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Illumination system with compound parabolic retro-reflector for single LCOS panel projection display

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Abstract: In this paper, a new illumination system with ultra high performance (UHP) lamp is proposed for projection display. Parabolic reflector (PR) and compound parabolic retro-reflector (CPR) were jointly used to collect and collimate the light generated from UHP lamp. A polarization converter system (PCS) was used to increase the light efficiency of the projection display system. A beam transformer between PCS and 2*f* imaging systems was directly used to make the illumination meet the requirement of projection display system. With the consideration of the loss of reflection, the light efficiency in this projection display system was estimated to be 15.6%.

Key words: Compound parabolic retro-reflector (CPR), Uniformity, Light efficiency, Etendue
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INTRODUCTION

The illumination system, as an important component of the projection display system, can be used to tailor the aperture size and the numerical aperture (NA) of the illuminating light so that it can meet the requirement of the projection display system. Therefore, the illumination system should be designed to match the light source with the image panel and the projection lens. In this paper, due to the fact that the brightness and the uniformity on the screen are mainly related with the illumination system, the design of the proposed illumination system was focused on how to improve them.

Liquid Crystal On Silicon (LCOS) (Jepsen *et al*., 2002) is a potential display technology for producing economical high-resolution and micro-display system. Although the LCOS panel has a limitation that it needs polarized illumination, the nature of reflection enables the illuminating and the imaging light beams to share space and to make the whole system more compact. So the single LCOS panel which integrates color filters (Huang *et al*., 2005) on silicon is used in the proposed projection display system as the light modulator to manipulate three primary colors.

OPTICAL DESIGN OF SINGLE LCOS PANEL ILLUMINATION SYSTEM

Taking ultra high performance (UHP) lamp as the light source, the projection display system includes the illumination system, the LCOS panel, and the projection lens. As shown in Fig.1, in order to transform light from the light source, the illumination system is composed of the collimator, the polarization converter system (PCS), the beam transformer, the 2*f* imaging system, and the polarizing beam splitter (PBS) (Chen *et al*., 2007). In the computer simulation, the software package of Tracepro® is used to evaluate the illumination system performance.

Collimator

In order to increase the light efficiency of the projection display system, the light generated from UHP lamp is collected and collimated by the collimator which is composed of parabolic reflector (PR) and compound parabolic retro-reflector (CPR) (Zhen *et al*., 2007). The combination of PR and CPR is shown in Fig.2a. In 3D system, the reflecting surface of PR can be obtained by rotating a parabolic curve around its axis shown in Fig.2b. The reflecting surface of CPR can be obtained by rotating a parabolic curve around the chord passing through the focal point and perpendicular to the axis shown in Fig.2c.

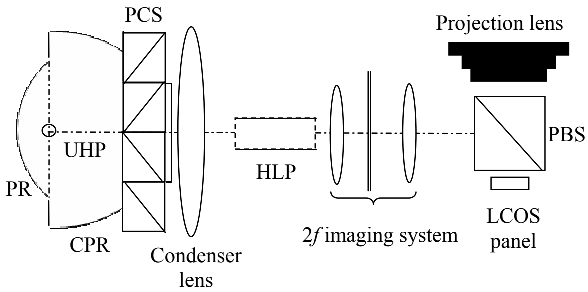

Fig.1 Optical layout of single LCOS panel illumination system with UHP lamp
UHP: ultra high performance; PR: parabolic reflector; CPR: compound parabolic retro-reflector; PCS: polarization converter system; PBS: polarizing beam splitter; HLP: hollow light pipe

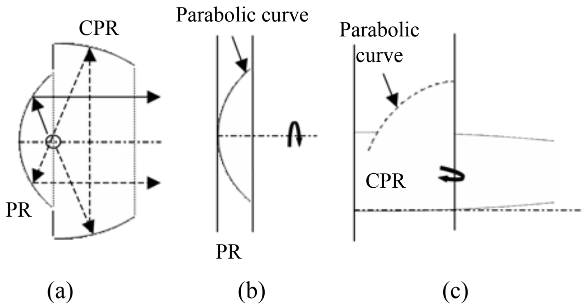

Fig.2 The light collection and the generation of parabolic reflector (PR) and compound parabolic retro-reflector (CPR). (a) The light collected by PR and CPR; (b) PR; (c) CPR
Solid rays: directly collected and collimated by PR; Dashed rays: collimated by PR after it is collected and reflectd twice in CPR

As shown in Fig.2a, UHP lamp is placed at the focus of PR, and the portion of light (depicted in solid rays) is directly collected and collimated by PR. But the portion of light (depicted in dashed rays) is collimated by PR after it is collected and reflected twice in CPR. As a result, most of the light generated from UHP lamp was effectively utilized and collimated. In contrast with the light collected by the conventional spherical retro-reflector (Kim *et al*., 2004), the light collected by CPR is reflected two times, which is twice more than that of the conventional spherical retro-reflector. Therefore, with the same collection ability, the size of CPR is smaller than that of the conventional spherical retro-reflector.

Viewing the polar candela distribution on the plane at the exit aperture of CPR shown in Fig.3, it is obvious that most of the light collected by PR and CPR has been collimated in the reflection process.

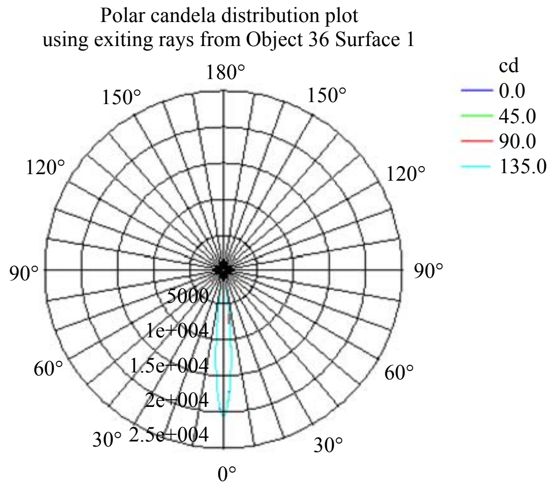

Fig.3 The polar candela distribution on the plane at the exit aperture of CPR (29939 rays). Efficiency: 0.94526, Min: 1.3054e-012 cd, Max: 20678 cd, Total flux: 1323.4 lm

Fig.4 shows the energy distribution on the same plane at the exit aperture of CPR. Since the collimated beam shape is nearly round, the light exiting from CPR cannot be directly used as the illumination light for LCOS panel.

Polarization converter system (PCS)

PCS is used in the projection display system to improve the light efficiency of the projection system. As shown in Fig.5, some portion of the collimated light will directly enter PCS; another portion of light will be reflected between the collimator and PCS until it reaches the surface of PCS without mirror. In the cube beam splitter, the light of P-polarization is transmitted, while the light of S-polarization is reflected (Lee *et al*., 2004). The polarization of the transmitted light is converted from P-polarization to S-polarization by the $\lambda/2$ plate.

Fig.6 shows the energy distribution on the plane at the exit surface of PCS. Comparing Fig.6 with Fig.4 showed that PCS disperses the light from center to sides. So PCS is beneficial to improve the uniformity of the energy distribution in addition to the enhancement of the light efficiency. The size of PCS is designed to be $\sqrt{2}R/2\times\sqrt{2}R\times2\sqrt{2}R$, where R is the radius of the PR exit aperture, so that most of the collimated light can directly enter PCS.

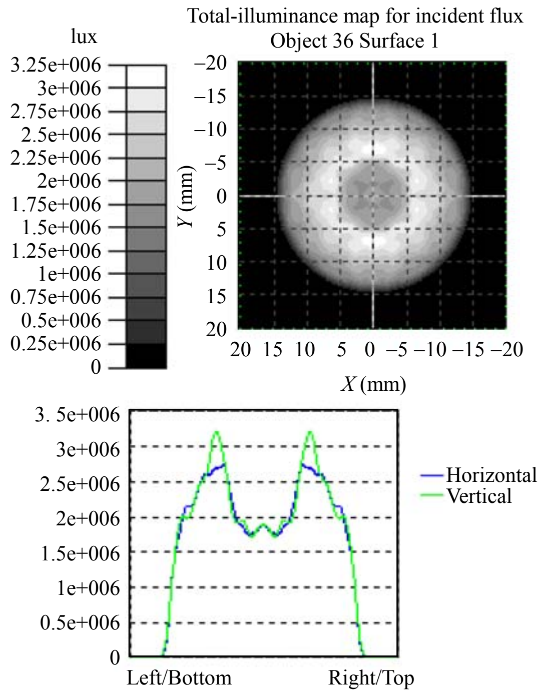

Fig.4 The energy distribution on the plane at the exit aperture of CPR (29939 incident rays). Illuminance: Min: 9.3356e-006 lux; Max: 3.2088e+006 lux; Avg.: 8.2707e+005 lux. RMS: 1.0601e+006, total flux: 1323.3 lm

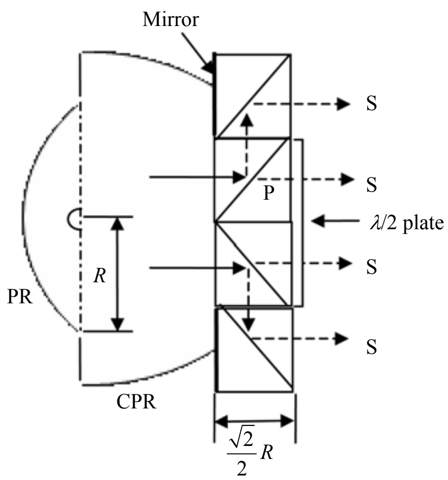

Fig.5 The polarization converter system

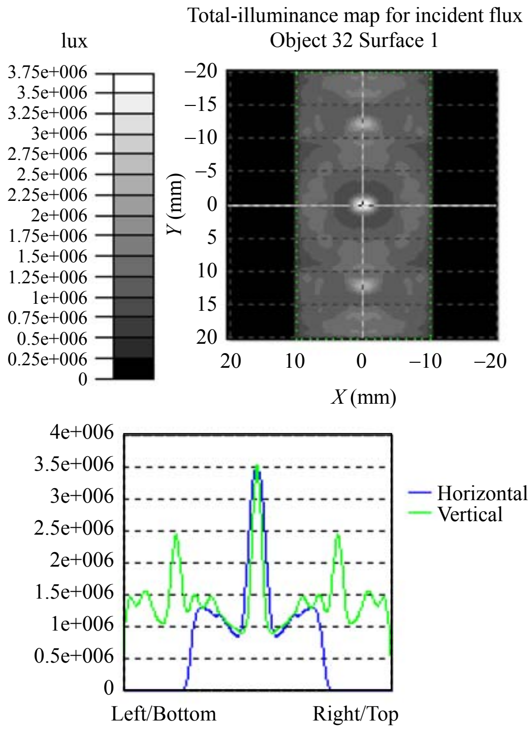

Fig.6 The energy distribution on the plane at the exit surface of the PCS (51433 incident rays). Illuminance: Min: 1.6507e-006 lux, Max: 3.5329e+006 lux; Avg.: 5.9665e+005 lux. RMS: 6.0621e+005, total flux: 964.2 lm

Beam transformer

Since the beam shape and NA of the polarized light exiting from PCS does not meet the requirement of the LCOS panel, the polarized light cannot be directly used to illuminate the LCOS panel without beam transforming. The beam transformer is composed of the condenser lens and the hollow light pipe (HLP). The polarized and collimated light exiting from PCS concentrated through the condenser lens and the input end of HLP is placed near the focus of the condenser lens. The use of condenser lens is to change NA of the polarized light and to make most of the illuminating light pass through the projection display system smoothly. The use of HLP (Jacobson and Gengelbach, 1997; Li *et al*., 2004) is to improve the uniformity of energy distribution on the screen by light multiple reflections in HLP.

For the ideal HLP which can keep energy conservation, the etendue of its input end is equal to that of its output end according to the etendue-conserving transformation. As the geometry property of the optics, etendue is defined by the product of solid angle of the beam and the cross section area of the beam (Jacobson *et al*., 1998). So the etendue-conserving equation of ideal HLP is calculated as:

$$E_\mathrm{i} = \pi A_\mathrm{i} \sin^2\theta_\mathrm{i} = \pi A_\mathrm{o} \sin^2\theta_\mathrm{o} = E_\mathrm{o}, \tag{1}$$

where E is the etendue, A is the area of HLP end and θ is the beam angle. The subscripts i and o represent the input end and output end of HLP, respectively.

In this illumination system, because the area of the HLP input end is equal to that of the HLP output end, HLP contributes little to change NA of the illumination light as an approximate etendue conservation device. So the f number of the condenser lens is designed to be identical with that of the projection lens.

The size of the HLP end is designed to be a little bigger than that of the 0.47″ LCOS panel with 4:3 aspect ratio to relief the dimness in the corner of LCOS panel. The length of HLP (Jacobson and Gengelbach, 1997) is defined by

$$L = \Lambda \frac{D}{\tan\{\arcsin[(2F/\#)^{-1}]\}}, \tag{2}$$

where Λ is the dimensionless quantity, D is HLP cross-section diagonal, $F/\#$ is the ratio of the focal length of the projection lens to the diameter of the aperture. In practice, although longer HLP can improve the uniformity of energy distribution, the energy loss induced by reflection will increase. In this system, when Λ=0.55, the output beam of HLP can provide the desired uniformity. So the length of HLP is designed to be 25 mm.

Figs.7a~7c show the polar candela distribution, the S-polarized light distribution and the energy

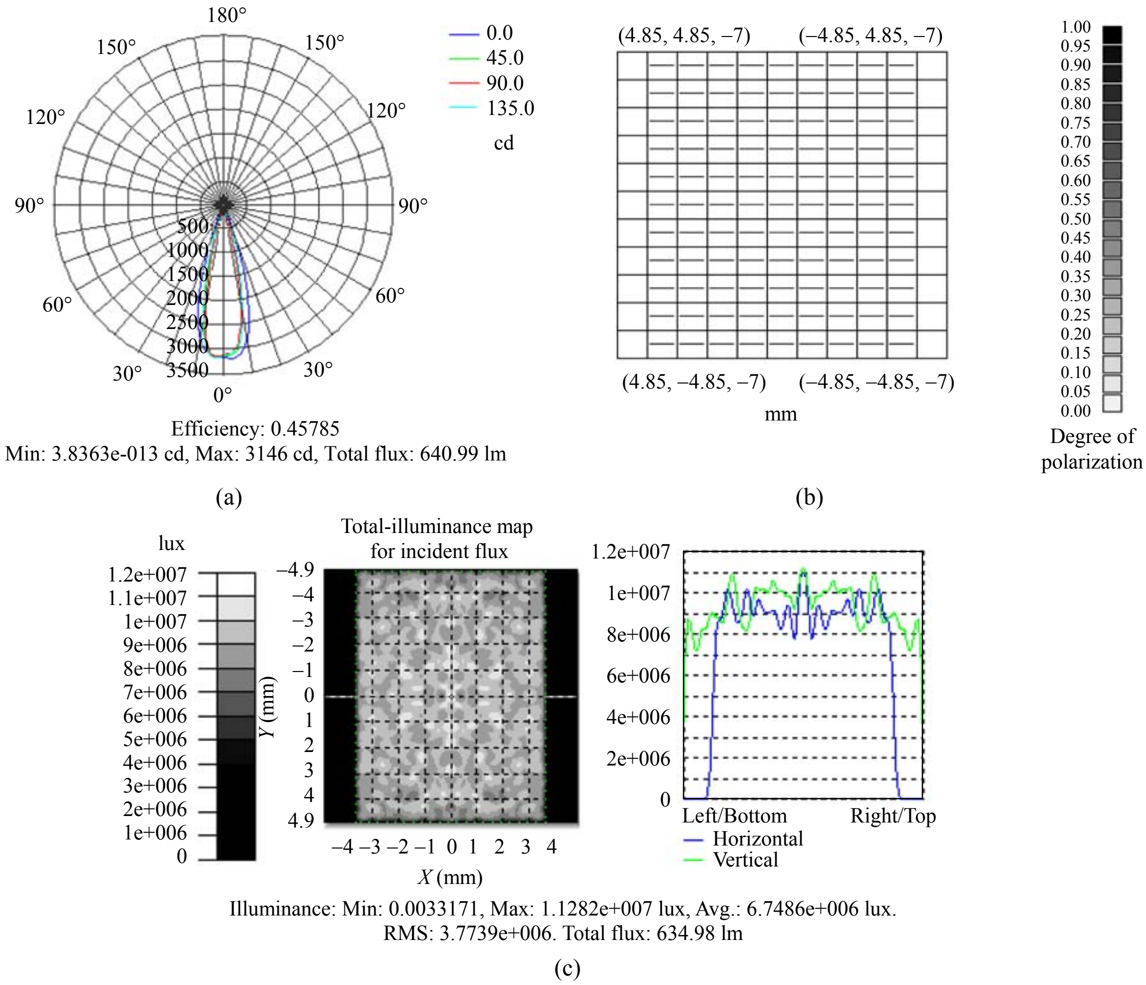

Fig.7 The light distribution on the plane at the TLP out end for Object 17 Surface 0 with 30530 incident rays
(a) Polar candela light distribution; (b) Polarization; (c) Energy distribution

distribution on the plane at the HLP output end, respectively. They show that the combination of the condenser lens and HLP has accomplished the task to transform the beam shape and *NA*.

Simulation result

Since the light distribution and the beam shape on the plane at the HLP output end can meet the illuminating requirement of the LCOS panel, the output end of HLP is imaged onto the LCOS panel by 2*f* imaging system with no magnification selected. In this process, the stray ray can also be diminished. Then the light modulated by the LCOS panel is projected on screen by passing through the projection lens.

The computer simulation of the projection display system using Tracapro was performed to evaluate the light efficiency of the entire system. In the simulation model, except that the reflectivity of LCOS panel is set to be 70%, the reflectivity of all reflective surfaces is set to be 97%.

Fig.8 shows the energy distribution on the LCOS panel. Fig.9 shows the energy distribution on the screen which is placed 1.3 m away from the LCOS panel. Comparing Fig.9 with Fig.8, the uniformity of energy distribution on the screen is decreased because of the effect of the projection lens.

The light efficiency of the projection display system is defined as:

$$\text{Efficiency}=\frac{\text{Energy on screen}}{\text{Energy of light source}}\times 100\%. \quad (3)$$

The computer simulation shows that the light

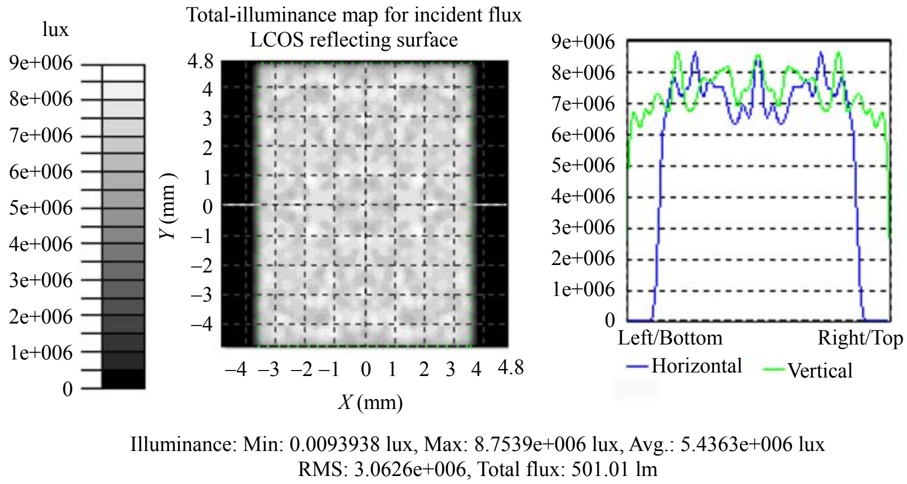

Fig.8 The energy distribution on the LCOS panel (29653 incident rays)

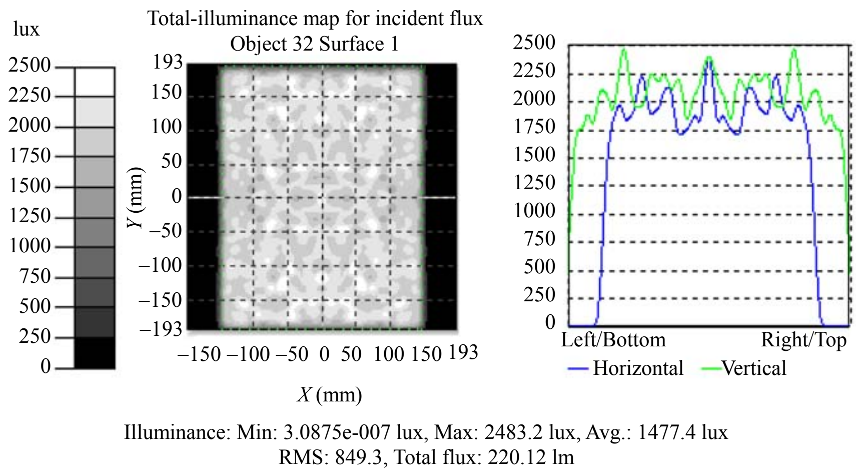

Fig.9 The energy distribution on the screen (26850 incident rays)

efficiency of this projection display system is about 15.6%. In the efficiency calculation, the effect of the color filters on efficiency is not considered.

The uniformity calculation of the image is specified by an ANSI/NAPM IT7.228-1997 (ANSI/NAPM, 1997). By measuring the brightness of 13 positions shown in Fig.10, the uniformity of the image on screen is calculated to be 90% in Eq.(4).

$$\text{Uniformity} = \frac{\min(1 \sim 13)}{\text{average}(1 \sim 9)} \times 100\%. \tag{4}$$

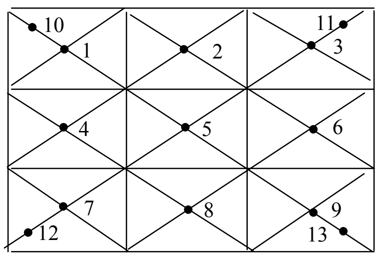

Fig.10 The position of measurement points

CONCLUSION

An illumination system with UHP lamp for single LCOS panel projection display is proposed in this paper. From the flux and uniformity result on screen, the illumination system composed of CPR and several conventional optical devices is beneficial for improving the property of this projection display system. In the real situation, if all the mechanical parts contribution is taken into account, the flux and the uniformity on screen will be smaller.

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