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Short Note

High-Efficiency Polarized Light Illumination System for Liquid-Crystal-Display Projectors

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We present a new optical system with two identical s- and p-polarized light paths for converting a random polarized beam into a linearly polarized one. The system also provides a uniform and rectangular cross-section beam on the light valve. The geometrical factor of the polarization-conversion efficiency of 190% and the uniformity at the liquid crystal display (LCD) plane of above 90% has been achieved by this optimized optical system.

KEYWORDS: liquid crystal display, illumination system, projector, polarization conversion, shape conversion, offset design

Projection displays based on liquid crystal displays (LCDs), with the advantages of excellent picture quality, large screen images, and light weight, are promising candidates for high-information-content display systems.[1–3] The LCD, used to control the transmittance or reflectance of each pixel, requires polarized light for light modulation. Conventional illumination systems employ polarizers or polarizing beam splitters (PBSs) to obtain polarized light from unpolarized sources, leading to a >50% light loss. The issues associated with the uniformity and shape conversion must also be addressed in order to realize effective illumination optical systems. To improve light utilization, many polarized light illumination systems have been proposed.[2,3] A planar PBS-array plate incorporating two lens-array plates is a common approach to providing polarized, uniform and rectangular-shape illumination beams for LCD projectors. However, the PBS-array scheme requires a number of narrow strip-shape prisms with polarizing and mirror coatings to accomplish the polarization conversion.

In this paper, a polarized light illumination system with a single PBS prism is proposed to improve the light efficiency and uniformity. The system comprises a short arc lamp, a parabolic reflector, a BPS cube, two mirror-array plates, a lens-array plate, and wave plates, as shown in Fig. 1. The BPS transmits p-polarized light and reflects s-polarized light. The quarter-wave plate cemented between the PBS and the mirror-array plate induces a phase retardation of 45° to convert linear polarized light into circular polarized light and vice versa. Figure 2(a) depicts a plane view of a mirror-array plate, consisting of a plurality of spherical mirrors with a rectangular cross section similar to the LCD light valve. The center of each spherical mirror in the array plate has been shifted along the horizontal direction by an offset of the 1/4 mirror aperture width. Because the two mirror-array plates are offset in opposite directions, these array plates produce two separated arrays of the source images at the following lens-array plate. The offset design of the mirror-array plates can minimize the apparent size of the light source, yielding higher efficiency. The lens-array plate, comprising an array of lenses, is used to superimpose these virtual sources onto the LCD panel. The half-wave plates with a narrow striped shape, shown in Fig. 2(b), are sandwiched between the BPS and the lens-array plate. The half-wave plates associated with each column of the lens-array plate are used to rotate the light from one of the mirror-array plates by 90°, so the illumination light beams are polarized in the same direction.

The polarization-conversion efficiency is the primary concern of a polarized light illumination system, and is the ratio of the polarized light flux delivered to the light valve by this system to that delivered by a reference system without polarization conversion.[4] The polarized light flux provided by an illumination system can be estimated in terms of the geometrical optical efficiency.[5] In our system, the p- and s-polarized light paths are identical, implying that the geometrical optical efficiencies associated with these light paths are equal, which is denoted by $\Gamma_{\rm POL}$. Consequently, the polarization-conversion efficiency of our system, $\xi_{\rm POL}$, is given by

$$\xi_{\rm POL} = \left[\eta_{\rm QWP}^2\eta_{\rm PBS}^2\left(\frac{1+\eta_{\rm HWP}}{2}\right)\right]\left[\frac{2\Gamma_{\rm POL}}{\Gamma_{\rm UNP}}\right], \qquad (1)$$

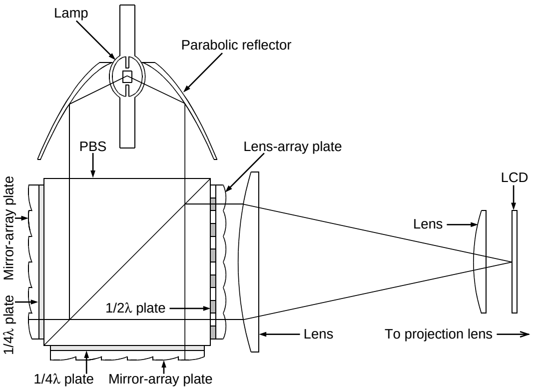
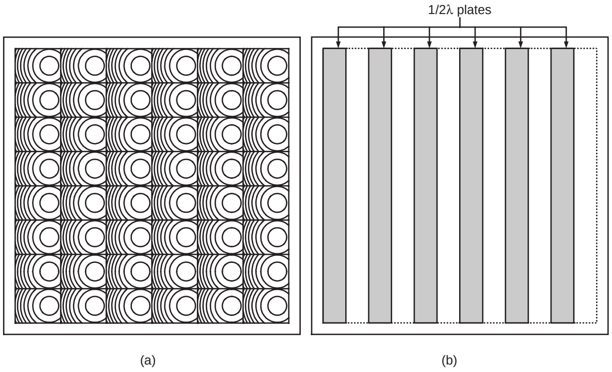


Fig. 1. Optical layout of the polarized light illumination system.



(a)

(b)

Fig. 2. Plane views of (a) the offset mirror-array plate and (b) the half-wave plates.

where Γ_{UNP} is the geometrical optical efficiency of a reference system without polarization conversion, η_{HWP} is the single-pass spectral efficiency of the half wave plate, and η^2_{QWP} and η^2_{PBS} are the double-pass spectral efficiencies of the quarter-wave plate and the PBS, respectively. In eq. (1), the first term, $\eta^2_{\mathrm{QWP}}\eta^2_{\mathrm{PBS}}(1+\eta_{\mathrm{HWP}})/2 \approx 85\%$,[4] referred to as the spectral factor, is determined by the coatings of the optical components, while the second term, $2\Gamma_{\mathrm{POL}}/\Gamma_{\mathrm{UNP}} \leq 200\%$, referred to as the geometrical factor, is dependent on the optical configuration and the light source.[5]

The geometrical factor dependency of the light source was investigated using a commercial ray-tracing program (Advanced Systems Analysis Program, Breault Research Organization, Inc.). In the analysis, an emitting cylinder of finite length, Z_{ARC}, and diameter, D_{ARC}, was used as the light source, and a lens-array integrator, comprising two lens-array plates, was chosen as the reference system.[1] The system and the reference system were optimized according to the LCD with a 0.9-inch diagonal aperture, an aspect ratio of 4 : 3, and an acceptance cone of 17°. The geometrical factor $2\Gamma_{\mathrm{POL}}/\Gamma_{\mathrm{UNP}}$ is plotted in Fig. 3 as a function of Z_{ARC} for various values of D_{ARC}. When $Z_{\mathrm{ARC}} = 1.0\,\mathrm{mm}$, $2\Gamma_{\mathrm{POL}}/\Gamma_{\mathrm{UNP}} > 180\%$ can be achieved. For $Z_{\mathrm{ARC}} < 0.8\,\mathrm{mm}$, $2\Gamma_{\mathrm{POL}}/\Gamma_{\mathrm{UNP}}$ can be boosted to above 190%, very close to the maximum of 200%. Thus, theoretically, the usable light flux can be nearly doubled by means of this polarization conversion scheme. However, the light beam passes through the quarter-wave plate and the PBS twice, leading to a spectral factor lower than that given in ref. 2. If the optical elements with higher spectral efficiencies are available, the proposed optical system will improve the light efficiency of the LCD projectors even further.

This system also permits the shape conversion and enables the light valve to be illuminated more uniformly. The mirror-array plates divide the collimated light beam into a number of sub-beams with a rectangular cross section, and then image these light beams towards the corresponding lenses at the lens-array plate. Then, the lens-array plate superimposes these sub-beams to produce a uniform flattop profile on the light valve. The irradiance distribution at the LCD plane is calculated and its cross-sectional profiles along the horizontal and vertical directions are shown in Fig. 4. The irrandance profiles have sharp edges and are relatively flat, implying that the overlap of the sub-beams can effectively smooth out the nonuniform light distribution. The irradiance variation is above 90% by the American National Standards Institute (ANSI) standard, where the irradiance at each of the nine points is calculated and then normalized to that of the maximum value.[1]

In practical applications, the system employing the signal-PBS design has the advantage in terms of fabrication and alignment, because the wave plates and the array plates can easily be integrated together via the PBS. However, the PBS cube placed between the mirror-array and lens-array plates introduces a plane-parallel block of glass, and results in a slightly longer separation distance than that reported in ref. 2. Since the dimension of the PBS is proportional to size of the light valve, the system is preferred for projection systems using small-size LCD panels.

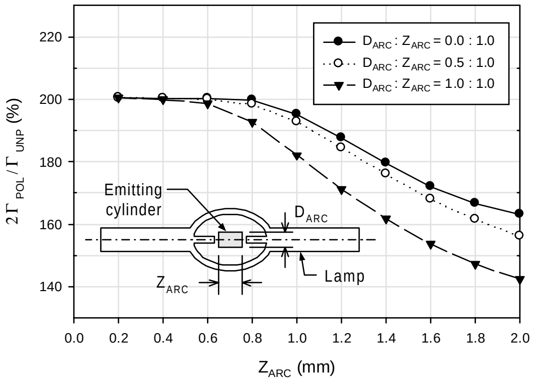


Fig. 3. Geometrical factor $2\Gamma_{\mathrm{POL}}/\Gamma_{\mathrm{UNP}}$ versus Z_{ARC} and D_{ARC}.

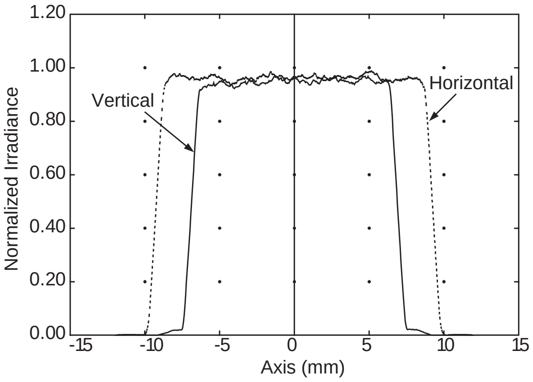


Fig. 4. Profiles of the normalized irradiance distribution at the LCD plane.

In conclusion, we have designed and evaluated a new illumination system to perform polarization conversion, shape conversion, and uniformity improvement. The s- and p-polarized light paths of the system are identical, and can be optimized in parallel, such that the geometrical factor of the polarization-conversion efficiency comes close to 200%. In addition, uniformity at the LCD plane of above 90% has been achieved.

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