Application of wire-grid polarizers to projection displays

Xing-Jie Yu and Hoi-Sing Kwok

We have measured the optical properties of wire-grid polarizers (WGPs). The implications of these results to the application of WGPs in projectors that use reflective light valves are discussed. In particular, the brightness and the contrast ratio of the projection system are investigated as functions of the angle of incidence of the light beam onto the WGP. It was found that the optimal incident angle is dependent on the physical design of the wire grids. In the sample that we describe, the optimal incident angle was 35° instead of 45°. At the optimal incident angle, both the transmission and the reflection extinction ratios can be quite good. However, WGPs suffer from the drawback of free-carrier absorption by the metal grid.

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1. Introduction

Polarizing beam splitters (PBSs) are used extensively in projection systems that employ either transmissive or reflective light valves. In any projection system that employs reflective light valves that are based on polarization manipulation, such as the liquid crystal on silicon (LCOS) microdisplay, a PBS is needed to separate the input and the output light beams, which are of orthogonal polarization. The PBS should have a high extinction ratio in either transmission or reflection, depending on the optical arrangement of the projector. Additionally, it should have a large numerical aperture (NA), which is consistent with the etendue of the input light, to have high light throughput. A large extinction is needed to improve the overall system contrast ratio (CR) of the system, and a large NA is needed to increase the system's brightness. Additionally, the PBS should be able to withstand a strong light flux and have good optical uniformity.

Common MacNeille-type PBSs are based on the polarization splitting effect of multilayer dielectric coatings at nonnormal angles of incidence.[1] They can provide an extinction ratio of more than 1000:1 in transmission. However, extinction in reflection is generally less than 50:1. Moreover, it is difficult for this type of PBS to have a large NA. The *f*-number is limited to $f/2.5$ in practical devices that use special glasses. There are also PBSs that are based on total internal reflection.[2,3] They can have good extinction ratios in both transmission and reflection and are capable of large NA. However, they are bulky and their construction is complicated. A large angle of incidence of 60° is required, making it difficult to design the optical system. Polarizers that are based on birefringent multilayers such as stretched polymer films have been developed recently.[4] They have large NA, but the extinction ratios are not yet suitable for projectors.

Wire-grid polarizers (WGPs) are another class of polarizer that can be used as PBSs. They have been used effectively in infrared and longer wavelengths.[5–7] Recently WGPs have successfully been made for the visible wavelength region by use of nanofabrication technology. It is our purpose in the present paper to characterize and analyze such WGPs when they are applied to projection displays.

One can obtain a heuristic explanation of the WGP by considering the movement of electrons in the metal wires. If the incident wave is polarized along the direction of the wires, the conduction electrons are driven along the lengths of the wires with unrestricted movement. The physical response of the wire grid is essentially the same as that of a thin metal sheet. As a result, the wave is totally re-

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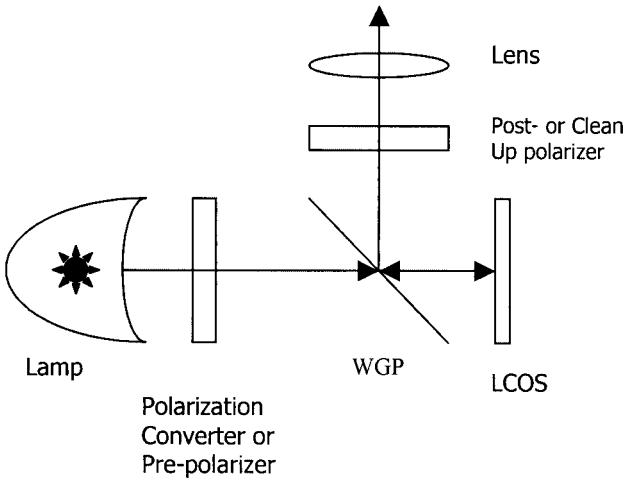

Fig. 1. Basic structure of the LCOS projection system, Config-1.

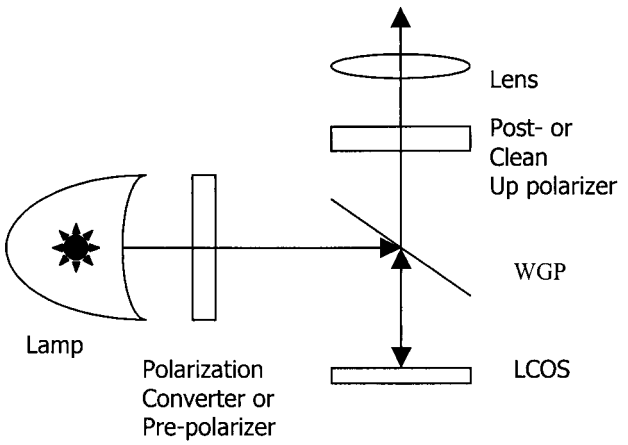

Fig. 2. Basic structure of the LCOS projection system, Config-2.

flected, and there is no transmission in the forward direction.

In contrast, if the incident wave is polarized perpendicularly to the wire grid, the oscillating electrons are spatially separated along the polarization direction. For wavelengths longer than the grid size, the collective movement of the electrons cannot generate a wave that can cancel the incident wave in the forward direction, as it can for a continuous metal sheet. The wire grid thus behaves as a dielectric, and the incident wave is therefore totally transmitted.[8]

There have been many theoretical explanations of the WGP, including the effective media theory,[9,10] the form birefringence theory,[11,12] and the rigorous diffraction theory.[13] In a separate paper we provide a full theoretical analysis of the optical WGP and compare the theoretical predictions with experimental results.[13] However, in this paper we shall be concerned only with the characterization of the optical properties of the WGP, especially it is when applied to projectors.

The WGP can exhibit the significant advantages of larger NA and larger extinction in transmission compared with other types of PBS. However, there is significant Joule heating, which is a potential problem for projection systems. In this paper we analyze the various optical configurations in which the WGP can be used in a reflective light-valve projection system. We show that both the transmission and the reflection contrast ratios can be large if the proper optical arrangement is chosen. Finally, we show that the best operating incident angle for these WGPs is seldom 45°. For the sample that we describe here, the optimal incident angle is actually 35°.

2. Theoretical Analysis for Reflective Light Valves

The basic structures of a reflective or LCOS projection system are shown in Figs. 1 and 2. The difference between these two figures is in the placement of LCOS panel. We refer to these configurations as Config-1 and Config-2. In both cases we have assumed that there is a prepolarizer, which can also be a polarization converter that converts unpolarized light into light of a specific polarization, and a postpolarizer, which is also called a clean-up polarizer. These prepolarizers and postpolarizers serve important functions in the overall performance of the projector.

The WGP can be placed in either of two ways as well, namely, with the wire perpendicular (structure S) or parallel (structure P) to the plane of incidence. Thus there are four possible optical arrangements for the single-panel projector. We call them S1, S2, P1, and P2 respectively. In devices S1 and S2, the WGPs transmit *p*-polarized light and reflect *s*-polarized light. In devices P1 and P2, the WGPs transmit *s* light and reflect *p* light. In this sense the WGPs offer more design freedom for the projection system.

The most important optical properties of the projection system are its brightness (light-utilization efficiency) and its CR. The CR of the projection system is limited by the extinction ratio of the prepolarizers, the postpolarizers, and the PBS and by the polarization conversion efficiency η of the liquid crystal (LC) cell in both the on and the off states.

The WGP in structure S behaves in exactly the same manner as a MacNeille PBS. So the analysis of structure S is the same as for a conventional projection that uses a MacNeille PBS. We assume that there is a prepolarizer with an extinction ratio ε_{pre} and an output postpolarizer with extinction ratio $\varepsilon_{\text{post}}$. For this structure S, we define the transmission extinction ratio ε_T of the PBS as

$$\varepsilon_T = \frac{T_p}{T_s} \tag{1}$$

and reflection extinction ratio ε_R as

$$\varepsilon_R = \frac{R_s}{R_p}. \tag{2}$$

Obviously, both ε_T and ε_R are larger than 1. In general, $\varepsilon_R \ll \varepsilon_T$. For example, in most commercial

MacNeille PBSs, ε_R is at best 30, whereas ε_T can be larger than 1000.

Then, for Config-1, the overall CR of the projection system is given by

$$\mathrm{CR} = \frac{T_{s,\mathrm{pre}} T_s \eta_{\mathrm{on}} R_p T_{p,\mathrm{post}}}{T_{s,\mathrm{pre}} T_s \eta_{\mathrm{off}} R_p T_{p,\mathrm{post}} + T_{s,\mathrm{pre}} T_s (1-\eta_{\mathrm{off}}) R_s T_{s,\mathrm{post}} + T_{p,\mathrm{pre}} T_p (1-\eta_{\mathrm{off}}) R_p T_{p,\mathrm{post}}} = \frac{1}{\frac{1}{\varepsilon_{\mathrm{post}}\varepsilon_R} + \frac{1}{\varepsilon_{\mathrm{pre}}\varepsilon_T} + \frac{1}{\varepsilon_{\mathrm{LC}}}}, \tag{3}$$

where

$$\varepsilon_{\mathrm{LC}} = \frac{\eta_{\mathrm{on}}}{\eta_{\mathrm{off}}} \tag{4}$$

is the extinction ratio provided by the LC cell.

In most projection systems the input light to the PBS is polarized by the application of a polarization converter device that converts most of the light from the light source into one polarization. Hence $\varepsilon_{\mathrm{pre}}$ is large. If there is no postpolarizer, then the overall system contrast is given by

$$\mathrm{CR} = \frac{1}{1/\varepsilon_R + 1/\varepsilon_{\mathrm{LC}}}. \tag{5}$$

Because most light valves have high polarization-conversion efficiency, $\varepsilon_{\mathrm{LC}}$ is large. Therefore CR $\sim$ ε_R. Thus the contrast of the projection system is limited by the poor reflective extinction ratio ε_R of the PBS. The best way to remedy this situation is to use a postpolarizer. In this case the system's contrast ratio is approximated by

$$\mathrm{CR} = \frac{1}{1/\varepsilon_{\mathrm{post}}\varepsilon_R + 1/\varepsilon_{\mathrm{LC}}}. \tag{6}$$

So in this configuration the postpolarizer is more important than the prepolarizer if $\varepsilon_T \gg \varepsilon_R$.

In Config-2, the system's CR can be derived similarly and is given by

$$\mathrm{CR} = \frac{1}{1/\varepsilon_{\mathrm{pre}}\varepsilon_R + 1/\varepsilon_{\mathrm{post}}\varepsilon_T + 1/\varepsilon_{\mathrm{LC}}}, \tag{7}$$

which is similar to Eq. (1) except for the interchanged roles of the prepolarizers and the postpolarizers. In most cases, $\varepsilon_{\mathrm{pre}}\varepsilon_R$ and ε_T are both larger than $\varepsilon_{\mathrm{LC}}$. Therefore CR $\sim$ $\varepsilon_{\mathrm{LC}}$, with or without the postpolarizer. Thus the system's contrast is limited only by the polarization-conversion efficiency of the reflective light valve. Thus the optics of Config-1 and Config-2 are quite different when it comes to the overall system contrast. Obviously, Config-2 is preferable because a postpolarizer is not necessary.

The brightness of the projection system can be estimated readily for Config-1 and Config-2. For both cases,

$$B = T_P R_S. \tag{8}$$

In structure P for the WGP, predominantly s polarization is transmitted. Here we should define the transmission and reflection extinction ratio of the PBS as

$$\varepsilon_T' = \frac{T_s'}{T_p'}, \tag{9}$$

$$\varepsilon_R' = \frac{R_p'}{R_s'}, \tag{10}$$

where a prime indicates a different orientation of the wire grids. The analysis of the contrast is the same as for structure S. For Config-1 the contrast ratio of the system is given by

$$\mathrm{CR} = \frac{1}{1/\varepsilon_{\mathrm{post}}\varepsilon_R' + 1/\varepsilon_{\mathrm{pre}}\varepsilon_T' + 1/\varepsilon_{\mathrm{LC}}}. \tag{11}$$

For Config-2 the contrast ratio is given by

$$\mathrm{CR} = \frac{1}{1/\varepsilon_{\mathrm{pre}}\varepsilon_R' + 1/\varepsilon_{\mathrm{post}}\varepsilon_T' + 1/\varepsilon_{\mathrm{LC}}}. \tag{12}$$

The analysis is the same as for structure S, except that the transmission and extinction ratios are different. The light-utilization efficiency is given by

$$B = T_s' R_p'. \tag{13}$$

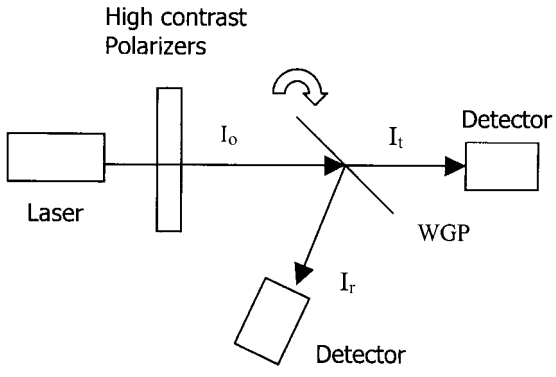

Fig. 3. Experimental arrangement.

Fig. 4. Transmission of the WGP as a function of incident angle for structure S.

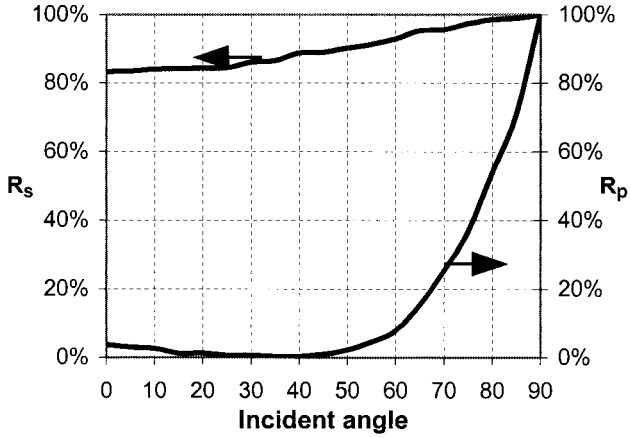

Fig. 5. Reflection of the WGP as a function of incident angle for structure S.

3. Experimental Results

The WGP sample was obtained from Moxtek, Inc. (Orem, Utah). The period, the height of the wires and the aperture ratio of the WGP were approximately 150 nm, 180 nm, and 0.55, respectively. In our experiment the transmittance and reflectance of the WGP in both S and P structures are measured as a function of incident angle. The experimental arrangement is shown in Fig. 3. Two high-contrast polarizers are used to filter the output of the green He–Ne laser at a wavelength of 543.5 nm to ensure perfect polarization for the measurement. The purity of the polarized light used in the experiment is better than 10^6. When the WGP is used in a LCOS projector the wire-grid side always faces the LCOS panel for the best optical performance. On the other side of the WGP an antireflection coating is used to prevent stray light reflection. The transmittance changes only a little if the light passes through the WGP from the antireflection-coated side. So in the experiments the wire-grid side should face the laser for the correct transmittance and reflectance information to be obtained.

The same detector is used to measure the original light intensity I_o and the reflected (I_r) and transmitted (I_t) light. The distance from the detector to the laser was always made the same, so we could obtain the absolute transmittance and reflectance simply by dividing the signals as $T = I_t/I_o$ and $R = I_r/I_o$. By rotating the high-contrast polarizers, either p or s light could be obtained. Thus the transmittance and reflectance of the WGP in either S or P geometry can be measured as a function of the incident angle.

In structure S, the WGPs transmit p light and reflect s light. Figure 4 shows the transmission of both s- and p-polarized light as a function of its angle of incidence onto the polarizer. It can be seen that T_p remains large until an incident angle of 50° is reached. T_S, however, remains small at all angles. Figure 5 shows the measured reflectivity for s- and p-polarized light. In this case, R_s remains large and R_p shows a minimum at 35°. This is the effective Brewster angle of the WGP.

The existence of this small Brewster angle can be used to infer some physical properties of the WGP. If we use the form birefringence model, tan(35°) should be equal to the effective refractive index of the WGP. That is, the effective refraction index in this structure should be less than 1. Obviously this is not physical. Hence the existence of this minimum proves that the form birefringence model is not a good one for a WGP.[11,12] We performed a modeling calculation of the WGP by using rigorous diffraction theory. The modeling results can fit our experimental results well. As we mentioned above, the physics of the WGP and the fits to our experimental results for different theories will be published elsewhere.[13]

In Fig. 6, ε_T and ε_R are plotted. It can be seen that ε_T for structure S can be very large at all incident angles. ε_R for structure S shows a large peak at 35°. This peak corresponds to the minimum in R_p. At this incident angle, ε_R can be greater than 300, which is actually good enough for a LCOS projector. For S2, if a prepolarizer is used we do not even have to worry about ε_R, and the projector can always have a good CR.

As we mentioned above, the major drawback of the

Fig. 6. Reflection and transmission extinction ratios of the WGP as a function of incident angle for the structure S.

Fig. 7. Absorption of the WGP as a function of incident angle for structure S.

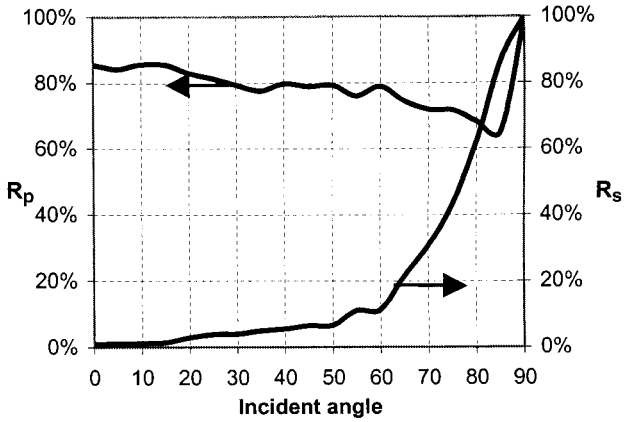

Fig. 9. Reflection of the WGP as a function of incident angle for structure P.

WGP is the large absorption that is due to the presence of free carriers. In Fig. 7 the absorption of the WGP is plotted as a function of the incident angle. The absorption is simply taken as 1-R-T for each polarization. It can be seen that the absorption is quite significant for both *s*- and *p*-polarized light. The absorption is larger for *s* polarization. This is understandable because the polarization of the light and the wire grids are parallel in this geometry. The electrons are completely free to move. The absorption in the *p* polarization is less but is also significant. It is also to be expected, because free-carrier absorption is not inhibited by the thinness of the wires. This absorption is a big problem when one wishes to apply the WGP to reflective projection displays. The efficiency of utilization of light for projectors is discussed more thoroughly below.

From these experimental results it can be concluded that the WGPs in structure S can be used as PBSs with larger ε_T and ε_R. For transmission the NA can be large, as there is little angular dependence of the extinction ratio. For reflection, however, a large extinction, of more than 200, can be maintained only within an angle of 10°. This corresponds to $f/5.5$, which is not good. Notice that ε_R is smaller than 100 at the usual incident angle of 45°. So, unlike traditional PBSs, this WGP-based PBS should not be used at a 45° incident angle.

A similar set of measurements can be made for structure P. In this case the WGPs transmit *s* light and reflect *p* light. Figure 8 shows the transmission of *s* and *p* light as a function of angle of incidence. Behavior similar to that for structure S is observed. T_p remains large until an angle of 70° is reached. Figure 9 shows the reflection of *s* and *p* light as a function of angle. ε_T and ε_R are plotted in Fig. 10. Here ε_T can be greater than 800 up to an incident angle of 60°. However, the value of ε_R is bad for all incident angles. The incident angle that corresponds to the maximum ε_R is 0°. The absorption is shown in Fig. 11. It can be seen that the absorption loss is very large indeed. More than 20% of *p* light and 10% of *s* light is absorbed over a large range of incident angles. Compared to structure S, structure P has a lower extinction ratio and larger absorption and is unsuitable for projection displays.

In Fig. 12, the light-utilization efficiency of WGPs when they are used as PBSs for a reflective projector

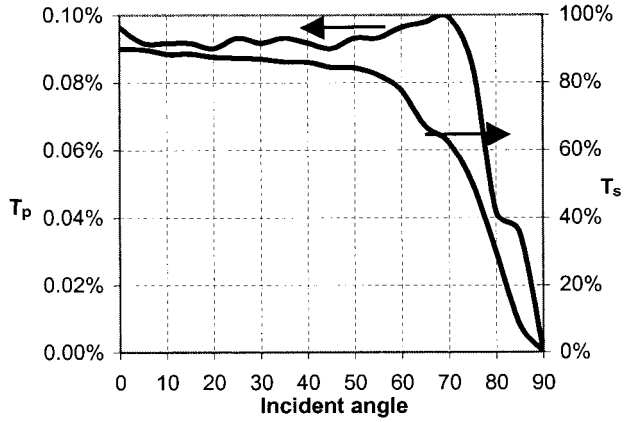

Fig. 8. Transmission of the WGP as a function of incident angle for structure P.

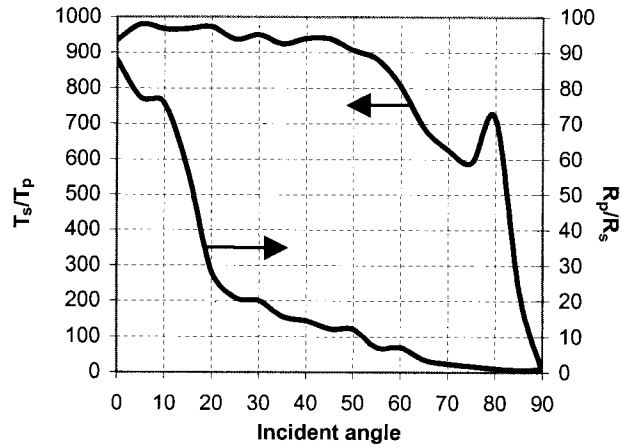

Fig. 10. Reflection and transmission extinction ratios of the WGP as a function of incident angle for structure P.

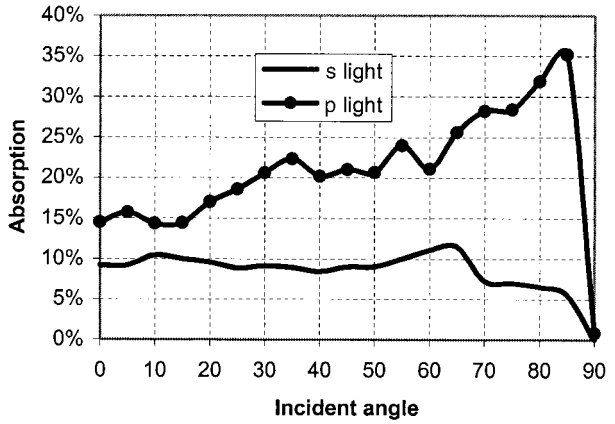

Fig. 11. Absorption of the WGP as a function of incident angle for structure P.

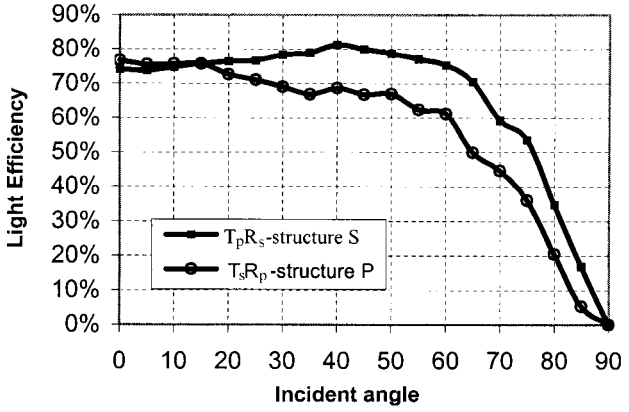

Fig. 12. Light-utilization efficiency of the WGP-based PBS when it is used in a projector with reflective light valves.

is plotted. There are two values, depending on whether structure S or structure P is used. In the former case, i.e., for both S1 and S2, the optical efficiency is given by T_pR_s, according to Eq. (6). In the latter case the efficiency is given by R_pT_s. For these expressions it is assumed that the incoming light is totally polarized as it goes into the WGP. It can be seen that the efficiency is generally much lower than for the conventional MacNeille-type PBS, whose efficiency can be larger than 92%.[1] The maximum light utilization for the LCOS projection system is only 80% for the best case (S). In practice, if we take the efficiency of the prepolarizer (or polarization converter) into account, the total system's light efficiency will even be lower. These are important points to consider when one is applying the WGP to projectors.

4. Conclusions

We have reported the optical properties of wire-grid polarizers for projection displays. Most importantly, the brightness and the extinction ratios of the projection system were investigated as functions of incident angle for system structures S1, S2, P1, and P2. Such angular dependence is crucial for identifying the optimal operating conditions for the WGP when it is applied to projection applications. We found that the optimal incident angle is at 35° and not the usual 45°. At the optimal angles, both the transmission and reflection contrast can be quite high. From the theory of WGPs,[13] it can be calculated that the optimal angle for the best extinction ratio is dependent on the wire spacing and depth. The angle for maximum reflective contrast can be shifted between 30° and 60° by proper choice of the physical dimensions of the wire grids.

The effects of the extinction ratio of the WGP on the systems contrast ratio were analyzed in detail; ε_R was found to be the dominating factor in determining the overall system's CR. The WGP can show good NA and optical uniformity. But, owing to low ε_R and larger absorption, only structure S can be used in LCOS projection systems if one is to obtain the higher CR and higher brightness.

For the optimal structure S, a prepolarizer and a postpolarizer can be used to achieve extinction ratios greater than 1000:1 for the projector, with an *f*-number smaller than *f*/1. Thus the light-collection efficiency is much improved compared with that of the conventional MacNeille PBS. However, there is also Joule heating and absorption in the WGP, which reduce the light efficiency to 80%. In a real projector, this 80% light-utilization efficiency can be compensated for by the much larger NA of the WGP. The overall performance of the reflective projector may still be enhanced by this WGP-based PBS, depending on the collimation of the light beam used in the projection system. One therefore has to perform a detailed overall system simulation, taking into account the etendue of the arc lamp and the polarization converter as well as the *f*-number of the projection lens and other optical components, to determine whether the WGP or the conventional PBS is better for a projection system that uses LCOS.

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