Broadband, large acceptance angle polarizing beam splitters for reflective LCD projectors

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ABSTRACT

In projectors employing reflective liquid crystal light valves, polarizing beam splitters (PBS) have to be used. However, ordinary wide bandwidth PBSs have relatively small acceptance angles. This reduces the optical efficiency of the projectors. In this paper we present new designs for the PBS which has the advantage of large acceptance angles without compromising the operating bandwidth.

Keywords: Polarizing beam splitter, broadband, numerical aperture, acceptance angle, LCD, projectors

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1. INTRODUCTION

Polarizer is a key component in any liquid crystal projectors, whether it be transmissive or reflective. In reflective mode liquid crystal light valve projectors, polarizing beam splitters (PBS) are often used both as polarizers and analyzers [1]. The PBS passes through p-polarized light and reflects s-polarized light. It is usually a MacNeille type prism, using a multilayer dichroic coating as its polarizing element [2]. This kind of PBS is easy to make and is relatively low cost. It also has the advantage that the incident beam and the reflected beams are at 90° to each other.

This MacNeille PBS has very high extinction ratio, usually above 1000:1. It should be noted that the extinction ratio is different for the reflection and transmission directions. It is because of the leakage of p-polarized light in the s-polarized light direction. Hence the extinction ratio is much lower in reflection than in transmission.

Unfortunately, the acceptant angle of commercial PBS is very small. Usually the incident angle of the light in air has to be within $\pm 2^\circ$ to the surface normal. Otherwise the transmittance of the p-polarized light will decrease significantly. This is illustrated in Fig. 1 where we plot the transmittance of the p- and s-polarized light at various incidence angles and at various wavelengths. It can be seen that leakage of p-polarized light is very severe as the incident angle of light is increased, especially near 550nm. Wide bandwidth operation can only be achieved at small incident angles. Conversely, large acceptance angle is only possible if the input light is narrow band. In the present example, the light has to be around 600-650nm in the red.

In a LCD projection system, the illuminating light usually has an incident angle of $\pm 7^\circ$ or more in air. Small F# or large numerical aperture (NA) optics is therefore necessary. The relationship between the F# and the angular radius of the light cone is given in Table I. For any of the F numbers listed, the light cone of the input is definitely larger than the acceptance angle of the PBS. As a result, the light efficiency

and contrast ratio of the projection system is reduced. Besides a loss of efficiency, this PBS will also cause color changes as seen in Fig. 1.

A PBS with high extinction ratio for both reflection and transmission and with a wide acceptance angle was proposed by Li et al [3]. It is based on the Bertrand-Feussner design [2]. In this polarizer, a birefringent layer is used to separate the s- and p-polarizations. Li was able to replace the birefringent layer by a multilayer coating stack. This Li PBS can achieve a very large acceptance angle and a very broad bandwidth at the same time. However, a large angle of incidence is required. In the Li PBS, the angle of incidence is 70° . This 70° incident angle and the high refractive index of the glass required ($n_g > 1.75$) make the Li PBS rather bulky and expensive. It also introduces difficulties in designing the projection lens because of the large back focal length.

Table I Relationship between F# and the beam cone angle

F#	NA	θ in air	θ in glass (1.5)
3.0	0.17	9.6°	6.4°
3.5	0.14	8.2°	5.5°
3.8	0.13	7.6°	5.0°
4.0	0.125	7.2°	4.8°
4.5	0.11	6.4°	4.25°

Fig. 1 Transmission of p- and s-polarized light for a conventional PBS

In this paper, we report a MacNeille type PBS design that is capable of large acceptance angle, after it is optimized properly. It overcomes the problem of low extinction ratio in reflection of the MacNeille type PBS. After optimization, it can also have high light efficiency. A wide acceptance angle of over $\pm 7^\circ$ (in air) is possible. It corresponds to F/4 optics, which is acceptable in matching the etendue of UHP arc lamps [4].

2. DESIGN CONSIDERATIONS

The most important considerations in designing the optical system of an LCD projector are the brightness, the contrast ratio and the color saturation. The contrast ratio is mainly decided by the PBS. The brightness and color are influenced by the transmission spectrum of the PBS, and of course, by the color separation and recombination filters. For the latter, we have reported previously a trichroic prism assembly (TPA), which can be used as both a color separator and a color recombination system [1]. In this paper, we shall concentrate on the optical properties of the PBS.

In reflective LCD projectors, the polarizing prism and the reflective LCD panel are usually arranged as shown in Fig. 2. The s-polarized light is reflected by the multilayer coating in the prism and illuminates the LCD panel. The LCD panel transforms part of the light into p-polarization and reflects it back to the prism. The PBS then passes through this p-polarized light which is subsequently projected onto the screen through a projection lens.

Fig. 2 Reflective light valve using a PBS for projection

For the system as shown in Fig. 2, if the input light is unpolarized, we can write the intensity of the illuminating light on the LCD panel as:

$$I = R_s + R_p \quad (1)$$

The light output onto the screen for the bright state is:

$$I_{\text{on}} = R_s T_p + R_p T_s \quad (2)$$

where R_s , R_p , T_s , T_p are the reflectance and the transmittance of s- and p-polarized light of the PBS respectively. We assume that the input light is perfectly randomly polarized and the LCD panel is ideal,

i.e. it can turn all the s-polarized light into p-polarized light and the reflectance of LCD is 100%. Likewise, the dark state on the screen is given by

$$I_{\text{off}} = R_s T_s + R_p T_p \quad (3)$$

For the PBS, both R_p and T_s are much smaller than R_s and T_p so that they can be neglected in eq. (2). A similar approximation, however, cannot be made for eq. (3). If we define the efficiency η of the PBS as the on-state light intensity, then:

$$\eta = R_s T_p \quad (4)$$

The contrast ratio C of the projector is defined by

$$C = \frac{I_{\text{on}}}{I_{\text{off}}} = \frac{R_s T_p + R_p T_s}{R_p T_p + R_s T_s} \approx \frac{R_s T_p}{R_p T_p + R_s T_s} = \frac{1}{\left(\frac{R_s}{R_p}\right)^{-1} + \left(\frac{T_p}{T_s}\right)^{-1}} \quad (5)$$

where R_s/R_p and T_p/T_s are the extinction ratios for reflection and transmission directions of the PBS respectively.

From eq. (5) we know that high extinction ratio of both reflection and transmission is needed for obtaining a high contrast ratio. But this is impossible for a MacNeille type PBS with broadband and wide incident angular range. What can be done, however, is a compromise to obtain broadband operation at the expense of lowered extinction ratios. In this case, we can approximate eqs. (4) and (5) by

$$\eta \approx T_p \quad (6)$$

$$C \approx \frac{T_p}{T_s} \quad (7)$$

So our objectives for the optimization of the coating stack is to get T_p as high as possible with a certain high contrast ratio. For ordinary PBS, the objective is to obtain very high T_p/T_s such as a few thousands to one. This is unnecessary in the case of a projector because the contrast ratio required usually is only about 256:1. Therefore, in our design, we simply require the extinction ratio to be about this value as well. More importantly, T_p has to be as high as possible over the entire visible range.

The MacNeille type PBS is based on Brewster reflection [2]. In order to get the maximum performance of the prism, the prism glass (n_g), coating materials (n_L, n_H) and the reflecting angle θ should satisfy the following equation:

$$\sin^2 \theta = \frac{n_H^2 n_L^2}{n_g^2 (n_H^2 + n_L^2)} \quad (8)$$

Therefore, a proper choice of the materials and the refractive indices is necessary in order for θ to be 45° . Conversely, the material choice can be relaxed if θ is allowed to be non- 45° . Some of these choices are listed in Table II.

3. RESULTS AND PERFORMANCE OF THE NEW PBS

We have studied 4 different designs of the PBS using the above approach. These 4 combinations are listed in Table II.

Table II PBS design considered in this paper

Design	θ	n_g	n_H	n_L	Number of coatings
A	45	1.69	2.35	1.38	19
B	45	1.64	1.98	1.46	27
C	52	1.52	2.35	1.38	19
D	52	1.52	1.98	1.46	25

The combinations in Table II are chosen for ease of fabrication and for maximum performance. In general, 52° PBS's are easier to make while 45° PBS's have more desirable incident angles. As can be seen below, their performances are comparable.

Optimization of the PBS was carried out using a commercial software [5]. The performances of the various PBS's are plotted in Figs. 3-6. In these figures we plot the transmittance of both the s- and p-polarizations in a 3D plot as a function of both the incident angle on the PBS and the wavelength.

Fig. 3 Transmittance of s- and p-polarized light as a function of wavelength and incident angle. Design A.

Fig. 4 Transmittance of s- and p-polarized light as a function of wavelength and incident angle. Design B.

Fig. 5 Transmittance of s- and p-polarized light as a function of wavelength and incident angle. Design C.

Fig. 6 Transmittance of s- and p-polarized light as a function of wavelength and incident angle. Design D.

It can be seen that in all cases studied, the PBS works well over an incident angle of $\pm 7^\circ$, and over the entire visible wavelength range. The extinction ratios are also acceptable. In order to study the extinction ratio more carefully, we have to take into account of divergence of the light beam, which will be done next.

4. BEAM DIVERGENCE AND EXTINCTION RATIOS

The illuminating light distribution in angle is also very important when considering the design. In most cases, the illumination is telecentric. Therefore one can assume that the light forms a cone at each pixel and these cones are parallel to each other as shown in Fig. 7. The angle between the light beam and the coating surface of the PBS is shown in Fig. 8.

Fig. 7 The light cone on the LCD panel and on the PBS

Fig. 8 The light cone on the PBS reflection film. θ is the incident angle, θ_0 is the design angle

For light with a cone angle α , the actual angular deviation of the light to the designed incident angle of the PBS is distributed from $-\alpha$ to α . The angle between the light and the reflecting surface is given by

$$\theta = \cos^{-1}(\cos \alpha \cos \theta_0 - \sin \alpha \cos \beta \sin \theta_0) \quad (9)$$

where β is the polar angle of the incident light. If the light intensity is uniformly distributed inside the cone, the relative light flux as a function of the angular deviation $\theta - \theta_0$ can be easily calculated.

However, it is expected that the light flux distribution is not uniform. Therefore an averaging over the entire beam intensity distribution has to be performed. This can be done by assuming a weighing function $W(\theta - \theta_0)$. The actual T_P and T_S of the beam is therefore given by

$$\begin{aligned} T_P &= \int T_P(\theta) W(\theta - \theta_0) d\theta / \int W(\theta - \theta_0) d\theta \\ T_S &= \int T_S(\theta) W(\theta - \theta_0) d\theta / \int W(\theta - \theta_0) d\theta \end{aligned} \quad (10)$$

So the transmission curves of different angles have to be monitored in the same time with different weight when optimizing the PBS, in order to obtain high contrast and high efficiency.

Figs. 9-12 show the results of calculations of the extinction ratio for the PBS listed in Table II. In these figures, we present 2 curves, one for a cone angle of 5° and another for a cone angle of 7° for the light beam.

Fig. 9 Extinction ratio of the PBS assuming 2 different incident beam cone angles. Design A

Fig. 10 Extinction ratio of the PBS assuming 2 different incident beam cone angles. Design B.

Fig. 11 Extinction ratio of the PBS assuming 2 different incident beam cone angles. Design C.

Fig. 12 Extinction ratio of the PBS assuming 2 different incident beam cone angles. Design D.

It can be seen that in all cases, the extinction ratio exceeds 200:1 for most of the visible spectrum. In case higher extinction ratios are needed, a second plate type polarizer can always be used to suppress the s-polarized light.

5. CONCLUSIONS

In this paper, we have demonstrated that traditional MacNeille type PBS can be optimized to have wide acceptance angle and wide bandwidth operations. This is due to a new set of optimization conditions that was introduced. From our results, it is seen that an average transmission of more than 95% and extinction ratios of over 200:1 can be achieved. These new PBSs are suitable for applications to reflective LCOS projectors.

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