Trichroic prism assembly for separating and recombining colors in a compact projection display

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A trichroic prism assembly design, believed to be new, is proposed and demonstrated. This new design has the advantages of low *s*- and *p*-polarization dependence in the reflectance spectra of the optical coatings. Hence it can be used for both color separation and color recombination with polarization change. This new trichroic prism assembly is especially useful in a compact color projector employing reflective liquid-crystal light valves. © 2000 Optical Society of America

OCIS codes: 220.4830, 230.3720, 330.1690.

1. Introduction

Current liquid-crystal projection displays are based mainly on transmittive LCD light valves as the image generator. A major drawback of this kind of transmittive light valve is that the aperture ratio (AR) of the pixels is small. It gets smaller as the resolution of the light valve increases. For example, the AR is ~0.67 for SVGA (super video graphics adapter) displays and is ~0.5 for XGA (extended graphics array) LCD panels.[1] In addition to low-light utilization efficiency, low AR also requires a black matrix to hide the transistors. This black matrix produces a pixelation effect on viewing and is quite noticeable. Depixelization techniques such as optical filtering are therefore necessary, adding complexity to the optical system design. In this type of transmittive projector different sets of color filters are used for the separation of the input light into three primary colors and for recombining them after they travel through the LCD light valves. Color recombination is usually performed with the *X* cube.[2]

Reflective-mode silicon complementary metal-oxide semiconductor (CMOS) liquid-crystal light valves can overcome the drawback of low AR in transmittive LCD panels.[3,4] The AR of silicon-based CMOS LCD can be as high as 92%, regardless of the resolution. This is because the transistor can be hidden beneath the reflective mirror on the pixel.[3–5] The size of the reflective mirror and hence the AR is limited only by the microfabrication resolution of the wafer process. Thus light utilization efficiency for the CMOS light valve is very high. Moreover, no black matrix is necessary, and the quality of the projected image can be greatly improved. No pixelation can be observed in these reflective displays on projection, and the image appears continuous, which is highly desirable for high-quality projectors.

Obviously, there are other advantages for the CMOS light valve, such as much easier electronic integration of the drivers.[3] In this paper, however, we concentrate only on the optics of these projectors, and in particular, on the color filters. The projection optics of the reflective light valve are considerably more complicated than the transmittive ones. For example, the optical system etendue is quite limited so that all the optical elements have to be carefully designed.[6] In the case of the color filters, one particular difficulty with reflective light valves is the change of *s* and *p* polarization upon reflection. This presents significant challenges to optical coating designs, because it is difficult to achieve coatings that are insensitive to light polarization. Current approaches use separate coatings for color separation and for color recombination. In this paper we propose what to our knowledge is a new scheme whereby color separation and recombination can be performed in a single set of optical elements with high color fidelity and high light efficiency. In addition to being compact, this new optical subassembly should

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Received 10 May 1999; revised manuscript received 3 September 1999.

0003-6935/00/010168-05$15.00/0

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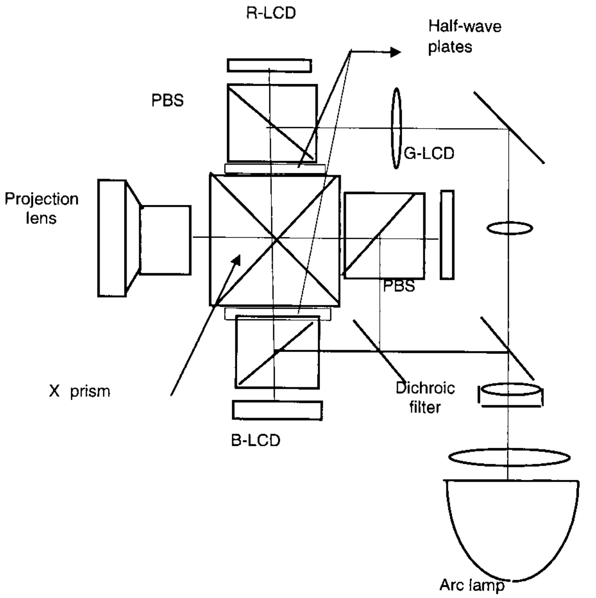

Fig. 1. Optical system for a reflective color projector with conventional configuration. R-LCD, G-LCD, and B-LCD stand for red, green, and blue LCD light valves.

potentially save considerable costs in that fewer optical elements and coatings are needed for the projector.

2. LCD Projector Optics

A full-color projector can be either a time-sequential type[5] that employs one reflective LCD panel or a three-panel type with all three primary colors on at the same time. Here we shall be concerned with the latter. Such projectors require an optical subsystem to separate the primary colors from the input white-light source (typically an arc lamp) and another subsystem to recombine the three 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. For a compact projection system the former is much preferred.

There are several designs for the optical subassembly for color projectors based on reflective light valves. The basic element for a reflective light valve is a polarizing beam splitter (PBS), which reflects *s*-polarized light and transmits *p*-polarized light. In the most straightforward designs, three PBS's can be used for the three primary-color panels. Color separation and color recombination can be performed in separate sets of filters similar to the transmittive projectors. Figure 1 shows the basic setup. Dichroic reflectors are used to separate the three primary colors from the arc lamp. The red, green, and blue channels are sent to the three PBS's and to the three light valves. The image-modulated reflected lights are then sent to the color-recombining *X* cube for projection. Because the reflective coatings in the *X* cube work best for *s*-polarized light, half-wave plates are usually needed for the red and the blue channels to rotate the *p*-polarized light from the reflective LCD. This system is thus quite complex.

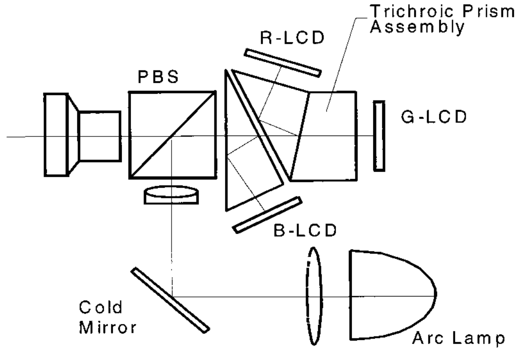

Fig. 2. Optical system for a reflective color projection display employing a TPA.

Alternatively, for compact color projectors employing reflective light valves, the color separation and the color recombination can be performed with the same set of optical coatings. A common optical assembly for accomplishing this task is the so-called Philips prism.[7] This trichroic prism assembly (TPA) works in conjunction with only one PBS to form the core of a compact color reflective projector. This system is shown in Fig. 2.

The PBS first sends either the *s*- or the *p*-polarized light into the TPA. The choice of *s* or *p* polarization depends on the position of the arc lamp and the projector lens. The coatings on the prism surfaces are used to separate out the blue and the red colors. Air gaps are provided as shown so that total internal reflection (TIR) can occur to reflect the red and the blue beams out of the way.

The three separate red, green, and blue channels impinge on the respective reflective LCD light valves. The function of the nematic liquid-crystal light valve is to modulate the polarization state of the reflected light.[8] Many optical modes have been proposed for the LCD panels. In all cases the reflected light remains linearly polarized with the polarization ideally rotated by 90° with respect to the input for the selected pixels. On reflection the light beams retrace the same light paths as the incident beams. They recombine inside the TPA as the opposite polarization.

Hence the high-reflectance coatings for both the blue and the red lights have to function for both *s*- and *p*-polarized light. This is a difficult requirement for coating design. It is well known that it is impossible for a dichroic coating to have no polarization dependence unless the angle of incidence is zero.[9] Because of the requirement of TIR, the angle of incidence on the blue color filter surface is limited to at least 25°. Usually a 30° prism is used. Thus the conventional TPA has severe polarization dependence in its reflectance spectrum. This so-called *s*–*p* polarization split causes severe loss of light efficiency and loss of color fidelity in the display.

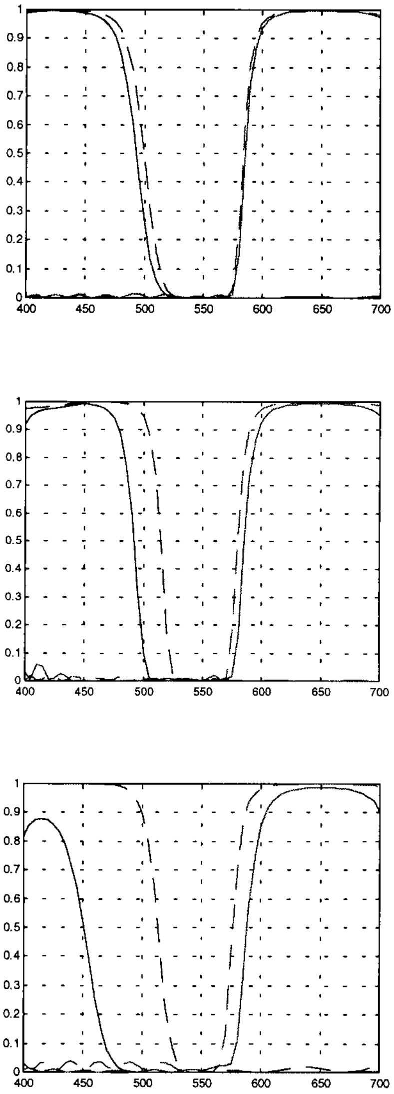

Fig. 3. Calculated reflectance spectra for the red and the blue edge reflection coatings for incidence angles of (a) 16°, (b) 30°, and (c) 45°. Solid curves, p-polarized light; dashed curves, s-polarized light.

Figure 3 shows the calculated reflectance spectra for the red and the blue coatings for three different incidence angles of 16°, 30°, and 45°. The red and the blue edge filter spectra are plotted in the same figures, representing three-color separation. The solid curves are for the p-polarized light, and the dashed curves are for the 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. This so-called s–p polarization split will cause a loss in reflected light intensity. There will also be a shift in the color coordinate of the separated and the recombined light.

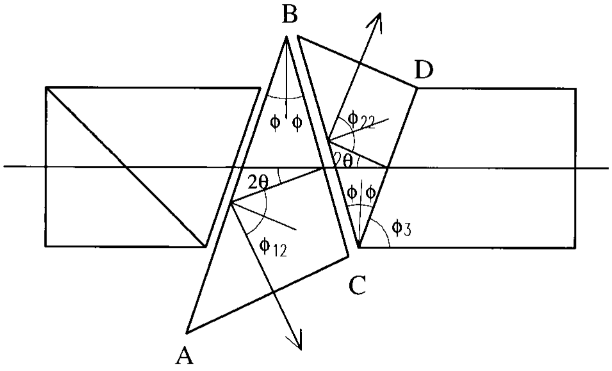

Fig. 4. New TPA together with the new noncubic PBS.

3. Trichroic Prism Assembly

The s–p polarization split for optical coatings comes from the fact that the specific admittance of light is different for s- and for p-polarized light. The admittances are functions of the incident angle and the polarization state of the light.[10] They are given by

$$\eta_{is} = n_i \cos\theta \qquad \text{for } s \text{ polarization,} \tag{1}$$

$$\eta_{ip} = \frac{n_i}{\cos\theta} \qquad \text{for } p \text{ polarization.} \tag{2}$$

In Eqs. (1) and (2) the subscript i stands for the ith layer in the coating stack. It is obvious 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 the p polarization spectra becomes much larger as the incident angle increases. Therefore large incident angle will induce a large separation between the reflectance spectra of s- and p-polarized light. This is evidenced in the calculated spectra in Fig. 3.

The crux of the problem of optimizing the trichroic color separation–recombination prism is in reducing the incidence angle of the light on the dichroic coatings. This incidence angle is limited by the requirement of TIR for the blue and the red channels. We propose here a new trichroic color separation–recombination prism assembly in which the incidence angle on the dichroic coatings is reduced to 16°.

The design of this prism is shown in Fig. 4. The main idea is that we can allow the PBS to have an odd shape rather than the conventional cubic shape. This will relax the design conditions and allow for a smaller angle of incidence. The basic construction of this new TPA is similar to the conventional one. The blue high-reflectance coating is applied on surface *BC*, and the red high-reflectance coating is applied on surface *CD*. We assume that the incident angles of the two dichroic coatings are the same and denote them as θ. Now the condition of TIR on the two inside surfaces (*AB* and *BC*) must be maintained. Moreover, we can assume surfaces *AB* and *CD* to be parallel. The relation between the various angles of the TPA must satisfy the following conditions:

$$\theta = \phi, \tag{3}$$

$$\phi_{12} \geq \sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} \mathrm{NA}, \tag{4}$$

$$\phi_{22} \geq \sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} \mathrm{NA}, \tag{5}$$

$$\phi_3 = 90° - \theta. \tag{6}$$

Therefore

$$\theta > \frac{1}{3}\left[\sin^{-1}\left(\frac{1}{n}\right) + \sin^{-1} \mathrm{NA}\right]. \tag{7}$$

In these equations, n is the refractive index of the prism material 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. (8) the smallest angle of incidence θ allowed is 16°. Additionally, we can see that $\phi = 16°$ and $\phi_3 = 74°$. The size of the prisms, of course, depends on the size of the LCD light valves.

Our prism assembly is a simple one in which the two dichroic coatings have the same angles of incidence. Prisms *ABC* and *BCD* are similar, thus making mass production easier. It is obvious from Fig. 3 that this TPA has small and acceptable polarization effects. Moreover, the small angle of incidence implies a smaller dispersion effect on the incidence angle. Therefore the dichroic coatings can have large acceptance angles or a large etendue. All in all, this new prism structure can improve the numerical aperture of the entire optical system greatly while maintaining excellent color-separation properties.

4. Experimental Results and Conclusions

Both the conventional TPA and the new TPA were constructed for comparison. The dichroic coatings applied have been optimized for red and for blue light separation. Eighteen layer stacks were used to ensure reasonable sharpness in the reflectance spectra. Figure 5 shows the measured results for the conventional 30° TPA. The data were taken with a Photo Research Model PR650 spectrometer. The reflectance for the various polarizations and color coatings has been normalized for comparison. The three peaks in Fig. 5 correspond to the output from the red, green, and blue channels of the TPA. It can be seen that, in general, the designated 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. These data are in general agreement with the numerical calculations presented in Fig. 3.

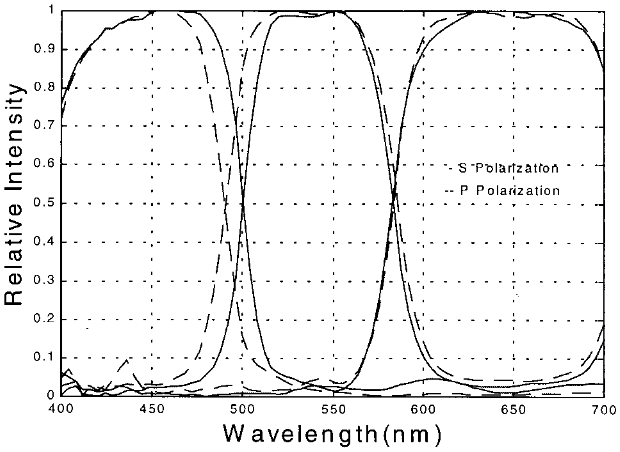

Fig. 5. Measured reflectance spectra for the conventional 30° TPA.

Figure 6 shows the measured reflectance spectra for the new TPA, with an angle of incidence of 16°. In this case it can be seen that there is negligible s–p polarization split. This result again is in good agreement with the numerical results in Fig. 3. The spectra for both the s-polarized and the p-polarized light are sharp and identical. This TPA should be useful for a compact color projector as shown in Fig. 2.

In summary, we have shown that the major limitation for the design of a compact color projector with reflective LCD light valves is in the design of the color separator and recombiner. By modifying the design of the conventional TPA, we have been able to achieve a marked improvement in the problem of s–p polarization split.

The optical etendue and the spectral–polarization effects are the two major properties of the optical projection system that need to be optimized. This is true for both reflective- or transmittive-mode projectors. For reflective projectors the optical coatings are the major limits to the system etendue. The polarization splitting effect on the TPA is a significant cause of degradation of the optical system performance. The optical system proposed here provides a significant improvement over existing designs. The new TPA should find major applications

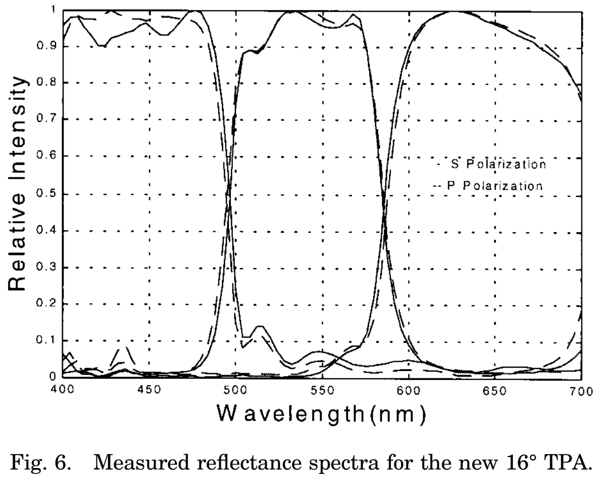

Fig. 6. Measured reflectance spectra for the new 16° TPA.

in compact projectors such as desktop monitors and flat-panel televisions.

Research at Zhejiang University was supported in part by the Natural Science Foundation of Zhejiang Province, China. Research at the Hong Kong University of Science and Technology was supported by the Hong Kong Government Industry Department and by Varitronix Limited.

References

1. N. Okamoto, Y. Itoh, and J. Ito, "High brightness technology of p-Si TFT-LCD front projector," in *Proceedings of the International Conference on Display Works* (Kobe, Japan, 1998), p. 813–816.
2. X. Liu, H. F. Li, P. F. Gu, and J. F. Tang, "The application of thin film techniques in LCLV devices," in *Optical Interference Coatings*, F. Abeles, ed., Proc. SPIE **2253,** 858–862 (1994).
3. H. C. Huang, P. W. Cheng, W. C. Yip, H. S. Kwok, C. S. Li, and Y. Liao, "AMLCD on a silicon substrate with integrated digital data driver," in *Proceedings of the Fifteenth International Display Research Conference* (*Asia Display '95*) (Hamamatsu, Japan, 1995), pp. 481–484.
4. R. L. Melcher, M. Ohhata, and K. Enami, "High-information content projection display based on reflective LC on silicon light valves," *Society for Information Display Symposium Digest* (Society for Information Display, San Jose, Calif., 1998), pp. 25–28.
5. H. C. Huang, P. W. Cheng, J. Chen, and H. S. Kwok, "Color sequential miniature silicon display using reflective twisted nematic mode," in *Proceedings of the Eighteenth International Display Research Conference* (Seoul, Korea, 1998), pp. 411–414.
6. H. F. Li, Z. R. Zheng, P. F. Gu, X. Liu, P. W. Cheng, J. Chen, H. C. Huang, and H. S. Kwok, "Improved projection optics for reflective silicon CMOS light valves," in *Projection Displays V*, M. H. Wu, ed., Proc. SPIE **3634,** 123–133 (1999).
7. D. B. Dove, "Arrangement for projection displays employing reflective light valves," U.S. patent 5,658,060 (19 August 1997).
8. 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," in *Proceedings of the Seventeenth International Display Research Conference* (Boston, Mass., 1997), pp. 155–158.
9. J. A. Dobrowoski, "Optical properties of films and coatings," in *Handbook of Optics: Fundamentals, Technique, and Design*, Vol. I, M. Bass, ed. (McGraw Hill, New York, 1995), pp. 42.1–42.130.
10. M. S. Brennesholtz, "Light collection efficiency for light valve projection system," in *Projection Display II*, M. H. Wu, ed., Proc. SPIE **2650,** 71–79 (1997).