Improved Projection Optics for Reflective Silicon CMOS Light Valves

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ABSTRACT

The optical sub-systems for reflective mode silicon based CMOS-LCD projection display are discussed in this paper. Various methods to improve the optical efficiency of the projection system are proposed. First, new optical modes for the reflective light valve are discussed. The emphasis is on improving the reflectance. Second, a new high throughput projection system employing a 2-step process is proposed. It employs a conventional LCLV projection system capable of very high luminous output. Finally, the color separation and recombination schemes for a full color projector are discussed. A new trichroic prism assembly design is described which has the advantages of low s and p polarization splitting in the reflectance spectrum. Hence it can be used for both color separation and recombination. Thus a compact optical system for reflective projectors is possible with good light efficiency.

Key words: Projection display, CMOS-LCD, reflective modes, LCLV, trichroic prisms

1. INTRODUCTION

Current liquid crystal projection displays are based mainly on transmittive TFT-LCD panels as the image generator. The drawback of this kind of LCD projector is the low aperture ratio of the LCD panel of about 0.67 even for moderate resolution (SVGA) displays. The problem is even more serious for the case of high definition LCD panels. For example, the aperture ratio of XGA LCD panel is only 0.5 [1]. In addition to low light efficiency, low aperture ratio also introduces black grids or pixelation. Depixelization is often necessary, adding complexity to the optical system design.

Reflective mode silicon CMOS liquid crystal light valves can overcome this drawback of TFT-LCD projection systems. The aperture ratio of silicon based CMOS LCD can be as high as 92% regardless of the resolution, since all the electronics can be hidden beneath the reflective mirror on the pixel. Thus the light efficiency and the quality of projected image can be greatly improved [2]. Moreover, the production process of the silicon based CMOS-LCD is consistent with the current standard silicon CMOS technology. Therefore, it can be expected to have low cost and mass production capability.

Unfortunately, the optical system for the reflective mode light valve is not as straightforward as transmitted type TFT-LCD projectors. The main difference is that, in the transmitted TFT-LCD system, organic polarization sheets can be used, making the optical system compact and simple. Transmittive polarizers also have very large acceptance angles making the collimation requirement for the light source less stringent. The disadvantage of sheet type polarizer is that it cannot sustain high power light flux [3], so that it becomes one of the factors limiting the brightness of the projection image. In a reflective mode LCD projection system, the polarization has to be realized by a polarizing beam splitter (PBS) which can sustain much higher light fluxes. However, the drawback is that the collimation requirement is more stringent due to the limited acceptance angle of the PBS. Also the optical system is less compact as the optical path has to be folded many times.

Several important considerations must be taken into account in order to have a good performance for the reflective type projection system. First, the optical invariance (or etandue) of the system must be matched to the LCD panel. Second, dual polarization utilization must be introduced. Thirdly, the efficiency of the color separation and combination system must be optimized specifically for the reflective system. The issue of polarization splitting must be resolved. In this paper, we shall examine these issues carefully. We shall first discuss the optical mode of the LCD panel, which is the crucial problem in obtaining high efficiency and good image quality. Then a new optical system design is introduced utilizing a 2-stage projection method. This system has the advantage of high brightness. Finally we shall examine the optical elements for color separation and recombination carefully with the proposal for a new optical design in order to improve the performance of the reflective projection systems.

2. REFLECTIVE LCD MODES

The reflective LCD light valve is the single most important optical element of the CMOS-LCD projector. Here, we need a good design that gives the best reflectance. Wavelength dispersion is usually not a concern since narrow band R G B lights are going to be used anyway in the projector. This is especially true if optical coatings are going to be applied onto the light valves in order to enhance their reflectivities at particular wavelength bands. So in this discussion, we shall concentrate on LCD optical modes that have the highest reflectivities.

The optical mode of reflective LCD has been discussed in several previous publications [4-7]. For projector applications with a PBS, the normally white mode is preferred. The common modes are the ECB, TN-ECB [4], MTN [5] and the SCTN modes [6]. We recently showed that all of these optical modes are simple variations of each other and can be seen clearly on the parameter space diagram [7]. Fig. 1 shows a series of parameter spaces for the reflective display. These parameter spaces are basically constant reflectance contour maps with the twist angle ϕ and retardation $d\Delta n$ as the variables. Here d is the cell gap and Δn is the LC birefringence.

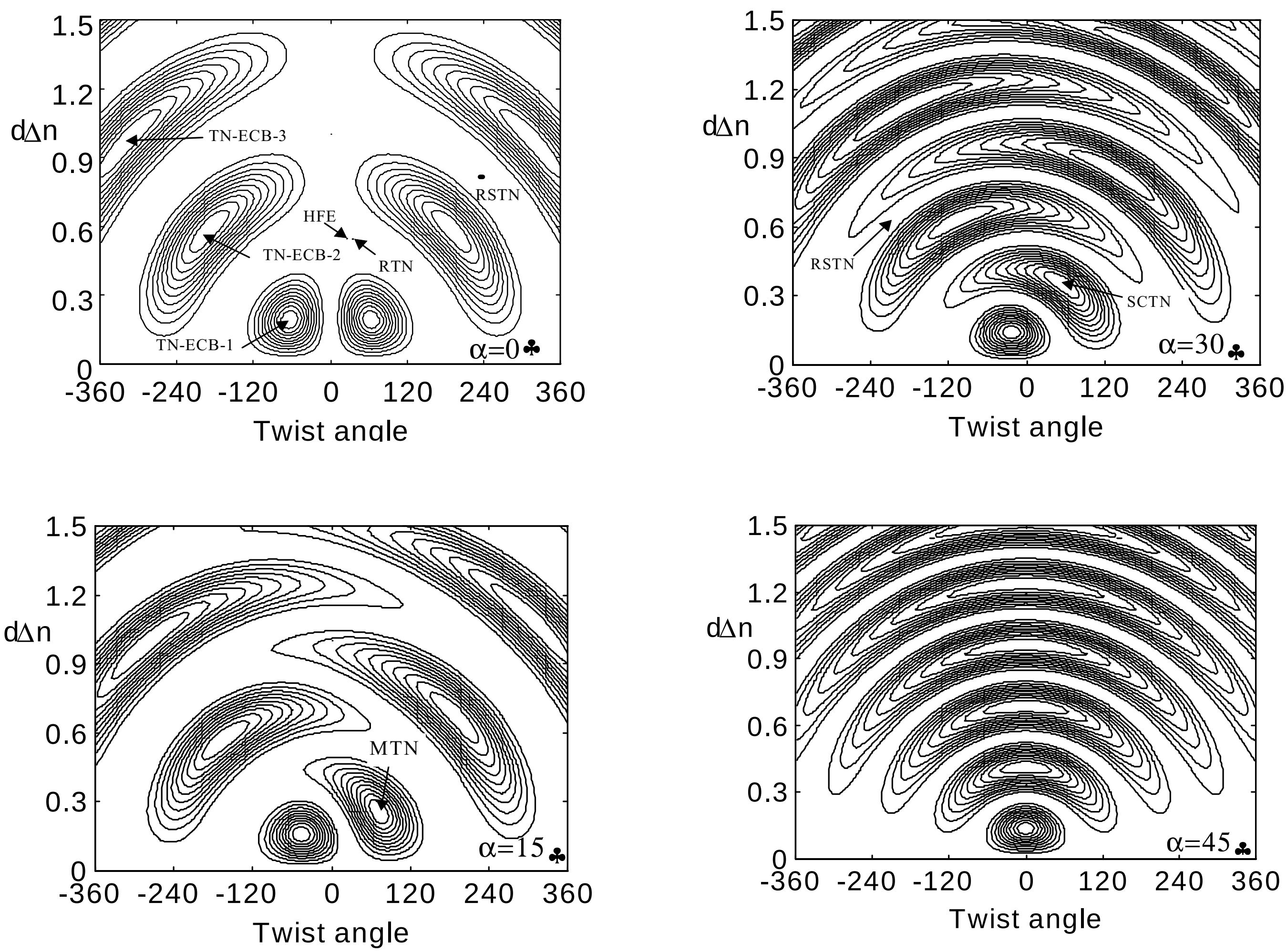


Fig. 1 Parameter space for the reflective display at polarizer angles of 0°, 15°, 30° and 45°.

The reason why the parameter space can be used is that the reflectance of any LCD at no voltage bias condition is simply a function of 3 variables:

$$R = R(\alpha, \phi, \delta) \quad (1)$$

where α is the polarizer angle (the angle between the polarizer axis and the input director of the LC cell), and δ is the retardation given by

$$\delta = \frac{\pi d \Delta n}{\lambda} \quad (2)$$

Here λ is the wavelength of the incident light. In Fig. 1, α is fixed for each parameter space and ϕ and δ are varied. It can be seen that for each PS, there are regions where the reflectance equals to 1.0. These are called the mixed TN and birefringence (MTB) modes. If α = 0, the MTB modes are the TN-ECB modes. If α = ϕ/2, the MTB modes becomes the SCTN modes. If α = 0, the MTB modes are identical to the ECB modes. Thus it can be seen that the most general mode for the reflective LCD with a single polarizer is the MTB modes as depicted in Fig. 1.

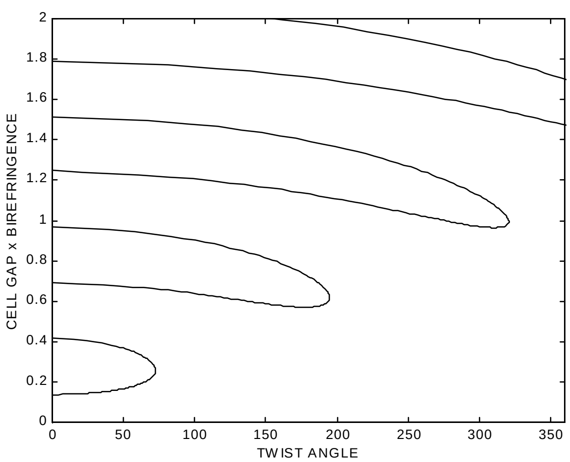


Fig. 2 Locus plot of all the MTB modes as the polarizer angel is changed. The curves represent unity reflectance.

The behavior of the MTB mode can further be visualized if we connect the R = 1.0 points of the various PS at various α, and plot them together on the same graph (Fig. 2). It is then 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.

3. SYSTEM OPTICAL EXTENT OR ETANDUE OF THE SYSTEM

The optical etandue is a key parameter that describes the quantity of light flux that can pass throughout an optical system. It is given by the formula [8]:

$$H = n\pi S \sin^2\theta \quad (3)$$

where n is the refractive index of the medium, θ the convergence angle of the light, and S is the area of the lighting aperture.

The most important etandues of the projection system are the etandue of the illumination system, the etandue of the optical coatings and the etandue of the LCD panel. In designing the optical system, in transforming the light flux from the lamp to the LCD panel, it is important to match the etandues of the various components. It is also necessary to make the etandue as large as possible in order to have the maximum light output.

As for the projective system using reflective LCD panels, the convergence angle of the illumination light beam is limited by the LCD panel and the coatings on the PB, the dichroic filters, and the color recombiner, and possibly retardation films. The most stringent limitation is usually given by the PBS. Usually, the convergence angle is less than $\pm 10^{o}$ in air for the reflective projector.

Also, from eq (3), we can see that, for a fixed convergence angle, the etandue of the LCD panel depends on its size. Generally the CMOS-LCD panel has a size of $16*12mm^2$ or $192mm^2$ in order to save silicon (or have more dies per wafer). On the other hand, the light valves in a TFT-LCD projector are usually 1.3" diagonal or about $523.4mm^2$ in area. This is 2.5 times bigger than a CMOS-LCD panel. It is a reason why the system optical etandue of the transmittive projector is so much better.

4. A TWO STEP OPTICAL PROJECTION SYSTEM

It is obvious that the small size of the CMOS-LCD panel is a disadvantage in a projection display. High luminance on the screen necessarily implies extremely high light intensities at the reflective light valve. Several methods have been proposed to prevent the leakage of light onto the silicon substrate [9]. But problems persist due to both thermal heating of the substrate and photo-induced currents. Here we describe a two steps light amplifier system [10]. In this system, the CMOS-LCD light valve sees only low intensity light. The main high intensity projection light is imaged by a liquid crystal light valve (LCLV). LCLV projector is a mature technology and is commonly used in large size high output projection systems [11]. So the problem of high luminous intensity on the CMOS-LCD light valve can be mitigated.

The schematic diagram of this system is shown in Fig. 3. In the present rendition, it is a monochromatic projection system. A 10W-halogen lamp is used to illuminate the CMOS-LCD light valve. The light can be very well collimated as light throughput and efficiency is not a concern at all. This enables a CMOS-LCD light valve with a small etandue to be used. A short conjugate distance imaging lens projects the image from the CMOS-LCD panel onto a photo-addressed LCLV. A powerful light

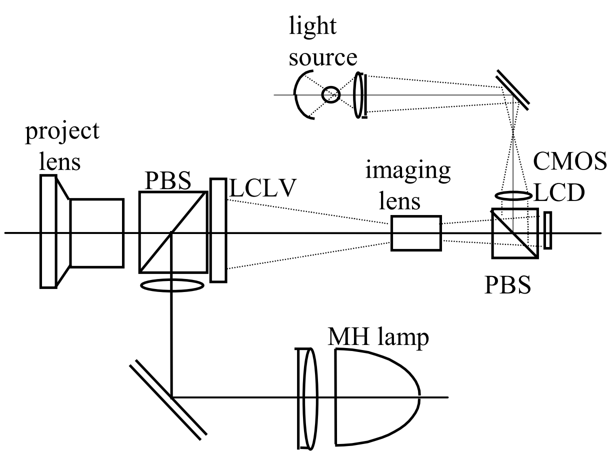


Fig. 3 Schematics of the CMOS-LCD driven LCLV projector system

source is then used to read out the signal of the LCLV and project it onto the screen. This is essentially an optical amplifier. It is the same arrangement as a conventional LCLV projector with the CRT replaced by a CMOS-LCD light valve.

Traditional LCLV is quite large in size in order to have a large etandue. In the present system, the imaging lens between the CMOS-LCD and the LCLV provides a two times amplification, so that the area of the LCLV can be four times bigger than the area of CMOS-LCD light valve. The etandue is therefore 4 times larger on the LCLV. Fig. 4 shows the monochrome projection system based on this idea.

The disadvantage of this 2-step system is that an additional light valve has to be used. Moreover, the compact Philips prism for color separation and recombination cannot be used easily for such color projectors. With this 2-step approach, the color separation and recombination has to be done separately, adding to system cost and complexity. However, for extremely high light levels, it may be the only solution as there is an upper limit to the amount of light one can put onto the CMOS-LCD light valve directly.

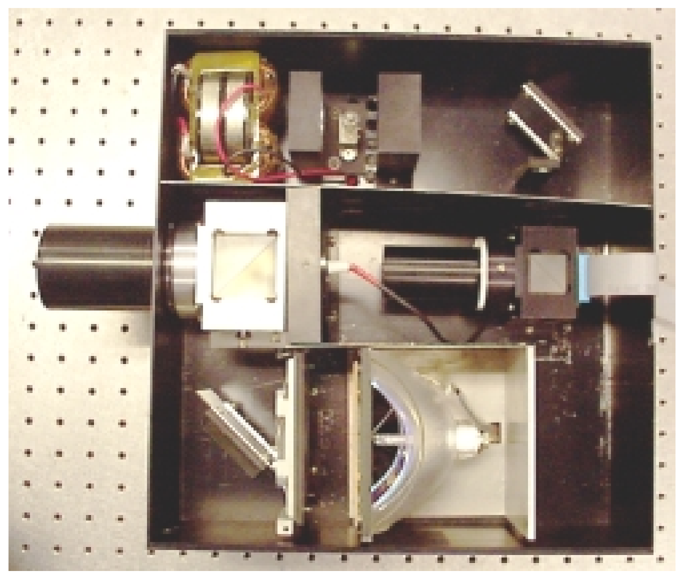
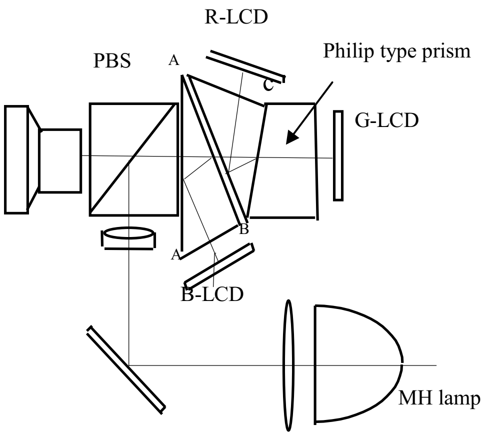


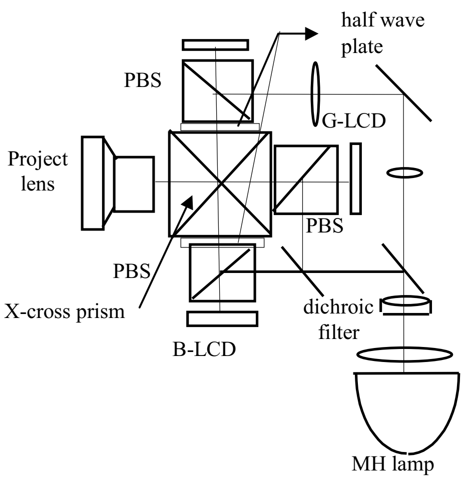
Fig. 4 The LCLV/CMOS-LCD system

5. OPTICAL SYSTEM DESIGNS FOR COLOR PROJECTION

A full color projector can either be time sequential type employing one reflective LCD panel, or a 3-panel type with all 3 primary colors on at the same time. We shall be concerned with the latter. Such projectors requires an optical sub-system to separate the primary colors from the input white light source (typically an arc lamp), and another sub-system to recombine the 3 primary colors after modulation by the reflective 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 the 3 LCD panels. Fig. 5 shows examples of these 2 kinds of optical systems.



(a)



(b)

Fig. 5 Reflective mode LCD projector system designs. (a) One PBS arrangement, (b) Three PBS arrangement.

In Fig. 5(a), a compact optical system using a trichroic prism assembly (TPA) is shown. The same optical assembly is used for color separation and color recombination. It is in principle very simple and especially suitable for small LCD projectors. However, the optical design, for example the dichroic coating design, is far from simple. In this optical system, the light beam from the metal halide lamp is first polarized by a PBS. The s-polarization light then enters the TPA. Usually the blue part of the light beam is first reflected by surface AB, then totally internally reflected by surface AA, and illuminates the blue LCD panel. Because of the requirement for TIR, the angle of incidence of the light on the dichroic coating is usually about 30^o. The reflected light from the LCD panel will be p-polarized. This light beam retraces the same light path as the incident beam. Hence the coating on surface AB has to function for both s and p polarized light.

The same is true for the other primary colors. Basically the TPA acts as both a color separator for s-polarized light, and as a color recombiner for p-polarized light. Therefore, the reflectance spectra of the coatings on the prism must be the same for both s and p polarized light. Otherwise, there will be a loss in reflected light intensity. There will also be a shift in the color coordinate of the reflected and reconstructed light. Presumably that can be renormalized by adjusting the reflectivities of the light valves, at the cost of losing light intensities. Therefore the requirement for the dichroic coatings to function for both p and s polarized light is a stringent requirement indeed. There are some existing designs such as the Philips prism for accomplishing this partially [3]. However, there is much room for improvement. We shall show in the next section a new trichroic prism design that can significantly improve the performance of such compact systems.

Fig. 6 shows the reflective projector assembled using the design shown in Fig. 5(a). All the driver electronics can be fitted into a small space because of the use of the compact trichroic prism. A 50W metal halide lamp is used and the brightness obtained was about 100 lumens, with reasonable color saturation. A projected image is shown in Fig. 7.

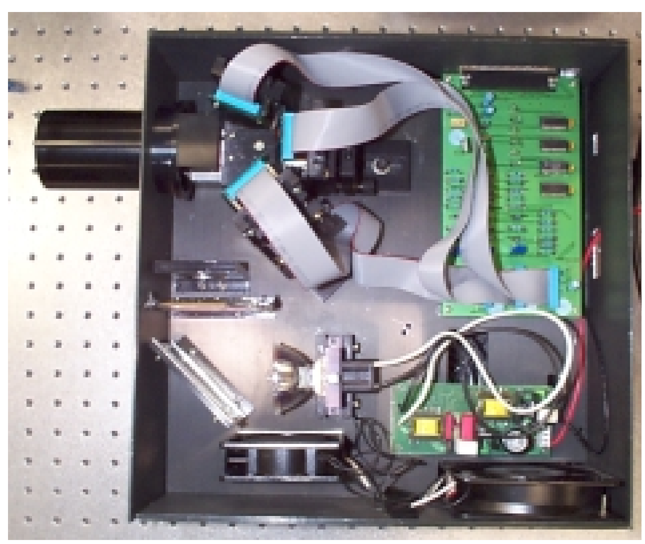


Fig. 6 A color projector using a single TPA.

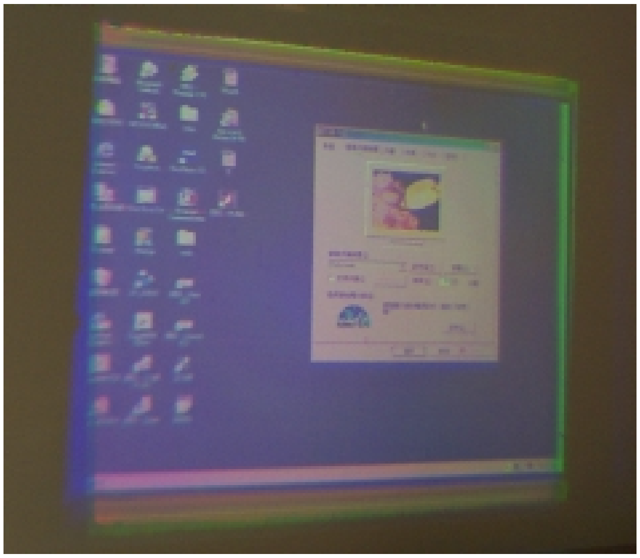


Fig. 7 Projected image on the screen (in color)

The TPA used in Fig. 6 was fabricated at Zhejiang University. The dichroic coatings applied have been optimized for red and blue light separation. Fig. 8 shows the measured results using a spectrometer. The three peaks correspond to output form the red, green and blue channels of the TPA. It can be seen that in general, the deigned colors can be achieved. But there is a shift in the spectra for s and p-polarizations. The p-polarized reflectance is shifted to the blue by as much as 10 nm. As will be explained in the next section, this is due to the polarization splitting effect of dichroic filters at non-zero angles of incidence.

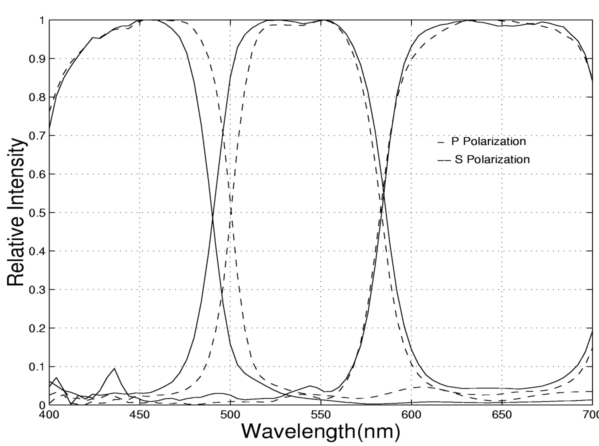


Fig. 8 Measured RGB output from the ZJU fabricated TPA

Figure 5(b) shows another possible optical arrangement where the color separator and recombiner are on different pieces of optics. The primary colors are first separated by conventional dichroic mirrors. The 3 light beams see 3 different PBS on the 3 separate reflective LCD panels. Because of the separate coatings involved in color separation and recombination, the coating design requirements are much relaxed. However this is achieved at the expense of a more complex and larger optical system. There are many possible arrangements for the color separation and recombination sub-systems. It may be based on glass plate dichroic filters as shown, or it may be based on Philips type trichroic prism or the X-prism. The X-prism is used in Fig. 5(b) for color recombination.

The system shown in Fig. 5(b) is a direct modification of the system commonly used in transmittive TFT-LCD projectors. The only complication is that because the reflective light from the LCD panel is p-polarized, a half wave plate is needed to turn it into s-polarization before entering the X-prism. It is because that a 45^o p-polarization three color recombiner is more difficult to realize than one for s-polarization.

6. A NEW TRICHROIC PRISM

As mentioned above, it is difficult to have the same optical coatings to function as both a color separator and recombiner. This is because of the s-p polarization split of the reflectance spectrum for dichroic coatings [12]. We can use the following calculations to illustrate this point. If dielectric multilayer optical coatings are used to form the dichroic coating, it should consist of periodic multilayer stacks of high refractive index layer (H) and low refractive index layers (L). The reflectance spectrum is given by (in case of $n_H d_H = n_L d_L = \lambda/4$) [13]:

$$\frac{\Delta\lambda_R}{\lambda} = \frac{4}{\pi}\sin^{-1}\left|\frac{\eta_H - \eta_L}{\eta_H + \eta_L}\right| \qquad (4)$$

where $\Delta\lambda_R$ is the reflective band wavelength, η_H and η_L are the effective admittances of the H and L layers respectively. They are the functions of the incident angle and the polarization state of the light.

$$\eta_{is} = n_i \cos\theta \quad \text{for s-polarization,} \qquad (5)$$

and

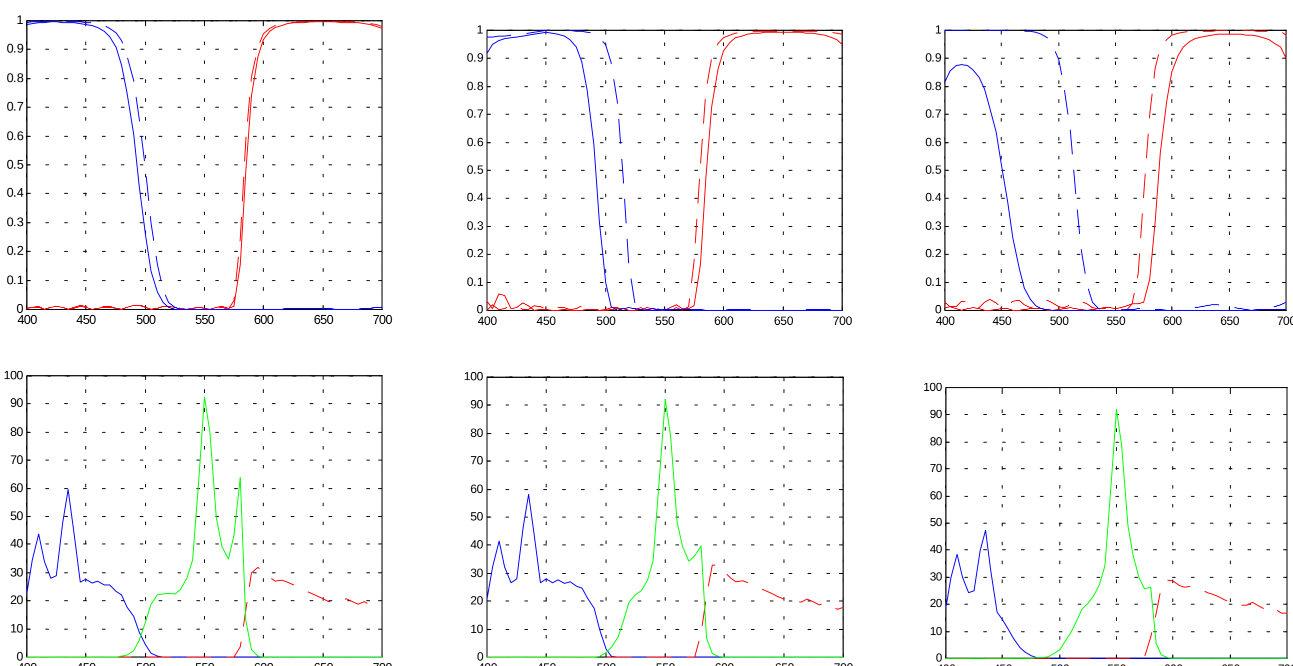
$$\eta_{ip} = \frac{n_i}{\cos\theta} \qquad \text{for p-polarization, i = H or L.} \tag{6}$$

It is obviously that the effective admittance η of the thin film changes as the incident angle of light is changed. And the difference between the s and p polarization spectrum becomes much larger as the incident angle is increased. Therefore large incident angle will induce a large separation between the reflectance spectra of s-polarized and p-polarized light.

Fig. 9 presents the spectral reflectance of a dichroic filter in 16°, 30° and 45° incidence angles. The red and blue edge filter spectra are plotted in the same figures, representing 3-color-separation. The solid curves are for the p-polarization while the dashed curves are for s-polarized light. The coatings are assumed to be wedged between glass with an index n_g of 1.5163. It can be seen clearly that, as the angle of incidence increases, the separation of the spectra between s and p polarizations increases greatly. As a matter of fact, this is the principle of ordinary PBS! The 30° curve in Fig. 9 agrees quite well with the experimental results shown in Fig. 8.

Also shown in Fig. 9 are the expected output spectra of the 3 primary colors, taking into account of the spectral output of the Hg halide arc lamp. From these curves, one can calculate the loss in intensities of the 3 primary colors upon spectral separation and recombination, assuming of course, ideal reflective light valves.

The Philips type prism design as shown in Fig. 5(a) is commonly used in color video camera systems. The incident angles on the two dichroic coatings are about 30° [3]. These incident angles cannot be decreased, because of the requirement of total internal reflection of the light beams at surfaces AA and AB. Furthermore, surface AA has to be normal to the principle axis of the light beam, as the PBS used is cubic in shape. Obviously, from Fig. 9, the 30° Philips prism is far from ideal as applied to reflective mode LCD projectors, when it has to be used both as a s-polarization color separator and as a p-polarization color recombiner. (In the application of color separation in video cameras, it is fine because the light is not polarized.) Therefore, the crux to the problem of optimizing the trichroic color separation/recombination prism is in reducing the angle of incidence of the light on the dichroic coatings.



(a) 16 degrees (b) 30 degrees (c) 45 degrees

Fig. 9 Reflectance spectra and output light spectra of the different angle of incident of the prism assembly.

We propose here a new trichroic color separation/recombination prism assembly where the angle of incidence on the dichroic coatings has been reduced to 16°. The design of this prism is shown in Fig. 10. The main idea is that we can allow the PBS to have an odd shape. This will relax the design conditions and allow a smaller angle of incidence. In particular, we can make the PBS to have the same shape as one of the prisms of the TPA as shown. Now the condition of total internal reflection on the two inside surfaces must be maintained. We assume that the incident angles of the two dichroic coatings (AB and BC) are the same and denote it as θ. The relation between the various angles of the TPA must satisfied following conditions:

$$\theta = \phi_{11} \qquad (7)$$

$$\phi_{12} = \phi_{10} + 2\phi_{11} \geq \sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} NA \qquad (8)$$

$$\phi_{20} = \theta + \phi_{11} = 2\theta \qquad (9)$$

$$\phi_{22} = \theta + \phi_2 \geq \sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} NA \qquad (10)$$

and

$$\phi_3 = 90^0 - \theta \qquad (11)$$

Therefore

$$\theta > \frac{1}{3}\left(\sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} NA\right) \qquad (12)$$

In these equations, n is the refractive index of the prism and NA is the numerical aperture of the projection system. Therefore, if the refractive index of the prism is 1.52, and the F-number of the optics is 4, then from eq. (12), the smallest angle of incidence θ allowed is 16°. From the above equations, we can also get $\theta_{10}=16^0$, $\phi_2=32^0$, $\phi_3=74^0$. The size of the prisms of course depends on the size of the LCD panel.

It is a very simple prism assembly where the two dichroic coatings have the same angles of incidence. Prisms AAB and ABC are similar, thus making mass production possible. It is obvious that, from Fig. 9 that this TPA has very small polarization effects. Moreover, the small angle of incidence implies a small dispersion effect on the incidence angle. Therefore the dichroic coatings can have large acceptance angles or a large etandue. All in all, this new prism structure can improve the numerical aperture of the entire optical system greatly, while maintaining excellent color separation properties.

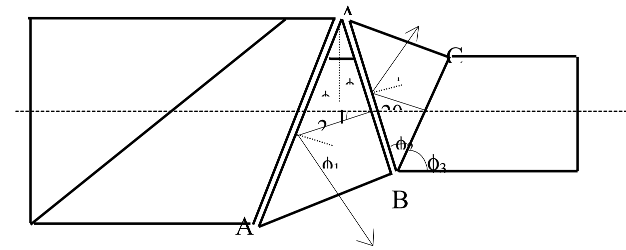


Fig. 10 Structure of the improved PBS / trichroic prism assembly

7. CONCLUSIONS

(8)

In this paper, we have discussed several optical aspects of reflective projectors based on CMOS-LCD light valves. In particular, we introduced the parameter space of all reflective LCD modes for such CMOS-LCDs. The 2-stage concept for high intensity light projectors is also implemented. Finally a new design for the trichroic prism assembly is discussed. This new design improves the optical efficiency and numerical aperture of the optical system considerably.

The optical etandue and spectral/polarization effects are the two major properties of the optical projection system that need to be optimized. This is true for both reflective mode or transmittive mode projectors. For reflective projectors, the optical coatings are the major limits to the system etandue. The polarization splitting effect on the trichroic prism assembly is a significant cause of degradation of the optical system performance. The optical systems proposed here provide a significant improvement over existing designs. In particular, the optical efficiency, the polarization splitting effect, and also the acceptance angle and numerical aperture are much improved. The new TPA should find major applications in compact projectors such as desktop monitors and TVs.

8. ACKNOWLEDGEMENTS

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