Liquid-Crystal-on-Silicon XGA Projection Display Using Mixed-mode Twisted Nematics

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Abstract

We have developed a highly integrated liquid-crystal-on-silicon display for three-panel color projector. The silicon panel was designed and fabricated by a custom 0.5 μm 3-metal CMOS technology with a spatial resolution of 1024 x 768 pixels. The pixel pitch was 13.8 μm and the fill factor was 91%. 6-bit digital data drivers and gamma-correction resistor network were integrated within the silicon panel for true gray scale and full color image representation. The display was made with an optimized mixed twisted nematic and birefrigence cell configuration for high contrast ratio at CMOS compatible voltage. Contrast ratio was 70:1 at 3.5Vrms. With a compact optical projector, vivid image and good color saturation were demonstrated.

Key words: projection display, silicon light valve and liquid crystal display

I. Introduction

Current liquid crystal projection displays mainly rely on the transmissive thin film transistor liquid crystal display (TFT-LCD) for image generation. The major drawback of this kind of projector is the low aperture ratio of the TFT-LCD panel and hence, the low light efficiency of the system. The aperture ratio of a high-resolution XGA TFT-LCD panel is only 0.5 [1]. In addition to the low light efficiency, the low aperture ratio also introduces black grids or pixelilation. Depixelization is often necessary, adding complexity to the optical system design.

Reflective mode silicon CMOS liquid crystal display (CMOS-LCD) based on liquid-crystal-on-silicon technology can overcome this drawback of the TFT-LCD projector. The aperture ratio of the silicon CMOS-LCD panel can be as high as 90%, since all the electronics can be hidden beneath the reflective mirror of the pixel [2]. As a result, the light efficiency and the quality of projected image can be greatly improved. Moreover, the fabrication process of the silicon CMOS-LCD is consistent with the standard silicon VLSI technology. Display drivers can be fully integrated with the silicon light valves, making a whole display system on a chip possible.

In this paper, we describe the design and fabrication of a reflective XGA silicon light valve for three-panel color projector. We chose a reflective mixed twisted nematic and birefrigence (MTB) cell configuration in order to achieve high contrast ratio at CMOS compatible voltage. With a compact optical projector made with a new trichroic prism assembly, stable images of linear gray scales and good color saturation were demonstrated.

II. Silicon Panel

Figure 1 shows functional block diagram of the XGA silicon panel. The display is easy to interface with only two control signals, one pixel clock and one scan clock. The control signals are responsible for display data manipulation and signal synchronization. Whereas, FLM marks the first row and DISP points to the first pixel of each row. The data drivers have 6-bit resolution and are divided into odd and even columns. Pixel data are shifted in series to the data drivers and transferred in parallel to the D/A converters where D/A conversions are performed. Gamma-correction resistor network is integrated onto the silicon panel in order to provide 64 reference voltages for the D/A conversion. Fine tune of the reference voltages is possible through external gamma correction voltages VG1, VG2, VG3 and VG4.

The silicon panel can accept standard 5V digital data input at a pixel rate of 65 or 75 MHz for XGA signal. The panel can further raise the voltage up to 3.5Vrms through built-in level shifters for efficient driving of the liquid crystal (LC) cell. Bi-directional scanning feature was included for both the horizontal data drivers and vertical scan driver. The display panel had 1024 x 768 spatial resolution in mosaic arrangement. The pixel pitch was 13.8μm and the fill factor was 91% as a result of 0.5μm layout rules.

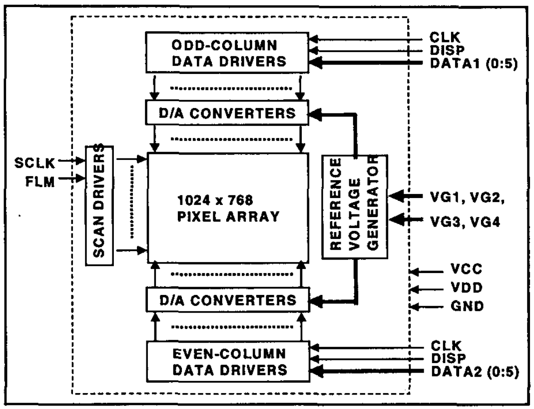


Figure 1 Functional block diagram of the XGA silicon panel.

III. Reflective LCD modes

The reflective liquid crystal (LC) cell is the most important optical element of the CMOS-LCD projector. We need a good LCD mode that gives the best reflectance. Wavelength dispersion is usually not a concern since narrow-band red, green and blue lights will be used in the projector. In addition, we need the LCD mode that gives a good contrast ratio at CMOS compatible voltage. For these requirements, the normally white (NW) mode operated with a polarizing beam splitter (PBS) is preferred. The common NW modes are the ECB, TN-ECB [4], MTN [5] and the SCTN [6] modes. We recently showed that all of these LCD modes are simple variations of each other and can be seen clearly on the parameter space diagram [3].

All these LCD modes can be characterized by three parameters; twist angle, ϕ, retardation, $d\Delta n$, and polarizer angle, α. Here, d is the cell gap, Δn is the LC birefringence and α is the angle between the polarizer axis and the input director of the LC cell. By searching parameter space of ϕ, $d\Delta n$ and α, we identify the LCD modes with 100% reflectance. These are called the mixed twisted nematic and birefringence (MTB) modes.

The behavior of the MTB modes can further be visualized if we plot them together on the same graph as shown in Figure 2. It is seen that the peak of the MTB mode describes a closed path as shown. The lowest closed path is the first MTB mode (MTB-1) and the second one is the MTB-2 mode etc. So for any polarizer angle, there is a corresponding LC twist angle that will give $R = 1$. The reverse is not true however. If the twist angle is too large, $R = 1$ cannot be obtained for any α, especially if one want to stick to small dΔn values or near the MTB-1 mode. If the higher MTB modes are utilized, then R = 1 can be obtained for any ϕ as well.

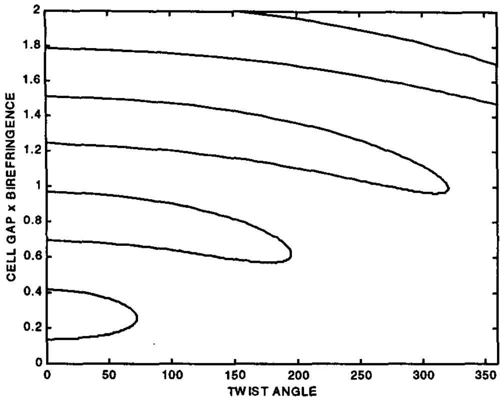


Figure 2 Locus plot of all the MTB modes as the polarizer angel is changed. The curves represent unity reflectance of MTB-1, MTB-2, MTB-3 and MTB-4 modes, respectively.

Figure 3 shows the reflectance-vs-voltage (RVC) curve of the MTB mode as characterized by a collimated narrow-band green light source. The contrast ratio was 70:1 at 3.5Vrms. With polynomial curve fitting of this RVC curve of the green, we proceeded to obtain gamma-correction resistor network to provide 64 gray-scale reference voltages for the green light illumination. This gamma-correction resistor network of the green was integrated onto the silicon panel for the D/A conversion. The gamma corrections of the red and blue could be obtained through four external gamma correction voltage VG1, VG2, VG3 and VG4 which defined 100%, 75%, 25% and 0% reflectance of the RVC curves, respectively, as shown in Figure 3, too. The gamma-correction is deemed required in order to implement a good color projector of true colors.

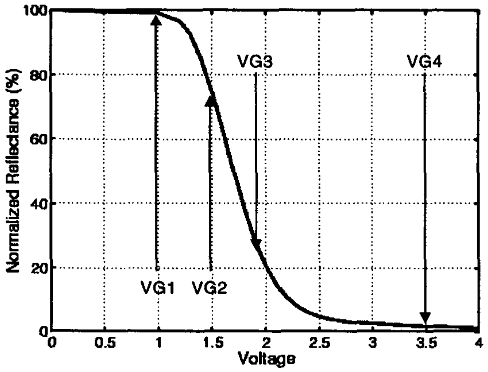


Figure 3 Fine tune of the green RVC curve of the MTB mode through four gamma correction voltages.

IV. Optical Projector

The optical projector requires an optical sub-system to separate the three primary colors from the input white light source, and another sub-system to recombine the three primary colors after modulation by the reflective silicon light valves. For a compact optical projector design, we use a trichroic prism assembly (TPA) for both the color separator and recombiner. The optical system using the PTA and one PBS for all the three LCD panels are shown in Figure 4.

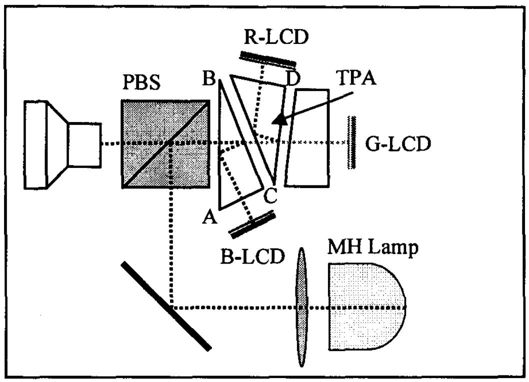


Figure 4 Layout of the compact optical projector with one PTA and one PBS.

In this optical system, a PBS first polarizes the light beam from the metal halide lamp. The *s*-polarization light after the polarization then enters the TPA in which the blue part of the light beam is reflected by surface BC. Thereafter, this blue light is totally internally reflected by surface AB, and illuminates the blue LCD panel. The reflected light from the blue LCD panel after modulation will be *p*-polarized. This reflected *p*-polarized light beam retraces the same light path of the incident *s*-polarized beam.

The same is true for the other primary colors. Whereas, the red part of the light beam is reflected by surface CD, totally internally reflected by surface BC, and illuminates the red LCD panel. The green part of the light beam goes through surfaces BC and CD and illuminates the green LCD panel. Both the reflected red and green *p*-polarized light beams also retrace the same paths of the incident *s*-polarized beams. As a result, the TPA acts as both a color separator for *s*-polarized light, and as a color recombiner for *p*-polarized light.

Figure 5 shows the optical projector assembly using the design as shown in Figure 4. A 50W metal halide lamp was used as the white light source. A band-pass mirror was used to filter out infrared and ultra-violet parts of the light beam. The measured brightness was about 100 lumens with reasonable color saturation.

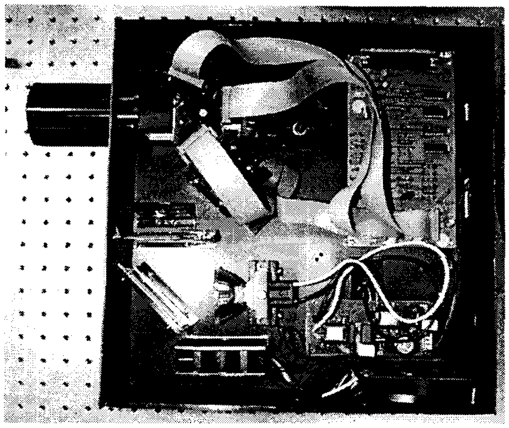
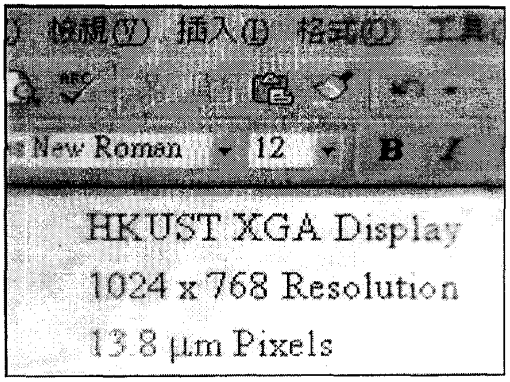


Figure 5 The compact optical projector assembly with one PTA and one PBS

V. System Demonstration

We interfaced the silicon light valve with the personal computer (PC) through a display interface controller, and installed three light valves into the optical projector as shown in Figure 5. Because the silicon panel was highly integrated, the required external driving functions were very minimal. As a result, we were able to fit the display interface board into the compact optical projector. With the high bandwidth of the integrated digital data drivers and the better noise immunity of the digital drive scheme, we were able to display extremely stable image of XGA resolution. Figure 6 show a microscope picture of stable image and fine pixel of the display.



HKUST XGA Display
1024 x 768 Resolution
13.8 µm Pixels

Figure 6 The microscope picture of the silicon light valve shows stable image and fine pixels.

With the integrated gamma-correction resistor network for reference voltage generation, we were also able to drive the LC cell accordingly and obtained linear gray scales. We further tuned gamma corrections for three primary colors through external gamma correction voltages and obtained images of good color saturation. Figure 7 shows a projected image of linear gray scales and good color saturation.

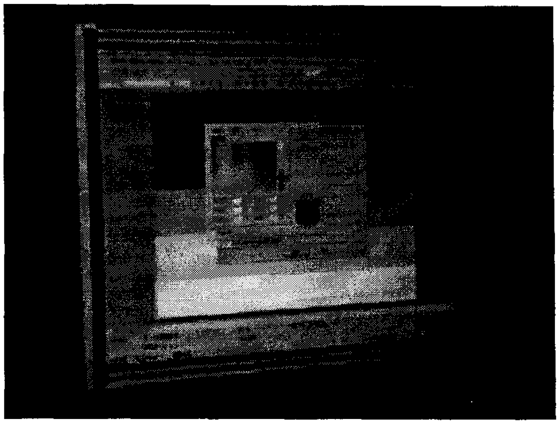


Figure 7 The projected image of the silicon light valves shows gray scales and colors.

VI. Conclusion

In conclusion, we have developed a highly integrated liquid-crystal-on-silicon XGA display for three-panel color projector. The silicon was made with an optimized mixed twisted nematic and birefrigence cell configuration for high contrast ratio at CMOS compatible voltage. The contrast ratio was 70:1 at 3.5Vrms. We further designed a compact optical projector with one trichroic prism assembly to host three silicon light valves for color projection. With integrated high-bandwidth digital data drivers, stable images of XGA resolution were demonstrated. With gamma correction feature, projected images of linear gray scales and good color saturation were demonstrated.

VII. References:

[1] N.Okamoto, and Y.Itoh and J.Ito, "High brightness technology of p-Si TFT-LCD front projector", Proceeding of IDW'97, 813 (1998)

[2] R.L. Melcher, M.Ohhata and K.Enami, "High-information content Projection Display Based on reflective LC on silicon light valves", SID 98 Digest, 25 (1998).

[3] F. H. Yu, J. Chen, S. T. Tang and H. S. Kwok, "A new TN-ECB mode Reflective LCD with Large Cell Gap and Low Operating Voltage", Proc. of 17th Int'l. Display Research Conf. 155 (1997).

[4] T. Sonehara, "Photo-addressed liquid crystal SLM with twisted nematic ECB (TN-ECB) mode", Jap. J. Appl. Phys., **29**(7), L1231 (1990).

[5] S. T. Wu and C. S. Wu, "Mixed-mode twisted nematic liquid crystal cells for reflective displays, " Appl. Phys. Lett., **68**(11), 1455 (1996).

[6] K. H. Yang, "A self-compensated twisted nematic mode for reflective light valve, ", Proc. of 16th Int'l. Display Research Conf. (Euro Display), 449 (1996).