Full Color Image Splitter Based on Holographic Optical Elements for Stereogram Application

Qing-Long Deng, Wei-Chia Su, Chien-Yue Chen, Bor-Shyh Lin, and Hsin-Wei Ho

***Abstract*—A color holographic beam splitter (CHBS) applied to an autostereoscopic display is proposed in this study. With high-stability polymer-dispersed-liquid-crystals (PDLC) being the holographic materials, holographic grating is utilized as a full-color beam splitter to split left and right field of views (FOVs) of a stereoscopic display. When CHBS is attached, the experimental results show that the correct left/right FOVs images could be successfully obtained at the preset observing distance of 25 cm. Moreover, the diffraction efficiency of the red, green and blue (RGB) left/right FOVs of the PDLC materials remained at 30.0% on average. Apparently, the brightness efficiency of the proposed CHBS stereo-displays is better than the traditional stereo-displays with a parallax barrier (22.4%). In addition, a crosstalk contrast with 95.0% indicates the crosstalk problem is almost avoided in the proposed technique.**

***Index Terms*—Crosstalk, diffraction, displays, holographic optical components.**

I. INTRODUCTION

THE common spatial-multiplexed autostereoscopic display technology can be categorized into two types: the lenticular lens and parallax barrier. In general, the lenticular types are not easily produced owing to a slight structural curvature errors will induce spherical aberrations and result in a distortion of stereoscopic images. The shadow structure of the parallax barrier, on the other hand, reduces the luminance efficiency of panels to 22.4% [1]–[3]. Even though ultra precision optics process technology is utilized for enhancing the performance of lenticular lens [4] and a chrome-plating reflection layer promotes the light guide rate of barrier-type [3], the brightness level of a traditional autostereoscopic display can be improved but still within a very limited amount. Nonetheless, before the emergence of other spatial-multiplexed stereoscopic technology, the two technologies still occupied plenty of the autostereoscopic display market. Chen *et al.* first proposed the diffractive optical element (DOE) as the splitting element for autostereo-displays in 2010 [5]. A continuous-relief blazed grating film was attached on the LCD surface to generate a stereoscopic image pair for both left and right eyes. Su *et al.* further verified the left/right images can be transmitted to the corresponding eyes of observers by a holographic optical element (HOE) in 2011 [6]. It not only corresponded to the splitting idea of DOE, but further began to replace micro relief films with smooth grating films. However, such a technology was merely presented with monochromatic stereo-image and could not satisfy the requirement of color images. Besides, the selected Dichromated Gelatin (DCG) materials for generating HOE [6] were instability and the complex treatment process is a drawback for mass production and the practical applications on LCD panel [7].

With the rapid study and development of polymer-dispersed-liquid-crystals (PDLC) in recent years, it has been widely applied to Gaussian filters, holographic storage, and HOE [9], [10] owing to its stable performance. Therefore, polymer-dispersed-liquid-crystals are chosen as the recording holographic materials for generating the required image splitter in this study. With the probe illumination of a collimated laser beams, the $+1$ order diffraction efficiency of the PDLC grating was about 58%, which was higher than the $+1$ order diffraction efficiency of DCG grating (45%) [6]. Based on the high-efficiency PDLC material, the original monochromatic grating in the previous study was modified to produce a beam splitter matching to the RGB sub-pixels so that the color display of the LCD could be retained. And then a color holographic beam splitter (CHBS) for an autostereoscopic display can be obtained. The CHBS was proposed to be precisely attached on the flat panel displays so that the left and right FOVs of stereoscopic images are redirected to the left and right eyes of the viewer without the need of wearing eye glasses. Furthermore, holographic technology was utilized for producing the color beam splitter. From the experimental results, the correct RGB spectrum of the panel can be viewed with CHBS. With the contrast of crosstalk and the analysis of overall diffraction efficiency, the contrast of red, green, and blue was about 95% and the diffraction efficiency of the left/right FOVs images was about 30%. In this study, the CHBS produced by the PDLC presented good contrast so that it becomes an alternative outstanding splitter for stereoscopic applications. Moreover, when lenticular and barrier grating were applied to the panel displays with laser backlight, serious diffraction might

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Manuscript received July 12, 2012; revised January 14, 2013; accepted April 10, 2013. Date of publication May 02, 2013; date of current version August 07, 2013.This work is supported by the National Science Council of Taiwan under Contract NSC 100-2221-E-018-016 and Contract NSC 100-2221-E-224-040.

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Digital Object Identifier 10.1109/JDT.2013.2258137

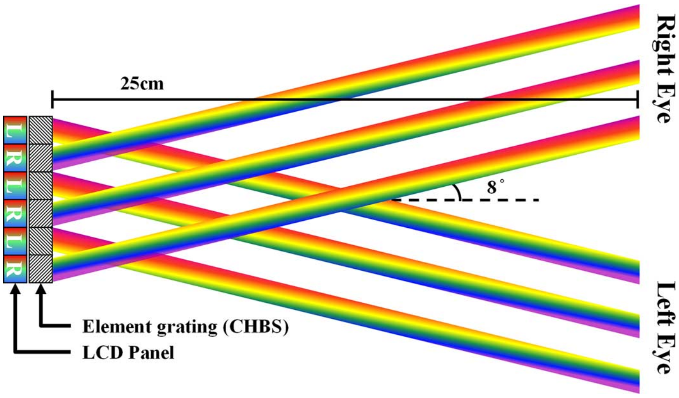

Fig. 1. A color holographic image splitter for stereograms.

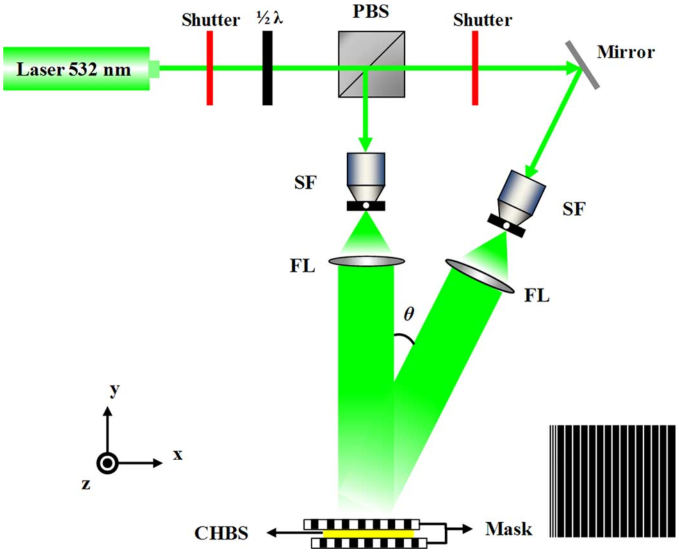

Fig. 2. Experimental setup for fabrication of a color holographic image splitter.

occur and result in unnecessary crosstalk, which could seriously affect the quality of stereoscopic images. Comparatively, the CHBS with diffraction splitting could become the stereoscopic display technology for a new generation.

II. Parameter Calculations and Design

Based on the parallax of optometry, both eyes and the object would form a triangular relationship. With positive and negative parallax, the illusion of stereoscopic images can be generated [11]. Consequently, when both eyes (with a binocular distance of 7 cm) were 25 cm away from the object, the viewing angle for both eyes is about 8.0° [6]. As a result, in order to form a stereoscopic vision on a 2.2-inch flat plane at the same distance, the left/right FOVs of the stereoscopic images should be interlaced on the odd column pixels and even column pixels. When the CHBS was precisely attached on the panel surface, the left/right images were transmitted to the corresponding eyes along its diffraction direction, as shown in Fig. 1.

The CHBS in Fig. 1 was a spatial-multiplexed phase grating. For monochromatic stereoscopic image application, we only have to generate a spatial-multiplexed HOE and let each element grating match to one left or one right pixel [6]. However, for color stereoscopic image application, each left/right pixel actually contains three RGB sub-pixels. To avoid the dispersion within one element grating, each element grating is further divided into three sub-gratings in this study. Each sub-grating takes charge of the diffraction of each RGB sub-pixel. The width of each sub-grating is accordingly designed to match the width of each RGB sub-pixel. In addition, the diffraction angle for each sub-grating is kept the same angle, 8.0°. The green sub-grating can be generated by holographic interference directly because the PDLC performs high exposure sensitivity on the wavelength 532 nm. However, it did not show sufficient sensitivity on wavelengths of 633 nm and 473 nm for the holographic generation of red and blue sub-gratings. To overcome the issue, the required gratings for red and blue sub-pixels were produced by the interference of 532 nm lasers instead. From (1), when the interference angle was 8.0°, the periods of the RGB gratings were 4.54 μm, 3.82 μm, and 3.40 μm, respectively. Equations (2) and (3) were further applied to calculate the interference angles for generating red and blue gratings by using green writing beams with 532 nm wavelength. The required interference angle for generating red and blue gratings with 532 nm wavelength are 6.7° and 9.0°, respectively, where Λ is the grating period, λ is the wavelength ($\lambda_r = 632$ nm; $\lambda_g = 532$ nm; $\lambda_b = 473$ nm), and θ, θ_r, θ_g and θ_b are the interference angles of the corresponding wavelengths

$$\Lambda = \frac{\lambda}{\sin\theta} \tag{1}$$

$$\theta_r = \sin^{-1}\left(\frac{\lambda_g}{\lambda_r}\sin\theta_g\right) \tag{2}$$

$$\theta_b = \sin^{-1}\left(\frac{\lambda_g}{\lambda_b}\sin\theta_g\right). \tag{3}$$

When the RGB gratings were produced, the +1 order diffraction angles were 8.0° after being probed by the corresponding RGB laser. The red, green, and blue color of stereoscopic image on the panel, therefore, could be transmitted to the eyes with the same direction without dispersion.

III. Optical Experiments

A. Fabrication of CHBS

Fig. 2 shows the experimental framework for producing a CHBS. A polarized beam splitter (PBS) divides the 532 nm diode-pump-solid state laser into two beams with a spatial filter (SF) in each path. In this case, Fourier lens (FL) were used to transform spherical waves into plane waves with the same vertical polarization (S:S = 1:1), and it was illuminated on the CHBS with two masks from the interference angle θ so that PDLC was exposed to produce gratings. The two masks were interlaced up and down in order to distinguish the mask of the left/right FOVs. The mask structure was made with the proportion of transparent area to opaque area being 1:5 in order to divide the width of one element pixel into three equal parts for the generation of the RGB sub-gratings (Fig. 3). The whole dimension of the mask is 5 cm×4 cm, and width of one transparent line on the mask is 180 μm. And width of one opaque line on the mask is 900 μm. In addition, three line pairs with one line width 180 μm were designed as an alignment key for the mask.

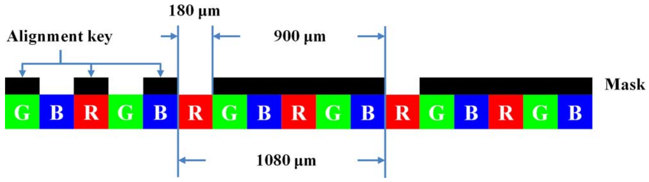

Fig. 3. Diagram of a exposure mask.

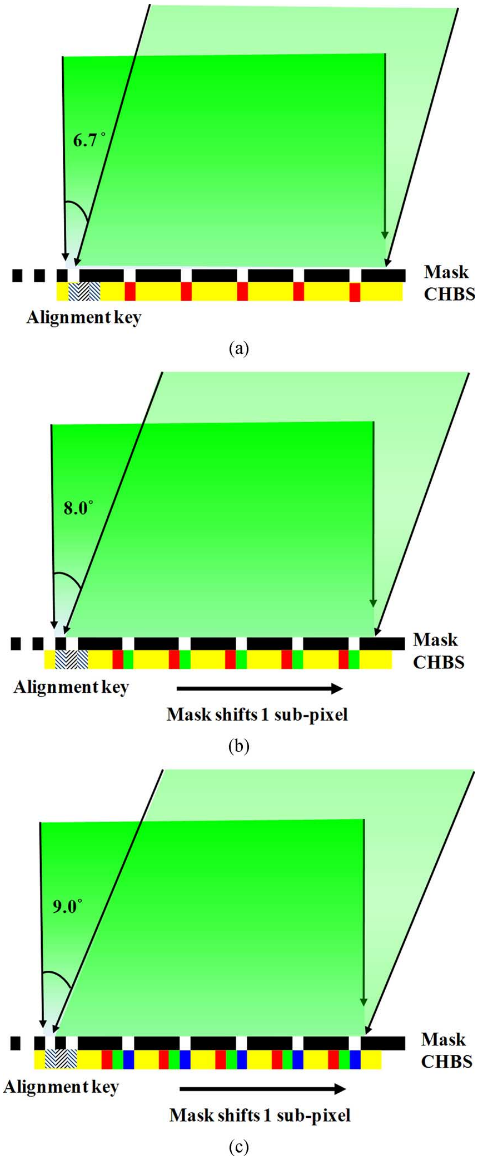

Fig. 4. (a) Exposure of red sub-gratings for left FOVs. (b) Exposure of green sub- gratings for left FOVs. (c) Exposure of blue sub- gratings for left FOVs.

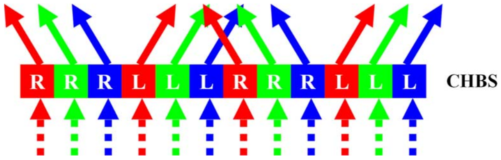

Fig. 5. Diffraction of the generated CHBS.

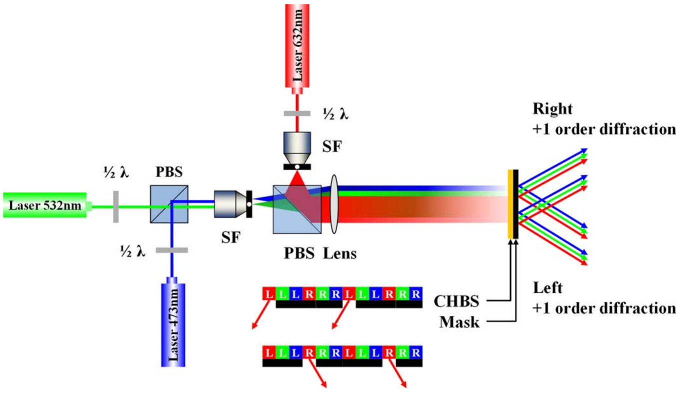

Fig. 6. Framework for measuring diffraction efficiency of CHBS.

When producing the grating for the left FOVs of the CHBS, (2) and (3) were applied to calculate the interference angles of red and blue sub-gratings, which are 6.7° (θ_r) and 9.0° (θ_b), respectively. First, the interference angle of the two writing beams was adjusted to 6.7° for exposure of generating red sub-grating as shown in Fig. 4(a). And then, the mask was horizontally shifted by one sub-pixel for the second exposure to produce the corresponding green sub-grating. Simultaneously, the interference angle of two writing beams was changed to become 8.0° for the exposure as shown in Fig. 4(b). For generating blue sub-grating matching the blue sub-pixel, the mask was horizontally shifted one sub-pixel again, and the interference angle was further changed to 9.0° for the third exposure [Fig. 4(c)]. After these three exposure process, the gratings for the left FOVs on the CHBS were completed. In current stage, only left pixels of the CHBS were generated and all the right pixels were unexposed. Furthermore, before producing the grating of the right FOVs on the CHBS, the CHBS should be turned 180° along the x-axis. And then, the above three steps were repeated again to complete the required grating for the right FOVs in this CHBS. Fig. 5 shows the completed CHBS. When the three laser light incident on their corresponding RGB sub-gratings, $+1$ order diffraction of each sub-grating on left column pixel column will propagate to the left eyes of observers and $+1$ order diffraction of each sub-grating on the right column pixel will propagate to the right eyes of observers.

B. Result of Image Split

After completing the CHBS, three backlights for the panel with 632 nm, 532 nm, and 473 nm wavelength were allotted to become a collimated wave, as shown in Fig. 6. And then, the diffraction intensity of three colors light through the CHBS was measured for getting the luminance of the designed CHBS. Equation (4) was applied to calculate the diffraction efficiency, where $D.E.$ is the $+1$ order diffractive efficiency, I_{+1} is the $+1$ order diffraction intensity, and I_i is the diffraction intensity. The left/right $+1$ order diffraction efficiency of the red grating was measured when each red sub-grating for left/right FOVs was aligned with the transparent area of a specific mask, which blocks the diffraction from the green and blue sub-gratings. In this way, only left/right diffraction of red sub-grating from red backlighting was measured. Similarly, left/right diffraction efficiency of green and blue sub-gratings was measured in the same way as shown in Table I.

TABLE I
LEFT/RIGHT +1 ORDER DIFFRACTION EFFICIENCY OF RGB GRATINGS IN CHBS

Grating	*D.E.*(Left view)	*D.E.*(Right view)
Red	33.5%	29.0%
Green	37.4%	32.9%
Blue	31.5%	28.3%

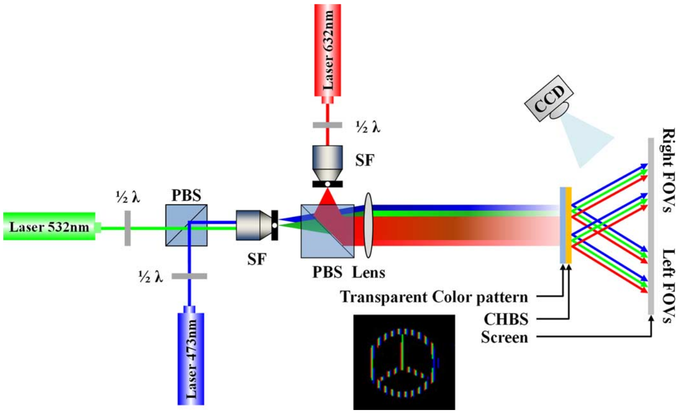

Fig. 7. Experimental setup for image splitting.

Fig. 8. A color image splitting with white backlighting.

After measuring the diffraction efficiency of the left/right FOVs, the mask was removed and a left/right interlaced color images with dimension of 2 cm×2 cm pattern instead of a LCD was attached on another side of the CHBS. The spatial arrangement and width of each RGB sub-pixel in this designed left/right interlaced color pattern totally matches to the specification of a color LCD panel. When the white collimating light mixed by RGB laser beams passed through the pattern and the CHBS, the left/right diffraction images was projected on the screen and was obtained via CCD camera (as shown in Fig. 7). The result as shown in Fig. 8 proves that the split images could be clearly observed at a viewing distance of 25 cm, and the left FOVs was the three-pointed star image and the right FOVs was the circle image. The width of viewing zone is 70 mm, and the pitch size of each sub-pixel in this pattern is 180 μm. Moreover, there was no obvious crosstalk between the left/right FOVs images, and even no color dispersion

$$D.E. = \frac{I_{+1}}{I_i} \times 100\%. \tag{4}$$

IV. DISCUSSIONS

From Fig. 8, it was proven that the proposed CHBS could split left/right FOVs of a color images successfully. In comparison with the monochromatic holographic image splitter [6], an advanced CHBS with sub-gratings matching to the RGB sub-pixels was presented by using PDLC as recording materials.

A. *Diffractive Efficiency and Brightness*

This study presented an effective way to produce a color holographic beam splitter for stereo-displays with PDLC. Actually, the diffraction efficiency of a holographic grating in PDLC can reach 58% in our study, which was higher than the gratings produced by DCG [6]. The high diffraction efficiency is induced by the TMPTA (Dipentaerythritol pentaacrylate, $C_{15}H_{20}O_6$) and APTMS (3-aminopropyltrimethoxysilane, $C_9H_{18}O_5Si$) in PDLC resulting in a better phase separation [12]. Nevertheless, the diffraction efficiency of RGB left/right FOVs for CHBS was only 30% on average, which was worse than the ideal saturation performance (58%). The main reason is presumably induced by the diffusion effect of reaction molecules within the PDLC. Actually, the CHBS for the left/right FOVs were separately divided into RGB sub-structures in our experiments. When recording a sub-grating on the PDLC materials, the reaction molecules could diffuse from the unexposed area to the exposed area and then the concentration of reaction molecules within unexposed would become less. Therefore, the saturation diffraction efficiency for the next exposed grating becomes worse. Moreover, response of exposure time to the diffraction efficiency accompany with the diffusion effect is nonlinear. Accordingly, diffraction efficiency with 30% on average for each sub-grating is the optimal result can be obtained in our experiments. However, the overall performance of the presented CHBS was still better and brighter than the traditional stereo-displays with a parallax barrier [3]. Besides, the diffraction efficiency in this experiment shows slightly difference for each RGB sub-gratings. With precision holographic exposure time, the diffraction efficiency of each RGB gratings can be further modulated and then they can be balanced. Alternatively, the unbalance of luminance issue could be improved by controlling the RGB backlight intensity.

In addition, even though the zeroth-order image as in Fig. 8 was appearance, the zeroth-order diffraction will not propagate to both eyes of an observer with laser backlighting. In other words, when viewing such stereo-displays, stereo-vision will not affected by the zeroth-order diffraction. Alternative way to suppress the zeroth-order diffraction is to enhance the diffraction efficiency of of +1 order diffraction. Possible method is to increase the thickness of the PDLC materials to generate a true volume hologram such that the +1 order diffraction can be enhanced and zeroth-order diffraction would be much eliminated.

B. *Crosstalk*

For analyzing the crosstalk in stereo-displays, the contrast ratio (CR) is an important evaluated [13]–[15]. The formula is defined as (5), where CR_R is the CR of the right image, and CR_L is the CR of the left image. R_l is the left FOVs diffraction intensity measured by the right eye, and R_r is the right FOVs diffraction intensity measured by the right eye. L_l is the left FOVs diffraction intensity measured by the left eye, and L_r is the right FOVs diffraction intensity measured by the left eye

$$\begin{aligned} CR_R &= \frac{R_r - R_l}{R_r + R_l} \times 100\% \\ CR_L &= \frac{L_l - L_r}{L_l + L_r} \times 100\%. \end{aligned} \tag{5}$$

TABLE II
632 nm DIFFRACTION INTENSITY FROM EVEN AND ODD PIXELS MEASURED AT THE LOCATION OF RIGHT AND LEFT EYE

Diffraction signal	Diffraction intensity (μW/cm^2)	Contrast ratio
R_r	19.0	96.9%
R_l	0.3	
L_l	11.0	96.4%
L_r	0.2	

TABLE III
532 nm DIFFRACTION INTENSITY FROM EVEN AND ODD PIXELS MEASURED AT THE LOCATION OF RIGHT AND LEFT EYE

Diffraction signal	Diffraction intensity (μW/cm^2)	Contrast ratio
R_r	17.0	93.2%
R_l	0.6	
L_l	11.0	93.0%
L_r	0.4	

TABLE IV
473 nm DIFFRACTION INTENSITY FROM EVEN AND ODD PIXELS MEASURED AT THE LOCATION OF RIGHT AND LEFT EYE

Diffraction signal	Diffraction intensity (μW/cm^2)	Contrast ratio
R_r	19.0	97.9%
R_l	0.2	
L_l	12.0	95.1%
L_r	0.3	

The ideal condition for stereo-displays is the left viewed image should not appear any right viewed image, and vice versa. The crosstalk is less when CR is larger. Usually, the critical value of CR for commercial application is defined as 10% only. Actually, higher CR value indicates crosstalk would not cause a serious affection on stereogram quality. In our measurements, the probe intensity of each three collimated laser beam was 35 $\mu\mathrm{W/cm}^2$, and the mask as shown in Fig. 6 was used to block the sub-gratings sequentially for measurements. L_l and L_r comes from the $+1$ order diffraction of left FOV and the -1 order diffraction of right FOV, respectively. Similarly, R_l and R_r comes from the -1 order diffraction of left FOV and $+1$ order diffraction of right FOV, respectively. According to (5), the contrast of the left/right FOVs at 632 nm were 96.9% and 96.4%, at 532 nm were 93.0% and 93.2%, and at 473 nm were 95.1% and 97.9%, respectively. They are shown in Tables II–IV.

From the results, the contrast ratio of 532 nm is lower than the other wavelengths, because -1 order diffraction efficiency of green sub-grating is higher than the others. Nevertheless, from the above data, the RGB contrast ratio of the proposed CHBS was larger than critical value of 10%, and very close to 100%, which implies that image stereogram quality is almost not affected by the crosstalk.

C. Diverging Backlighting

In practical application, when a collimated backlight is used in the system, the visible area for each diffracted image is as small as pupil size, and therefore only a small part of the display is visible. According to the issue, a divergence backlight should be adopted to enhance the view angle for practical application. The divergence angle of the backlight can be designed according to the system geometry to increase the visible area but simultaneously avoid crosstalk. The detail analyses are shown in Fig. 9. Owing to the CHBS is designed for a small panel (2.2 inch), the image size is only about 2 cm. The distance between right and left eye is 6.5 cm, and distance between eyes and CHBS is 25 cm. The diffraction from margin pixel M is 8 degree. However, the divergence of this diffraction should cover the eye point R. As shown in Fig. 9, the distance of PR is therefore 2.25 cm, and accordingly the offset angle θ is 5.15 degree. The difference between the diffraction angle (8.0°) and the offset angle (5.15°) is the half angle of the diverging, 2.85°, and accordingly the required diverging full angle is 5.7°.

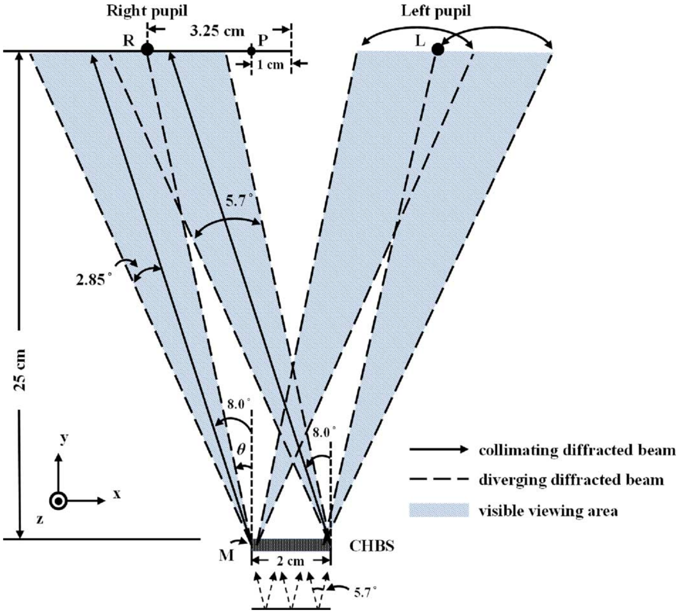

Fig. 9. The schematic diagram of diverging angle and visible viewing area.

When the diverging angle of incident light for each pixel is 5.7 degree, the diffracted light is also a diverging beam with the same angular divergence. And with the angular divergence, diffractions from each corresponding pixels can propagate to the eye. The visible area is therefore broadened and the whole stereo image can be observed.

V. CONCLUSION

A color holographic beam splitter for autostereoscopic displays was proposed in this study. PDLC was used as the recording material, and a monochromatic laser light with 532 nm wavelength was utilized for producing RGB sub- gratings to complete the production of the CHBS. The experimental results showed that the CHBS could successfully split the left/right FOVs color images, and the correct splitting images could be viewed at the distance of 25 cm. It proved the feasibility of a CHBS being applied to autostereoscopic displays. Moreover, the performance of RGB contrast ratio could prove that there was ultra-low crosstalk. In the discussion section, it was proposed that a volume holographic material could promote the

+1 order diffraction intensity of sub-gratings as well as eliminate the zeroth-order diffraction intensity so that holographic elements could be widely applied to stereo-displays.

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