A COMPACT AND HIGH-RESOLUTION VIDEO PROJECTOR BASED ON SILICON LIGHT VALVES

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Abstract

We have developed a highly integrated liquid-crystal-on-silicon light valve for three-panel color projector. The silicon panel was designed and fabricated by a custom 0.5μm, 3-metal CMOS technology with a spatial resolution of 1024 x 768 pixels. The pixel pitch was 13.8μm and the fill factor was 91%. Six-bit digital data drivers and gamma-correction circuitry were integrated within the silicon panel for true gray scale and full color representation. The display panel was assembled with a mixed twisted nematic and birefringence liquid crystal cell for high contract ratio at CMOS compatible voltage. Contrast ratio was 100:1 at 3.5Vrms. The optical system utilized a trichroic prism assembly for both the color separation and recombination. With this trichroic prism assembly incorporating three silicon light valves, a compact and high-resolution video projector was demonstrated.

I. Introduction

Current liquid crystal video projectors mainly rely on transmissive thin film transistor liquid crystal display (TFT-LCD) for image generation. The major drawback of this kind of projector is low aperture ratio of the TFT-LCD and hence, low light efficiency of the system. The aperture ratio of a high-resolution XGA TFT-LCD panel, which has 1024 x 768 pixels, 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 light valve based on liquid-crystal-on-silicon technology can overcome this drawback of the TFT-LCD projector. The aperture ratio of the silicon light valve can be as high as 90%, since all the electronics can be hidden beneath reflective mirrors of the pixels [2]. As a result, the light efficiency and the quality of projected image can be greatly improved. Moreover, the fabrication process of the silicon light valves is consistent with the standard silicon VLSI technology. Display drivers can be fully integrated within the silicon light valves, making a whole display system on a chip possible.

In this paper, we describe the development of a compact and high-resolution video projector based on silicon light valves. The silicon panel was designed with sub-micron design rules and fabricated by a custom CMOS technology emphasizing on back-end planarization. Very sophisticated driver circuitry and very fine pixel can be integrated together as a self-contained high-resolution display panel. We chose to assemble a reflective mixed twisted nematic and birefringence (MTB) liquid crystal cell on top of the silicon panel. The MTB mode has advantages of high reflectance and can achieve high contrast at CMOS compatible voltage. In order to incorporate three silicon light valves in a compact manner, a trichroic prism assembly (TPA) of high fidelity was developed. This TPA can efficiently separate and recombine three primary colors for three silicon light valves, and lead to a compact optical projector.

II. Silicon Panel

The heart of this compact video projector is the silicon panel, which integrates display drivers and fine pixel array together. Figure 1 shows functional block diagram of the XGA silicon panel. The display is easy to be interfaced 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 for ease of layout. The partition of the pixel array into odd and even columns also reduces the pixel clock by half.

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 circuitry is integrated onto the silicon panel in order to generate 64 reference voltages for the D/A conversions. Fine tune of the reference voltages is possible through the external gamma correction voltages VG1, VG2, VG3 and VG4.

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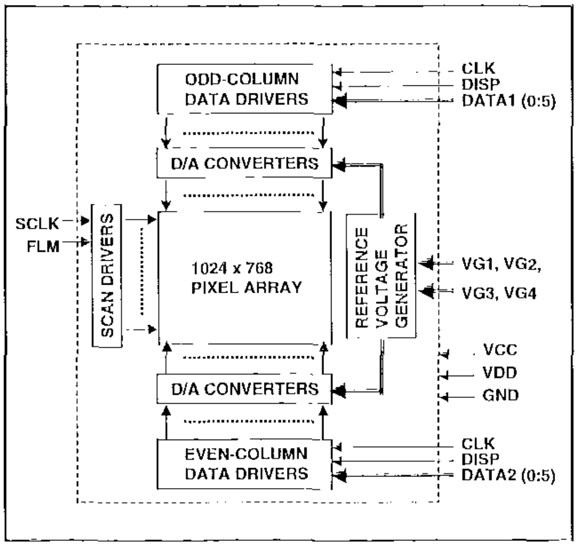

Figure 1 Functional block diagram of the XGA silicon panel.

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 efficiently driving 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 2 shows photograph the silicon light valve in action. The data drivers are on the top and bottom, the scan driver is on the left, and the pixel array is the center.

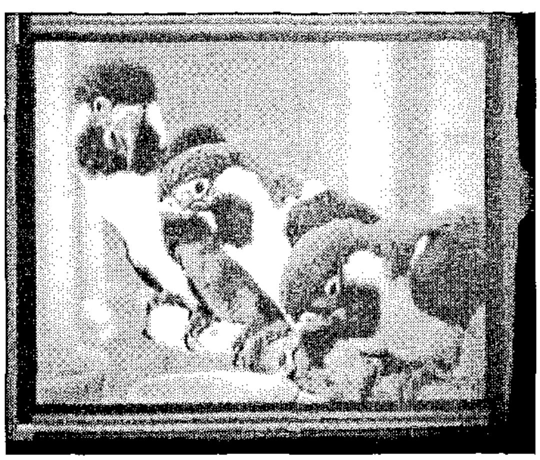

Figure 2 Photograph of the silicon panel showing peripheral drivers and pixel array.

As the silicon panel is used as the back plane for the silicon light valve, surface finish is very important. The custom CMOS fabrication process employs a backend planarization process to ensure an optically flat silicon surface. Figure 3 shows the SEM picture of the pixel array. Topographic variation of less than 100Å within the pixels was achieved. With this back-end planarization process, optical performance of the silicon light valve was greatly improved. The improvements are three folds. Firstly, the flat surface improves the mirror quality of the pixel metal, and hence, increases the optical reflectance. Secondly, the flat surface improves the liquid crystal alignment in the liquid crystal cell fabrication at a later stage. Finally, a dielectric mirror is coated onto the pixel metal for further improvement of the metal reflectivity. The reflectivity of the pixel metal can be improved from 86% of bulk metal to more than 95% within the visible spectrum.

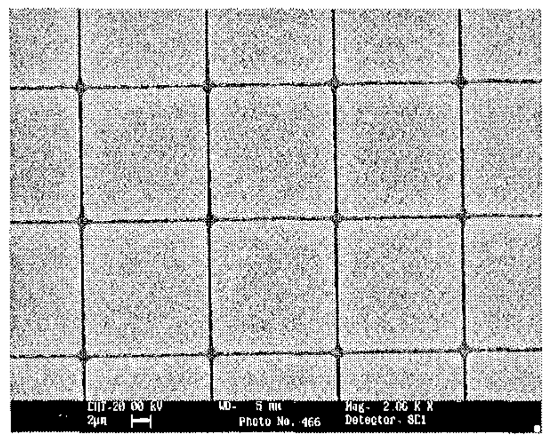

Figure 3 SEM picture of the pixel array. The pixel pitch is 13.8μm and the fill factor is 91%.

III. Reflective LCD modes

The silicon panel can accept and generate electronic image on the panel. The reflective LC cell on top of the silicon panel is to convert the electronic image into the optical image though optical modulation. One important criterion for the LC cell is to do efficient conversion at CMOS compatible voltage. The LC cell should also be able to give the best optical reflectance. Wavelength dispersion is usually not a concern since narrow-band red, green and blue lights will be used in the projector. In addition, the cell gap should be in the range of 3 to 4μm for ease of cell assembly and to maintain a good aspect ratio with the pixel pitch of 13.8μm. For these requirements, the normally white (NW) mode operated with a polarizing beam splitter (PBS) is preferred [3].

The common NW modes are the ECB, TN-ECB [4], MTN [5] and the SCTN [6] modes. 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 have identified a set of LCD modes with 100% reflectance. These are called the mixed twisted nematic and birefringence (MTB) modes. The advantage of the MTB mode is the combination of twisted nematic and birefringence effects for optical modulation, and hence, high contrast can be achieved at low voltage. Figure 4 shows the normalized reflectance-vs-voltage (RVC) curve of the MTB mode under red, green and blue light illuminations. The contrast ratios are 169:1, 101:1 and 68:1, respectively, for the red, green and blue light illuminations at 3.5Vrms.

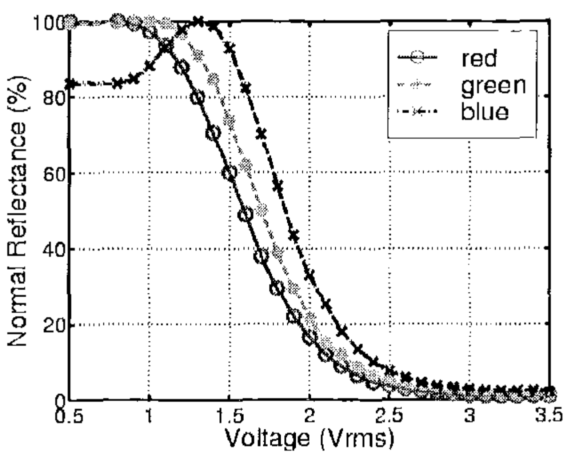

Figure 4 Normalized RVC curves of the MTB cell on the XGA silicon panel.

With polynomial curve fitting of the RVC curve of the green, we proceed to obtain gamma-correction network to provide 64 gray-scale reference voltages for the green light illumination. This gamma-correction network of the green was integrated onto the silicon panel in order to generate 64 reference voltages for the D/A conversion. The gamma corrections of the red and blue could be obtained through four external gamma correction voltages VG1, VG2, VG3 and VG4 which defined 100%, 75%, 25% and 0% reflectance of the RVC curves, respectively, as shown in Figure 5. In this arrangement, we are able to obtain linear gray scales for the red, green and blue images on the same silicon light valve. The gamma correction is deemed required in order to implement a good video projector of true colors.

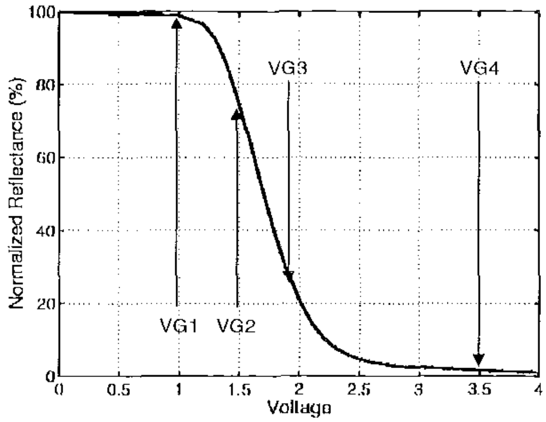

Figure 5 Fine tune of the green RVC curve of the MTB cell through four gamma correction voltages.

IV. Optical System

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. The color separator and the color recombiner can be the same piece of optics or they can be physically different. The former uses one PBS for all the three LCD panels while the latter employs three PBS for 3 LCD panels.

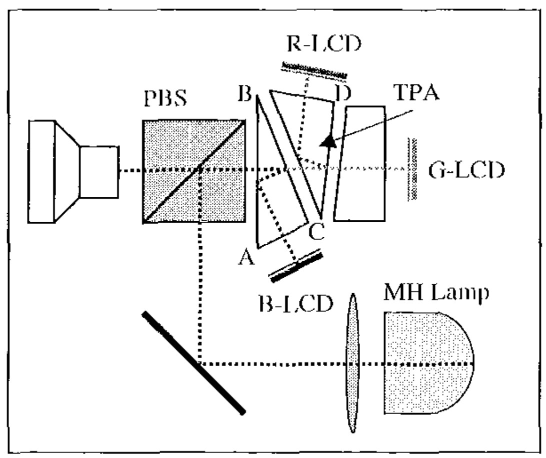

Figure 6 Layout of the compact optical projector with one PTA and one PBS.

For a compact optical projector design, we used 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 6. 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 7 shows the measured reflectance spectra for this TPA. From the result, it can be seen that there is negligible s-p polarization split. The spectra for both s-polarized and p-polarized light are very sharp and identical. Hence, this TPA should be good for a compact color projector application.

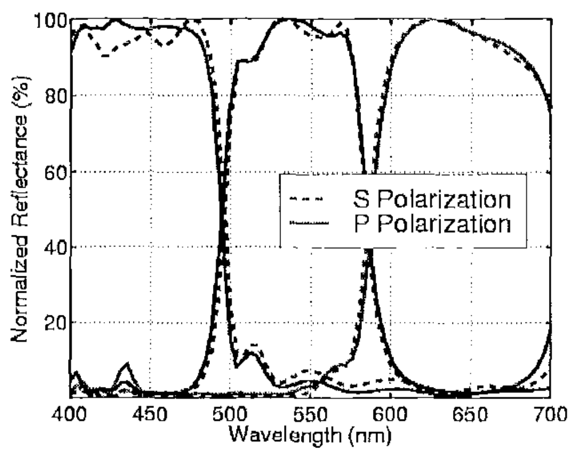

Figure 7 Measured RGB output from the TPA.

V. Video Interface Controller

Figure 8 shows block diagram of a video interface controller interfaced the video inputs with three silicon light valves. The video interface controller consists of analog and digital parts. The interface controller firstly extracts video data and synchronization signals by a video signal decoder. The synchronization signals are used to generate pixel clock through a phase-locked-loop frequency synthesizer. The analog video data are amplified by video amplifiers and converted to 6-bit digital data per color through flash A/D converters.

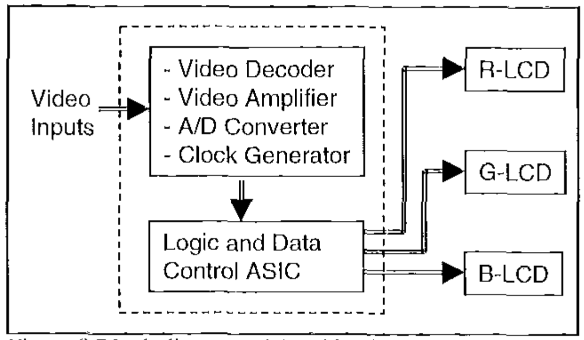

Figure 8 Block diagram of the video interface controller.

The heart of the video interface controller is the logic and data control application specific integrated circuit (ASIC) implemented by Xilinx field programmable gate array (FPGA). The logic and data control ASIC is responsible for video data manipulation and display timing synchronization. Auto detection of display formats, image scaling and other features were also implemented. The use of FPGA as the logic control ASIC has advantages of fast prototyping and flexible in-circuit reconfigurations for different display applications. With the high bandwidth of the integrated digital data drivers and the better noise immunity of the digital drive scheme, we are able to display extremely stable image of XGA resolution. Figure 9 show a microscope picture of stable image and fine pixels of the display.

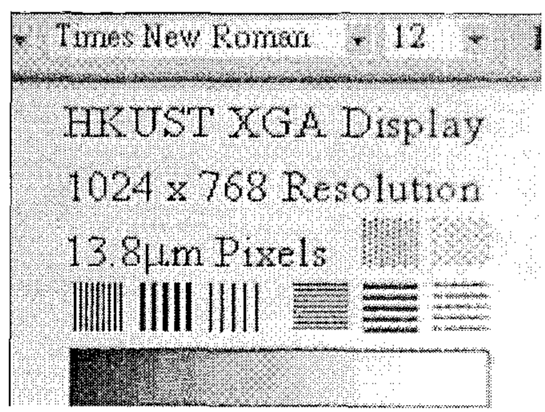

Figure 9 The microscope picture of the silicon light valve showing fine and resolvable pixels.

VI. Video Projector Prototype

Figure 10 shows the appearance of our silicon-based liquid crystal video projector prototype. A 50W metal halide lamp is used as the white light source. A band-pass mirror is used to filter out infrared and ultra-violet parts of the light beam. The optical system which consists of TPA and one PBS for all the three XGA silicon LCD panels is used to color separation and recombination and then projects the image to the screen through the projection lens. The measured brightness is about 100 lumens with reasonable color saturation.

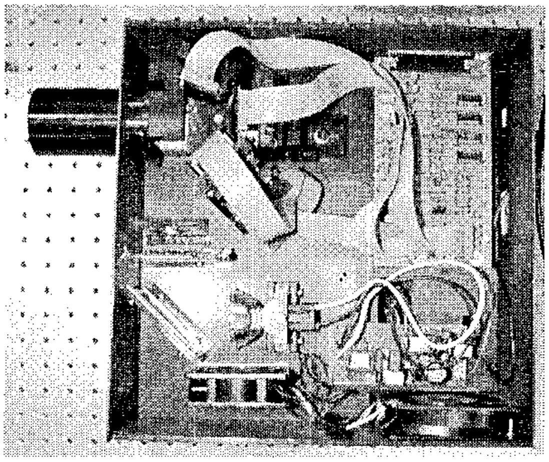

Figure 10 A compact video projector prototype employs one TPA and three silicon light valves.

With the integrated gamma-correction resistor network for reference voltage generation, we are 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 11 shows a projected image of linear gray scales and good color saturation. Table 1 summarizes the specifications of this video projector prototype.

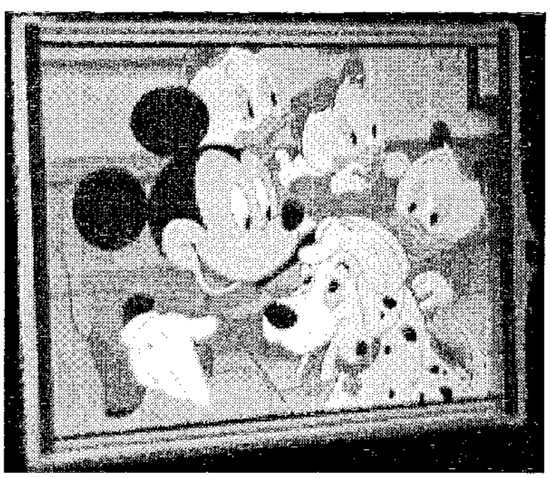

Figure 11 The projected image of the video projector shows gray scales and colors.

Table 1 Specifications of the video projector prototype

Parameter	Value
Resolution	1024 H x 768 V
Pixel Size	13.8μm
Aperture Ratio	91%
Pixel Arrangement	Mosaic
Array Area	14.1mm H x 10.6mm V
Die Area	17.2mm H x 15.4mm V
LC mode	Reflective NW MTB mode
Contrast Ratio	100:1, typically
Luminous Flux	100 lumens
Color	262,144
CIE Coordinates	Red: x = 0.66, y = 0.34 Green: x = 0.30, y = 0.65 Blue: x = 0.17, y = 0.12 White: x = 0.31, y = 0.32
Driving Scheme	Frame Inversion
Frame Rate	60 Hz
Power Consumption	50W MH Lamp 2W Interface Controller 300mW per light valve

VII. Conclusion

In conclusion, we have developed a compact and high-resolution video projector based on silicon light valves. The silicon panel was designed and fabricated by a custom CMOS technology in order to make electronic devices suitable for optical application. Very sophisticated display driver and very fine pixels were integrated together as a self-contained and high-resolution display panel. The LC cell configuration was an optimized MTB mode, which can achieve high reflectance and contrast ratio at CMOS compatible voltage. We have also developed a compact optical system, which employed a trichroic prism assembly to incorporate three silicon light valves. The color separation and recombination was conducted through this compact prism assembly. With integrated high-bandwidth digital data drivers, we have demonstrated stable images and fine pixels of XGA resolution. With integrated gamma-correction feature, we have also demonstrated projected images of linear gray scales and good color saturation. We believe this compact and high-resolution video projector is useful for both the high-definition television (HDTV) and PC monitor applications.

VIII. Acknowledgment

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IX. 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).

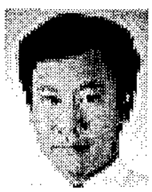
[3] F. H. Yu, J. Chen, S. T. Tang and H. S. Kwok, "A new TN-ECB mode Reflective LCD with Large Cell Gap and Low Operating Voltage", Proc. of 17th Int'l. Display Research Conf. 155 (1997).

[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).

X. Biography



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