Tripling LCD-BLU Efficiency by Simultaneous Color and Polarization Recycling

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Abstract:

We propose an efficient LCD system to simultaneously recycle the backlight according to its color and polarization. These novel polarizing color filters offer high transmittance, high extinction ratio and large angular tolerance. In combination with a directional backlight, our system can achieve ~3X higher optical efficiency for ultra-low power operation.

Keywords: polarization recycling, green display, liquid crystal display, color filters

1. Objective and Background

Low power consumption is a critical issue for all kinds of LCDs. In a conventional LCD, the polarizer absorbs 50% and pigment-based color filters (CFs) absorb 66% of the incoming unpolarized white backlight. To eliminate CFs, one can employ field-sequential-color (FSC) technique [1,2]. However, FSC demands a fast LC response time (<1ms), which is still challenging for nematic LCDs. To reduce the light loss from polarizers, one can employ reflective polarizer to introduce polarization recycling in the backlight system [3,4]. By now, there is no satisfactory solution that can simultaneously eliminate the light loss from polarizers and CFs.

In this paper, we propose a LCD backlight system with specifically designed polarizing color filters. These polarizing color filters only transmit the light with specific polarization and colors, while reflecting the rest for recycling. Thus, the backlight system can simultaneously recycle the light according to its color and polarization. Compared to conventional backlight, our new backlight system offers ~3X higher optical efficiency, as well as high ambient contrast ratio and wide view.

2. Polarizing color filters

Figure 1(a) depicts the device structure of the newly proposed backlight [5-7]. Here, the directional light guide plate (LGP) is a key element. It extracts the light by its bottom microstructure, and then collimates the light by the microlens on its top surface. We simulate the LCD system with LightTools software. As Fig. 1(b) shows, the light incident onto the LC cell is highly collimated, with angular full width half maximum (FHWM) of only ±10˚. This highly collimated light input assures a high contrast ratio in the LCD without using multi-domain structures. After the light exits from the LC panel, it is spread out by the top diffuser and the angular distribution is shown in Fig. 1(c). The narrow incident light is diffused to a wide cone, with FHWM= ±43˚ [7]. Therefore, the display device can still maintain wide view with high contrast ratio. The black matrix on top of the diffusers covers ~80% area. It reduces the surface reflection of ambient light, and greatly enhances the ambient contrast ratio.

The polarizing color filter shown in Fig. 1(a) plays dual roles as a polarizer and a non-absorptive color filter [6]. Each polarizing color filter only transmits TM polarization with a specific color, and reflects the other TM polarized light outside the transmission band as well as all the TE polarized light. The reflected light is recycled within the backlight system. In Fig. 1(a), we intentionally laminate one anisotropic A-plate on top of the bottom reflector to enhance the polarization conversion. The system optical efficiency is enhanced as the recycled TE wave is partially converted to TM. Moreover, during light recycling, TM light with a different color has probability to be transmitted from the appropriate polarizing CFs. In this way, the polarizing CFs redistribute the light output with an appropriate polarization and color, and significantly reduce the light loss due to polarization or color mismatch.

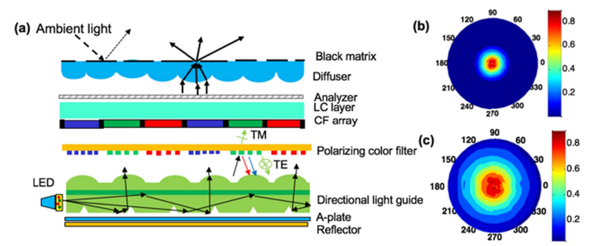

Figure 1. (a) Device structure of the proposed backlight system. (b) Simulated angular distribution of the backlight before it enters the LCD panel. (c) Angular distribution after the light is diffused by the top diffuser.

Figure 2(a) shows the structure of proposed polarizing CF; it is actually a sub-wavelength grating array. The flexible PMMA structure (n=1.48) is first coated with a thin layer of magnesium fluoride (MgF_2) with thickness h_1= 40nm, and then covered by a compound grating of Aluminum (Al) and MgF_2 with thickness of h_2= 100nm. Different CF has different grating period Λ and duty cycle f: (Λ=150nm, f=0.76) for blue, (Λ=110nm, f=0.86) for green, and (Λ=110nm, f=0.92) for red.

Figure 2(b) depicts the TM transmission spectra for blue, red, and green CFs. They exhibit evident color filtering properties. Fig. 2(c) shows the TM reflection spectrum, which is the reversal to the transmission spectrum. By adding the reflectance and transmittance together, we find the grating structure has very little absorption loss (~3.3%) for the TM light. Most of TM polarized light is either transmitted or reflected for recycling.

The TE reflection and transmission spectra are also shown in Figs. 2(d) and 2(e). It has a fairly low transmittance to TE light. The extinction ratios for RGB polarizing CFs are 4.2E4, 1.0E5, and 1.8E5, respectively, and are much larger than that of commercial sheet polarizers (~6E3). Therefore, this polarizing

 ISSN 0097-966X/16/4702-0830-$1.00

CF can replace the commercial sheet polarizer in LCD display to further improve the contrast ratio.

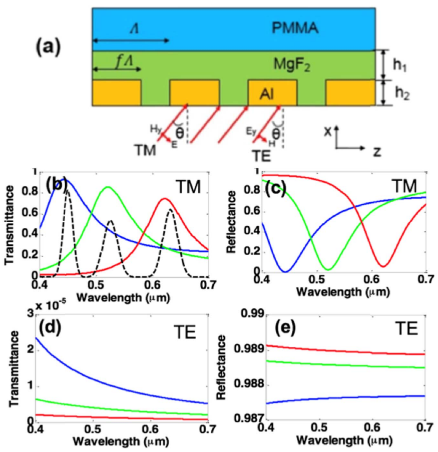

Figure 2. (a) Schematic of the proposed grating structure. (b) Simulated TM transmission spectrum for RGB grating CFs and the input light spectra (black lines). (c) TM reflection. (d) TE transmission. (e) TE reflection. The black dashed line in (b) is the emission spectrum of quantum dot LED ligth source.

To ensure excellent color quality, we employ quantum dot enhanced white LED as light source [8-10]. These light sources have a relatively narrow emission bandwidth and thus less affected by the CFs. Moreover, we still use the absorptive CFs after the polarizing CF to ensure good color purity. The transmission spectra of absorptive CFs can be found in Ref. [8] and they match with those of polarizing CFs well. The polarizing color filters redistribute the output light with different colors to match the transmission band of the absorptive CFs. Therefore, the optical loss in each absorptive CF is minimal.

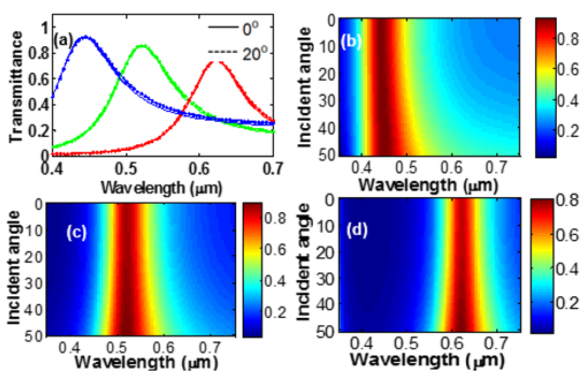

Figure 3. (a) TM transmission for light incident at 0˚ and 20˚. (b,c,d) The transmission spectra versus incident angle for blue, green and red polarizing CFs, respectively.

One unique advantage of our proposed grating is large angular tolerance. Typical grating CFs [11-12] filter the light by grating resonance, i.e., the constructive interference from periodic structure. This grating resonance is strongly angular dependent and cannot be applied in LCD systems. On the other hand, our proposed grating CF filters light via localized Fabry-Perot resonance and therefore is angular insensitive [13-14]. Figure 3(a) compares the TM transmission spectra for light incident at 0˚ and 20˚. Their difference is very small. Figures 3(b), 3(c) and 3(d) further show the transmission spectra vs. incident angle for the R, G, and B polarizing CFs. As the light incident angle increases from 0˚ to 50˚, both peak transmission wavelength and full width half maximum (FWHM) of the transmission band maintain almost the same. This angular independence is an important advantage of our proposed design. It can be used in LCD backlight without introducing angular-dependent color variation.

3. LCD system performance

Our polarizing CF has large angle tolerance and can be directly applied in the LCD backlight. However, a typical edge-lit LCD backlight with light guide plate (LGP) and crossed brightness enhancement films has a large output cone angle ±50~60˚. To further mitigate the angular-dependent color variation, here we propose to combine the polarizing CF with directional backlight

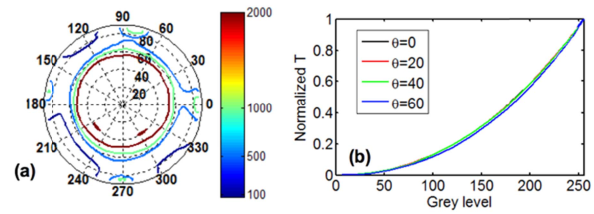

Figure 4. Simulated isocontrast contours of a single-domain VA LCD system. (b). Gamma curve of LCD system along azimuthal angle 45˚ direction. No compensation film is included in the LCD system.

We developed an integral geometrical optics/wave optics simulation to simulate the viewing angle performance of proposed LCD system [5]. Without losing generality, we consider the single-domain vertical aligned (VA) LCD mode [15]. The LC material is Merck MLC-6882 (Δn=0.097 and $\Delta\varepsilon$=–3.1) and cell gap is 4μm. Fig. 4(a) shows the simulated isocontrast contour, where the viewing cone with CR≥100:1 extends to 80o. If we add compensation films, then the isocontrast of CR=3000:1 would cover the entire 80° viewing cone [8]. Moreover, with a directional backlight the gamma curves are almost indistinguishable (Fig. 4(b)) from 0° to 60° viewing angles. That means the image quality maintains almost the same at different viewing angle. With our proposed LCD system, the single-domain VA LCD can manifest superior viewing angle performance to complicated multi-domain VA LCD.

Our LCD system has higher light efficiency than traditional counterpart. Let us consider an unpolarized backlight source and focus on the blue part transmission. Let us assume RGB polarizing CFs have transmittance (T_1,T_2,T_3) and reflectance (R_1,R_2,R_3) for TM wave, and zero transmittance and unity reflectance for TE. During each light recycling the light intensity would reduce by a factor of T. Without the polarizing CF, the backlight only has 1/6 probability to pass through the absorptive CFs and polarizers. After inserting the polarizing CF, the light output increases to:

$$T_{out} = \frac{1}{6}T_1 + \left(\frac{1}{6}(R_2+R_3)+\frac{1}{2}\right)T*\frac{1}{6}T_1 + \left(\frac{1}{6}(R_2+R_3)+\frac{1}{2}\right)^2 T^2*\frac{1}{6}T_1 + ... \quad (1)$$

$$= \frac{T_1/6}{1-\left[\frac{1}{2}+\frac{R_2+R_3}{6}\right]T}$$

On the other hand, without applying polarizing CF, the light from backlight has 1/6 probability to reach the LC panel (1/2 transmission due to absorptive polarizers and 1/3 transmission due to the absorptive pigment -CFs). Therefore after introducing the polarization and color recycling, we can obtain the optical gain factor *G* as:

$$G = \frac{T_1}{1 - \left[\frac{1}{2} + \frac{R_2 + R_3}{6}\right] T} \tag{2}$$

Let us assume the recycle efficiency T=0.9 and use the reflection/transmission spectra shown in Fig. 2 to calculate the gain spectra for our polarizing CFs. As Fig. 5(a) plots, each polarizing CF can provide a large optical gain (220-300%) at its peak transmission wavelength. Fig. 5(b) further compares the LCD output spectrum with and without light recycling. It is evident that the light intensity of all three colors is almost tripled. Moreover, the output spectrum still maintains excellent color purity after recycling, and covers ~132% AdobeRGB in CIE 1976 color space. Light efficiency can be enhanced without sacrificing color performance.

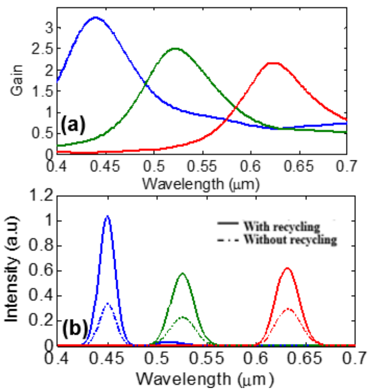

Figure 5. (a) Simulated optical gain for RGB grating color filters. (b) Backlight output intensity with and without recycling.

4. Conclusion

We proposed an LCD system that can simultaneously recycle backlight according to its color and polarization. To the best of our knowledge, this is the first time that such concept is proposed. A novel polarizing CF is also designed and it exhibits several advantages: high transmittance (>90%), low absorption loss (~3.3%), high extinction ratio (>10,000:1) and large angular tolerance (up to ±50°). Combined with directional backlight design, the proposed LCD system can achieve ~3X system efficiency enhancement, as well as high ambient contrast ratio and wide view. Our approach opens a new door for ultra-low power LCD without applying complicated field sequential color technique.

5. References

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