and yz planes impede the film from being used in LCD backlights. Moreover, the angular selectivity realized in the experiment is somewhat weak. Therefore, it still needs improvement in order to be employed in practical mini-LED backlight systems.

3 | SAMPLE FABRICATION AND CHARACTERIZATION

To experimentally prove the effectiveness of the proposed BLSF, PDLC films were fabricated using a thin vertical-alignment (VA) cell. The surface anchoring layer can provide decent alignment to the LC droplets near the surface, reduce the droplet size, and narrow the droplet size distribution.[14,15] In experiments, a PDLC precursor mixture was developed, consisting of 49.21 wt% ZLI-2144 (Merck; birefringence $\Delta n = 0.19$), 4.90 wt% RM 82 (reactive mesogen), and 45.89 wt% NOA 60 (prepolymer with $n_p = 1.56$). After being injected into a 5-μm VA cell, the PDLC precursor was exposed under UV light with an irradiance of 2 mW/cm^2 for 40 min, either with or without 4 V/μm electric field applied. To characterize its selective scattering properties, the passive PDLC was fixed on a rotation stage and set to the center of a cylindrical glass container filled with 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 normalized to the case where the PDLC is absent and the collection angle of the detector is 2.4°. Here, an angular range of 90° in air was measured. The measured results are plotted in Figure 2. The 5-μm PDLC cured without voltage (the blue line in Figure 2A) shows some angle-dependent transmittance, indicating that the surface anchoring can somewhat align the LC droplets. However, in comparison with the 5-μm PDLC cell cured with 4 V/μm (the orange line in Figure 2A), 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 obtained.

In addition to transmittance measurements, the angle-dependent scattering property of the PDLC can also be observed visually. As illustrated in Figure 3, the PDLC film (BLSF) is put in between a camera and a display. The light coming out from the display is linearly polarized along z-axis. At the normal angle where

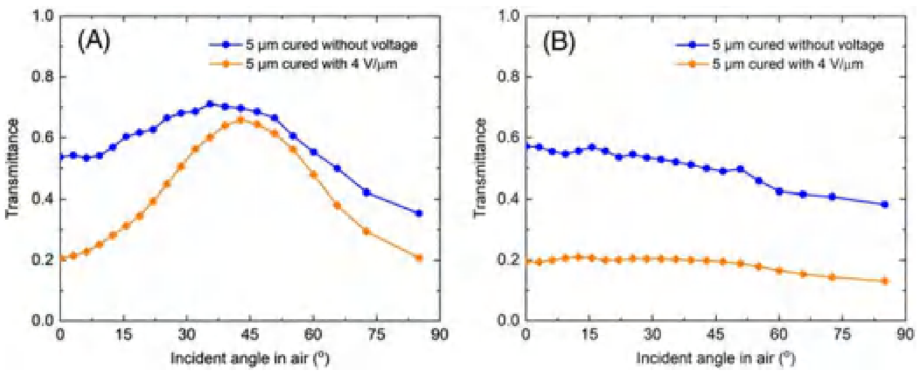


FIGURE 2 Angle-dependent transmittance measurements for (A) p-polarized and (B) s-polarized input light in glass

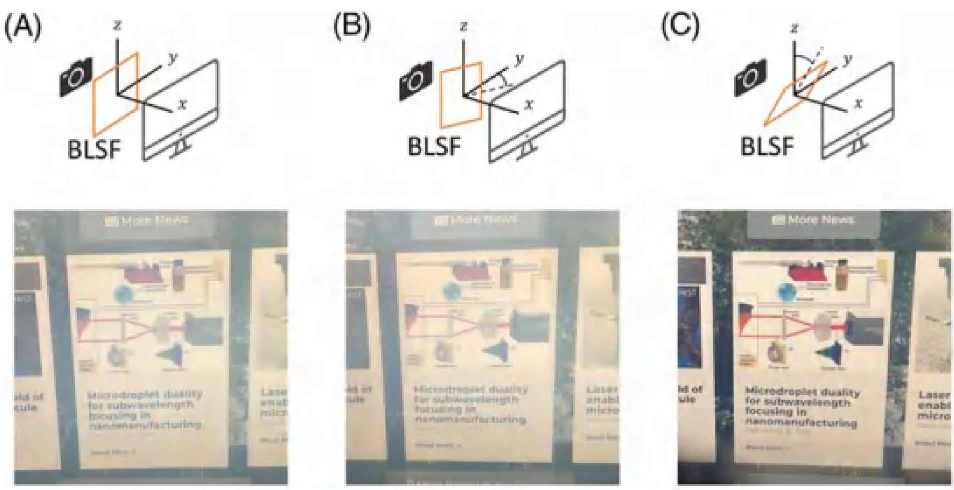


FIGURE 3 Visual effect of the BLSF where a BLSF is (A) in the yz plane, (B) rotated along z-axis, and (C) rotated along y-axis. The display emits linearly polarized light along z-axis

the BLSF is in the yz plane (Figure 3A), the captured image is hazy. Rotating the BLSF along z-axis (Figure 3B) results in an even hazier image because s-polarized light is always scattered. However, rotating the BLSF along y-axis (Figure 3C) can substantially reduce the haze as expected.

To characterize the LC droplet size, polarized optical microscope (POM) images are captured and exhibited in Figure 4. The size of the droplets is in the order of several microns, and the size variation among the droplets is small. Further reducing the size of the droplet to be closer to working wavelengths may result in a stronger scattering. But because the LC droplets are not mono-dispersed, caution must be taken when optimizing the size distribution because the subwavelength droplets will result in a weaker scattering. By rotating the film in reference to the polarizer, the pattern of most droplets remains the same. This again indicates that the droplets are mostly aligned vertically.

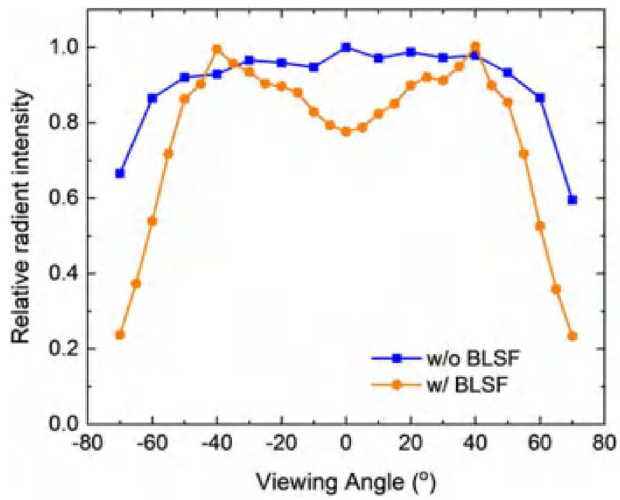


FIGURE 5 Measured angular intensity distribution of a commercial blue LED without (blue) and with (orange) BLSF. All data points are normalized to a specific data point (0°, w/o BLSF)

4 | APPLICATION IN MINI-LED BACKLIGHTS

Next, we apply our BLSF which exhibits outstanding angular selectivity, to a commercial blue LED (unpolarized light source) and study how the angular intensity distribution is tailored. In the characterization, four 5-μm PDLC films cured at 4 V/μm are stacked together and adhered to the blue LED directly. Here, four films are utilized to increase the contrast of angle-selective scattering. As Figure 5 shows, the angular intensity distribution of the LED without BLSF is already quite broad with a peak at the normal view. After the BLSF is applied, the angular intensity distribution of the LED becomes batwing-like, with a peak at around 40° in air and the intensity at normal view is about 77% of that at 40°. It should be noted that although the BLSF is not intended for light extraction but for light reshaping, a relatively high transmission efficiency is still desired. In our measurement, there is an air gap between the LED and the BLSF. Thus, the reflection from the air/BLSF interfaces will decrease the light efficiency. This decrease can be mitigated by applying anti-reflection coatings to BLSF or eliminating the air gap. Meanwhile, the BLSF will also introduce some back scattering. A good back reflector can recycle the light more effectively. Nevertheless, the key here is to reshape the angular distribution of light. 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 examine how this angular distribution change influences the mini-LED backlight system, we build a simplified ray-tracing simulation model in LightTools. As demonstrated in Figure 6A, mini-LEDs with a size of 200 × 200 μm^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 depicted in Figure 5 to the

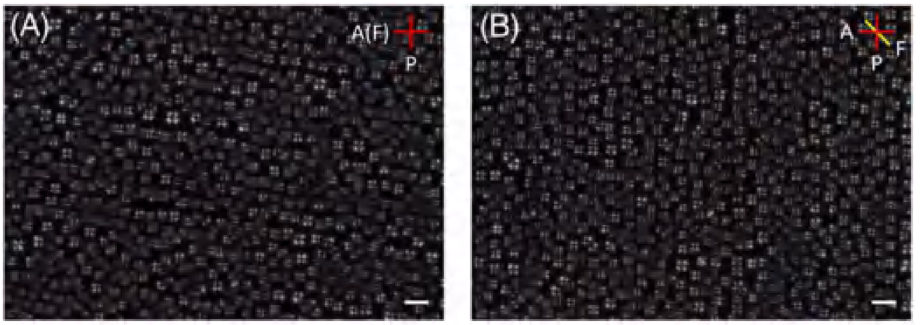


FIGURE 4 Polarized optical microscope images of the fabricated BLSF where (A) the film is parallel to the analyzer and (B) the film is at 45° to the analyzer. A, analyzer; F, film; P, polarizer. Scale bar: 10 μm

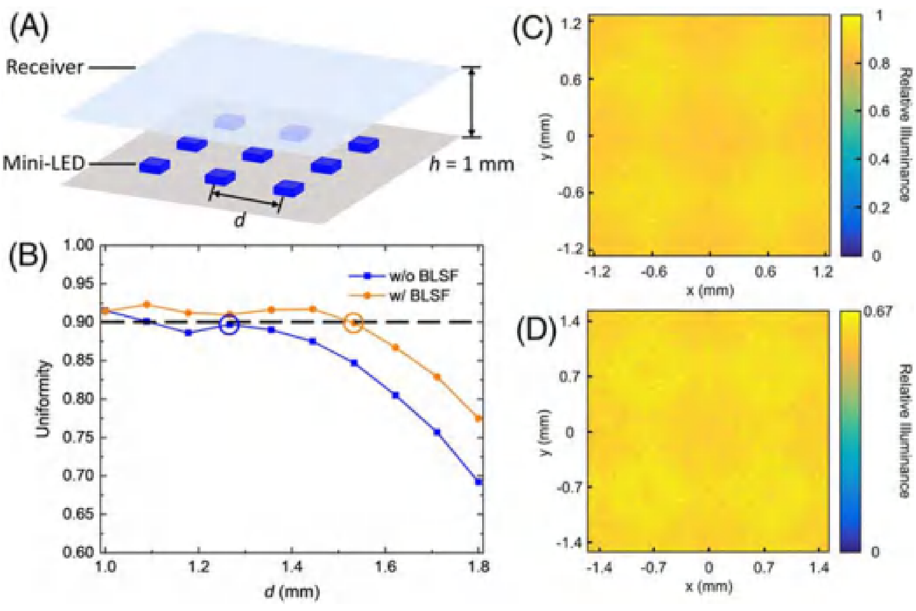


FIGURE 6 (A) Schematic plot of the simplified ray tracing model; (B) uniformity of the two mini-LED backlights as a function of LED pitch length d where the normalized light illuminance distributions of the blue circle and the orange circle are plotted in (C) and (D), respectively

LEDs and setting a fixed total emitting power to each LED, 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 6B. If we set a target uniformity of 90%, then the largest pitches for the LED without BLSF and the LED with BLSF are about 1.26 and 1.53 mm, respectively. These two cases are circled in Figure 6B, and the corresponding normalized illuminance distributions are plotted in Figure 6C (without BLSF) and Figure 6D (with BLSF). The illuminance distribution plots have a dimension of 2d × 2d, which encloses four mini-LEDs. By utilizing the BLSF, about 32% (=1-[1.26/1.53]^2) of the mini-LEDs can be saved to achieve the same uniformity. On the other hand, the maximum relative illuminance of LED with BLSF is about 67% to that of LED without BLSF. This means, the emitting power of each LED needs a 0.5-fold boost to match the maximum illuminance of densely arranged LEDs. The saving of the LED numbers can also be transferred to the reduction of the backlight thickness. For example, if the pitch keeps the same, the mini-LED with BLSF applied will show a shorter propagating distance while maintaining the same uniformity.

It should be pointed out that our simulation model is simplified for the purpose of concept proof. In real cases, brightness enhancement films (BEFs) and/or other films will still be required to narrow the angular distribution of light, turn the illuminance uniformity to luminance uniformity, and depolarize the light before entering the LC module so that the light intensity distribution after passing through the polarizer of the LC module remains uniform. Back reflectors are also useful for recycling the reflected light from the BLSF.[16] Nevertheless, because the effective thickness of the BLSF is only about 20 μm in

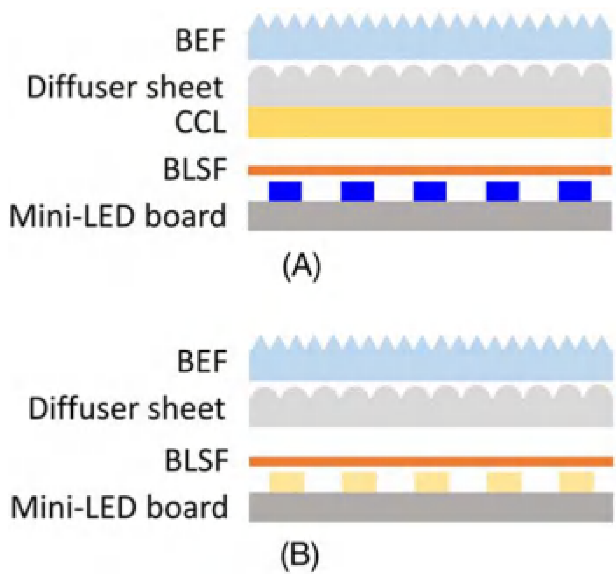


FIGURE 7 Two mini-LED backlight configurations using BLSF: (A) blue LED plus color conversion layer (CCL); (B) white LED. The BLSF can be attached to LED directly and extra diffuser sheets and/or brightness enhancement films (BEFs) are still needed to depolarize the light and narrow the angular distribution before the light entering LC module

our case, applying the BLSF 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 color conversion layer is indispensable if only blue LEDs are employed. But fortunately, the BLSF is intrinsically broadband. Consequently, they are highly promising to be directly applied to white LEDs. These two configurations, blue LED with color conversion layer and white LED, are illustrated in Figure 7A,B, respectively.

The optical properties of the BLSF can also be tailored according to different application requirements. Taking PDLC as an 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 BLSF 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.

5 | CONCLUSION

A new birefringent light-shaping film (BLSF) for mini-LED backlit LCDs is proposed and experimentally demonstrated using a passive PDLC film. Such films are scattering at the normal angle but highly transparent at a designed angle α, achieved by vertically aligning the LC droplets in the polymer matrix and matching the refractive index of the polymer with the effective refractive index of the LC at a designed angle α. By laminating a stack of four 5-μm films (resulting in a total effective thickness of 20 μm) onto a blue LED, a batwing-like angular intensity distribution with a peak at 40° is obtained. Further simulations show that with such a BLSF, about 32% of LEDs can be saved while maintaining a 90% uniformity. The BLSF has a large design degree of freedom in terms of shaping the angular distribution, responds 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 film designs.

FUNDING INFORMATION

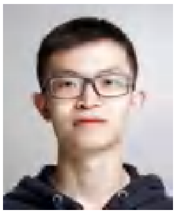
This study is supported by a. u. Vista, Inc.

ORCID

REFERENCES

1. Huang Y, Tan G, Gou F, Li MC, Lee SL, Wu ST. Prospects and challenges of mini-LED and micro-LED displays. J Soc Inf Disp. 2019;27(7):387–401.
2. Wu T, Sher CW, Lin Y, et al. Mini-LED and micro-LED: promising candidates for the next generation display technology. Appl Sci. 2018;8(9):1557.
3. Tan G, Huang Y, Li MC, Lee SL, Wu ST. High dynamic range liquid crystal displays with a mini-LED backlight. Opt Express. 2018;26(13):16572–16584.
4. Zheng B, Deng Z, Zheng J, et al. An advanced high-dynamic-range LCD for smartphones. SID Symp Dig Tech Papers. 2019;50(1):566–568.
5. Masuda T, Watanabe H, Kyoukane Y, et al. Mini-LED backlight for HDR compatible mobile displays. SID Symp Dig Tech Papers. 2019;50(1):390–393.
6. Huang CH, Kang CY, Chang SH, et al. Ultra-high light extraction efficiency and ultra-thin mini-LED solution by freeform surface chip scale package array. Crystals. 2019;9(4):202.
7. Doane JW, Golemme A, West JL, Whitehead JB, Wu BG. Polymer dispersed liquid crystals for display application. Mol Cryst Liq Cryst. 1988;165(1):511–532.
8. Doane J, Vaz N, Wu BG, Žumer S. Field controlled light scattering from nematic microdroplets. Appl Phys Lett. 1986;48(4):269–271.
9. Montgomery GP. Angle-dependent scattering of polarized light by polymer-dispersed liquid-crystal films. J Opt Soc am a. 1988;5(4):774–784.
10. Vaz NA, Smith GW, Montgomery GP. A light control film composed of liquid crystal droplets dispersed in a UV-curable polymer. Mol Cryst Liq Cryst. 1987;146(1):1–15.
11. Jiang J, McGraw G, Ma R, Brown J, Yang DK. Selective scattering polymer dispersed liquid crystal film for light enhancement of organic light emitting diode. Opt Express. 2017;25(4):3327–3335.
12. Yeh P, Gu C. Optics of Liquid Crystal Displays New York: John Wiley & Sons; 1999.
13. O'Neill MB, Stover CA, Weber MF, inventor; 3M Innovative Properties Co., assignee. Direct-lit backlight with angle-dependent birefringent diffuser. United States patent US 8,007,118. 2011 Aug 30.
14. Lin YH, Ren H, Wu ST. High contrast polymer-dispersed liquid crystal in a 90^o twisted cell. Appl Phys Lett. 2004;84(20):4083–4085.
15. Lin YH, Ren HW, Wu YH, Liang X, Wu ST. Pinning effect on the phase separation dynamics of thin polymer-dispersed liquid crystals. Opt Express. 2005;13(2):468–474.
16. Kim B, Kim J, Ohm WS, Kang S. Eliminating hotspots in a multi-chip LED array direct backlight system with optimal patterned reflectors for uniform illuminance and minimal system thickness. Opt Express. 2010;18(6):8595–8604.

AUTHOR BIOGRAPHIES



Ziqian He received his BS degree in Material Physics from Nanjing University in 2016 and is currently working toward a PhD degree from the College of Optics and Photonics, University of Central Florida. His current research interests include novel liquid crystal devices, nanocrystals, and color science.

Kun Yin received her BS degree in Opto-Electronics from Tianjin University in 2016 and is currently working toward a PhD degree from the College of Optics and Photonics, University of Central Florida. Her current research interests include optical elements for augmented reality and virtual reality displays.

En-Lin Hsiang received his BS degree in 2014 and MS degree in 2016, both are from National Chiao Tung University, Hsinchu, Taiwan. Currently, he is working toward a PhD degree at College of Optics and Photonics, University of Central Florida. His current research focuses on micro-LED and mini-LED displays.

Ming-Chun Li received his BS degree in Electronic Engineering, Feng Chia University, Taiwan, in 2000, and MS degree from National Sun Yat-Sen University, Taiwan, in 2005. Currently, he is a manager at AU Optronics, in charge of LCD cell material and process technology development.

Seok-Lyul Lee received his BS degree in Electronic Communication Engineering, Kwangwoon University, Korea, in 1992, and MS degree from Chonbuk National University, Korea, in 2010. Currently, he is a director and AUO fellow. He is one of the key inventors of fringe-field switching (FFS) liquid crystal display. He contributed to development and commercialization of mobile, tablet, and monitor TFT-LCD products using the FFS mode. He received SID Special Recognition Award in 2012 and SID Fellow Award in 2018.

Kun-Cheng Tien received his BS degree in Electrical Engineering, National Taiwan University, Taiwan, in 2004, and PhD degree in Photonics and Optoelectronics, National Taiwan University, Taiwan, in 2010. Currently, he is a senior engineer at AU Optronics Corporation. His work mainly focuses on advanced liquid crystal displays.

Shin-Tson Wu is Pegasus Professor at the College of Optics and Photonics, University of Central Florida. He is among the first six inductees of the Florida Inventors Hall of Fame (2014) and a Charter Fellow of the National Academy of Inventors (2012). He is a Fellow of the IEEE, OSA, SID, and SPIE and an honorary Professor at Nanjing University (2013) and at National Chiao Tung University (2017). He is the recipient of 2014 OSA Esther Hoffman Beller Medal, 2011 SID Slottow-Owaki Prize, 2010 OSA Joseph Fraunhofer Award, 2008 SPIE G. G. Stokes Award, and 2008 SID Jan Rajchman Prize. Presently, he is serving as SID honors and awards committee chair.

How to cite this article: He Z, Yin K, Hsiang E-L, et al. Birefringent light-shaping films for mini-LED backlights. J Soc Inf Display.