Time-sequential autostereoscopic 3-D display
with a novel directional backlight system based
on volume-holographic optical elements

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Abstract: A novel directional backlight system based on volume-holographic optical elements (VHOEs) is demonstrated for time-sequential autostereoscopic three-dimensional (3-D) flat-panel displays. Here, VHOEs are employed to control the direction of light for a time-multiplexed display for each of the left and the right view. Those VHOEs are fabricated by recording interference patterns between collimated reference beams and diverging object beams for each of the left and right eyes on the volume holographic recording material. For this, self-developing photopolymer films (Bayfol® HX) were used, since those simplify the manufacturing process of VHOEs substantially. Here, the directional lights are similar to the collimated reference beams that were used to record the VHOEs and create two diffracted beams similar to the object beams used for recording the VHOEs. Then, those diffracted beams read the left and right images alternately shown on the LCD panel and form two converging viewing zones in front of the user’s eyes. By this he can perceive the 3-D image. Theoretical predictions and experimental results are presented and the performance of the developed prototype is shown.

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1. Introduction

In general, autostereoscopic three-dimensional (3-D) displays requiring no special glasses to view the two images for 3-D perception, can be largely classified into the spatial- and time-multiplexed methods [1–16]. In spatial multiplexing, optical stripe panels such as the parallax-barrier and the lenticular-sheet [1–6, 17–23], which are designed for dividing the visual fields, are attached to the front side of the flat panel display to separate the left-and right-eye images of a 3-D scene. Therefore, this method can allow the viewer to see different image information within the left and right fields separated at an appropriate viewing point. Thereby, the viewer can perceive the 3-D image.

Thus far, this spatial-multiplexing has been regarded as the most popular approach for autostereoscopic 3D display because of its compatibility with the current high resolution LCD panel technology. However, it has several drawbacks such as degraded image resolution, low light efficiency and narrow viewing angle as well as it may require a precise alignment of optical stripe panels to the LCD pixels [20]. Above all, the decreased image resolution visible in each viewing zone depending on the number of views seems to be the essential disadvantage of this scheme. More accurately, the spatial-multiplexed display couldn’t technically provide the full-panel-resolution stereoscopic images.

To overcome this drawback, several types of time-multiplexed autostereoscopic LCD displays were proposed [7–11, 24–27], which allow keeping the full-panel-resolution for each stereoscopic image. Since the left and right views are time-sequentially displayed in these methods, they may inevitably require a means to direct the views exclusively to the one single eye they are designed for. Therefore, various directional backlight systems to control the direction of light have been suggested [9–11, 24–27]. N.A. Dodgson et al. proposed a projection-type time-multiplexed autostereoscopic display based on the backlight system...
composed of a fast switching LCD, a convex lens and two light sources [7,8]. A. Hayashi et al. also proposed a field-sequential autostereoscopic LCD with elliptical mirror-based directional backlights [27]. However, relatively large volumes of these displays have prevented them from being used for mobile applications [7,8,27].

Recently, several slim-structured time-sequential autostereoscopic LCD displays that adopt the light-guide-plates (LGPs) and 3-D prism films have been proposed [9–11,24,26]. Sasagawa et al. suggested a compact field-sequential stereoscopic LCD with the directional backlight system based on a double-sided prism sheet [9]. K. -W. Chien et al. presented another type of the time-multiplexed 3-D display using a fast-switching LCD and a grooved LGP combined with an asymmetric focusing foil [11]. Moreover, C. -H Chen et al. suggested an autostereoscopic display with dual directional backlight based on two micro-grooved LGPs and a driving scheme of light sources synchronized with parallax images [24]. Horii et al. developed a digital 3-D camera system with a directional backlight-based autostereoscopic display based on the prism-patterned film [25]. J. C. Schultz et al. also proposed an autostereoscopic 3-D display system by combined use of a nanometer-sized 3-D film of the double-sided prism, a directional backlight and a fast-switching LCD panel [26].

While in spatial-multiplexed autostereoscopic displays, the precise production of micrometer-sized 3-D prism films, and their accurate alignment to the LCD structures might be the most critical concerns, they do have other problems such as low light efficiency, narrow viewing zones and crosstalk [25–27].

Accordingly, in this paper, we propose and demonstrate results of a novel directional backlight system based on volume-holographic optical elements (VHOEs) for the slim-structured time-multiplexed autostereoscopic 3-D LCD mobile displays. Here, VHOEs are used for controlling the direction of light for a time-multiplexed display of the left and the right view [13,14,28]. Those VHOEs are fabricated by recording the interference patterns between two pairs of collimated reference beams and diverging object beams for each of the left and right eyes on the photopolymer films. For this, self-developing photopolymer films are employed in this paper, because those make the manufacturing process of VHOEs much simpler and easier. By time-sequentially illuminating the fabricated VHOEs by a light front similar to the reference beam, two object beams are formed by diffraction, which illuminate the left and right images alternately shown on the LCD panel. While the light is passing through the LCD panel, two converging light fields are formed in front of the observer’s eyes in sequence, from which he can perceive the 3-D image.

To confirm the feasibility of the proposed backlight system, in this paper, we present a new VHOE-based time-multiplexed autostereoscopic 3-D display system, which is designed, implemented and characterized in terms of diffraction efficiency, transmittance, viewing zone, crosstalk and color dispersion through theoretical analysis and optical experiments.

2. Proposed VHOE-based autostereoscopic 3-D display system

2.1 System configuration

Figure 1(a) shows an overall configuration of the proposed time-sequential autostereoscopic 3-D display system based on the VHOE-based directional backlights, which is composed of two arrays of the white LED light sources, a grooved LGP, a pair of the stacked 3-color VHOEs, a fast-switching LCD panel, LED switching and LCD driving modules.

Here, the VHOE is a thin optical device employed for controlling the direction of light for time-sequential display of the left and right views. Just by recording the interference patterns between the collimated reference beams and the diverging object beams for each of the red, green and blue colors into the photopolymer films they form volume phase gratings. Each set of 3-color VHOEs for each of the left and right eyes are fabricated and then stacked together and laminated on the backside of the LCD panel.

In this system, two arrays of the white LEDs located at both sides of the grooved LGP are used as the light sources: one (Light source-1) for the left eye and the other (Light source-2) for the right eye. Whenever the light sources switch on alternately, the light coming from the
Light source-1 or the light coming from the Light source-2 propagates along the grooved LGP, and are reflected from each east or west angle of the prisms of the LGP to the bottom surface of the stacked 3-color VHOEs to form the two kinds of quasi-collimated light beams with their own specific slant angles. Here, the grooved LGP is designed to have a structure of one-dimensional (1-D) prism pattern with a symmetry geometry between the east and west angles.

Then, these two quasi-collimated beams reflected from the grooved LGP illuminate the stacked 3-color VHOEs and form their corresponding object beams recorded into them. In response to these quasi-collimated reference beams, two directional object beams converging to two eyes are alternately diffracted from the stacked 3-color VHOEs with the specific angles.

![Configuration of the proposed VHOE-based time-sequential autostereoscopic display system](image)

Fig. 1. Configuration of the proposed VHOE-based time-sequential autostereoscopic display system: (a) Operational concept of the proposed system, (b) Schematic of the VHOE-based directional backlight.

While these diffracted object beams are passing through the LCD panel, they are modulated by the LCD panel and are directed to the positions of the viewing zones formed for the left and right eyes. Thus, by a combined use of the VHOE-based directional backlight system with a LCD panel, two converging light fields are sequentially formed just in front of the observer’s left and right eyes, from which he can finally perceive the 3-D images.

Here, the left and light images must be synchronized with the corresponding left and right light sources on the LCD panel. Moreover, for flicker-free display of the left and right images, a LCD panel with 60 Hz display frequency for each eye must be employed because otherwise the human visual system perceives flicker. The LED switching and LCD driving module is divided into two parts: a moving-image part and a signal-processing part. In the moving-image part, the left and right images are formatted utilizing the top-down method and time-sequentially sent to the LC panel. In the signal processing part, two types of synchronizing pulses are used for each of the LED arrays. Figure 1(b) shows an operational structure of the stacked 3-color VHOEs that forms a dual directional backlight. The 3-color VHOEs for each of the left and right eyes make the corresponding viewing zones, respectively. As shown in Fig. 1(b), two white object beams are sequentially emanating from the VHOE-based switching backlight system. Therefore, by combined application of this VHOE-based directionally switching backlight with the LCD panel, a binocular disparity for full color 3-D perception is achieved.
2.2 VHOE-based directional backlights

2.2.1 Theoretical analysis of the VHOEs

Basically, the VHOE is just a holographic optical element (HOE) known as a wave-shaping optical element whose grating patterns are recoded as the forms of volume phase holograms in a thick hologram-recording material such as the photopolymer film, and its diffraction operation can be analyzed based on the Bragg condition [29]. Here, the VHOE is employed for generation of the directionally switching backlights in the proposed slim-structured time-multiplexed autostereoscopic 3-D display system, which may act just as the 3-D prism film mostly used in the conventional directional backlight systems.

Figure 2 shows a process of recording and reconstruction of volume phase holograms on the holographic photopolymer films to manufacture the VHOEs for the directional backlights employed in the proposed system. In the recording process, two sets of parallel reference beams and diverging object beams for each of the left and right eyes are incident on their photopolymer films, and then volume phase gratings are recorded there as the forms of refractive-index modulations related to the corresponding interference intensity patterns.

![Diagram of VHOE recording and reconstruction](image)

Fig. 2. Recording and reconstruction processes of VHOEs on the photopolymers: (a) For the case of a single-color VHOE for the left eye, (b) For the case of the stacked 3-color VHOEs for both eyes.

Figure 2(a) simply shows the recording and reconstruction process of a single-color volume phase grating on the photopolymer only for the right eye. Of course, for eventual full-color display of 3-D images, three kinds of volume phase gratings for each of the red, green and blue colors, must be recorded on their photopolymer films one by one. The 3-color VHOE for the left eye can be also made from the same fabrication process mentioned above for the right eye. Figure 2(b) shows the stacked 3-color VHOEs for both eyes, which may alternately diffract two converging object beams for display of stereoscopic images.

Now, the recording process of a volume phase hologram on the photopolymer film can be theoretically explained with a schematic diagram of Fig. 2(a). That is, for recording the volume phase hologram, one set of the parallel reference beam and the diverging object beam is adapted. Here, the reference and object beams can be expressed as follow.
\[ E_R(x, y, z) = I_{R}^{1/2} \exp(-j\mathbf{k}_R \cdot \mathbf{r}) \]
\[ E_S(x, y, z) = I_{S}^{1/2} \exp(-j\mathbf{k}_S (r - r_{o1}) \cdot (\mathbf{r} - r_{o1})) / |\mathbf{r} - r_{o1}| \]
\[ (r_{o1} = (-D/2, 0, L), \mathbf{r} = (x, y, z)) \]  
(1)

Where \( E_R(x, y, z) \) and \( E_S(x, y, z) \) represent the parallel reference and diverging object beams. Moreover, \( D, r_{o1} \) and \( \mathbf{r} \) means the inter-ocular distance at the viewing distance of \( L \) and the coordinates for the origin of the point light source used as an object beam, and for the light field, respectively. \( I_{R} \) and \( I_{S} \) also denote the intensities of the reference and object beams, respectively. Then, the interference intensity pattern to be recorded on the photopolymer film as the volume phase grating can be given by

\[ I(r) = |I_{R}^{1/2} \exp(-j\mathbf{k}_R \cdot \mathbf{r}) + I_{S}^{1/2} \exp(-j\mathbf{k}_S (r - r_{o1}) \cdot (\mathbf{r} - r_{o1})) / |\mathbf{r} - r_{o1}||^2 \]
\[ = I_{R}(r) + I_{S}(r - r_{o1}) / |\mathbf{r} - r_{o1}|^2 + 2(I_{R}(r)I_{S}(r - r_{o1}) / |\mathbf{r} - r_{o1}|)^{1/2} \cos(k_{G}(r - r_{o1}) \cdot (\mathbf{r} - r_{o1}) - k_{R} \cdot \mathbf{r}) \]  
(2)

\[ (k_{G}(r - r_{o1}) = k_{S}(r - r_{o1}) - k_{R}, k_{G}(r - r_{o1}) = 2k \sin(\theta(r - r_{o1}) / 2), \Lambda = 2\pi / |k_{G}(r - r_{o1})|) \]

Where \( k_G, k_S, k_R \) and \( \Lambda \) denote the wave vectors of the grating, object and reference beams, and the period of the modulated grating, respectively. The \( \theta(r - r_{o1}) \) represents the angle between the object and reference beams at any points in the fabricated VHOE, which means that \( \theta \) may vary according to the coordinates on the cross-section between the reference beams and object beams at the fabricated VHOE.

Here, the relationship among the wave vectors, which is known as the Bragg’s condition for reconstruction of the converging object beam, can be expressed by \( k_G = k_S - k_R \) as shown in Eq. (2). Maximum phase index-modulation on the VHOE can be obtained under the condition of \( I_{R}^{1/2}(r) = I_{S}^{1/2}(r - r_{o1}) / |\mathbf{r} - r_{o1}| \), which means that the intensity of the divergent object beam on the VHOE must be equal to that of the reference beam. In addition, the interference pattern for the left eye can be formulated just by changing the coordinate of \( r_{o1} \) into \( r_{o1} = (D/2, 0, L) \) in Eq. (2). For white light diffraction, two sets of 3-color VHOEs for each of the left and right eyes are fabricated and stacked together in parallel as shown in Fig. 2(b).

Now, the reconstruction process of a converging object beam from the fabricated VHOE can be explained as follows. If a conjugated version of the parallel reference beam used for recording is incident on the VHOE, a converging object beam is diffracted along the reverse direction of the object beam used for recording as shown in Fig. 2(a), which is so-called Bragg-diffraction angle. Thus, the reconstructed object beams from the stacked 3-color VHOEs are converged to the designed viewpoints where two eyes are located.

If a distance of the converging focal point \( L \) is given, the intensity distribution of the diffracted beams on the focal point for both of the left and right eyes can be given by Eq. (3).

\[ I(x, y, L) = \left| I_{S}^{1/2} \exp(jk_{S} \cdot L) \exp(-jks \frac{x^2 + y^2}{2L}) + cc \right|^2 \]  
(3)

Where \( x \) and \( y \) represent the coordinates of the light field at the focal point of \( L \), and \( cc \) means the compensation constant. Here, the index-modulation distribution recorded under the Bragg-angle condition can be estimated from Eq. (2), while the beam intensity distribution diffracted to the focal point can be also estimated from Eq. (3). Moreover, from these equations, the viewing zones formed for the left and right eyes and their separation condition could be predicted just by calculating the wavelength-dependent beam intensity distributions as well.

Basically, diffraction efficiency \( \eta \) of a slanted transmission hologram with two plane waves can be formulated by Eq. (4) based on the Kogelnik theory [29].
In Eq. (4), the incident angles of the reference and object beams $\alpha$ and $\beta$, which are measured outside the recording medium, are basically equal for the non-slanted recording case, whereas they are different for the slanted recording case. $\Delta n$ and $\Delta \alpha$ also denote the index modulation and the angular deviation from the Bragg angle as well as $n_p$, $d$ and $\Lambda$ represent the refractive index and thickness of the recording medium and the grating period, respectively.

For estimating the diffraction efficiency of the VHOE for the given parallel reference and diverging object beams, the recorded phase grating pattern in the VHOE can be approximately calculated as the slanted transmission hologram pattern formed with two plane waves. If a parallel reference beam is incident on this phase grating, a diverging object beam looking very closely to the form of the parabolic wave, is diffracted, and it can be expressed as a sum of many parallel plane beams at the intersections between the reference and object beams along the $x$-coordinates of the VHOE plane as shown in Fig. 2(a).

Thus, the total diffraction efficiency $\eta_{\text{total}}$ of the VHOE can be estimated with the summed average of diffraction efficiencies for the recorded phase gratings among many parallel plane beams decomposed from the diverging beam, which is given by Eq. (5) and $w$ means the width of the recording medium.

$$\eta_{\text{total}} = \frac{1}{wd} \sum_{x=0}^{d} \sum_{z=-w/2}^{w/2} \eta(\beta(x,z))$$  (5)

On the other hand, for the case of fabricating the 3-color VHOEs for each of the left and right eyes with the single green laser (532 nm), the relative recording angles of the reference and object beams for the other colors of the red (633 nm) and blue (490 nm) need to be calculated. As shown in Fig. 2(a), the Bragg condition of the phase grating recorded on the VHOE can be defined as $k_R - k_S = k_\alpha$. Here, the magnitudes of the incident and diffracted wave vectors inside the recording medium are given by $|k_R| = |k_S| = 2 \pi n_p / \lambda$ with the incident angles of $\alpha'$ and $\beta'$ inside the medium, and they can be given by Eq. (6) using the Snell’s law.

$$n_w \sin \alpha = n_p \sin \alpha', \text{ and } n_w \sin \beta = n_p \sin \beta'$$  (6)

Hence, the magnitude of the grating vector given by $|\vec{K}_\alpha| = 2 \pi / \Lambda$ can be broken into two components which are parallel and perpendicular to the incident surface, so the Bragg condition can be expressed by Eq. (7)

$$k_R \sin \alpha' + k_S \sin \beta' = K_R \text{ and } k_R \cos \alpha' + k_S \cos \beta' = K_\perp$$  (7)

Equation (7) implies that at the same grating magnitude of $|\vec{K}_\alpha|$, only one solution of $\alpha'$ and $\beta'$ exists for a given $\lambda$ or only one solution of $\lambda$ for the given $\alpha'$ and $\beta'$. Here, on the recording plate, $\theta = (\alpha + \beta) / 2$ and $\theta' = (\alpha' + \beta') / 2$ can be defined as the half angle outside and inside the recording medium, which represent the intersection angles between the reference and object beams. Therefore, the grating vector can be expressed with the wave vectors of the object and reference beams as follows.
From Eq. (8), the vertical and parallel components of the grating vector are found to be \(2 \sin(\theta)\) and zero, respectively, and based on this equation, the grating period can be derived as follows.

\[
\Lambda \equiv \frac{\lambda}{2 \cdot n_p \cdot \sin(\theta')}
\]  
(9)

The grating periods can be calculated for each of the 3-color wavelengths using Eq. (9). If the incident and the half angles of the reference and object beams inside the recording medium are given, the grating periods satisfying the Bragg-angle condition for 3-color wavelengths are calculated as follows.

\[
\Lambda_{r,g,b} = \frac{\lambda}{2 \cdot n_p \cdot \sin(\theta'_r)} \quad \theta'_0 = \frac{\alpha'_r + \beta'_r}{2}
\]  
(10)

Where \(\Lambda_{r,g,b}\) and \(\theta'_0\) represent the grating periods calculated for each of the 3-color wavelengths, and the wavelengths of the 3-color laser sources (633 nm, 532 nm, 490 nm), respectively. \(\theta'_0\) becomes \(\theta'_{g}\) for the center green wavelength of \(\lambda_g\) at the recording medium. If the grating periods are given for 3-color wavelengths, \(\theta_0\) can be calculated by using the Snell law of Eq. (6). Thus the corresponding half angles outside the recording medium are calculated as follows.

\[
\theta_{g,b} = \sin^{-1}\left(\frac{\Lambda_{g,b}}{\Lambda_{r,g,b}} \sin \theta_0\right) = \frac{\alpha_{g,b} + \beta_{g,b}}{2}
\]  
(11)

Where \(\Lambda_0\) and \(\theta_0\) become \(\Lambda_{g}\) in the recording medium and \(\theta_{g}\) outside the recording medium, respectively for the center green wavelength of \(\lambda_g\), and the slanted angle is given by \(\phi_{r,g,b} = \theta_{r,g,b} - \beta_{r,g,b}\). From Eqs. (10) and (11), the input angles of the reference and object beams can be finally calculated for fabrication of the 3-color VHOEs for each of the left and right eyes only with a green laser of 532 nm.

2.2.2 Recording of volume phase gratings on the photopolymers for 3-color VHOEs

As mentioned above, the 3-color VHOEs for each of the left and right eyes are employed for generation of directionally switching backlights in the proposed slim-structured time-multiplexed autostereoscopic 3-D display system. Here, the 3-color VHOEs can be fabricated from two types of recording methods; multiplexed-recording and single-recording methods. In the multiplexed-recording, grating patterns for three colors are simultaneously recorded on a single photopolymer film based on the pre-designed time-scheduling, whereas in the single-recording, each of the 3-color grating patterns is separately recorded on its own photopolymer film and they are stacked together. In this paper, the single-recording method is employed because it shows a higher diffraction efficiency compared to the multiplexed-recording method, so overall enhanced performance can be achieved [30].

In addition, for fabricating the 3-color VHOEs, single-color or three-color lasers can be used for recording the 3-color phase gratings on the photopolymer films. Here, in this paper, only one green laser of 532 nm is used for fabricating the 3-color VHOEs because of its simple recording structure. For the single-color laser, the recording angles of the reference and object beams for each of the red, green and blue lasers need to be calculated with Eq. (11).

Figure 3(a) shows a schematic diagram of the recording angles for 3-color phase gratings with a green laser. In case that the incident and diffracted beam angles of \(\beta_{g}\) and \(\alpha_{g}\) for the green laser (532 nm) are designed to be 55.0° and 6.0°, their corresponding angles for the red (633 nm) and blue (490 nm) lasers are calculated to be 48.7°, 1.4°, and 58.8°, 8.5°,
respectively. Accordingly, based on Fig. 3(a), three VHOEs for each of the red, green and blue colors were fabricated on photopolymer films by holographic exposure and subsequent bleaching with incoherent light. No additional post processing was needed [31].

![Fig. 3. Systematic diagrams for (a) recording of the 3-color phase gratings on the photopolymer films with a green laser, and (b) stacking of two sets of 3-color VHOEs for each of the left and right eyes.](image)

Figure 3(b) shows a stacking process of 3-color VHOEs recorded on the photopolymer films for each of the left and right eyes. As shown in Fig. 3(b), the 3-color VHOEs for the left eye can be made just by stacking three VHOE films for each of the red, green and blue colors together in parallel, whereas the same but 180°-rotated versions of three VHOE films for three colors are stacked together for fabrication of 3-color VHOEs for the right eye. Furthermore, these two sets of 3-color VHOEs for both left and right eyes are attached together and finally laminated on the backside of the LCD panel. Thus, when two conjugated reference beams alternately illuminate their respective set of 3-color VHOEs, converging object beams are formed by diffraction to each of the left and right eyes symmetrically aligned viewing zones.

2.2.3 Color dispersion and whiten-light diffraction of 3-color VHOEs for the white LEDs

Contrary to the conventional prism sheet-based directional backlight system, color dispersion needs extra care in any VHOE-based system because the viewing zones are generated based on diffraction optics utilizing white-light illumination. Color dispersion is a common phenomenon in refractive optics, but is usually more pronounced in diffraction. So the spectral distribution of the employed LED sources poses a challenge for homogeneously white-light illuminated viewing zones.

Figure 4 shows the color dispersion of the stacked 3-color VHOEs for the white LED light illumination. Color dispersion causes the diffracted object beams to laterally spread, which potentially results in an increased overlap between the left and right viewing zones. As seen in Fig. 4, responding to each of the collimated reference beams coming from the left and right sides, their corresponding object beam disperses the light, so that red light is bend more than blue light. On the other hand the recording reference beam and object beam angles were adjusted so that with a 532\(\text{nm}\) recording wavelength, the resulting diffraction efficiency of the red (or respectively blue) portion of the white light is effectively diffracted in the correct angle (see Fig. 2). By this the diffraction efficiency of the 3-color VHOE for white light is the highest in the angles defined for the viewing zone (cycled blue in Fig. 4).

Accordinly, from the simultaneous superposition of these three sets of laterally dispersed object beams depending on the colors (depicted in Fig. 4: rectangular by red color), two white-diffraction zones (in Fig. 4: circled with blue color) can be generated along the Bragg-angle directions, but the viewing zone for the left and right eyes can't be clearly separated because of the lateral color dispersion.
To alleviate this functional drawback of the 3-color VHOEs, two converging object beams instead of the plane object beams can be used, which may result in a considerable reduction of color-dependent lateral spread of the diffracted object beams, and also allow us to make a clear separation of the white viewing zones for each of the left and right eyes [28].

2.2.4 Grooved LGP for generation of the collimated reference beams

In the proposed VHOE-based directional backlight system, two arrays of white LED light sources located at both sides of the grooved LGP are used for the backlight sources for the left and right eyes as shown in Fig. 5(a). Here in the groove LGP, a prism structure is used on its bottom surface as seen in Fig. 5(b). Angles of the prisms may linearly vary in the one-direction showing a symmetrical angle distribution of the prisms. From this prism structure, both left and right directional beams could be generated by alternate illumination of the LED white-light sources.

The principal function of this groove LGP is to make the out-coming lights from the LGP formed as the quasi-collimated beams with two symmetrical light directions, which are used for the reference beams when they go through the stacked 3-color VHOEs for readout of the corresponding converging object beams. Therefore, the groove LGP with the east and west angles is designed to guide the light beams coming from the LED light sources to produce the directional backlights for two collimated reference beams based on its total internal reflection (TIR). With a ray structure of the grooved LGP of Fig. 5, we can derive Eqs. (12)–(14) showing the angular relationship between the incident and reflected rays on the inclined surfaces of the prisms and the refracted rays on the top surface of the LGP as follows.

\[ \rho = \frac{\pi}{2} - (\theta + \gamma + \alpha), \] (12)
\[
\varphi = \rho - \alpha = \frac{\pi}{2} - \left( \theta + \gamma + 2\alpha \right), \quad (13)
\]
\[
\varphi' = \sin^{-1}\left( \frac{n_{\text{LGP}}}{n_{\text{air}}} \sin(\varphi) \right) \quad (14)
\]

Where \( \varphi \), \( \varphi' \) and \( \varphi'' \) represent the reflected angle on the surface of a prism, the incident angle of the ray toward the top of the LGP and the refracted angle of the out-going ray, respectively. In addition, \( n_{\text{LGP}} \) and \( n_{\text{air}} \) denote the refractive index of the LGP and the index of air, and \( \alpha \) and \( \theta \) are the west angle and the diverging angle of the source incident into the LGP, respectively.

Here, the inclined angle \( \phi \) defined as \( \pi/2 - \varphi \), may determine the incident angle onto the stacked 3-color VHOEs located on the top surface of the LGP. Moreover, Eqs. (12)–(14) may imply that a beam divergence of the LED light source may induce the corresponding divergence of the output rays from the LGP while passing through the surface of the prism formed at the bottom of the LGP. A small number of rays may directly incident onto the prisms locating very near to the LED light sources, which are the cases of (1) and (2) in Fig. 5, have the relatively large diverging angles, so they may cause the negative effects on the quality of the collimated output rays. However, this diverging angle problem can be much alleviated just by introduction of some flat LGP areas without having the grooves near to the LED light sources.

On the other hand, most rays are propagating along the grooved LGP under the process of multiple TIRs as shown in (3) and (4) of Fig. 5. Here, the multiple TIRs may cause a non-uniform spread of the output ray density and the refracted angles on the top surface of the LGP. These non-uniformities resulting from the multiple TIRs on the west and east surfaces of the prisms could be made to be somewhat even at the specific ranges of the west and east angles of the prism. That is, by considering the number of multiple TIRs, the refracted angle \( \varphi \) from the grooved LGP can be calculated as follows.

\[
\varphi = \rho - \alpha = \frac{\pi}{2} - \left( \theta + \gamma + 2n\alpha - 2m\beta \right) \quad (15)
\]

Where \( n \), and \( m \) mean the numbers of total internal reflections occurred on the west and east surfaces. The number of total reflections may range from 3 to 30 according to the structure of the employed prism on the bottom of the LGP. Here, for the white LED incident to the LGP with the diverging angle of about 120°, the diverging angles of the refracted output rays from the grooved LGP gets decreased down to the range of 30° ~40°.

### 3. Experiments and results

To demonstrate the feasibility of the proposed VHOE-based directional backlight system, a new type of the VHOE-based time-multiplexed autostereoscopic 3-D display system is implemented, and its operational performances are analyzed in terms of diffraction efficiency, viewing angular distribution, crosstalk, and color dispersion through experiments with the test stereo video images. Here, the operational procedure of the proposed system is largely composed of 3 processes: 1) Fabrication of two sets of 3-color VHOEs (R, G, B) for each of the left and right eyes by using photopolymer films, 2) Implementation of VHOE-based directional backlights by combined uses of the stacked 3-color VHOEs, the grooved LGP with two LED bars composed of ten LEDs and the LCD panel with the switching and driving modules, and 3) Demonstration of autostereoscopic 3-D displays through experiments with test stereo videos.

#### 3.1 Optical setup for recording the RGB gratings on the photopolymers with a green laser

Figure 6 shows an optical setup for the slanted recording of the volume phase gratings for each of the red, green and blue colors on their photopolymer films by using a green laser of 532nm. Here in the experiment, a slanted transmission-type recording setup is employed.
because the beam angles incident on the stacked 3-color VHOEs and the beam angles diffracted from them are different each other.

Fig. 6. Optical setup for recording the 3-color phase gratings on the photopolymers with a green laser.

As seen in Fig. 6, the DPSS Nd: YAG green laser with 532 nm wavelength and 1 watt output power (Model: Cobolt 04-01, Cobolt Co., Sweden) is used as a recording laser source. The laser light emitting from this DPSS green laser is transformed into the collimated beam with a diameter of 100 mm by combined uses of a spatial filter (SF), a beam expander (BE) and a beam collimator (BC). Then, this beam is divided into the reference and object beams by passing through a cube beam splitter (BS) with the 1:1 power ratio. By combined use of the Mirror 2 and Mirror 3, the reference and object beams come into the recording medium of the photopolymer film. Since the 3-color VHOEs are to be fabricated with a green laser in the experiment, each angle of the reference and object beams for three colors are calculated from Eq. (10).

At first, for fabrication of the green-color VHOE on the photopolymer film, the optical components on the recording system of Fig. 6 have to be adjusted according to the following procedures. The incident angle of the object beam to the photopolymer film is designed to be 6° because the viewing distance and the inter-ocular distance are assumed to be 300 mm and 65 mm, respectively in this paper. Moreover, this object beam is formed as the diverging beam with a converging lens (CL) located in front of the recording plate. A CL with a focal length of 300 mm is used here and it must be located on the right plane between the BS and the Mirror 2 where the beam path apart from the recording plate is always kept to be 600 mm. The grooved LGP with a dimension of 54 mm × 120 mm is designed to refract the out-coming reference beam with an angle of 55°. Therefore, the incident angle of the reference beam for recording must be also 55°, which is the same value with that of the LGP’s output angle. For fabrication of the other red and blue-color VHOEs, the same recording process explained above for the green color can be also applied just by re-adjusting the optical components.

Table 1 shows the calculated angles of the Mirror 2 and the Mirror 3 as well as the calculated locations of the recording plate from the BS to be adjusted for satisfying the recording conditions of the incident angles of the reference and object beams for 3-color VHOEs from Eq. (10). As seen in Fig. 6, a probe laser with a wavelength of 633 nm is also employed for real-time measurement of the variations of diffracted beam powers from the photopolymer films for obtaining the diffraction efficiency.
Table 1. Calculated angles and locations of the optical components for recording the 3-color VHOEs with a green laser.

| Wavelength (nm) | CL distance from the recording plate (mm) | Slanted angle (°) | Mirror2 (°) | Mirror3 (°) |
|-----------------|------------------------------------------|-------------------|-------------|-------------|
| Red             | 633                                      | 610               | 25.07       | 58.42       | 55.17       |
| Green           | 532                                      | 570               | 30.50       | 56.30       | 53.05       |
| Blue            | 490                                      | 650               | 33.63       | 54.19       | 50.94       |

By using the calculated angles and lens distances from the recording plate in Table 1, 3-color VHOEs having the same diffraction angles for all colors are fabricated. Here, the physical size of each VHOE is tailored to be a little bit larger than that of the LGP.

3.2 Optical properties of the employed photopolymer films

In the experiments, the BMS (Bayer MaterialScience) photopolymer film is used as the holographic recording medium. Table 2 shows the specifications of the employed customized experimental photopolymer film [30,31].

Table 2. Specification of the customized photopolymer film (Bayfol® HX)

| Items                                | Specifications |
|--------------------------------------|----------------|
| • Sensitive wavelength range          | 450–680nm      |
| • Peak sensitive wavelength           | 532 nm         |
| • Refractive index                    | 1.485          |
| • Index modulation                    | 0.017          |
| • Substrate thickness                 | 125μm          |
| • Photopolymer thickness              | 16μm           |

From the experiments, diffraction efficiency of the employed photopolymer film has been found to be maximized at a total exposed light dosage of ~30 – 45 mJ/cm² and dropped above 50 mJ/cm² due to the over-modulation. Here, the diffraction-efficiency is defined as

\[ \eta = \frac{P_{\text{Diffracted}}}{P_{\text{Transmitted}}} + \frac{P_{\text{Diffracted}}}{P_{\text{Transmitted}}} \]

in which \( P_{\text{Diffracted}} \) and \( P_{\text{Transmitted}} \) mean the powers diffracted and transmitted from the fabricated VHOEs when the parallel beam is incident, respectively.

Figure 7 shows the variations of the diffracted beam power from the VHOE, which are measured with a probe laser with the wavelength of 633 nm in real-time while the green-color VHOE is under recording. Here, the output power of the probe laser is adjusted to be 10 μW/cm² to avoid an additional optical reaction in the VHOEs. In the experiments, the recordings of grating patterns on the photopolymer films are performed for about 200 sec, and the diffraction efficiency is calculated for three types of light exposures such as 0.3 mW/cm², 1.2 mW/cm² and 1.8 mW/cm². After the light exposures, the recorded VHOEs are bleached for about 10 min fixing exposure times using a regular fluorescent lamp with some UV spectrum for the complete polymerization. The diffraction efficiencies for each of the 3-color VHOEs are measured to be very similar with each other. As shown in Fig. 7, the diffraction efficiency of the recorded VHOE sharply increases up to the maximum value of 92% around the exposure time of 120 sec for the case of 150 μW/cm² light exposure with the green laser. Moreover, the VHOEs with the diffraction efficiency up to almost 99% expects to be fabricated through more sophisticated handling of lamination of the VHOEs on the glass, angle adjustments of the optical components, generation of the collimated plane waves, and so on. The thickness shrinkage of the employed photopolymer film during the photopolymerization process has been estimated to be about 0.8%.
3.3 Fabrication of stacked 3-color VHOEs

In this paper, 3-color phase gratings are recorded on their photopolymer films with a green laser of 532 nm based on the calculated angles and locations of Table 1 with the optical recording setup of Fig. 6. In the proposed system, as mentioned above, the viewing angles for each of the left and right eyes are designed to be 6° under the condition that the viewing distance and the inter-ocular distance are designed to be 300 mm and 65 mm, respectively. Therefore, the object beams for 3-color wavelengths must be diffracted along the same angle direction of 6° as shown in Fig. 9(a). The incident angles of the reference and object beams for each color to the photopolymer films are calculated by using Eq. (11), and the corresponding angles of the optical components in Fig. 7 are shown in Table 1. For each of the 3-color laser sources such as 633 nm, 532 nm, and 490 nm, the corresponding angles between the reference and object beams are adjusted by the half angles of θr,g,b, and the
recording plate is rotated with a slanted angle while its surface is set to be vertical to the path of the optical rail. Moreover, the sheared photopolymer film with a dimension of $70 \text{mm} \times 54 \text{mm}$ is laminated on the glass and fixed on the recording plate of which surface is set to be toward the incident beam.

Now, 3-color VHOEs are fabricated according to the following recording procedures. That is, based on the scheduled exposure time of $120 \text{sec}$ with a green laser power of $150 \mu \text{W}$, the photopolymer films are exposed to the interference pattern between three sets of collimated reference and converging object beams for the 3-color VHOEs and recorded. After recording 3-color VHOEs, they are tightly stacked together in the order of the red, green and blue VHOEs from the bottom.

![Fig. 9. (a) Schematic diagram of the symmetrical relations between the incident and diffracted beam angles on the 3-color VHOEs, (b) Photograph of two sets of fabricated 3-color VHOEs for both eyes.](image)

Then, the stacked 3-color VHOEs for the left eye and the right eye are combined with a reversed stacking structure as shown in Fig. 3. Figure 9(b) shows two sets of optically fabricated 3-color VHOEs for both eyes and the dimension are much larger than that of the LCD panel of $43.9 \text{mm} \times 24.7 \text{mm}$.

After the beam angles diffracted from the fabricated 3-color VHOEs for the collimated white-light illumination are confirmed to be almost same, 3-color VHOE films for the red, green, and blue wavelengths are stacked together in parallel and put on the groove LGP. Here, the diffraction efficiencies for each of the red, green and blue-color VHOEs have been estimated to be 93%, 92%, and 88%, respectively.

Figures 10(a) and 10(b) show three color beams diffracted from each of the fabricated 3-color VHOE films and the white beam diffracted from the stacked 3-color VHOEs, respectively.

![Fig. 10. Photographs of the diffracted beams from the 3-color VHOEs: (a) Diffracted red, green and blue beams from each of the 3-color VHOEs, (b) White beam formation diffracted from the stacked 3-color VHOEs.](image)

Here, since the bandwidths of the red-, green- and red-color VHOEs resulted from the color dispersion for the white-light illumination, might be estimated around $50 \text{nm}-100 \text{nm}$ along the viewing angle of about $6^\circ$, the white beams could be successfully formed from the stacked 3-color VHOEs around the viewing-angle. Moreover, the intensities of the diffracted beams in Fig. 10(a), have been also found to be almost uniform over the size of the LCD.
3.4 Viewing-zones of the stacked 3-color VHOEs-based dual directional backlights

Here, an optical system for measuring the viewing-zones of the proposed VHOE-based 3-D display system is set up to confirm the angular distributions of the viewing zones depending on the viewing angles for the diffracted object beams formed at the viewing distance of 300mm.

For this, two directionally collimated white-light sources are built with the halogen lamps for verification of the operation of our proposed system under the collimated white-light beams. By illuminating these collimated white-light beams on the LCD panel, on which time-multiplexed stereo video images are displayed, formation of the separated viewing zones between two symmetrically converging object beams could be verified. Here, a pair of stacked 3-color VHOEs for both eyes are laminated on the backside of the LCD panel and two white-light sources are illuminating alternately while being synchronized with the LCD panel through the shuttering devices. Then, with the optical detector to be rotated at the center of the viewing-distance of 300mm, the angular intensity distributions of the diffracted object beams can be measured.

Figure 11 shows two symmetrically separated viewing zones measured changing the viewing angles. The viewing angle is defined as the radial position of a detector. In the experiments, most light is found to be distributed along the viewing angle ranges of −30° and 0°, and of 0° and 30°, respectively for each of the left and right backlight illumination.

![Fig. 11. Angular distribution of the proposed VHOE-based directional backlights.](image)

As seen in Fig. 11, the left and right viewing zones of the proposed 3-D display system are measured to be well separated each other, which closely look like those of the conventional 3-D display systems. Moreover, the maximum luminous intensity of the diffracted beam from the VHOEs is measured to be 0.99μW on the viewing-angle of −6° for the left backlight illumination while the light intensity of 0.089μW is also detected on the viewing angle of 6° for the right eye, which means a crosstalk of 8.98% between two views, which meets a maximal accepted crosstalk of 10% [27].

Especially, the longitudinal viewing zone of the proposed system has been measured to be much longer than that of the conventional 3-D display systems. That is, it is found from the experiments that a clear separation between the left and right viewing-zones could be kept to be maintained along the long longitudinal ranges from −240mm to + 360mm [28], which means a binocular disparity for 3-D perception can be achieved on the wider ranges along the longitudinal direction than those of the conventional systems. Moreover, Fig. 12 also shows the photographs of the distinct viewing zones of the converging object beams for the left and right and both sides at the viewing-distance of 300mm, respectively. That is, Figs. 12(b) and 12(c) may conform that only the left and right viewing zones are formed for each of the left
and right white-light illuminations. Here, two white lines marked on the photographs in Fig. 12 indicate the inter-ocular width of 65\,mm at the viewing-distance of 300\,mm.

![Photograph of the viewing-zones of the proposed VHOE-based 3-D display system](image1)

Fig. 12. Photograph of the viewing-zones of the proposed VHOE-based 3-D display system: (a) Viewing-zone of the diffracted beams for both sides, (b) Viewing zone for the left-side diffracted beam, (c) Viewing-zone for the right-side diffracted beam.

3.5 Prototype implementation of the proposed VHOE-based autostereoscopic display system

Finally we implemented a prototype of the proposed VHOE-based autostereoscopic display system by assembling a pair of the fabricated 3-color VHOE films on the backlight mold frame with the grooved LGP and the LCD panel, and by connecting the assembled display module to the fabricated moving image player board incorporating the LED backlight switching function.

Figure 13 shows the implemented VHOE-based 3-D display system. On the left side, a stereo image processing module, and a backlight switching module being synchronized with the stereo video images are implemented on the circuit board. On the SD memory, stereo video images formatted with the top/down method are stored as the MPG format, and the CPU mainly functions to divide the stereo video images in the left and right images according to the vertical signals. MCU 1 and 2 control the synchronization of the left and right LED bars.

![Photograph of an overall prototype of the proposed VHOE-based time-multiplexed autostereoscopic 3-D system](image2)

Fig. 13. Photograph of an overall prototype of the proposed VHOE-based time-multiplexed autostereoscopic 3-D system.

Moreover, on the right side, an LCD panel and a backlight system adapting the grooved LGP and the stacked 3-color VHOEs are assembled on the black mold frame. Here, the LCD panel (NL9654HL06-01J, NEC) with a diagonal size of 2.7\," has the response time of 14.5\,ms and the resolution of 960 × 540 pixels. The LED bars are attached on both sides of the LGP. Here, the LGP is fabricated to be grooved with the prisms having the period of 80\,μm and the east and west angles of 7°, which are calculated, based on Eq. (15) for obtaining the outcoming beam with the inclined angle of 55°, and this grooved LGP guides the quasi-collimated reference beams.

Figures 14(a) and 14(d) show the photographs of the left and right video images of an animated moving space ship which are observed on the corresponding viewing-points at the
viewing-distance of 300mm. Actually, for the case that the left LED bar turns on, only the left viewing-zone for the left image is viewed while the counterpart viewing-zone for the right image is kept to be almost dark, and vice versa. Even though there exists a very small amount of crosstalk images as shown in Figs. 14(b) and 14(c), Fig. 14 confirms a clear separation between the left and right images with a crosstalk of much less than 9%. This good result may be rooted from the facts that the multi-reflected beams occurred in the LGP and the 3-color VHOEs could be almost absorbed with the adopted black-mold frame and the black-masks located on both sides of the LGP.

Finally, we observed the natural 3-D effects from these time-sequentially displayed stereo video images from the implemented prototype of Fig. 14. This good 3-D perception could be achieved, in the proposed system, with the continuously formed two white viewing-zones based on the color dispersion along the horizontal and longitudinal directions.

4. Discussions

In contrast to the state of the art spatial-multiplexed parallax barrier or lenticular sheet-based autostereoscopic displays, a new VHOE-based display design was implemented. A robust holographic recording scheme was developed and 3-color responsive VHOEs were made by a green only holographic recording. No precise fabrication of micrometer-sized 3-D prism films for generation of the directional beams is therefore needed, nor is an alignment to the display pixels required in the proposed VHOE-based backlight system. The proposed system also uses white, lambertian light sources which are usually difficult to apply to volume holographic diffractive optics instead of laser sources.

Moreover, in the proposed system only the reference beams satisfying the very selective Bragg-condition were diffracted to the pre-designed directions, so crosstalk can be kept to a small amount that did not lead to any visual disturbance, which may occur in the conventional system due to the light scattering between the LGP and the prism sheet. In the experiments, the optical power efficiency of the stacked 3-color VHOE films also shows a high diffraction efficiency of ~90%, which is competitive to the conventional 3-D films utilizing prism structures.
Furthermore, the proposed system incorporating the VHOE-based dual directional backlights offers the continuous viewing zones in the horizontal direction within the inter-ocular distance at the viewing distance of 300\text{mm}, and much wider viewing ranges of 240-360\text{mm} along the longitudinal direction compared to those of the conventional systems.

Hence, the proposed VHOE-based directional backlight system can be made as a very slim-structure. Here, the thickness of the fabricated 3-color VHOEs is estimated to be 0.87\text{mm} by using the photopolymer film with a substrate of 125\text{μm}. Moreover, it could be further reduced down to 50\text{μm} in case a time scheduling-based multi-recording schemes on a single photopolymer film would be employed.

In addition, light losses due to scattering or haze which mostly occur in the conventional photopolymers during the recording process do degrade the effective light efficiency and the beam separation performance of the fabricated VHOEs. This could be alleviated in the proposed system by using a new custom type of the photopolymer films. These self-developing photopolymer films used for fabrication of 3-color VHOEs also have several attractive advantages such as easy handling, dry processing, good stability, high sensitivity, large diffraction efficiency and high resolution.

Thus far, the proposed VHOE-based directional backlight system has been demonstrated on a 2.7” LCD mobile display here, but its application can be extended to large-size LCD displays if large-scale optical recording systems to fabricate the corresponding VHOEs are provided.

5. Conclusions

In this paper, a novel type of the directional backlight system based on 3-color VHOEs has been proposed for the slim-structured time-multiplexed autostereoscopic 3-D LCD mobile displays. The VHOEs have been fabricated using a new easy to handle photopolymer film requiring no post processing schemes and minimal shrinkage. A major advantage of this demonstrated system is a simplification of the backlight unit and display assembly process, keeping the original resolution of the display panel, an enlarged viewing zone and utilization of state of the art display components like a high speed LCD panel and conventional white LEDs as light sources.

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