22.2: Application and Optimized Design of Wire-Grid Polarizers

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Abstract

The properties of wire-grid polarizers (WGP) are studied and optimized. Experimentally, the efficiency and the contrast ratio of the projection system using WGP are investigated as a function of the incident angle. It is confirmed that WGP can afford large extinction ratios and large numerical apertures (NA). However, WGP suffers from the drawback of large absorption by the metal grid. We calculated the properties of the WGP as a function of its physical parameters using rigorous diffraction theory. Optimal designs are obtained based on the criteria of best optical performances (high efficiency, large NA, large extinction ratio). With these optimal physical parameters the WGP can show very good performance with efficiency >85%, large NA, and high extinction ratio >1000.

1. Introduction

In any projection system employing reflective as well as transmittive light valves that are based on polarization manipulation, such as the liquid crystal on silicon (LCOS) microdisplays, a polarizing beam splitter (PBS) is needed to separate the input and the output light beams. The efficiency and extinction ratio of the PBS affect directly the brightness and the contrast of the entire projection system. So the PBS should have a high extinction ratio, a large numerical aperture (NA) and good light efficiency.

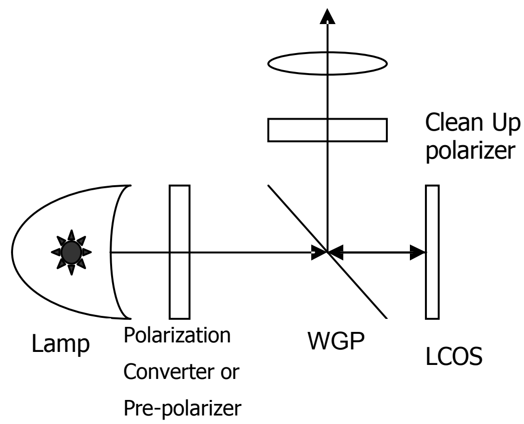
Wire-grid polarizers (WGP) can be used as a PBS [1,2]. It has been used effectively in the infrared for a long time [1]. Recently, WGP has been successfully made for the visible wavelength region using nanofabrication technology [3,4]. In this first part of this paper we show results on the measurements of WGP when used as a PBS. Parameters such as extinction ratios, f# and light efficiency are investigated.

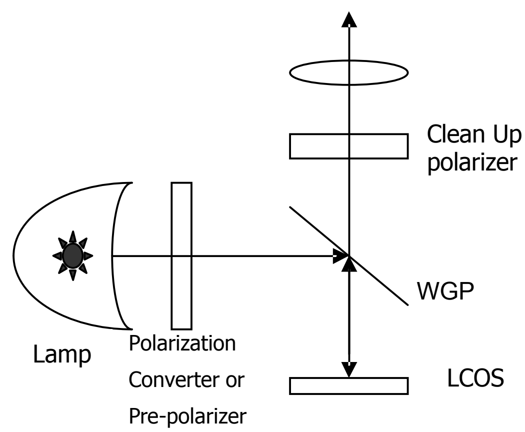
In the second part of this paper, we provide a theoretical understanding and calculation of these WGP. Using numerical simulation employing the rigorous diffraction theory, we calculated the properties of the WGP as a function of the physical parameters of its construction. Optimal designs of the WGP are obtained.

2. Application of Wire-Grid polarizers to projection displays

The basic structures of a reflective or LCOS projection system are shown in Figs.1 and 2. The difference is the position of LCOS panel. We shall call the structure in Fig. 1, 2 as Config-1 and Config-2, respectively. Additionally, the WGP can also have two possible configurations, namely, with the wire perpendicular (structure S) and parallel (structure P) to the plane of incidence. Thus for a reflective projector using the WGP, it is possible to have 4 different configurations: S1, S2 and P1, P2, depending on the placement of the LCOS panel and the alignment of the wire grid.

The contrast ratio of the projection system is limited by the extinction ratio of the polarizers and PBS, and the polarization conversion efficiency (PCE) of the LC cell.





Figs. 1 & 2. The basic structures of a LCOS projection system

We define the transmission extinction ratio e_T of PBS as

$$e_T = \frac{T_p}{T_s} \qquad (1)$$

and the reflective extinction ratio e_R as

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$$e_R = \frac{R_s}{R_p} \quad (2)$$

Both e_T and e_R are larger than 1. In general $e_R << e_T$. For example, in most commercial MacNeille PBS, e_R is at best 30 while e_T can be larger than 1000.

In structure S, the p-polarization is transmitted predominantly, in the same manner as a MacNeille PBS. So the analysis of structure S is the same as MacNeille PBS. If we assume that there is a pre-polarizer with an extinction ratio of e_{pre}, and an output clean-up post-polarizer with an extinction ratio of e_{post}, and h is the ratio of the PCE between the on-state and the off-state of the LC cell, then for Config-1, the overall contrast ratio of the projection system is given by

$$CR = \frac{1}{\frac{1}{e_{post}e_R} + \frac{1}{e_{pre}e_T} + \frac{1}{h}} \quad (3)$$

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 e_{pre} is large. If there is no post polarizer, then the overall system contrast is given by

$$CR = \frac{1}{\frac{1}{e_R} + \frac{1}{h}} \quad (4)$$

Since most light valves have high PCE, h is large. Therefore $CR \sim e_R$. Thus the contrast of the projection system is limited by the poor reflective extinction ratio of the PBS.

In Config-2, the system contrast ratio is given by

$$CR = \frac{1}{\frac{1}{e_{pre}e_R} + \frac{1}{e_{post}e_T} + \frac{1}{h}} \quad (5)$$

which is similar to eq. (1) except for the changed roles of the pre- and post-polarizers. In most cases, $e_{pre}e_R$ and e_T are larger than h, therefore $CR \sim h$, with or without the post-polarizer. Thus the optics of Config-1 and 2 are quite different when it comes to the overall system contrast. Obviously, Config-2 is preferable since a post-polarizer is not necessary.

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

$$B = T_P R_S \quad (6)$$

Next, let us analyze the case for structure P for the WGP. Here the wire grid is along the plane of incidence of the PBS. Hence the s-polarization is transmitted predominantly. Here we should define the transmission and reflection extinction ratio of the PBS as

$$e_T' = \frac{T_s'}{T_p'} \quad (7)$$

and

$$e_R' = \frac{R_p'}{R_s'} \quad (8)$$

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

$$CR = \frac{1}{\frac{1}{e_{post}e_R'} + \frac{1}{e_{pre}e_T'} + \frac{1}{h}} \quad (9)$$

For Config-2, the contrast ratio is given by

$$CR = \frac{1}{\frac{1}{e_{pre}e_R'} + \frac{1}{e_{post}e_T'} + \frac{1}{h}} \quad (10)$$

The analysis is the same as the structure S case except that the transmission and extinction ratios are different. The light utilization efficiency or brightness is given by

$$B = T_s' R_p' \quad (11)$$

We have measured carefully the optical properties of the WGP in both the S and P structures. Details of the measurement are discussed in reference 2. Basically, the reflection and transmission coefficients for all configurations are measured. The extinction ratios are then extracted. Figs 3 and 4 shows the the extinction ratios for the S- and P-structures.

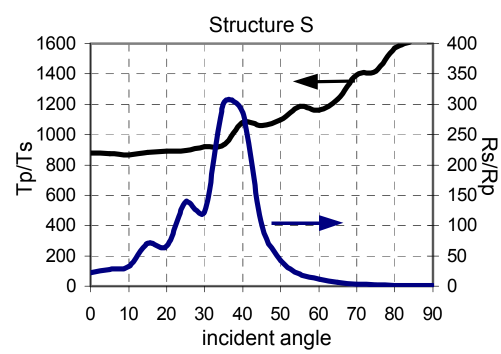

Fig. 3. Measured extinction ratios of the WGP

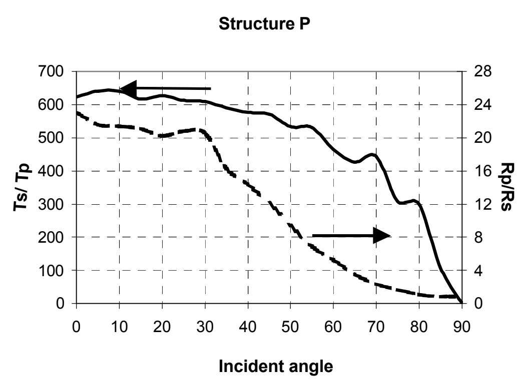

Fig. 4. Measured extinction ratios of the WGP

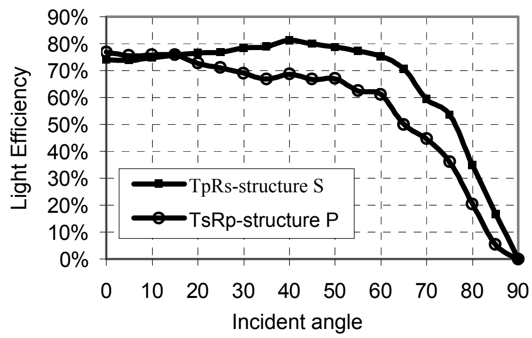

Fig. 5. Light utilization efficiency of the WGP based PBS when used in a projector with reflective light valves.

It can be seen from Figs 3&4 that the extinction ratio of the WGP can be larger than 1000. For the S2 structure, the extinction ratio is almost independent of the incident angle, implying a large NA. The f# can be as small as f/1. For reflection, the f# and the extinction ratios are considerably worse, however.

Notice that for reflection, the e_R shows the largest value at 35°, corresponding to the Brewster angle of R_p. A large extinction of over 200 can only be maintained within an angle of 10°. Thus the NA is rather limited. This corresponds to F/5.5 which is not exactly very good. However, if a pre-polarizer or post-polarizer can be used to clean up the signal, the reflective extinction ratio can be greatly improved.

One serious drawback of the WGP is absorption of light by the wire grid. Fig. 5 indicates the absorbance for the WGP. It can be seen that even if the optimal structure S is used, absorption can be kept about 20%. It is barely acceptable for a projector.

3. The Optimized Design of the WGP

As discussed above, WGP are promising for applications in projection displays as they can exhibit the large NA and e_T. To achieve these performances, the proper physical parameters of the WGP are required.

The physical parameters of the WGP include the grating period (d), the spacing width d_1 between the wire grids, the aperture ratio ($AR = d_1/d$), height of the wire grid (h), and the properties of the grating material. The common grating material is aluminum, which is enough for the optical performance. The most important optical performances of the WGP are the light utilization efficiency R_sT_p, the transmission extinction ratio e_T and the reflection extinction ratio e_R as a function of the incident angle [2]. The NA information will be provided by such angular dependences. Our goal is to produce the largest product R_sT_p across wider incident angle so that we can obtain the larger NA at the same time. Also the e_T and e_R should be high across wider incident angle.

Various theories, such as effective media and form birefringence theory [3,4] and the rigorous diffraction grating theory [5,6], have been developed to model these WGP. But as discussed in the reference 7, the rigorous diffraction grating theory is the only one that can be used in the WGP design. Our design is based on this. Because the optimal operating condition of WGPs for projectors is the structure S, our design will focus on this.

The wire grid period should be less than 0.2mm so that only the zeroth diffraction order propagates. At this time the most important performance factor of the WGP, the efficiency, doesn't change too much. So it's convenient to fix the grating period to be some reasonable value in the WGP design according to the fabrication limits and manufacturing yield. We select the grating period to be 150nm for our calculations.

We've calculated R_sT_p, e_T and e_R for many combinations of the aperture ratio AR and grating height h. We found that when the AR is less than 1/3, the efficiency is low. When AR is larger than 3/4, it's impossible to get large NA. So it is practical that AR only ranges from 1/3 to 3/4. Fig. 6 shows the "average efficiency" $[R_sT_p(30^o){*}R_sT_p(45^o){*}R_sT_p(60^o)]^{1/3}$ and e_T contour plots versus AR and h in the same figure. The angle in the parenthesis is the incident angle on the WGP. Such angular dependences will provide the NA information.

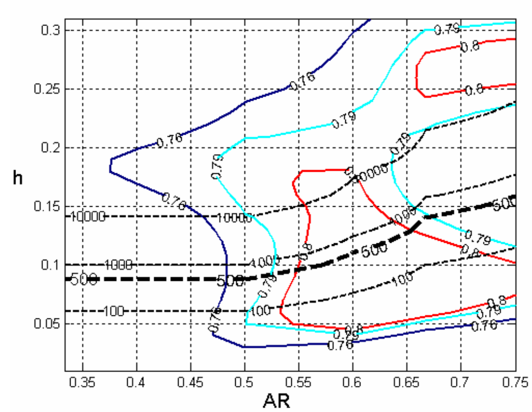

Fig. 6. The average efficiency $[R_sT_p(30^o){*}R_sT_p(45^o){*}R_sT_p(60^o)]^{1/3}$ and e_T contours.

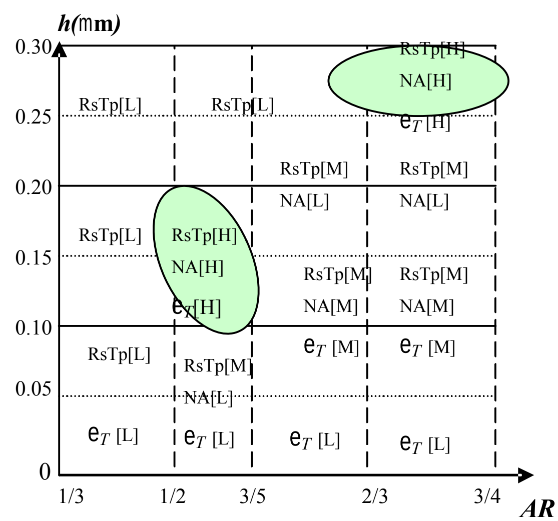

Fig. 7. The optimal design for the grating physical parameters (AR & h).

Fig. 7 shows the optimal physical parameters of gratings, with which WGP will exhibit the best optical performance, high efficiency (~85%), large NA, high ε_T(>10^3). In the optimal area I, the grating depth ranges from 0.05μm to 0.2μm, and the value of *AR* is between 0.5 and 0.6. In this area, the Brewster angle of R_p ranges from 30° to 55°. So $\varepsilon_{R\max}$ can be optimized at 45°, or $\varepsilon_{R\max}$ is selected to be around 55° (The depth *h* ranging from 0.1μm to 0.15μm) to obtain the larger NA. In the optimal area II, the grating depth is larger than 0.25μm, and the value of *AR* is between 2/3 and 3/4. In this area, the Brewster angle is larger than 55°. So the NA can be a little larger, but the efficiency will be lower than that in the optimal area I. Also it should be more difficult to make such gratings due to their larger *h*.

So the grating parameters in the optimal area I represent the best choice to make the WGP. The different physical parameters of gratings can be selected for the different purposes in this region. Generally, the higher the grating depth, the larger the ε_T is. But the higher depth in this region will result in the lower efficiency. Moreover, the bandwidth should be large. So *AR* should range from 0.5 to 0.6, and the depth *h* should range from 0.1μm to 0.18μm. The relationship between ε_R, Brewster angle and the grating physical parameters is discussed in reference 8 in more details.

4. Conclusions

We have reported the optical properties of the WGP for projection displays in this paper. The effects of the extinction ratio of the WGP on the system *CR* are analyzed in detail. Most importantly, the brightness and the contrast ratio of the projection system are investigated as a function of the incident angle, for the different system structures (S1, S2, P1 and P2). We also show that of the four possible combinations of configurations, only one (S2) offers the best contrast and efficiency.

We also discuss the effects of the WGP physical parameters on its optical performances. The reflective extinction ratio ε_R mainly depends on the Brewster angle of the WGP. The efficiency R_sT_p, NA and ε_T are chosen to be the WGP design criteria. Based on these criteria the optimized design for the grating physical parameters is given. *AR* ranging from 0.5 to 0.6, and the depth *h* ranging from 0.1μm to 0.2μm are preferred. With these optimal physical parameters the WGP will show very good performance such as high efficiency (~85%), large NA and large ε_T(>10^3).

5. Acknowledgments

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6. References

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