

Processes, characterizations, and system applications of color-filter liquid-crystal-on-silicon microdisplays

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Abstract — A color-filter liquid-crystal-on-silicon (CF-LCOS) microdisplay that integrates color filters on silicon for color will be presented. The color-filter process on silicon was optimized to achieve fine resolution and precise alignment of the color filters on the pixel array, good adhesion to the silicon surface, and a flat surface for the liquid-crystal cell assembly. Important optical and electrical parameters of the color filters were extracted to establish an electro-optical model of the CF-LCOS microdisplays for device simulation. Thermal, chemical, and light-stability characterizations were performed to ensure the stability of the color filters and CF-LCOS microdisplays. With color CF-LCOS microdisplays already available, the projection or viewing optics is greatly simplified. This CF-LCOS microdisplay is ideal for near-to-eye displays because of its low-power consumption and compactness. The CF-LCOS microdisplay could also withstand medium light illumination for medium-sized projectors. A single-panel projector based on one CF-LCOS microdisplay of $1280 \times 768 \times \text{RGB}$ resolution was demonstrated.

Keywords — Liquid-crystal display, LCOS, color filter, CF-LCOS, microdisplay.

1 Introduction

A liquid-crystal-on-silicon (LCOS) microdisplay is an advanced display that integrates LCOS very-large-scale-integration (VLSI) circuits.^{1,2} 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 be integrated into the microdisplay to achieve the goal of system on a chip. However, the LCOS microdisplay is monochrome and requires a color technique to produce color. Conventional three-panel designs, which use three panels for three primary colors, are expensive.^{3,4} It is also very difficult to align three panels together with good accuracy in assembling optical engines. Another method that uses one panel and time-sequential color has made the optical system simpler. But it has to work with an electronic system of high data bandwidth and a liquid-crystal (LC) cell with fast response time.^{5,6} As a consequence, the system cost is high and the optical efficiency is low. In short, the LCOS microdisplay is promising, but lacks a simple color method.

In this paper, we present a simple color method that integrates color filters into LCOS microdisplays.^{7,8} Color filters are used in conventional liquid-crystal displays (LCDs) to produce color. In these displays, color filters are coated on a glass plate and aligned with the pixels on another thin-film-transistor (TFT) plate. These color dots have a typical size of $100 \times 300 \mu\text{m}$ and a thickness of $1.5 \mu\text{m}$. The alignment accuracy between the color filter and TFT plates is typically $10 \mu\text{m}$. To apply this color filter technology to LCOS microdisplays, several modifications have to be

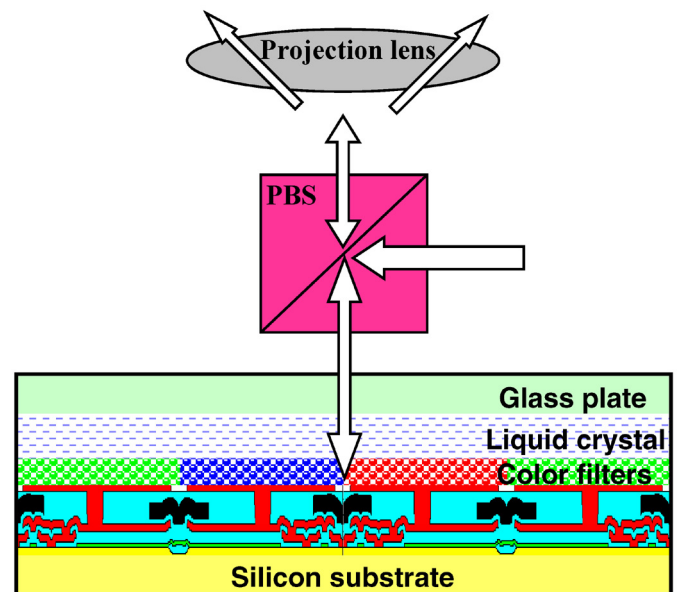


FIGURE 1 — Illustration of the CF-LCOS microdisplay.

made. First, the size of the color dots has to be reduced to less than $10 \mu\text{m}$ to match the fine pixels of the LCOS microdisplays. Second, the thickness of color filters should be reduced from 1.5 to $0.75 \mu\text{m}$, because the light transverses through the color filters twice in reflective LCOS microdisplays. Third, these color filters have to be coated directly onto silicon to achieve submicron alignment accuracy on the pixel array. Finally, and most importantly, a flat surface for the color-filter array should be obtained for good alignment

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of the LC molecules in the assembly of the color-filter LCOS (CF-LCOS) cells.

Figure 1 illustrates a CF-LCOS microdisplay in which the color filters were coated directly onto silicon. The projection optics is greatly simplified because color is already available. What it needs is just a polarizing beam splitter (PBS) that directs a polarized light into the display and back to a projection lens as also illustrated in Fig. 1.

2 Processing of color filters on silicon

There are four methods of processing color filters on silicon. They are electro-deposition, printing, dying, and pigment dispersion.⁹ The electro-deposition and printing methods have limitations in resolution and are only good for large-sized pixels. The dying method can produce fine color filters for small pixels, but it suffers from a light stability problem caused by bleaching and evaporation of dyes in the color filters. The pigment-dispersed color filter is more stable in terms of chemical, thermal, and light stability, and can also be patterned to small features. As a result, it is considered to be the best processing method for color filters in high-resolution displays.¹⁰

We used dye-based color filters in our previous works, but obtained, at best, 50- μm resolution and 3000- $\text{\AA}$ topographic variation due to complications in the fabrication process and immaturity of the dye materials.¹¹ With the recent advancements made in pigment-based color filters, we have developed a color-filter process that could achieve 5- μm resolution and 500- $\text{\AA}$ topographic flatness. Conventional pigment-based color filters were designed for the TFT-LCD panels at a thickness of 1.5–2.0 μm . Dilution of the color filters for red, green, and blue by proper solvents to a common, lower viscosity is required in order to achieve a thinner and uniform layer of color filters on silicon. In our work, we diluted all three primary color filters to the same viscosity of 4.0 mPa-sec, and spun the diluted color filters at 1000 rpm on silicon to achieve a uniform 0.75- μm thickness for all the three color filters.

The small color filters must adhere strongly to the silicon surface such that they would not be peeled off during the later rubbing process. There are several factors that affect the adhesion of small color filters on the silicon substrate. The silicon surface, which has direct contact with the color filters, is the most important factor. In the experiments, we coated the color filters onto the silicon substrate with three different surface treatments, which included bare metal, a thin oxide layer, and a thin oxide and nitride layer. Thereafter, we cured the color filters on the silicon substrate at 180°C for 30 minutes, and then rubbed the silicon substrate coated with color filters with a typical rubbing force. It was found that the color filters on the thin oxide layer had the best adhesion, while the color filters on the bare metal had the worst adhesion. It was believed that the intermediate oxide layer could relieve the stress between color filters and metal on the silicon during the thermal process. As a result, the

adhesion of color filters on silicon was improved. In addition, an adhesion promoter such as Hexamethyldisilazane was considered useful for improving the adhesion and was applied to the silicon oxide surface before the application of color filters.

The red, green, and blue color filters had similar polymer structures, but different pigments and light sensitivities that could affect the color-filter process. Some of the color filters were easier for processing than the others. The fabrication sequence of red, green, and blue color filters was therefore another important process parameter. At one optimal fabrication sequence, we could obtain a color-filter array with better resolution, adhesion, and flatness.

In our work, we processed first the green color filter whose binder resin had the least sensitivity to ultraviolet (UV) light, then followed by the red and blue color filters whose binder resins had higher UV-light sensitivities. The green color filter, which had the worst adhesion on silicon due to the least UV-light sensitivity of its binder resin, was processed onto a clean silicon surface for the best adhesion that we possibly could achieve. The red and blue color filters, which had a better adhesion, were processed later onto a silicon surface which had been slightly polluted during the green-color-filter process. The adhesion of the red and blue color filters on the polluted silicon surface was not as good as on a clean surface, but was better than that of the green color filter on a clean silicon surface. In our process, we actually exposed the patterned green color filter to the *i*-line of the stepper one more time before the process of the red and blue color filters to further solidify the adhesion of the green color filter on silicon. With this fabrication sequence, we achieved a color-filter array with a fine resolution of 5 μm , a flat topographic flatness of 500 $\text{\AA}$ and very good adhesion on silicon for all three color filters.

We applied this color-filter process to an LCOS microdisplay with a 688 $\times$ 480 $\times$ RGB spatial resolution. The silicon panel was designed and fabricated for a 3.3-/12-V dual-voltage LCD driver process, where 3.3 V was for data

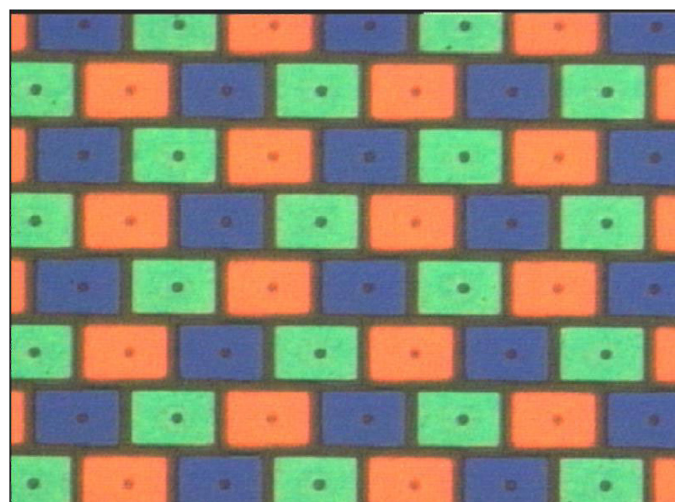


FIGURE 2 — A photograph of the color pixel array.

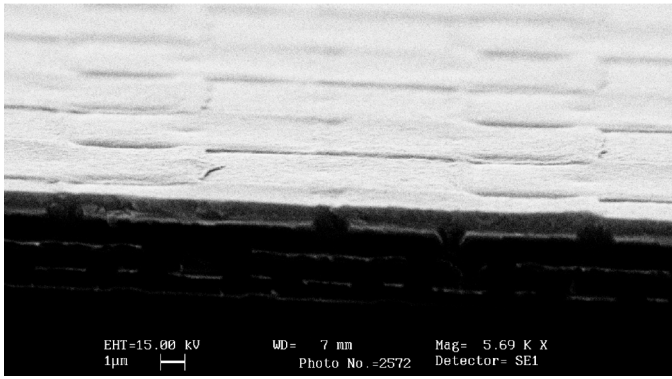


FIGURE 3 — An SEM picture of the cross section of the color pixel array for a tilt angle.

logic and 12 V was for driving the LC layer on top of the silicon panel. In this design, the pixels were arranged in delta configurations and the color filters were coated directly onto these pixels to render color. Figure 2 shows a photograph of the color pixel array. Each subpixel is $11.2 \times 8.4 \mu\text{m}$ and corresponds to a pixel pitch of $16.8 \mu\text{m}$.

The color-filter array could also serve as a passivation layer to improve the surface flatness in this CF-LCOS microdisplay. Figure 3 shows a scanning electron microscopy (SEM) photograph of the cross-section of the color-pixel array for a tilt angle. There were pixel gaps in the pixel array, and the step height between the pixel electrodes and the gaps was $4000 \text{ \AA}$ before the color filters were employed. After coating and re-flowing of a layer of $7500\text{-\AA}$ color filters on the pixel array, the pixel gaps were filled up by overlapping color filters. The topographic variation of the color-pixel array was then reduced to about $1000 \text{ \AA}$.

We have also applied the color-filter process to another LCOS microdisplay of $1280 \times 768 \times \text{RGB}$ spatial resolution. The subpixel was $10 \times 7.5 \mu\text{m}$ for a pixel pitch of $15 \mu\text{m}$ and a display area of 0.87-in. on the diagonal. The silicon panel was designed and fabricated for a higher 3.3-/15-V LCD driver process. With a higher voltage budget, we had more choices of LCD modes and could have a thicker color filter for better color saturation.

3 Characterization of color filters on silicon

The characterization of color filters was mainly divided into three parts. The first part was to characterize their optical properties, which included the refractive index, extinction coefficient, and birefringence. The second part was to characterize their electrical properties, which included the dielectric constant and resistivity. These optical and electrical parameters for color filters are required for optical modeling of the CF-LCOS microdisplays.¹² In addition to these two characterizations, the chemical, thermal, and light stabilities of the color filters were also characterized.

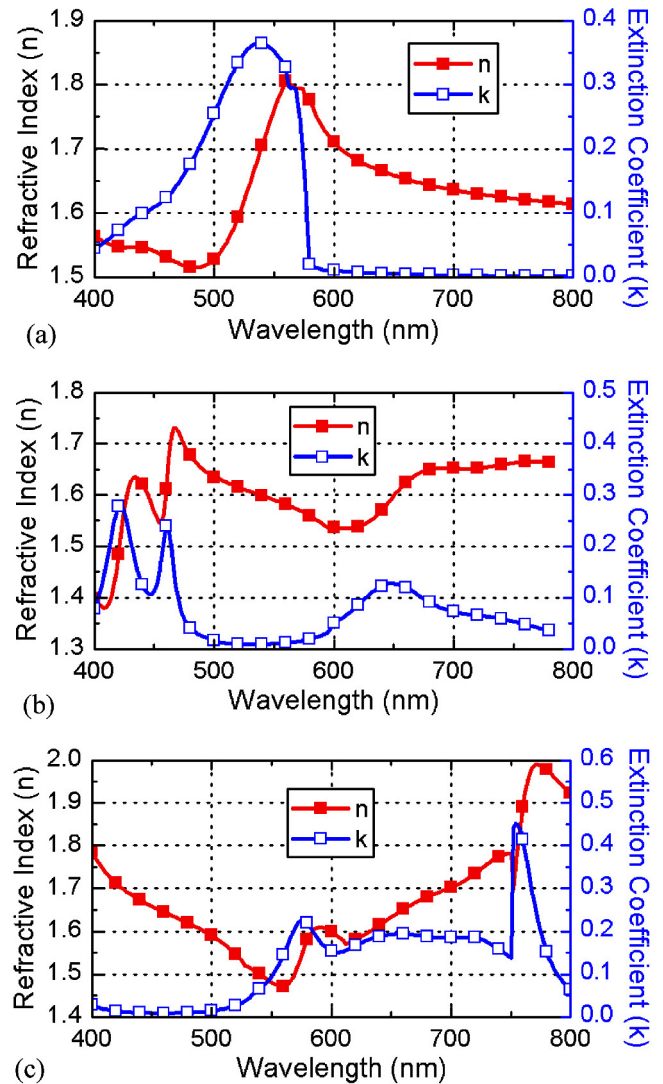


FIGURE 4 — The refractive index and extinction coefficient of (a) the red, (b) green, and (c) blue color filters in the visible spectrum.

3.1 Optical characterizations

For the optical characterization of color filters, we first used a spectroscopic ellipsometer to measure their optical reflectance in the visible spectrum. The refractive index, n , and extinction coefficient, k , of color filters in the transparent region can be described by the Cauchy dispersion formula as follows:

$$n(\lambda) = A_n + B_n/\lambda^2 + C_n/\lambda^4 \quad (1)$$

and

$$k(\lambda) = A_k + B_k/\lambda^2 + C_k/\lambda^4, \quad (2)$$

where A_n , B_n , C_n , A_k , B_k , and C_k are the Cauchy coefficients and can be obtained from curve fittings of the spectroscopic ellipsometer measurement.^{13,14} In the characterizations, we fitted the optical reflectance curve of the red color filter in its transparent region of 600–700 nm and obtained the Cauchy coefficients of the red color filters in this region as

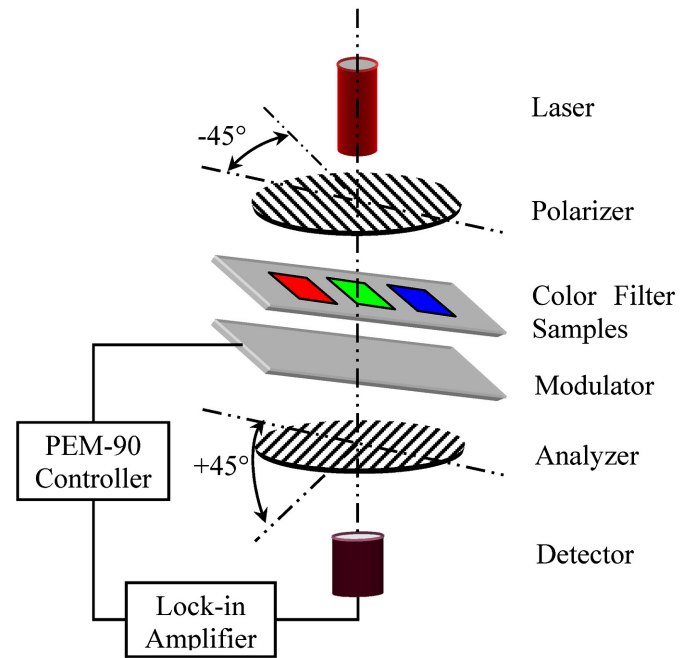
TABLE 1 — The Cauchy coefficients of color filters.

	A_n	B_n (nm ²)	C_n (nm ⁴)	A_k	B_k (nm ²)	C_k (nm ⁴)
Red	1.64	-1.26×10^5	4.54×10^7	-0.103	9.76×10^4	-2.09×10^7
Green	1.47	-6.23×10^4	1.94×10^7	-0.023	4.22×10^4	-7.91×10^5
Blue	1.33	-4.58×10^4	1.64×10^6	-0.015	3.90×10^4	-4.27×10^6

listed in Table 1. The Cauchy coefficients of the green color filter in its transparent region of 500–600 nm, and the blue color filter in its transparent region of 400 to 500 nm were also obtained and are listed in Table 1. Because the values of refractive index, n , and extinction coefficient, k , were obtained in the transparent region, the thickness of the color filter, d , could be derived. Thereafter, we fitted the refractive index and extinction coefficient point by point in the non-transparent or absorptive region with the known thickness of color filters. The refractive index and extinction coefficient of the color filters in the visible spectrum from 400 to 700 nm was therefore obtained and shown in Fig. 4.

Both the color filters and LC layer were between a common electrode on a glass plate and a pixel electrode on the silicon panel. Birefringence of color filters would introduce a retardation value and perturb the LC mode. The birefringence of color filters was therefore another important optical parameter that would affect the performance of the CF-LCOS microdisplays. We used an optical setup as shown in Fig. 5 to measure the birefringence of color filters. Whereas, a red laser with a peak wavelength of 632.8 nm was used for the red color filter and a green and a blue laser with a peak wavelength of 543.5 and 457 nm, respectively, were used for the green and blue color filters. The laser light passed through a -45° front polarizer, the color filters under characterization on a glass plate, a PEM-90 photoelastic modulator from Hinds Instruments, and a 45° rear analyzer to a photodetector. The PEM-90 controller controlled the photoelastic modulator to produce a variable birefringence value. The optical transmittance detected by the photodetector and lock-in amplifier would therefore be correlated to the birefringence modulation of the photoelastic modulator. From the readout of the transmittance, the birefringence of the color filters could be derived.¹⁵

The readouts of the retardation were small. In order to increase the value of the retardation for more accurate measurement, we prepared 4- μ m-thick color filters using a special process. The measured retardation were 7.2×10^{-6} , 9.9×10^{-6} , and 11.7×10^{-6} μ m, respectively, for the red, green, and blue color filters, and hence the birefringence were 1.8×10^{-6} , 2.5×10^{-6} and 2.9×10^{-6} for the red, green, and blue color filters at 632.8, 543.5, and 457 nm, respectively. It was observed that the blue color filter introduced more birefringence or retardation at the wavelength of 457 nm, while the red color filter introduced the least birefringence or retardation at 632.8 nm for the same thickness of color filters. All of the three red, green, and blue color filters are pigment based and have a similar polymer structure or

**FIGURE 5** — The optical setup for measuring the birefringence of color filters.

binder resin. They should have a similar birefringence as well. Nevertheless, all the birefringence values were sufficiently small that they would not introduce significant retardation values in the color-filter LC cells to perturb the LC mode. The color filters can therefore be treated as absorptive and isotropic media in the optical modeling of CF-LCOS microdisplays because of their low birefringence.

3.2 Electrical characterizations

For the electrical characterization of color filters, we modeled the color filters by an equivalent circuit of a resistor in parallel with a capacitor and measured their values using an LCR meter. The measured resistance and capacitance at 60 and 120 Hz are listed in Table 2. With these two values, we proceeded to calculate their dielectric constants and resistivity, which are also included in Table 2. Both the dielectric constants and resistivity of the color filters are important parameters for determining the electric-field distribution in the color-filter LC cells. These two parameters would be also used in the optical modeling of CF-LCOS microdisplays.¹²

One of the concerns of applying color filters in LC cells is the drop in voltage across the color filters. As a result, the voltage across the LC cells would be reduced and the contrast of the LC cell would be reduced as well. For our typical color filters, LC cells with 2.5- and 3.1- μ m LC layer thickness, the voltage drop on the 0.75- μ m color-filter layer was 38 and 30%, respectively. To compensate for this voltage drop, a higher driving voltage is required. The use of a low-voltage LC mode is also helpful. The optical properties of this color-filter LC cell depend greatly on the thickness of

TABLE 2 — The measured resistance and capacitance of the color filters at 60 and 120 Hz.

		Measured		Derived	
		Resistance ($M\Omega$)	Capacitance (pF)	Resistivity ($\Omega \cdot cm$)	Dielectric constant
60 Hz	Red	230	434.8	2.4×10^{11}	4.63
	Green	319	108.7	6.0×10^{10}	6.01
	Blue	273	833.3	5.7×10^{11}	4.52
120 Hz	Red	259	459.2	2.7×10^{11}	4.89
	Green	532	107.1	1.0×10^{11}	5.92
	Blue	235	861.0	4.9×10^{11}	4.67

the color filters, the thickness of the LC cell, the lateral electrical field and LC mode. Please refer to our other paper for the optical modeling and optimizations of CF-LCOS microdisplays with these parameters.¹²

3.3 Stability characterizations

In addition to both the optical and electrical characterizations of color filters, we have also performed a few other characterizations to ensure the thermal, chemical, and light stability of color filters to be used in the CF-LCOS microdisplays.

After the application of color filters onto the silicon substrate, a polyimide layer was coated onto the color pixel array for later LC alignment. The most severe thermal condition that the color filters would experience was curing of this polyimide layer at 250°C for 2 hours.

For the thermal-stability characterization, we cured the color filters under characterization at 250°C for 2 hours and measured their optical and electrical properties again. The optical reflectivity, dielectric constants, and resistivity

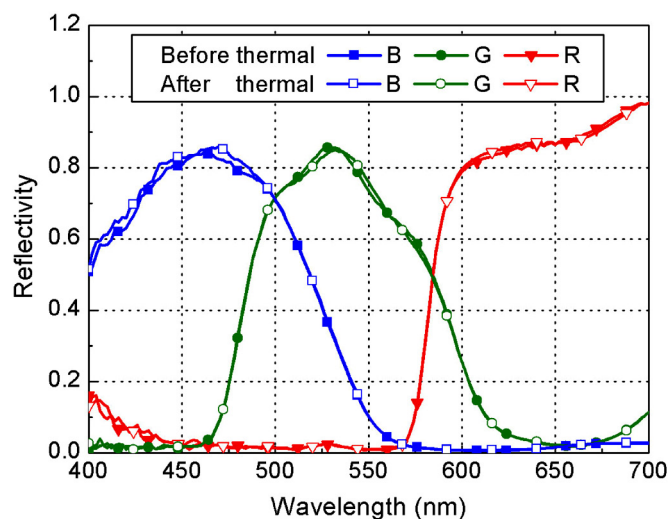


FIGURE 6 — The measured optical reflectivity before and after the thermal process.

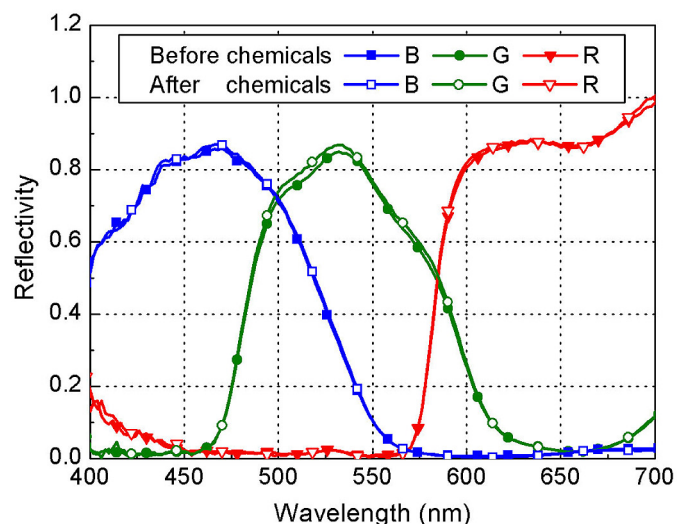


FIGURE 7 — The measured optical reflectivity before and after the chemical processes.

of color filters after the thermal characterization did not change much. Figure 6 shows the measured optical reflectivity before and after the thermal characterization. The color difference, ΔE_{ab} , was 2.9, 2.6, and 2.4, respectively, for the red, green, and blue color filters before and after the thermal process. This ensured that the color filters had good thermal stability for the CF-LCOS microdisplays during the cell-assembly process.

There were a few chemicals that would be used during the color filter and cell-assembly processes. The color filters should be resistant to these chemicals and maintain their optical and electrical properties intact. These chemicals include the developers of the color filters used in the color-filter process, solvents of polyimide used in the cell-assembly process, and organic strippers used in the wafer-cleaning process.

In the chemical-stability characterization, we exposed the color filters under characterization to the developers of color filters for 30 minutes, the solvents of polyimide for 30 minutes, and the organic strippers for 2 hours. We then measured the optical and electrical properties of the color filters again after these chemical processes to see if there was any significant change. Figure 7 shows the measured optical reflectivity before and after the chemical characterizations. The color difference, ΔE_{ab} , was 2.7, 2.5, and 2.8, respectively, for the red, green, and blue color filters before and after the chemical processes. This ensured again that the color filters had good chemical stability for the CF-LCOS microdisplays during the color-filter and cell-assembly processes.

The most important concern in applying the CF-LCOS microdisplays for projectors is their light stability. It was feared that strong light illumination on the color filters might bleach the pigments and reduce the saturation of color filters. It was also suspected that a strong light illumination on the color filters might break their binder resin,

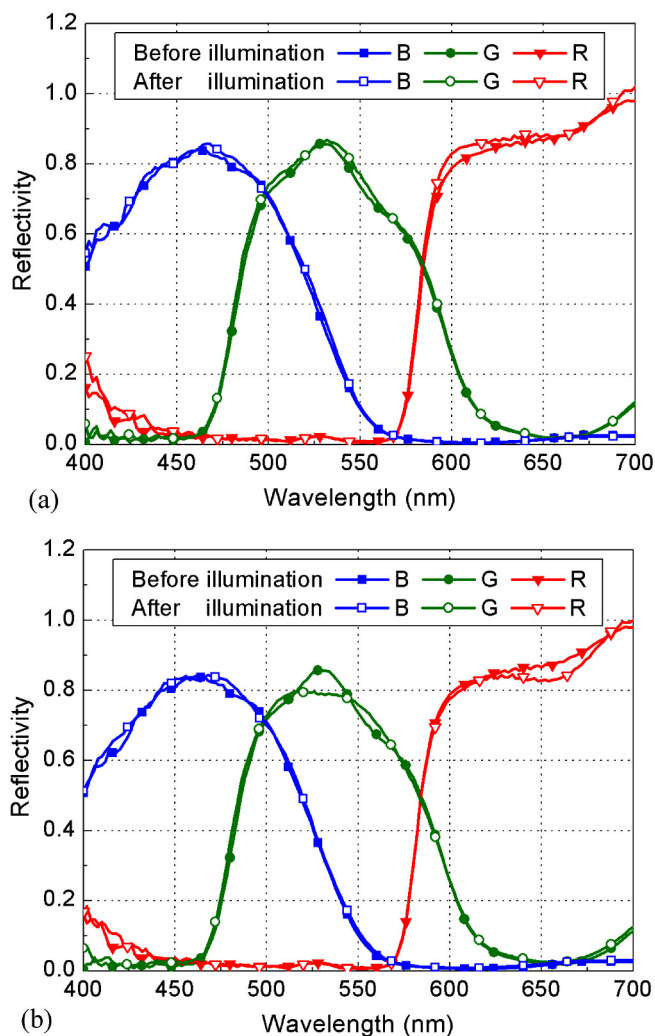


FIGURE 8 — The measured optical reflectivity before and after (a) 2000 and (b) 5000 hours of light illumination.

and the color filter particles might diffuse out into the LC cell.

In the light-stability characterization, we first sealed the color filters under characterization in an empty cell and filled the cell with inert nitrogen gas. This was to avoid the exposure of color filters directly to the air causing oxidation. Thereafter, we illuminated the color filters under characterization with a strong light flux of 10 million lux and measured their optical properties every 100 hours. It was observed that different types of color filters with different kinds of pigments could withstand different degrees of light illumination.

Figure 8 shows the measured optical reflectivity of the color filters that had good light stability before and after 2000 and 5000 hours of light illumination. The color filters degraded smoothly and slightly with the light illumination. The color difference, ΔE_{ab} , was 19, 16, and 11, respectively, for the red, green, and blue color filters before and after 2000 hours of light illumination. The color difference was slightly increased to 29, 22, and 15, respectively for the red, green, and blue color filters after 5000 hours of light illumi-

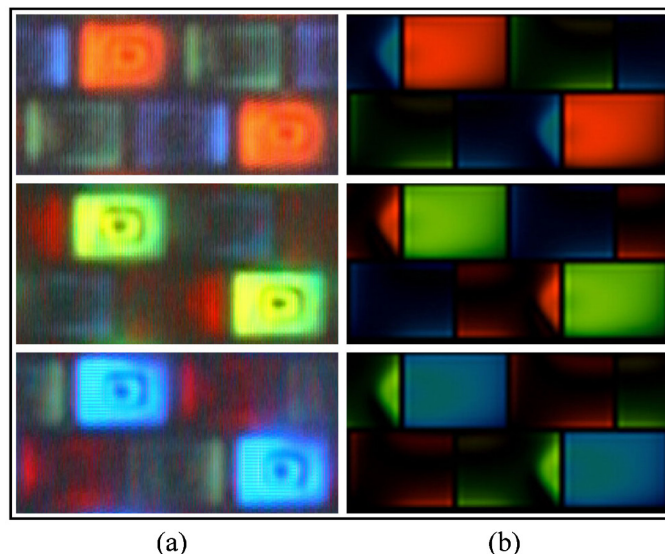


FIGURE 9 — (a) The observed and (b) simulated color pixels of a SCTN CF-LCOS microdisplay.

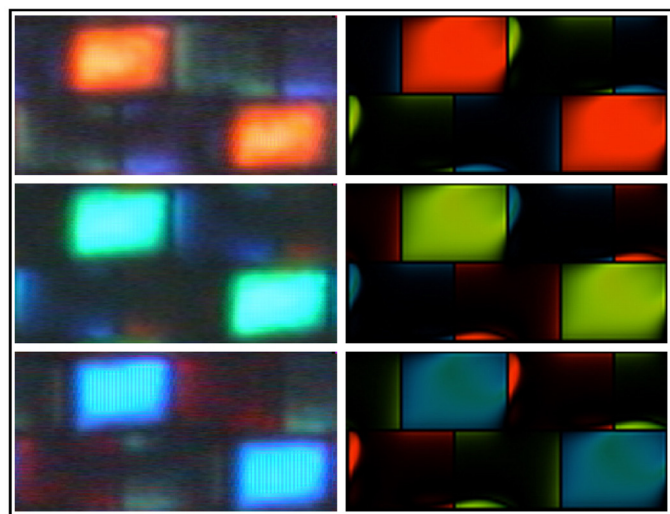
nation. This light stability was considered to be good enough for medium-sized projectors in which the light incidence onto the panel was below 10 million lux. Optimization of the color filters for better light stability with stronger light illumination is required in order to apply the CF-LCOS microdisplays for larger-sized projectors.

4 Liquid-crystal modes

4.1 Low-voltage SCTN mode

With the color filters between the pixel electrodes on silicon and the LC layer, the pixel voltages were partially dropped in the color filters. A low-voltage LC mode was preferred. We assembled a low-voltage 60° self-compensated twisted-nematic (SCTN) mode¹⁶ on the low-voltage CF-LCOS microdisplay of $688 \times 480 \times \text{RGB}$ spatial resolution and characterized its display performance. The microdisplay was operated at 12 V. The black-and-white contrast was good since there was still a root-mean-squared voltage of 2.8 V across the LC layer. But the color mixing due to the lateral fringing effect was severe.

Figure 9 shows photographs of this SCTN CF-LCOS microdisplay observed by a long-focus microscope for the red, green, and blue images. Simulated color images produced by a halogen light, the same as used in the microscope, are also included for comparisons. The simulated spatial color matched the observed one very well in that the leakage of the dark pixels occurred mainly on the left of the bright pixels. The measured color coordinates were (0.427, 0.287), (0.228, 0.509), and (0.169, 0.241) for the red, green, and blue images, 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



(a) (b)

FIGURE 10 — (a) The observed and (b) simulated color pixels of a MTN CF-LCOS microdisplay.

measured color saturation of this low-voltage CF-LCOS microdisplay could be improved to (0.579, 0.301), (0.262, 0.533), and (0.169, 0.178), respectively, with light-emitting diodes as the light sources. This measured color purity corresponded to 42% NTSC level, which was very close to the simulated color purity of 44%.

4.2 High-voltage MTN mode

For a high-voltage CF-LCOS microdisplay with a $1280 \times 768 \times \text{RGB}$ spatial resolution, we could have more choices of LC modes because we had more voltage across the color filter and LC layers. We, therefore, assembled a higher-voltage 90° mixed-mode twisted-nematic (MTN) cell¹⁷ to this CF-LCOS microdisplay and characterized its display performance. Figure 10 shows the microscope photographs and simulated color images of this MTN CF-LCOS microdisplay. The color fringing field was reduced and the color purity was improved, as is apparent from both the photographs and simulated images. It was found that the simulated color purity was improved slightly from less than a 44% NTSC level for the SCTN CF-LCOS microdisplay to larger than 46% for the MTN CF-LCOS microdisplay at the same driving voltage of 4 V across the color filter and LC layers.

In practice, the high-voltage MTN CF-LCOS microdisplay was operated at a higher voltage over the low-voltage SCTN CF-LCOS microdisplay. The color purity of the MTN CF-LCOS microdisplay could be further improved from a 46% to a 51% NTSC level when the voltage across the color filter and LC layers was increased from 4 to 5 V, where a root-mean-squared voltage of 3.1 V was across the LC layer. In addition, the MTN cell was less dispersive than that of the SCTN mode. As a result, we used the high-voltage MTN mode for projectors and the low-voltage SCTN mode for near-to-eye displays.

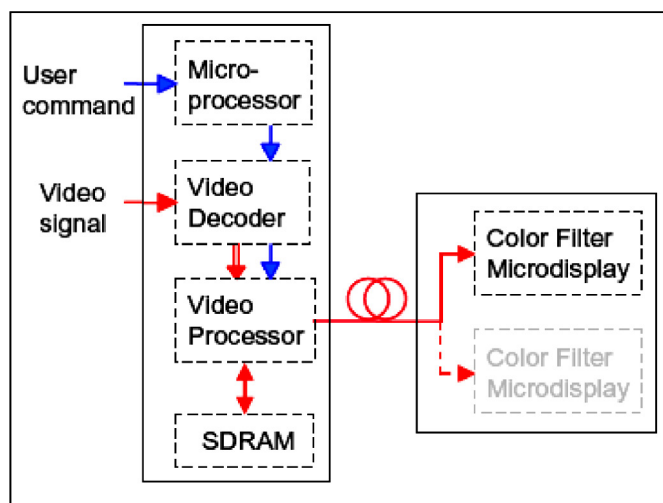


FIGURE 11 — Block diagram of the CF-LCOS microdisplay interfaced with common video signals for near-to-eye displays.

5 System applications

5.1 Near-to-eye displays

The CF-LCOS microdisplay resembles a miniature TFT-LCD with full driver integration. The utilization of this color microdisplay is therefore straightforward and can leverage on existing video decoders, video signal processors, and LCD controllers. Figure 11 shows a block diagram of the CF-LCOS microdisplay interfaced with common composite or S-video for monocular or binocular near-to-eye displays. 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 a flicker-free frame rate of 85 Hz, and a microprocessor for configuring both the video decoder and signal processor. The processed video signal is then transmitted in a low-voltage-differential-signal (LVDS) format to the head-wearable display, which is compact, lightweight, and consists of only a LVDS receiver, one or two CF-LCOS microdisplays, and viewing optics.

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 of $688 \times 480 \times \text{RGB}$ spatial resolution consumes 1.5 W. The video-interface box drains 1 W, and each CF-LCOS microdisplay and LED consumes 100 and 150 mW, respectively. The display has one million color pixels for a 0.55-in. diagonal area. A doublet aspherical lens is used to achieve a comfortable 32° field of view. All these parameters demonstrate that the CF-LCOS microdisplay is very suitable for near-to-eye displays.

The CF-LCOS microdisplay is ideal for near-to-eye displays because of its compactness and low-power consumption. The light illumination to the display is less than 10^4 lux, resulting in a comfortable brightness of 50 cd/m² through the eyepiece. The CF-LCOS microdisplay has no

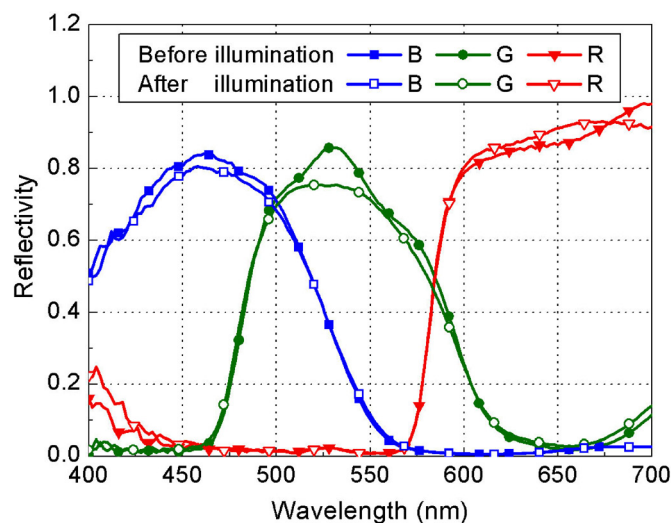


FIGURE 12 — The measured optical reflectivity of a CF-LCOS microdisplay before and after light illumination.

problem in meeting the light-stability requirement in this low-light illumination. The question is whether the CF-LCOS microdisplay could withstand a much stronger light illumination for projectors.

5.2 Single-panel projectors

We illuminated the CF-LCOS microdisplay with a light flux of 8 million lux for 1000 hours. Figure 12 shows the measured optical reflectivity before and after the light 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 a significant change in the LC layer, in which we have used an LC mixture with a high clearing temperature of 110°C. The measured color difference, ΔE_{ab} , was 55, 56, and 41, respectively, for the red, green, and blue images before and after the illumination. 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.

We also performed conventional high-temperature operation and storage tests, low-temperature operation and storage tests, high-humidity operation and storage tests, and thermal shock test. Because the CF-LCOS microdisplays were similar to miniature TFT-LCD panels, there was no significant difference in these environmental tests in comparison with conventional TFT-LCDs. The light stability was considered as the most severe lifetime test for the CF-LCOS microdisplays.

The block diagram of the single-panel color projector is similar to that of the near-to-eye displays in Fig. 11. But the frame rate has to be increased to 120 Hz to compensate for the light leakage and to increase the contrast. With the single-panel projector architecture, the design specifications of the projection lens are also greatly relieved. The

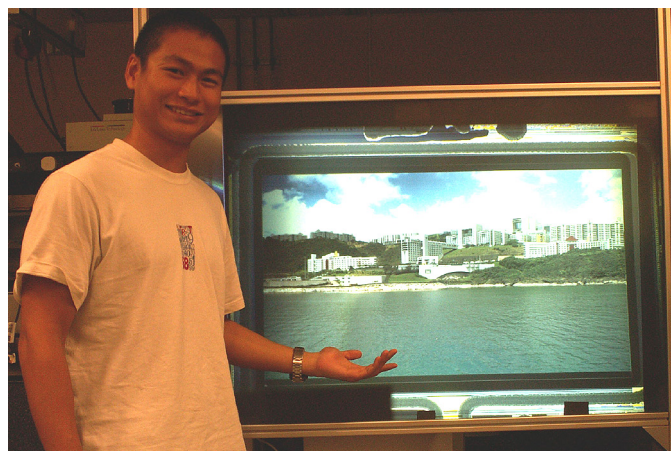


FIGURE 13 — A 38-in. projection image of the single-panel color projector.

projection lens is a telecentric design with seven mixed glass and plastic elements for a field of view of 82.5° (2 θ) and an f -number of 2.4. The back focal length includes 10 mm in air and 25 mm in a cube PBS. The total optical length from the first surface of the projection lens to the microdisplay is less than 13 cm for a compact optical engine.

We illuminated this compact optical engine of 1280 × 768 × RGB spatial resolution with a 120-W arc lamp. Figure 13 shows a 38-in. projection image of this single-panel color projector at a throw distance of 22 ft. This optical engine delivered an optical output of 300 lm and had a system contrast of 200:1, whereas the CF-LCOS microdisplay was designed to produce a contrast of slightly larger than 200:1 at $f/2.4$ optics. It should be noted that the contrast of the CF-LCOS microdisplay could be improved to larger than 400:1 using a different design, but the optical throughput would be reduced. This 300-lm projector might not be suitable for business data projectors that require an optical output larger than 1000 lm. But it should be good for 40–50-in. rear-projection televisions (RPTVs) or portable mini-projectors that required an optical output of 300 lm or less.

6 Conclusion

We have developed a color-filter liquid-crystal-on-silicon (CF-LCOS) microdisplay that integrated color filters on silicon to render color. This color method was very similar to that of conventional thin-film-transistor liquid-crystal displays (TFT-LCDs), except that the color filters were coated directly on the pixel array rather than on a separate glass plate. We have optimized the color-filter process to achieve fine resolution and submicron alignment of the color filters on the pixel array, good adhesion to the silicon surface, and a flat surface for the liquid-crystal cell assembly with a specific process sequence and parameters. The important optical and electrical parameters of the color filters were also extracted, so an electro-optical model of the CF-LCOS microdisplays could be established for device simulation. In addition, the thermal, chemical, and light stability of color

filters were also characterized to ensure that their optical and electrical properties remained the same after the color-filter process and liquid-crystal cell assembly. The projection or viewing optics of this breed of microdisplays is greatly simplified because color is already available on the display. This CF-LCOS microdisplay is ideal for near-to-eye displays where low-power consumption and compactness are required. The CF-LCOS microdisplays could also withstand medium light illumination for medium-sized rear-projection televisions (RPTVs). This single-panel RPTV is highly manufacturable and cost-effective compared with other LCOS projector technologies.

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