Invited paper: Dual-edge Color Sequential Front-lit LCOS for AR Glasses Applications

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Abstract

A novel color sequential (CS) Front-lit LCOS (FL-LCOS) with dual-edge illumination system is introduced. It enables better etendue matching and hence, a better light efficiency is realized. Accompanied with a tailormade FOV 30 deg. collimator, the projector volume is only 0.98 c.c. for a 1024x1024 display. With such efficient and compact FL-LCOS based projectors, we had demonstrated AR glasses with brightness-to-eye >1000nits with 2D diffractive waveguides. A newly developed 0.17" 720x720 FL-LCOS will also be introduced. The total projector size can be shrunk down to <0.4c.c., and it can provide 0.6lm~0.8lm out of the projector with only 200mW LED power. We believe that it can be a promising candidate for the AR glasses applications.

Author Keywords

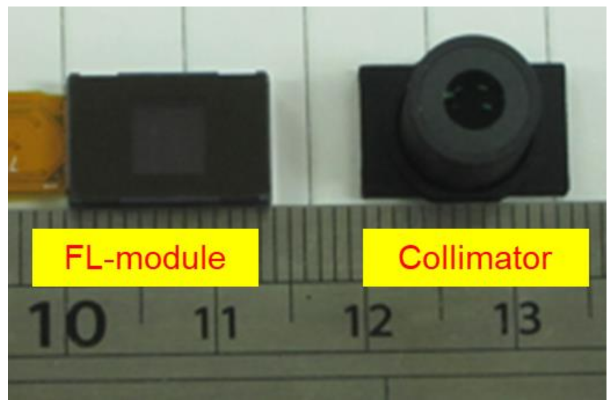
Color sequential LCOS; Front-lit LCOS; augmented reality displays.

Introduction

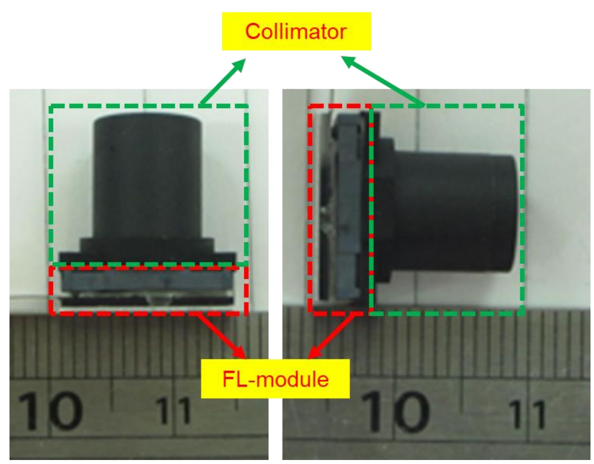
The fundamental requirements of an ideal augmented reality (AR) display include compactness, light weight, and high brightness efficiency. Liquid-crystal-on-silicon (LCOS) [1] micro-display has been one of the main candidates for AR displays. Our Front-lit LCOS [2-4] device is the only self-illuminated LCOS solution in the market, which fulfills all the requirements of an ideal AR display as mentioned above. A planarized polarization beam splitter (PBS) is realized by the inhouse nano-imprinting technology with special designed microstructures to become a light guide (LG). Accompanied with inhouse multi-layer coating processes, these microstructures are acting as micromirrors to reflect the s-polarized light and transmit the p-polarized light in sufficient incident angle ranges. In the previous study [5], we had adopted a freeform light pipe in front of the LED light bar to form two intensity peaks that helped increasing the in-couple efficiency significantly, and it also improved the light recycling rate with a reflective polarizer placed behind the light pipe. This FL-LCOS can provide 250k nits and 1.2lm with 300mW LED power. It was sufficient to support a 2D reflective waveguide [6,7]. However, for 2D diffractive waveguides [8-10], the typical light efficiency (<1%) is much lower than reflective type waveguides, such brightness level is not sufficient for the outdoor usage scenario. In order to further boost up the brightness efficiency, we disclose a whole new structure called dual-edge FL-LCOS. The dual-side illuminating system adopted in this front-lit module doubled the light in-couple area of the light guide. Therefore, more light is redirect to the LCOS active area with the same LED power comparing to the original single-edge illumination system. In the meantime, the brightness uniformity becomes much better with less light energy span.

Demonstrations of the Dual-Edge Front-lit LCOS Projector

Figure 1(a) shows the top view of our FL-LCOS and the projector with tailormade collimator individually. The direct measured max brightness of this dual-edge FL-LCOS in the display area has reached 400k nits at 300mW LED power. The lumen measured by an integration sphere after the collimator is about 0.45lm. The brightness at this level can support typical 2D diffractive waveguides with FOV range at 30~40deg. By using a tailormade collimator for our 0.243" 1024 x 1024 (trimmed from 1920 x 1080 native resolution) color sequential LCOS with FOV 30 deg. and the pupil size at 4 mm diameter, the total projector volume is 0.98 c.c. as shown in Figure 1(b).



(1a)



(1b)

Figure 1 (a) The top view and side view of a 0.43 c.c. dual-edge FL-LCOS module and the tailormade collimator at 0.55 c.c. (b) The FL-LCOS based with total volume at 0.98 c.c.

Figure 2(a) shows the prototype AR glasses using a 3D printing glasses frame with the dual-edge FL-LCOS based projector and the 2D diffractive waveguide. The measured brightness-to-eye of the glasses is more than 1000nits at 300mW LED power. The full-on-full-off contrast ratio is 120:1, and the sRGB color gamut is 140%. A photo captured through the waveguide is also shown in Figure 2(b). The technical summary of the AR glasses is shown in

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Table 1

(2a)

(2b)

Figure 2 (a) The dual-edge FL-LCOS based AR glasses prototype using a 3D printing frame (b) The image captured through waveguide.

Table 1. Technical Summary of the Prototype AR Glasses

Field of View (FOV)	30º
Brightness-to-eye	>1000nits
Contrast ratio (full on full off) in Eye box	120:1
Color gamut (sRGB)	140%
Resolution	1024x1024
Max Front lit module brightness	400k nits (1.7lm)
LED power	300mW

Dual-Edge Front-lit LCOS Structure

To further explain the technical details of the dual-edge FL-LCOS, Figure 3 depicts the structure of the dual-edge FL-LCOS. Two Lambertian light sources S1 and S2 are placed at the two edges of the LG. There are light pipes and coupling lenses placed in front of the light sources to split the light beams into a two-peak intensity profile, i.e., A1, A2 going upward and A1',A2' going downward. Both A1, A2 and A1', A2' will be polarized after passing the reflective polarizers, i.e., the wire grid film (WGF1 and WGF2) polarizers located between the LG and the coupling lenses. The reflected p-polarized light by WGFs will be recycled in the coupling lens system with suitable conversion surfaces. The s-polarized A1-s and A2-s will hit the micromirror arrays in the light guide and then be redirected to the CS LCOS panel. The A1'-s and A2'-s will propagate further in the LG by total internal reflection (TIR) with minimum loss. Eventually, A1'-s and A2'-s will hit the micromirror arrays that are located further away from the LG entrances, and then also be reflected downward to the color sequential LCOS underneath. After modulated by the LC layer in the LCOS panel, the s-polarized light will be converted into p-polarized light B (B1-p, B2-p and B1'-p, B2'-p) and reflect back to the LG. It will transmit the micromirror arrays this time to the observer or a collimator to couple the light into the following 2D expansion waveguides.

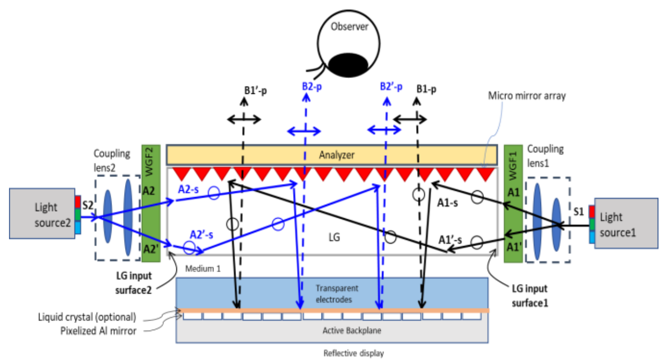


Figure 3. Structure of dual-edge Front-lit LCOS

Figure 4 shows the measured emission cone angle distributions of the dual-edge FL-LCOS. The full-width half-maximum (FWHM) of the emission cone along the direction parallel to the LED light bar (y-direction) will be larger, i.e., >+/-15°. And the FWHM of the emission cone at the direction perpendicular to the LED light bar (x-direction) will be smaller, i.e., > +/12°. The emission cone control is very critical. If the emission cone distribution is too large, then the light energy collected by the following collimator will be very limited. On the contrary, if the emission cone angle is too narrow, then there will be no image observed at some portions of the eye-box which degrades the visual quality. We believe the emission cone range between +/-10° to +/-20° will be the most suitable range for 2D waveguides. Nevertheless, the cone angle can be customized based on requirements by modifying the coupling lenses designs in the Front-lit module.

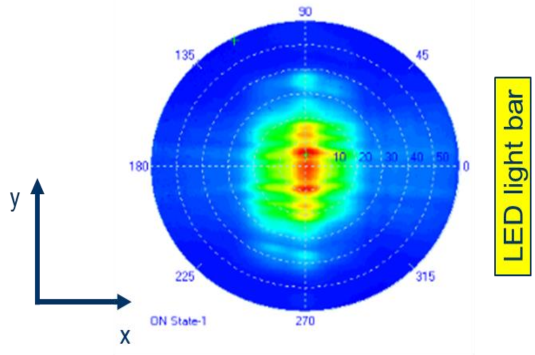
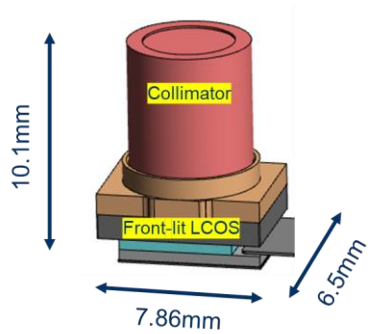


Figure 4. Emission cone angle distribution of the dual-edge Front-lit LCOS

0.17” 720x720 Dual-Edge Front-lit LCOS

A 0.17” 720 x 720 color sequential LCOS has been developed as the first product of the dual-edge Front-lit LCOS. With such display diagonal size, the total projector volume with a tailormade collimator can be shrunk down to < 0.4 c.c. Meanwhile, due to the smaller light emission area (hence, the smaller etendue), the optical efficiency of the collimator can be significantly improved. The projector can provide 0.6lm~0.8lm with the LED power reduced to 200mW. Figure 5(a) shows the photos of the mockup projector with FOV 30° and 4mm output pupil diameter. Figure 5(b) shows the 3D drawing of the 0.17” dual-edge Front-lit LCOS based projector.

(5a)



(5b)

Figure 5 (a) A photo of the 0.17” Front-lit LCOS based projector with total volume < 0.4 c.c. (b) 3D drawing and dimensions of the projector

Inorganic Alignment Mixed-Mode TN

In order to improve the optical performance of the LCOS panel, we introduced inorganic alignment layers deposit on the ITO glass substrate and the wafer substrate to replace the traditional organic alignment layers, i.e., typically polyimide layers. The benefits of the inorganic alignment layer including better endurability of high light flux illumination, higher LCOS reflectance, better contrast ratio, and free of rubbing defects. Table 2 lists the comparisons between the inorganic and organic alignment layers.

Table 2 Comparisons of Inorganic and Organic Alignment Materials

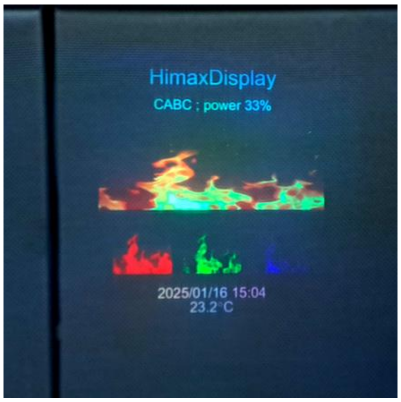
Alignment materials	**Inorganic**	**Organic**
Endurable Illumination	20 Mlux	2.2 Mlux
Reflectance	68%	58%
Contrast	1000:1	600:1
Rubbing defect	Free	Potential observable rubbing defects

The reflectance enhancement is due to less light absorption of the inorganic alignment layer and the contrast improvement is due to less light interference at the dark state since the refractive index of the inorganic material is very close to the ordinary index of the liquid crystal. For the LC mode selection, mixed-mode TN (MTN) [1] was chosen due to its faster response time and smaller fringing field effect [11].

Content Adapted Light Power Control

In order to further improve the image quality, especially for those images with lower APL (Average Pixel Level), content-adapted-light-power-control algorithm can be utilized to reduce the so-called “Postcard” effect in the dark background. We demonstrated the images without adjusting the light power and optimizing the gamma settings in Figure 6(a), one can easily see the bright spots especially at the top right corner. When reducing the light power to 33% and transfer the RGB grey levels based on the algorithm, one can see that in Figure 6(b), the postcard effect is totally eliminated while keeping the same image brightness and color gamut level. Similar content-adapted-backlight-control (CABC) methods had been widely used in the TFT LCD panels [12] in order to save the power and improve the image qualities. It can be easily adopted in the LCOS system as well. Moreover, some local dimming or zonal illumination approaches were also discussed in the LCOS projection system [13, 14]. The image qualities can be further improved to the level of self-emission displays while keeping the advantage of much lower power consumption even at the 100% APL.

6(a)



(6b)

Figure 6. (a) original image (b) Image with using content-adapted-light-power-control algorithm. The light power is reduced to 33%

Summary

We have developed a dual-edge CS Front-lit LCOS device that boost up the optical efficiency by 40% from the previous version [5], which brings the brightness to 400k nits and 1.7lm at 300mW LED power. Accompanied with a tailormade collimator, the total volume of the projector is around 0.98 c.c. A prototype demo with a 2D diffractive waveguide with FOV 30° got 1000nits brightness-to-eye at 100% average pixel level (APL), which is sufficient for outdoor usage. Based on this prove-of-concept, we have developed a 0.17” 720x720 dual-edge FL-LCOS micro-display module. The total projector size is <0.4 cc with the tailormade collimator. We believe that it will have great potential in the AR glasses industry.

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