P-151: Color Filter Liquid-Crystal-on-Silicon Microdisplays

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Abstract
We present a color liquid-crystal-on-silicon microdisplay that integrates color filters on silicon for colors. Fabrication parameters, color purity and light stability of this breed of microdisplays were characterized. A single-panel WXGA color projector based on this color filter microdisplay technology was demonstrated.

1. Introduction
Liquid-crystal-on-silicon (LCOS) microdisplay is an advanced display that integrates silicon very large-scale integration (VLSI) circuits with liquid crystal displays (LCD). The LCOS microdisplay has very high resolution and yet maintains a large aperture ratio or optical efficiency. Ancillary VLSI circuits such as display drivers or digital signal processors can also be integrated into the display for the goal of system on a chip. The LCOS microdisplay is monochrome and requires a color technique to produce colors. Conventional three-panel designs, which use three panels for three primary colors, are expensive and very difficult in manufacturing [1, 2]. Another method that uses time sequential color has limitations in bandwidth and response time of the display [3, 4]. In short, the LCOS microdisplay is promising, but lacks of a simple color method to make it prosperous.

In this paper, we present a simple color method that integrates color filters on LCOS microdisplays. Color filters are used in LCD for colors. The color filters are coated on a separate glass plate and aligned to pixels on a thin-film-transistor (TFT) plate. These color dots have a typical size of 100µm by 300µm and a thickness of 1.5µm. The alignment accuracy of these two plates is typically 10µm. To apply this color filter technology to LCOS microdisplays, several modifications have to be done. Firstly, the size of color dots shall be reduced to less than 10µm for matching fine pixels on silicon. Secondly, the thickness of color filters shall be reduced from 1.5 to 0.75µm, since the light transverse through the color filters twice in reflective LCOS microdisplays. Thirdly, these micro color filters shall be coated directly on silicon to achieve sub-micron alignment accuracy. Finally and most importantly, a very flat surface of this micro-color-filter array should be obtained for good liquid crystal alignment.

2. Micro-Color-Filter Process
We used dye base color filters in our previous work, but obtained at best 50µm resolution and 3000Å topographic variation due to process complication and material immaturity [5]. With recent advancement of pigment base color filters, we have developed a micro-color-filter process that could achieve 5µm resolution and 500Å topographic flatness. Commercial pigment based color filters are good for 1.5 to 2.0µm thickness. Dilution of these three color filters of red, green and blue by proper solvents to a lower and same viscosity is required in order to achieve a uniform 0.75µm thickness. There are several factors that affect the adhesion of color filters on the silicon substrate. The silicon surface, which has direct contact with color filters, is the most important factor. It was found that a thin buffer layer of silicon oxide could improve the adhesion of micro color filters on silicon. The adhesion prompter such as Hexamethyldisilazane was useful for adhesion, and was applied to the silicon surface during the micro-color-filter process.

We applied this micro-color-filter process to an LCOS microdisplay of 688 x 480 x RGB spatial resolution. Figure 1 shows photograph of this color pixel array and its SEM picture of cross session in tilt angle. Each sub-pixel is 11.2µm by 8.4µm and corresponds to a pixel pitch of 16.8µm.

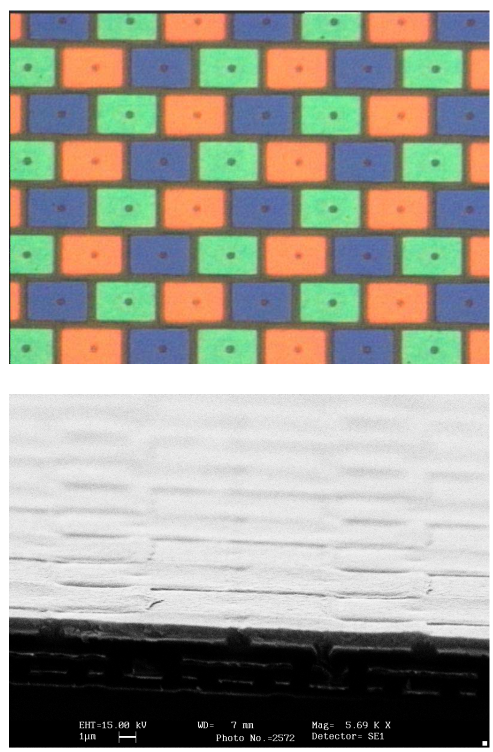

Figure 1 Photograph and SEM picture of a micro-color-filter array on silicon

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3. Optical Modeling

In addition to the process development, optical modeling of this new breed of color filter LCOS microdisplays was conducted. We have developed a three-dimensional optical simulator for analyzing twisted nematic LCD modes on color filter LCOS microdisplays. We firstly simulated for LC directors on color pixels by an electro-mechanical analysis of LC cells. Thereafter we calculated optical reflectance of color pixels for visible spectrum by extended Jones matrix. The reflectance spectrum was then converted to the CIE 1931 color space for color coordinates. We further expressed these color coordinates in standard RGB bitmap format proposed by Hewlett-Packard and Microsoft, so we were able to visualize the color fringing effects among small color pixels.

3.1 Low-Voltage SCTN Mode

With color filters between silicon pixels and liquid crystal layer, pixel voltages were partially dropped in color filters. A low-voltage LCD mode was preferred. We assembled a low-voltage 60° SCTN mode [6] on this color filter LCOS microdisplay and characterized its display performance. The microdisplay was operating at 12V. The black-and-white contrast was good since there was still a root-mean-squared voltage of 2.8V across the LC layer. But color mixing due to lateral fringing effect was severe.

Figure 2 shows photographs of this SCTN color filter LCOS microdisplay observed by a long-focus microscope for red, green and blue images. Simulated color images by a halogen light, the same as the one used in the microscope, are also included for comparisons. The simulated spatial color matched the observed one very well. The leakage of dark pixels occurred on the left of the bright pixels. The measured color coordinates were (0.44, 0.29), (0.23, 0.51) and (0.17, 0.24) for red, green and blue, respectively. The simulated color coordinates were (0.460, 0.300), (0.209, 0.560) and (0.139, 0.258), respectively. We did not include the decay of pixel voltages due to light leakage or heat in our simulation model, so the simulations had better color. It should be noted that the measured color purity of this microdisplay was improved to (0.58, 0.30), (0.26, 0.53) and (0.17, 0.18), respectively, with LED light sources.

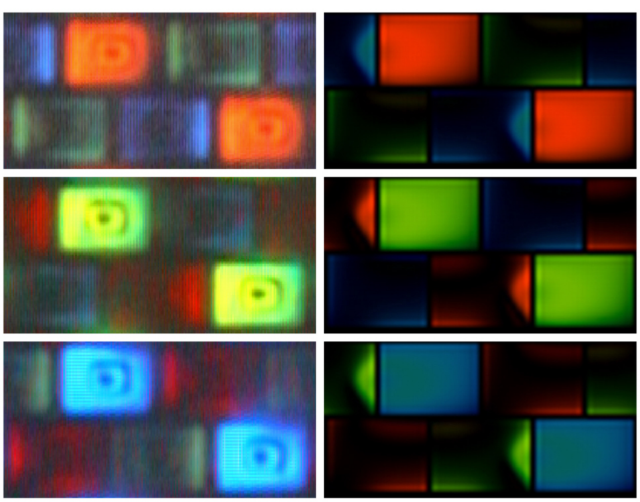

Figure 2 Photographs and simulated color images of a SCTN color filter LCOS microdisplay

3.2 High-Voltage MTN Mode

In order to have more voltage across the LC layer, we used a higher voltage process to fabricate silicon panels. The panel has a WXGA resolution of 1280 x 768 x RGB color pixels. The sub-pixel pitch is 10μm by 7.5μm for a pixel pitch of 15μm and the display area is 0.87" in diagonal. This WXGA microdisplay could operate at a higher voltage of 15V. With more voltage budget, we have more choices of LCD modes and could have a thicker color filter for better color saturation.

We assembled a 90° MTN mode [7] to this WXGA microdisplay and characterize its display performance. Figure 3 shows photographs and simulated color images of this MTN color filter LCOS microdisplay. The color fringing effect was reduced and the color purity was improved apparently from both the photographs and simulated images. It was found that the color purity was improved from less than 40% NTSC in Figure 2 to larger than 65% in Figure 3. In addition, the 90° MTN mode is less dispersive than that of the 60° SCTN mode. As a result, we used the MTN mode for projectors and the SCTN mode for near-to-eye displays.

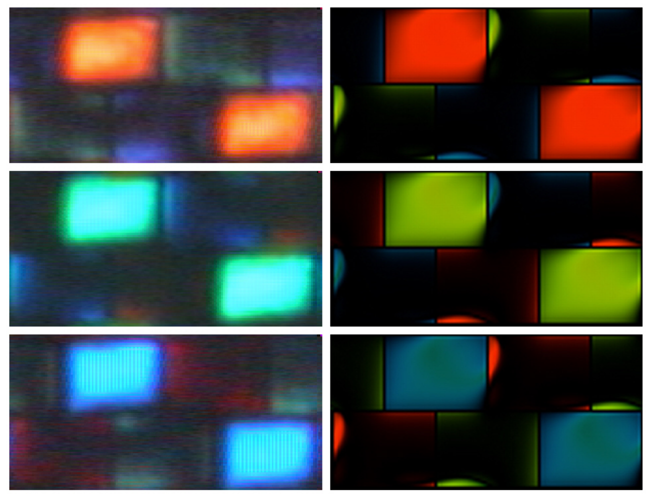

Figure 3 Photographs and simulated color images of a MTN color filter LCOS microdisplay

4. System Applications

4.1 Near-to-Eye Displays

The color filter LCOS microdisplay resembles a miniature TFT-LCD with full driver integration. The utilization of this color silicon microdisplay is therefore straightforward and can leverage on existing video decoders, processors and LCD controllers. Figure 4 shows a block diagram of the color filter LCOS microdisplay interfaced with common composite or S-video for monocular or binocular viewing. The video interface box includes a video decoder for digitizing the video signal, a video processor and SDRAM for processing the digitized video signal to 85Hz of flicker-free frame rate, and a microprocessor for configuring both the video decoder and processor. The processed video signal is then transmitted in low-voltage-differential-signal (LVDS) format to the head wearable, which is compact, lightweight and consists of only LVDS receiver, one or two microdisplays and viewing optics.

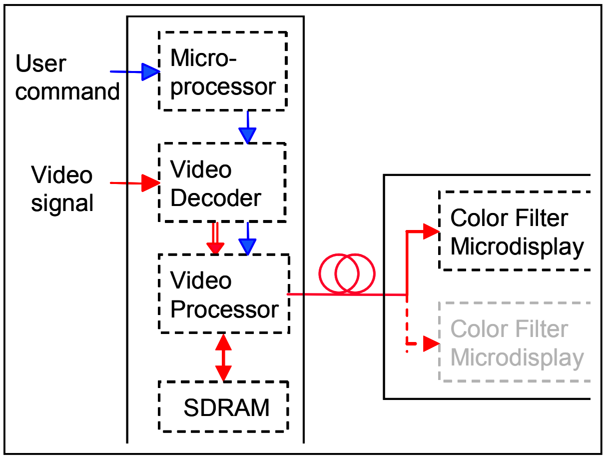

Figure 4 Block diagram of a near-to-eye display system interfaced with video signal

Binocular viewing is straightforward with identical images on both the left and right microdisplays. Stereoscopic viewing is also available by enabling and disabling the left and right microdisplays alternatively, so the left-eye image appears on the left display and the right-eye image appears on the right display. This wearable video display consumes totally 1.5W. Whereas, the video interface box drains 1W, and each color filter microdisplay and LED consumes 100 and 150mW, respectively. The display has one million color pixels in an area of 0.55" diagonal. A doublet aspherical lens is used to achieve a comfortable 32° field of view. All these parameters demonstrate that the color filter LCOS microdisplay is very suitable for near-to-eye display applications.

With colors available on LCOS microdisplays, the viewing optics is greatly simplified. A PBS for directing a polarized light into the microdisplay and back to an eyepiece or a projection lens is adequate [8]. This color filter LCOS microdisplay is ideal for near-to-eye applications because of its compactness and low-power consumption. The requirements of optical efficiency and light stability in the near-to-eye display applications are low, and the color filter LCOS microdisplay has no problem in meeting these specifications. The question is whether this color filter LCOS microdisplay could withhold a much stronger light illumination for projector applications.

4.2 Single-Panel Projectors

We illuminated this color filter WXGA microdisplay by 8 million lux light for 1000 hours. Figure 5 shows reflectance spectra measured by a colorimeter before and after the illumination. The color filters did not degrade or bleach significantly. They still maintained a good contrast and transmission efficiency after the illumination. We did not observe significant change in the LC layer, in which we have used LC mixture of high clearing temperature of 110°C. The measured color difference ΔEab before and after the illumination was 55, 56 and 41, respectively, for red, green and blue. This color difference has been much improved since we started this research, but it was still larger than our target of 30. Optimizations of LC mixtures, alignment layers and color filters should be continued.

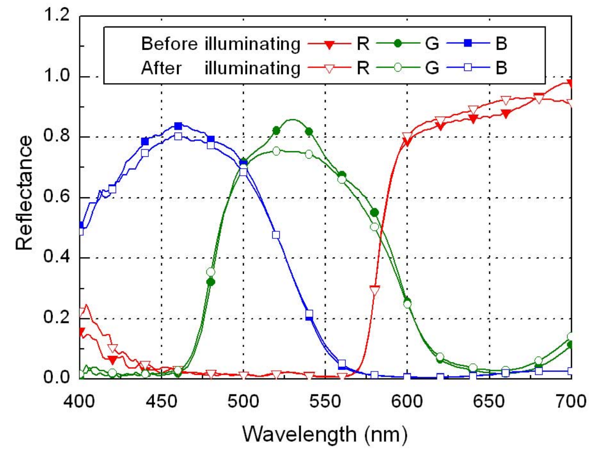

Figure 5 Light stability of the color filter LCOS microdisplay

The block diagram of the single-panel color projector is similar to that of the near-to-eye display in Figure 4. But the frame rate has to be increased to 120Hz to compensate for light leakage and to increase the contrast. Figure 6 shows a compact single-panel WXGA optical engine without illumination optics. The video interface board utilized common video decoder and processor and is very compact of a name card size. With single-panel projector architecture, the design specifications of the projection lens are also greatly relieved. The projection lens is a telecentric design with 7 mixed glass and plastic elements for a field of view of 82.5° (2θ). The back focal length includes 10mm in air and 25mm in cube PBS. The overall length of the projection length is less than 10cm for a compact optical engine.

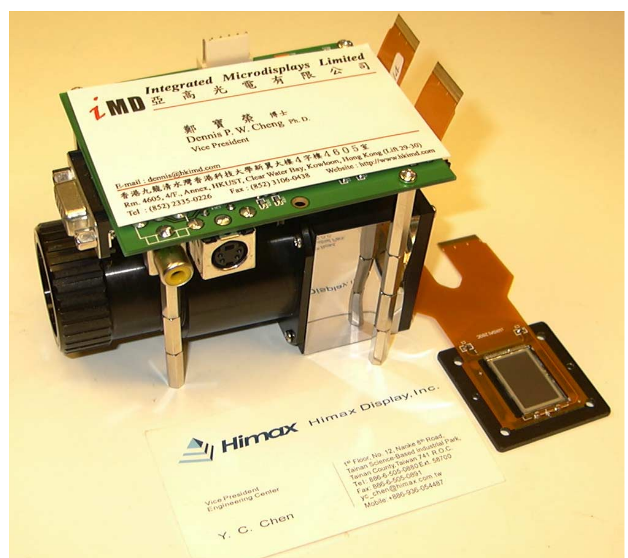

Figure 6 A compact single-panel WXGA optical engine

We illuminated this compact WXGA optical engine with a 120W arc lamp. Figure 7 shows a 38" projection image of this single-panel WXGA color projector. The projection or throw distance was 22", the optical output was 300 lm and the system contrast of this WXGA projector prototype was 200:1 at the moment.

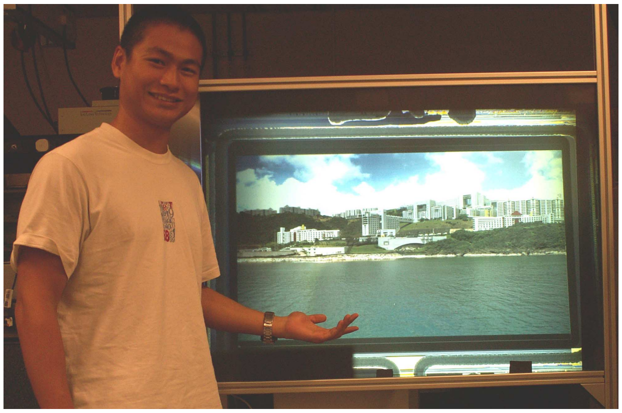

Figure 7 A projection image of the single-panel WXGA projector

5. Conclusion

We have developed a color filter LCOS microdisplay technology that integrated color filters on silicon for colors. The projection optics was greatly simplified since color was already available on microdisplays. The color filter LCOS microdisplay was ideal for near-to-eye applications where low-power consumption and compactness is required. The color filter LCOS microdisplay could also withhold strong light illumination for rear projection television (RPTV). This single-panel RPTV should have cost advantages over other projection display technologies.

6. Acknowledgements

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7. References

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