Viewing Angle Switchable Display with a Compact and Directional Backlight Module

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Abstract
A compact light guide plate (LGP) with special designed microstructures and dual collimated light sources was proposed to achieve an adjustable viewing angle backlight for eco-display. The micro-prisms were utilized to guide the emitting rays toward normal viewing cones while a set of strip patterned diffuser toward wide viewing cones. The uniformity of spatial luminous can reach 91% / 87% at view cone of ±3/ ±60 deg. in each mode. Only 5% of power consumption in narrow viewing angle mode was needed to keep the same luminance in wide viewing angle mode.

Introduction
Liquid Crystal Displays (LCDs) are currently dominating the display market due to their thin form factor and light weight. As the demand of multimedia information applications, LCDs are supposed to be used for various purposes and situations. Two different situations are often encountered: group viewing and privacy viewing. The former demands a wide viewing angle for sharing the contents of the display, but the latter prefers a narrow viewing angle in order to protect personal or confidential information and sometimes for low power consumption. Therefore, backlight module with viewing angle switchable is a good feature to meet various needs.

Typical viewing angle switchable displays can be classified into two categories, namely, by liquid crystal (LC) components and by backlight module design. The LC technologies for viewing angle switchable such as an ultra-super-twisted cell with a polymer-network LC cell[1], and a hybrid aligned nematic (HAN) LC cell with a negative C-plate[2], have shown some notable success for low power consumption, high-quality image and low distortion, but with the major drawback of additional viewing angle control panel and high cost. The other LC technologies such as a patterned vertical alignment (PVA) LC display using only one panel[3], an optically isotropic LC[4] with the feature of dividing a pixel into a main pixel and a sub-pixel for display images and controlling the viewing angle respectively, exhibit the merits of high contrast ratio (CR) and possibility of using similar fabrication process of conventional LC displays. Nonetheless, due to spatial-multiplex of one pixel, the transmittance and resolution are decreased. In order to maintain the luminance of the panel, the power consumption of the backlight module has to be increased. On the other hand, backlight with stacked dual light guide plate, that one offered narrow viewing angle, and the other offered wide viewing angle was also proposed with the benefit of low cost.

However, the weight and the thickness of the system became undesirable for mobile displays [5-6]. To simplify the module structure, a compact backlight module was proposed in this work to achieve switchable viewing angle with only one light guide plate (LGP) with special designed microstructures and dual collimated light sources.

Design Principle
In spite that LEDs are widely used as the light source for backlight in LCDs, the conventional LED of Lambertian angular distribution is not suitable for narrow viewing angle backlight design with eco-display[7-9]. Thus, the collimated point light source becomes a good candidate for the direction-dependent-displays. Two collimated point light sources are used in this proposed structure to expand a point collimated light source to a planar light source without changing the high directional characters. The proposed structure of viewing angle switchable backlight module with isometric view, top view, and front view are demonstrated in Figure 1.
The backlight module includes two parts: a light guide plate and dual collimated light sources located at the diagonal of LGP, as shown in Figure 1(a). The micro-prisms which can be divided into three groups and coated with silver reflective film, were located on all the surfaces of LGP except the top one, as shown in Figure 1(b) and (c) respectively. The strip patterned diffusers on top surface were located corresponding to the left half of micro-prisms of group C as illustrated in Figure 1(c).

In x-z plane, the LGP is not regular rectangle but incline to z-axis with the angle of $\alpha_1$. According to the total internal reflection (TIR) theory, Figure 2(a) illustrates the process of light propagation in the x-z plane: the incident light propagating along z-axis is reflected twice by the micro-prisms which function as transferring a point light source to a line light source. In y-z plane, the left/right surfaces of LGP also incline to y-axis with an angle of $\alpha_2$ except the incident region of light source. The light propagation in the y-z plane can be described as: the light from group B propagating along negative z-axis with a tilt angle, $\psi$, is reflected toward the normal direction by the micro-prisms of group C on bottom surface of LGP as illustrated in Figure 2(b). Therefore, a line light source is expanded to a planar light source. As the backlight works in different viewing angle, rays are coupled out from LGP directly or scattered by strip patterned diffuser according to the position where rays emit to the top surface of LGP. Compared with conventional backlight with LEDs, the light propagating in novel structure LGP has less scattering and trapping after the three reflections, which is benefitted for high optical efficiency.

### Results & Discussion

Optical efficiency, uniformity of spatial luminance, and angular luminance distribution are important parameters to evaluate the performance of viewing angle switchable display. In order to verify the effect of this novel structure, a 3D geometric model of the backlight module was established by ray tracing software Light tools 7.2, as illustrated in Figure 1(a). According to the fundamental principle of geometrical optics and equations in last section, the parameters of the backlight module were calculated and listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I: PARAMETERS OF BACKLIGHT MODULE</th>
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<tr>
<td>Material / Refractive Index</td>
</tr>
<tr>
<td>Backlight Dimension</td>
</tr>
<tr>
<td>$(L<em>W</em>H) \ (\text{mm})$</td>
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**Fig. 1. Sketch of backlight in different viewing angle (a) Isometric, (b) top, and (c) front view.**

**Fig. 2. Light propagation in LGP with different planes (a) x-z plane and (b) y-z plane.**
In order to verify the high optical efficiency of proposed structure, the backlight with different viewing angle modes were simulated with the conventional backlight (BL) as the reference. The different conditions and the simulation results were summarized in Table II.

**TABLE II: DIFFERENT CONDITIONS OF BACKLIGHT MODULE**

<table>
<thead>
<tr>
<th>Type</th>
<th>A Normal BL</th>
<th>B Novel BL with Wide Viewing Angle</th>
<th>C Novel BL with Narrow Viewing Angle</th>
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<tr>
<td>Optical Efficiency (%)</td>
<td>65</td>
<td>86.8</td>
<td>95.4</td>
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Compared with Type A, Type B and Type C could improve the optical efficiency by more than 33.5% and 46.7% respectively owing to the effect of novel micro-structure on LGP. As the scatter points of conventional backlight simply diffuse the rays from light source without controlling the directions of light transmission, a part of rays cannot be coupled out of the LGP if the incident angle is larger than the total reflection angle. However, the micro-prism of the proposed structure controls the most of rays in a precise manner and guides them to the normal direction instead of trapping in the LGP. Besides, in order to keep the high uniformity of spatial luminance distributions, the scatter points are only covered a part of bottom surface resulting in the energy loss, thus the optical efficiency of normal backlight is always lower than 70%. On the other hand, the novel backlight shows the high optical efficiency due to the collimated light source and micro-structures with compact arrangement which reduces the energy loss effectively. The simulation results in Table II demonstrated that the configuration could improve the optical efficiency obviously, consistent with our analyses mentioned in last section. The spatial luminance distributions were calculated to evaluate the uniformity of the novel backlight in different viewing angle mode (Narrow viewing angle mode / Wide viewing angle mode), as illustrated in Figure 3. The uniformity, defined as the minimum luminance divided by the maximum luminance, were of 91% in narrow viewing angle mode and 87% in wide viewing angle mode.

**Fig. 3. The spatial luminance distributions of the backlight (a) narrow and (b) wide viewing angle mode.**

The light distribution is the most important property for viewing angle switchable display. The characteristics of viewing angle in different modes were depicted in Figure 4. These results demonstrated that the novel backlight module offered the same functionality as a conventional backlight in wide viewing angle mode with ±60° of FWHM. Besides, the backlight offered ±3° of FWHM in narrow viewing angle mode with the ultra-low power consumption (only 5% power consumes at the same luminance) compared with conventional backlights.

**Fig. 4. Viewing angle of novel backlight.**
1. Conclusion
The viewing angle switchable display with special designed microstructures and dual collimated light sources was demonstrated for the application of eco-display. Compared with the conventional backlight module, the novel configuration can achieve high uniformity (91% and 87% in N/W mode respectively) with the optical efficiency increased to 46.7%. It can offer the same FWHM at ±60° as the conventional backlight in wide viewing angle modes and offer FWHM at ±3° in narrow viewing angle mode with ultra-low power consumption (5% power consuming of conventional backlight) at the same luminance.

2. Acknowledgements
This work was supported in part by 973 project (2013CB328804) and by NSFC (61275026).

References