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Performance measurement of broadband, wide-angle polarizing beam splitter*

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Abstract: Polarizing beam splitter (PBS) is a critical optical component in projection display system because PBS performance greatly influences the contrast and brightness of the system. PBS performance is usually measured by spectrophotometer after coating and cementing, but the measured result cannot represent the actual performance in practice because people usually change the incident angle in one plane (horizontal plane) and do not consider the other plane (vertical plane). Geometrical polarization rotation occurring at reduced F-number influences the measuring precision of s-polarization transmittance (T_s) and p-polarization reflectance (R_p). A more accurate and practical way to measure the performance of broadband, wide-angle PBS is presented in this paper.

Key words: Polarizing beam splitter (PBS), Projection display, Measurement, Contrast
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INTRODUCTION

A polarizing beam splitter (PBS) cube is an optical element used in projection display systems where light must be spatially separated into orthogonal linear polarizations. PBS is a key component in any liquid crystal projectors, whether they are transmitting or reflective. In reflective mode liquid crystal light valve projector, PBS is often used as both polarizer and analyzer.

PBS transmits p-polarized light and reflects s-polarized light (You *et al*., 2005). The important characteristics of a PBS include the wavelength range or bandwidth, the angular field of the incident beam, the extinction ratio, the transmittance and reflectance of the desired polarization.

PBS is usually a MacNeille type prism using a multilayer dichroic coating as its polarizing element. This kind of PBS is easy to make and relatively inexpensive, with the incident beam and the reflected beam being at 90° to each other. This MacNeille PBS has a very high extinction ratio, usually above 500:1. It should be noted that the extinction ratio is different in the reflection and transmission directions because of the leakage of p-polarized light in the s-polarized light direction, so that the extinction ratio in reflection is much lower than that in transmission.

PBS performance is usually measured by spectrophotometer at different incident angles after coating and cementing but cannot represent the actual performance in practice (Zhang *et al*., 2001; Yao *et al*., 2002) because people usually change the incident angle in one plane (horizontal plane) and do not consider the other plane (vertical plane). Software for thin film design nowadays also has this problem (Cojocaru, 1992; Baumeister, 1997; Li and Dobrowolski, 1996; Li *et al*., 1999). In the following sections geometrical polarization rotation experienced at reduced F-number is analyzed in detail and a more accurate and practical way to measure the performance of broadband, wide-angle PBS will be presented.

GEOMETRICAL POLARIZATION ROTATION

When illuminating light with large numerical

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aperture is incident on PBS, we must take geometrical polarization rotation into consideration. Fig.1 shows the definition of parameters of illuminating light. $\boldsymbol{N}$ represents the normal direction of polarizing multilayer thin film plane and it is in the xz plane. The incident ray $\boldsymbol{R}$ and $\boldsymbol{N}$ construct the incident plane. Normal direction of the incident plane is $\boldsymbol{S}$, and parallel direction is $\boldsymbol{P}$. The angle between $\boldsymbol{S}$ and y is defined as θ_y.

$$\boldsymbol{N}=(-\sin\alpha, 0, -\cos\alpha), \tag{1}$$

$$\boldsymbol{R}=(-\sin\theta\cos\phi, -\sin\theta\sin\phi, \cos\theta), \tag{2}$$

then the vector $\boldsymbol{S}$ can be expressed as

$$\begin{aligned}\boldsymbol{S}&=\boldsymbol{R}\times\boldsymbol{N}\\&=(\sin\theta\sin\phi\cos\alpha, -\cos\theta\sin\alpha-\sin\theta\cos\phi\cos\alpha,\\&\quad -\sin\theta\sin\phi\sin\alpha),\end{aligned} \tag{3}$$

the angle between $\boldsymbol{S}$ and y is

$$\begin{aligned}\theta_y=&\cos^{-1}[-(\cos\theta\sin\alpha+\sin\theta\cos\phi\cos\alpha)\\&\times[(\sin\theta\sin\phi\cos\alpha)^2+(\cos\theta\sin\alpha+\sin\theta\cos\phi\cos\alpha)^2]^{-1/2}]\end{aligned} \tag{4}$$

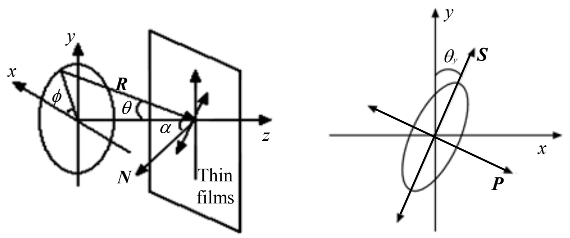

Fig.1 Cone beam incidents on thin films at oblique angle

Fig.2 shows θ_y as a function of θ and ϕ. The optical system certainly has dark-state output because of the existence of θ_y, even the PBS is an ideal polarizer in that the transmittance of p-polarization is 100% and the transmittance of s-polarization is 0. The dark-state output relates to θ_y,

$$I_{\mathrm{off}}=\sin^2\theta_y. \tag{5}$$

Fig.3 shows the relation between I_{off} and θ and ϕ. Fig.4 shows the polarization state in the exit pupil of PBS when F2.8 illuminating light passes the PBS. x-direction linearly polarized light is incident. In Fig.4, the positions of the lines are corresponding positions in the pupil, and the lines in these positions represent the transmitted polarization state of incident rays defined by different θ and ϕ. Horizon represents x-axis and vertical represents y-axis. From Fig.4, we can clearly see the geometrical polarization rotation.

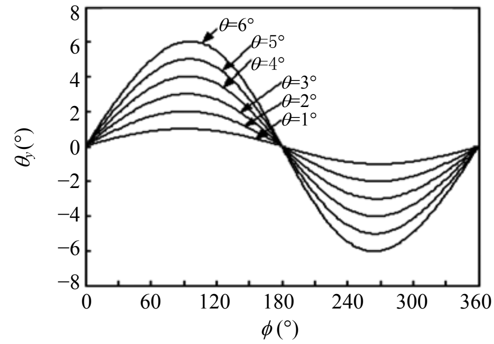

Fig.2 θ_y versus θ and ϕ

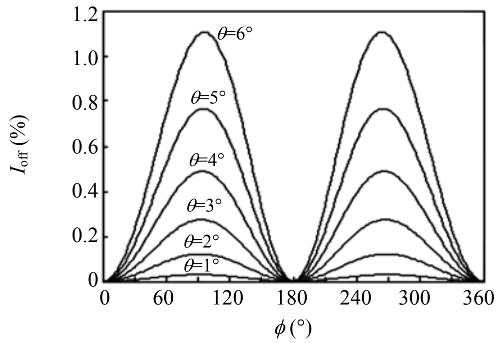

Fig.3 Dark-state output I_{off} versus θ and ϕ

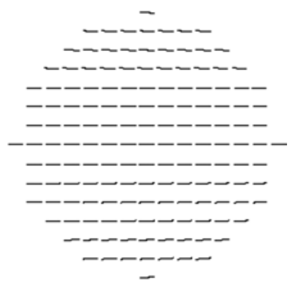

Fig.4 Transmitted polarization state in exit pupil of PBS (550 nm)

PBS PERFORMANCE MEASUREMENT

PBS performance is usually measured by spectrophotometer at different incident angles after coating and cementing. Fig.5 shows the measured performance of our novel broadband, wide-angle SF57 PBS. The measuring incident angles are 0°, ±5°,

±10.5° in the air. These measured results cannot represent the actual performance in practice. As shown in Fig.6, people usually change the incident angle in *xz* plane and can get satisfactory measured T_s data, generally lower than 0.1%. The measured contrast is usually higher than 1000:1. If they change the measuring incident angle in *yz* plane, the measured transmittance of s-polarization will obviously increase because of the geometrical polarization rotations of skew rays. Fig.7 shows the measured T_s data when we change the incident angle in *yz* plane. From Fig.7 we can find that the transmittance of s-polarization is rapidly increased because of geometrical polarization rotation. Furthermore, the spectrophotometer only measures PBS performance in one plane and at one incident angle, and so cannot represent the actual performance of PBS in application.

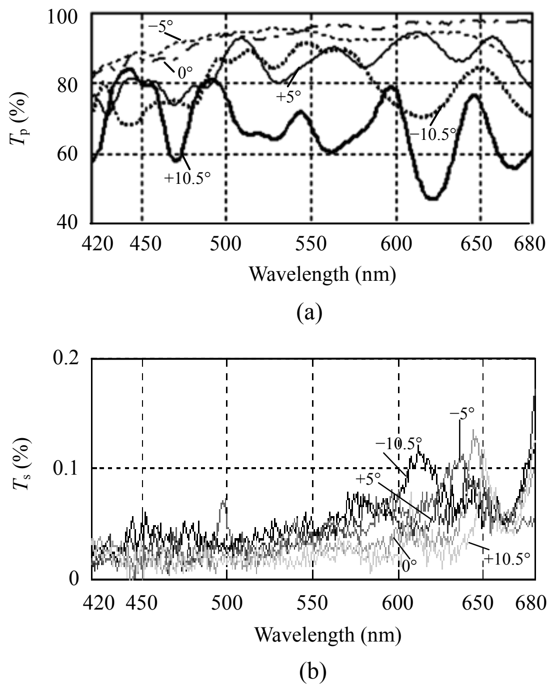

Fig.5 Measured performance of SF57 PBS by spectrophotometer (horizontal plane). (a) p-polarization transmittance; (b) s-polarization transmittance

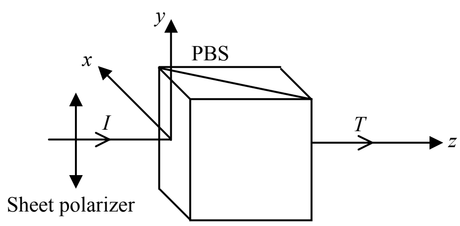

Fig.6 Scheme of spectrophotometer testing system

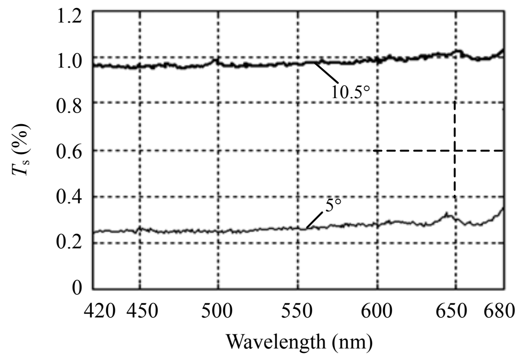

Fig.7 Transmittance of s-polarization (*yz* plane)

In order to measure the actual performance of PBS in practice, we use the testing system shown in Fig.8. This system also has a severe defect in measurement due to geometrical polarization rotation.

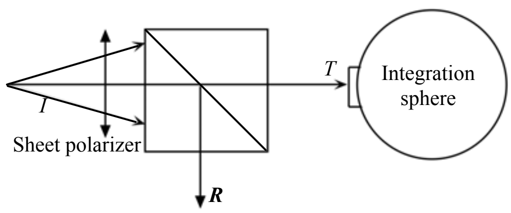

Fig.8 Testing system for measuring the performance of PBS

In what follows we calculate the minimum measured T_s and maximum contrast assuming the PBS is an ideal one if we use the testing system in Fig.8. We construct a mathematical model which uses discrete rays to substitute for the whole illuminating light. The principle of selecting rays is that there are equal rays in unit spatial angle. The illuminating light of F2.8 as seen in Fig.1 has a cone angle of 10.28°, with θ being 0 to 10.28°. The range of ϕ is 0 to 360°. In order to simplify the calculation, we select rays at every equal angle interval and assign to each ray a corresponding weight coefficient. We select a ray every 10.28°/150 of θ, and every 2° of ϕ. Weight coefficient of every ray is

$$val(\theta,\phi)=\cos\theta. \tag{6}$$

The calculated result shows that the minimum of T_s of the ideal PBS at F2.8 is 0.00148, and that the maximum contrast of transmission direction is 675. Thus, this testing system is impractical for measuring high extinction ratio PBS. Especially, it is impossible to use this testing system to measure T_s because of the weakness of s-polarization transmitted light.

In LCoS projection display systems, geometrical polarization rotations of skew rays are corrected by a quarter wave retarder placed between LCoS panel and PBS (Sharp *et al*., 2002). For example, in LCoS projectors, PBS and the LCoS panel are usually arranged as shown in Fig.9. The s-polarized light is reflected by the multilayer coating in the prism and illuminates the LCoS panel that modifies most of the light into p-polarization and reflects it back to the prism. The p-polarizing light passes through the PBS, and then projects onto the screen through a projection lens. Thus, we adopt a more appropriate testing system as shown in Fig.10 which can eliminate the influence of geometrical polarization rotation. Another PBS is placed between the integrating sphere and the former PBS in the testing system shown in Fig.8. The former PBS is regarded as a pre-polarizer to generate polarizing light which eliminates the influence of geometrical polarization rotation on the latter PBS. Thus this testing system can measure the performance of high extinction ratio PBS and represents the actual performance of PBS in application. Table 1 shows the measured performance of SF57 PBS performance at F2.8 illuminating light.

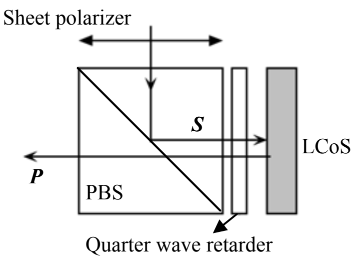

Fig.9 PBS in LCoS projection display system

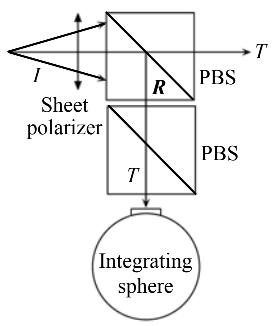

Fig.10 Modified testing system for measuring the performance of PBS

Table 1 Measured SF57 PBS performance at F2.8 illuminating light

Wavelength (nm)	T_s (%)	T_p (%)	R_s (%)	R_p (%)	T_p/T_s	R_s/R_p
420~460	0.097	88.08	99.22	5.86	908:1	17:1
460~680	0.093	93.40	99.12	3.12	1004:1	32:1

CONCLUSION

Geometrical polarization rotation experienced at low F-number must be taken into consideration because it greatly influences the measuring precision while it is corrected by a quarter wave retarder in actual projection display system. We modify the testing system to make it more reasonable in measuring PBS performance. The experimental results show a much lower transmittance of s-polarization than ever reported measuring result.

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