Invited Paper

High Contrast SXGA Silicon Light Valves for High Definition Video Projectors

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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 0.35μm, 3-metal and dual-voltage CMOS process with a spatial resolution of 1280 x 1024 pixels. The pixel pitch was 12μm, the fill factor was 90% and the display area was 0.77" in diagonal. Eight-bit digital data drivers and gamma-correction circuitry were integrated into 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 at CMOS compatible voltage. Contrast ratio was typically 200:1 at 5.5Vrms. In addition, silicon surface layers, liquid crystal materials, pixel structures and driving schemes were carefully optimized for the minimization of visual flicker. Flicker ratio of less than 3% was achieved at 60Hz frame rate. The optical sub-system utilized a trichroic prism assembly for both color separation and recombination. With this trichroic prism assembly incorporating three silicon light valves, a compact and high-contrast SXGA video projector was demonstrated.

Keywords: Silicon light valve, video projector

1. 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 projector system. The aperture ratio of a high-resolution XGA TFT-LCD, which has 1024 x 768 pixels, is only 0.5 [1]. In addition to low light efficiency, the low aperture ratio also introduces black grids or pixelilation. Depixelization is often necessary through microlens, and adds 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 are hidden beneath reflective mirrors of pixel [2]. As a result, the light efficiency and quality of projected image are greatly improved. Moreover, fabrication process of the silicon light valve is consistent with standard silicon VLSI technology. Display drivers and other electronic functions can be fully integrated onto the silicon light valve, and makes a whole display system on a chip possible.

In our previous work, we have developed a highly integrated liquid-crystal-on-silicon XGA video projector [3]. In this paper, we describe the development of another highly integrated liquid-crystal-on-silicon SXGA video projector of higher resolution, higher contrast and better performance. The silicon panel of 1280 x 1024 spatial resolution was designed with sub-micron design rules and fabricated by a custom CMOS technology emphasizing on back-end planarization. Very advanced display driver and very fine pixel were integrated together as a self-contained and high-resolution display panel. The silicon panel has low-voltage devices for logic control and data inputs. The silicon panel has also high-voltage devices for efficiently driving liquid crystal (LC) cell. We chose to assemble a reflective mixed twisted nematic and birefringence (MTB) LC cell on the panel. The MTB mode has advantages of high reflectance and high contrast at CMOS compatible voltage. Silicon surface layers, liquid crystal materials, pixel structures and driving schemes were carefully optimized for the minimization of visual flicker. 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 and high definition SXGA video projector.

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2. THE SILICON PANEL

The heart of this high-definition video projector is the silicon panel, which integrates display drivers and fine pixel array together. Figure 1 shows a functional block diagram of the SXGA 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 of data and DISP points to the first pixel of each active row. The data drivers have 8-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 one half.

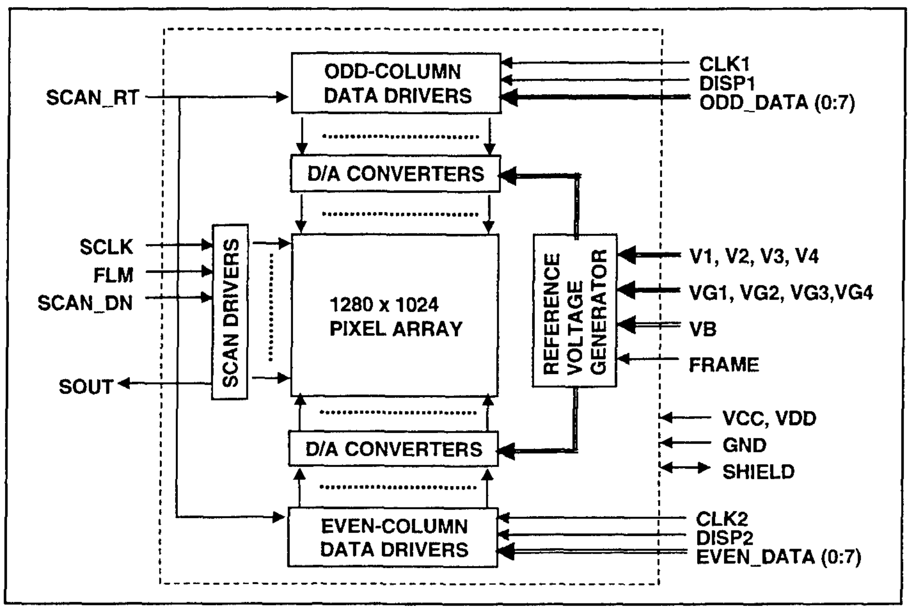


Figure 1 Functional block diagram of the SXGA silicon panel.

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 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 for red, green and blue light illuminations.

The silicon panel can accept standard 3.3V digital logic input at a pixel rate of 108MHz for the SXGA signal. The panel can further raise the voltage level up to 5.5Vrms through built-in level shifters for efficiently driving the LC cell. Bi-directional scanning feature was included for both the horizontal data drivers and vertical scan driver. The display panel had 1280 x 1024 spatial resolution in mosaic arrangement. The pixel pitch was 12μm and the fill factor was 90% as a result of 0.35μm layout rules. The display area is 0.77" in diagonal and the die size is 1.0" in diagonal. Figure 2 shows photograph of a packaged SXGA silicon light valve. The data drivers are on the top and bottom, the scan driver is on the right, and the pixel array is the center.

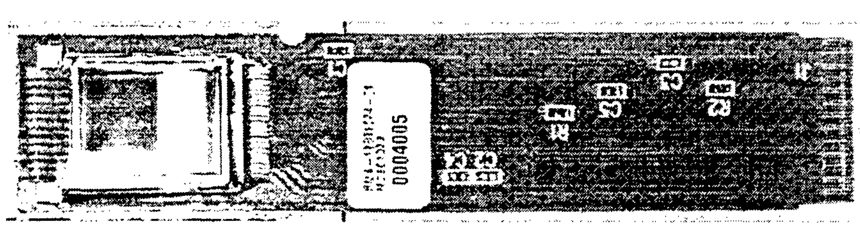


Figure 2 Photograph of a packaged SXGA silicon light valve.

Because the silicon panel is used as back plane for the silicon light valve, surface finish is very important. The CMOS fabrication process employs a back-end planarization process to ensure an optically flat silicon surface. Local topographic variation of less than 100Å within the pixels and global topographic variation of less than 500Å among pixels were achieved. With this back-end planarization process, optical performance of the silicon light valve was greatly improved. The improvements were three folds. Firstly, the flat surface improved mirror quality of the pixel metal, and hence, the optical reflectance was increased. Secondly, the flat surface improved liquid crystal alignment in the LC cell fabrication at a later stage. Reliability and performance of the LC cell were got better. Finally, a dielectric mirror was coated onto the pixel metal for further improvement of the metal reflectivity. The reflectivity of the pixel metal was expanded from 86% of bulk metal to more than 95% within the visible spectrum. In addition, there was a light shield beneath gaps of the pixels for light leakage protection. Light leakage into the silicon substrate could generate photocurrent and preclude proper circuit operation. The light shield could absorb most of the penetrated light and reflect only a small portion of the incident light back to the LC cell. Figure 3 shows reflectivity of the bare metal, the dielectric mirror and the black matrix.

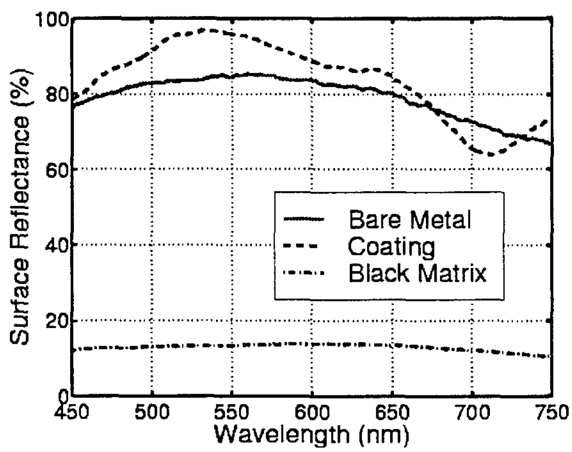


Figure 3 The reflectivity of the pixel metal, the dielectric mirror and the light shield.

3. 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 12μm. For these requirements, the normally white (NW) mode operated with a polarizing beam splitter (PBS) is preferred [4].

The common NW modes are the ECB, TN-ECB [5], MTN [6] and the SCTN [7] 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. As a result, high contrast can be achieved at low voltage.

We assembled a MTB mode onto the silicon substrate and performed reflectance-vs-voltage characterization with a DMS machine. A narrow-band PBS was used to direct the incident light onto the MTB LC cell and reflect the modulated light back to the DMS machine. Figure 4 shows characterized reflectance-vs-voltage curves of the MTB LC cell under red, green and blue light illuminations. The contrast ratios were 270:1, 190:1 and 150:1, respectively, for the red, green and blue light illuminations at 5.5Vrms. The contrast ratio was typically 200:1 for the white light illumination.

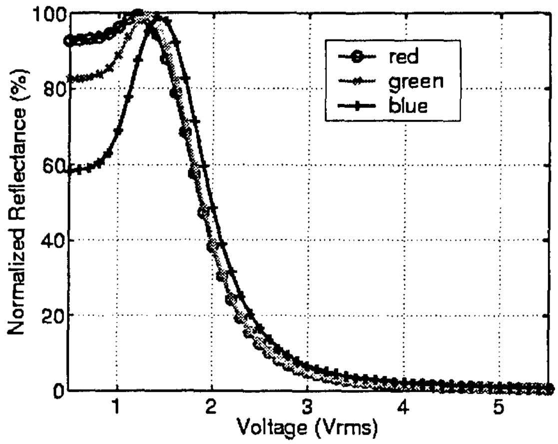


Figure 4 The characterized reflectance-vs-voltage curves of the MTB LC cell on the SXGA silicon panel.

With polynomial curve fitting of the reflectance-vs-voltage curve of the green, we proceeded to obtain gamma-correction network of the green in order to generate gamma-correction reference voltages for the green silicon light valve. This gamma-correction network of the green was integrated onto the silicon panel. The reflectance-vs-voltage curves of the red, green and blue have a similar shape, but appears in different voltage ranges. Whereas, the red curve appears to the left of the green curve and the blue curve appears to the right of the green curve. The gamma corrections of the red and blue could be obtained through the same gamma-correction network of the green by tuning four external gamma correction voltages. Whereas, VG1, VG2, VG3 and VG4 defined 100%, 75%, 25% and 0% reflectance of the reflectance-vs-voltage curves, respectively. A shift of these four voltages to the left defined the red reflectance-vs-voltage curve, while a shift to the right defined the blue curve, as shown in Figure 5. In this arrangement, we were able to obtain linear gray scales for the red, green and blue images on the same silicon light valve. The gamma corrections are deemed required in order to implement a full-color video projector.

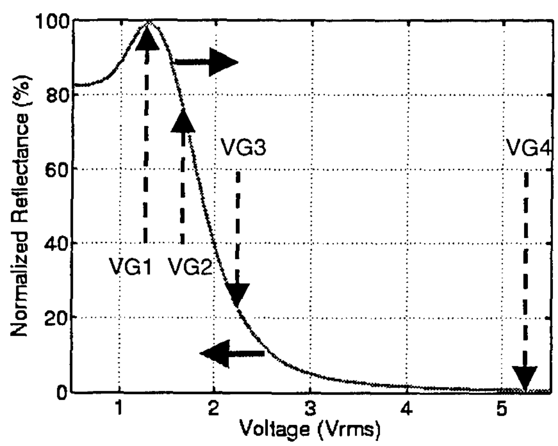


Figure 5 Fine tune of the green curve of the MTB cell through four gamma correction voltages.

4. 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.

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.

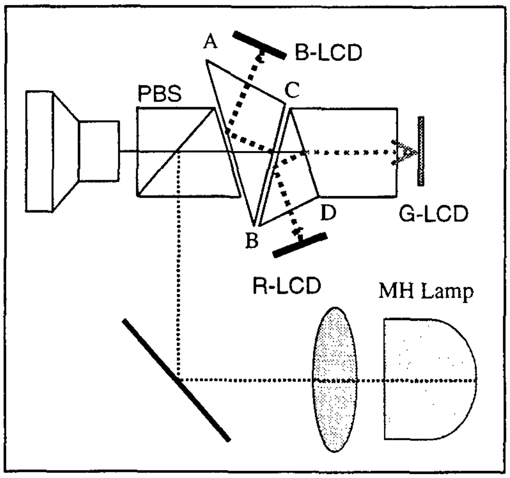


Figure 6 Layout of the compact optical projector with one PTA and one PBS.

The same is true for the other two 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. We used a collimated Oriel metal halide lamp with grating as light source to characterize color fidelity of the TPA. Figure 7 shows measured red, green and blue reflectance spectra for this TPA. From the results, 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 is good for a compact color projector application.

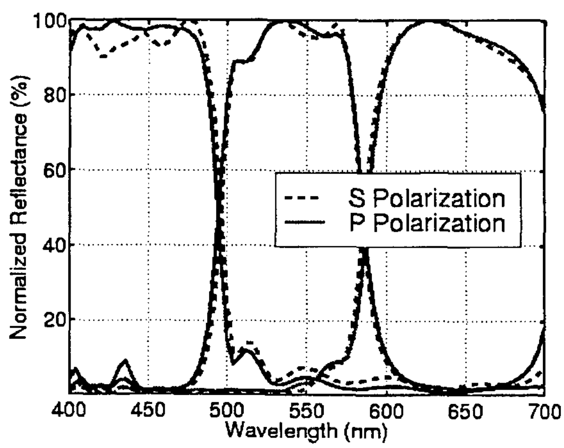


Figure 7 Measured red, green and blue reflectance spectra of the TPA.

5. ON THE MINIMIZATION OF VISUAL FLICKER

Flicker is the major visual defect of the silicon light valves. The silicon light valve depends on active devices to apply driving voltages to the pixels during address time and ability of the pixels to conserve the voltage for the rest of frame time. To avoid chemical degradation of the LC material, an alternating voltage waveform has to be applied to the LC cell. For this purpose, several modes of polarity inversion including frame, column, row and dot inversions are adopted. Each mode has its advantages and disadvantages. The frame inversion is commonly used in the silicon light valve for the purpose of minimizing lateral electric field in small pixels. The lateral electric field can result in an undesired reverse tilt domain in each pixel and lead to poor contrast ratio of the display [8]. While the frame inversion is good for minimizing the lateral field effect, it also produces higher degree of flicker and image retention compared with other modes of polarity inversion.

5.1. FLICKER MODEL

Flicker and image retention can be characterized by monitoring luminance of the same image on the display in alternative frames. A larger luminance difference corresponds to a higher degree of flicker. We defined the flicker as the ratio the AC root-mean-squared luminance over the DC root-mean-squared luminance. Since the luminance is controlled by pixel voltage, the flicker can also be characterized through monitoring of the pixel voltage. The voltage retention capability of the pixel is described by an equivalent circuit consisting of a storage capacitor connected to ground and a LC cell capacitor with a parallel leakage resistance connected to a common electrode on the glass plate.

The voltage holding ratio (VHR) is defined as the ratio of the root-mean-squared voltage divided by the applied voltage pulse on a pixel electrode. The value is mainly determined by the RC time constant of the LC pixel and auxiliary storage capacitor. The RC time constant can be calculated from resistivity and dielectric constant of the LC material and geometry of the pixel. There are two causes for the decrease of the VHR. One is leakage current through the pixel transistor. The other is existence of a depolarization field caused by the accumulation of extra charges on the surface of the LC cell. In addition, there are different conduction mechanisms in polar liquids in combination with other dielectric layers in the silicon light valve. The conduction mechanism can perturb charge distribution within the LC element and enhance the flicker and image retention. This conduction mechanism can be represented by a residual DC (R-DC) charge on the pixel.

In addition to the LC cell and pixel transistor, word and bit line voltages can also contribute to the flicker. The word line turns on the pixel transistor for charging. But the pixel voltage is dropped slightly through parasitic capacitor coupling when the word line turns off. The bit line voltage varies randomly and perturbs the pixel voltage randomly. But the perturbation becomes coherent when the polarity of the inversion is changed. These two couplings can be represented by two parasitic capacitors connected from the pixel to the word and bit lines, respectively. A flicker model of the pixel is illustrated in Figure 8.

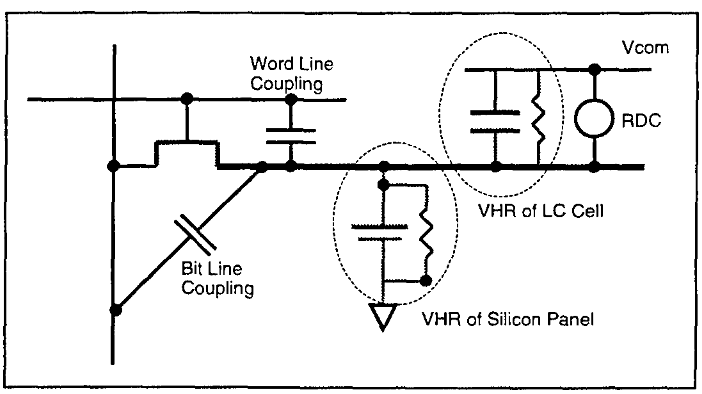


Figure 8 Flicker model of the pixel in silicon light valve.

5.2. FLICKER CHARACTERIZATIONS

For these four flicker mechanisms, we have designed four experiments to investigate causes of flicker and determine parameters of the flicker model. The first one was a capacitance-voltage (CV) measurement of the LC cell in order to determine the cell capacitance and parallel leakage resistance. The second one was an R-DC measurement of the LC cell in order to determine extra charge accumulation on the surface of the LC cell. The third one was a VHR measurement of a pixel made by the LC cell, an external transistor and a storage capacitor. A short pulse of voltage was applied to the pixel during the address time and the charge was held by the pixel during the rest of frame time. Pixel voltage was buffered and amplified by a high-impedance operational amplifier and monitored by a digital oscilloscope. Voltage holding capability of the pixel was recorded.

The last one was a direct measurement of the flicker due to both the LC cell and silicon panel. The light valve was placed on a hot chuck and illuminated by different light intensities. A video pattern generator was used to drive the silicon light valve at different frame rates and different polarities of inversion. A photo detector in connection with a digital oscilloscope was used to monitor luminance of the projected image. Flicker was recorded and a DC offset voltage was increased on the common electrode until the flicker was minimized. Different driving schemes can also be applied to compensate for the flicker for different causes.

Figure 9 shows the flicker measurements of a XGA silicon light valve. There were three flicker mechanisms observed in the luminance curve. One was the hot-state R-DC voltage caused by the passivation layer. The second was the bit line coupling which occurred when the polarity of frame inversion is reversed. The third was insufficient VHR of the pixel transistor and storage capacitor. Through the temperature characterization, it was found that the insufficient VHR of the silicon panel was mainly due to the temperature, which increased the saturation current of the transistor and caused the pixel voltage to decay. Light leakage also reduced the VHR of the storage capacitor.

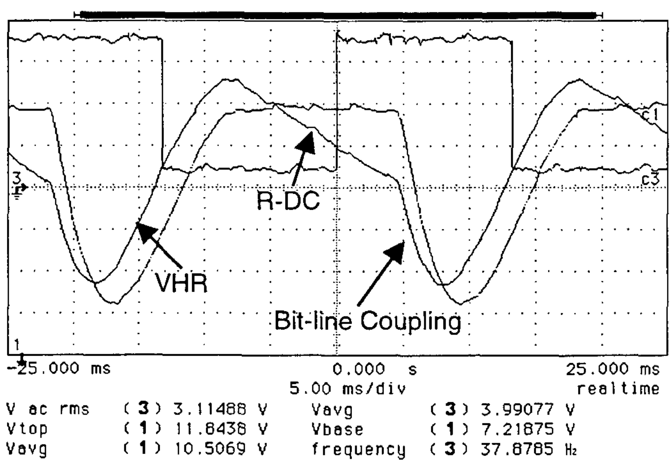


Figure 10 Flicker measurement of the SXGA light valve.

5.3. SOLUTIONS FOR FLICKER MINIMIZATION

Through these flicker characterizations, we have identified causes of flicker and proceeded to find solutions for the minimization of flicker. The R-DC charge accumulation was mainly caused by of different work functions of the ITO glass plate and silicon surface. Different passivation schemes have different work functions and affect the R-DC. From the R-DC measurements, we found that the bare metal had the smallest R-DC voltage, while the multi-layer passivation had the worst R-DC voltage. It was also found that the R-DC charge could be reduced by Vcom compensation.

The VHR of the LC cell was mainly determined by the specific resistivity of the LC mixture. A higher resistivity favored low VHR. It was found that the specific resistivity of the LC mixture had to be larger than 5×10^{12} Ωcm in order to achieve more than 97% VHR of the LC cell according to the VHR measurements.

The VHR of the silicon panel was determined by the temperature and light leakage. Whereas, the temperature increased exponentially the saturation current of the pixel transistor, and the light leakage drained the pixel charge through the storage capacitor. It was found that a good light shield protection is required to prevent from the light leakage. It was also found the temperature of silicon panel had to be reduced to room temperature in order to improve the VHR of the silicon panel.

The parasitic capacitor coupling was determined by magnitudes of parasitic capacitance and storage capacitance. A larger ratio of the storage and parasitic capacitance could reduce the coupling. It was found that a minimal ratio of 20 was required to minimize the coupling. However, a ratio of larger than 20 could not be achieved when the pixel was reduced to 10 m pitch. It was found that imbalance driving was useful to compensate for the charge deviation caused by the word line coupling.

With all these optimizations on silicon surface layers, liquid crystal materials, pixel designs and driving schemes, we have reduced the visual flicker to an extent. Flicker ratio of less than 3% at 60 Hz frame rate was achieved for the SXGA silicon light valve under 150W light illumination.

6. SXGA VIDEO PROJECTOR PROTOTYPE

6.1 VIDEO INTERFACE CONTROLLER

We used a video interface controller to interfaced digital video inputs with three silicon light valves. The video interface controller consists of analog and digital parts. The digital part extracts digital video data and synchronization signals by a Paneling receiver. The synchronization signals are used to generate pixel clock through a phase-locked-loop frequency synthesizer. The analog part fine tunes gamma correction voltages for red, green and blue light valves.

The extracted 8-bit digital video data and synchronization signals are fed directly into the digital-input SXGA light valves. 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 SXGA resolution. Figure 10 show a microscope picture of stable image and fine pixels on the display.

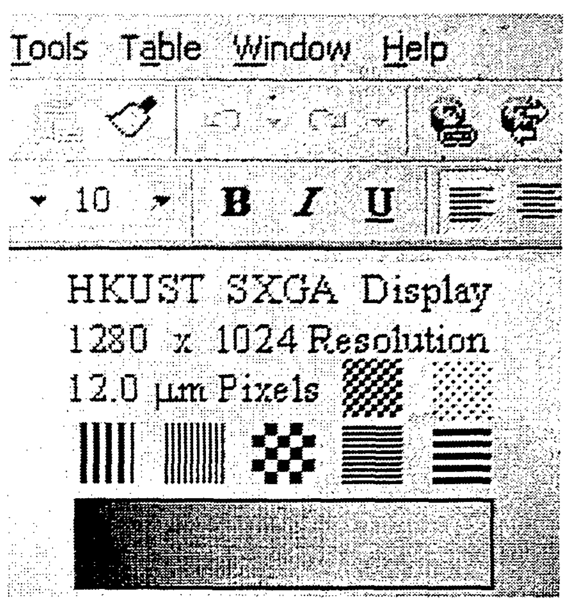


Figure 10 The microscope picture of the silicon light valve showing fine and resolvable pixels.

6.2 VIDEO PROJECTOR PROTOTYPE

Figure 11 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 SXGA silicon light valves 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.

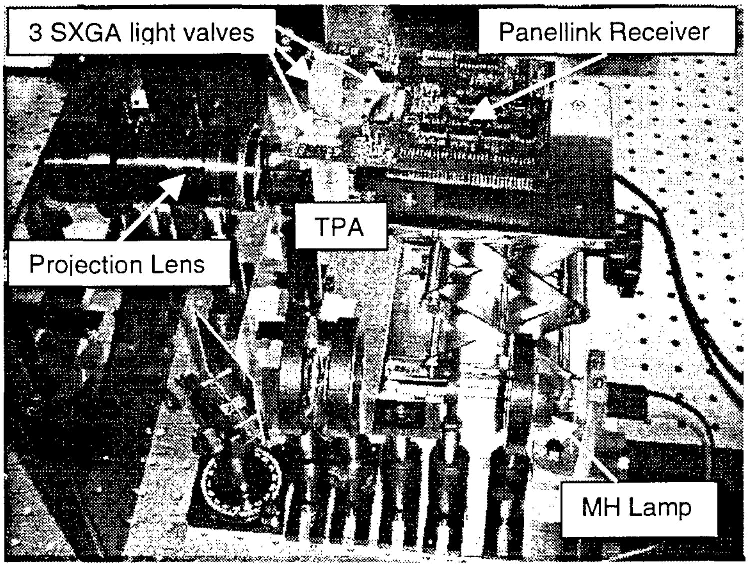
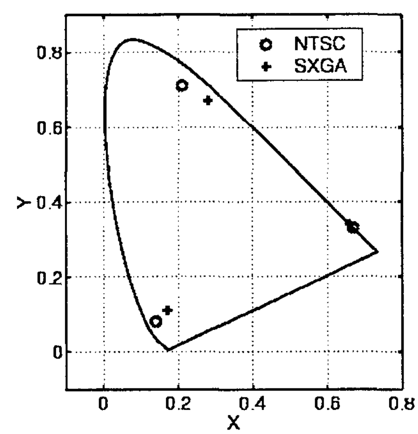


Figure 11 A compact video projector prototype employs one TPA and three SXGA silicon light valves.

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 12(a) shows a projected image of linear gray scales and good color saturation. Figure 12(b) shows color coordinates of the SXGA projector prototype. NTSC standard is also included for comparison.



(a) (b)

Figure 12 (a) A projected image and (b) color coordinates of the SXGA video projector prototype.

7. CONCLUSION

In conclusion, we have developed a compact and high-resolution SXGA 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 applications. Very advanced 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 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 SXGA resolution. With integrated gamma-correction feature, we have also demonstrated projected images of linear gray scales and good color saturation. In addition, silicon surface layers, liquid crystal materials, pixel structures and driving schemes were carefully optimized for the minimization of visual flicker. Flicker ratio of less than 3% was achieved at 60Hz frame rate. We believe this compact and high-resolution video projector is useful for both the high-definition television (HDTV) and PC monitor applications.

ACKNOWLEDGMENT

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