Design of autostereoscopic 3D display with full resolution by means of polarization gratings

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Abstract

Autostereoscopic 3D, a kind of display technology, can give people an amazing visual experience. A design of autostereoscopic 3D display based on the polarization gratings is proposed in this paper. The designed system is placed on the outside surface of LCD. Image from two video sources which have parallax, can be alternately displayed on the LCD screen at a rate of 48 frames per second, and owing to polarization gratings, the direction of emergent light of the system can be changed which depends on the handedness of the incident light. By using the unique diffraction characteristics of the polarization gratings and fast response of liquid crystal, the image from two different video sources enters people’s left and right eye respectively. Due to the existence of parallax, people can perceive depth of the image. The system is based on the time division multiplexing of LCD pixels, so there is no pixel loss and image with full resolution can be used.

1. Introduction

Three dimensional (3D) display is a particular device that enables a viewer to perceive the depth of an image [1]. Autostereoscopic 3D display can not only provide people with exciting visual impact, but also viewers do not need any auxiliary equipment. Multiple viewing points are needed for acquiring the 3D effect in different direction and zone. There are many kinds of implementation schemes for autostereoscopic 3D display. For example, some schemes are based on geometrical optics or parallax barrier, and using cylindrical lens or micro lens as the basic principle is also attracting the attention of the researchers [2–8]. But these schemes can only provide image with limited resolution, and the ghost images and visual fatigue always exist. A directional backlight scheme is proposed to solve these problems, however crosstalk between viewing zones still exist [9, 10]. Projecting the image on the rotating screen has also been studied, but it is very difficult to be applied to the portable electronic devices [11]. Electronic holography is once considered to be a promising 3D display scheme by many people, however due to the refreshable data volume, it has an amazing performance in autostereoscopic 3D field now could not be expected [12, 13]. Because these solutions for autostereoscopic 3D generally use the spatial division multiplexing of LCD pixels now, the images which they provide are all with low resolution. However the resolution is the most important for watching the video, low resolution can not give people a good experience.

Polarization gratings attract a lot of attention in research field due to unique diffraction characteristics [14, 15]. In this paper, a design of autostereoscopic 3D display with full resolution based on the polarization gratings is proposed, which is fabricated with a holographic setup by using orthogonal circularly polarized laser beams. The direction of diffraction light of polarization gratings is not the same for incident light with different circularly polarization. The diffraction angle can also be adjusted by changing the angle between two writing beams of light when fabricating the polarization grating. This feature of the polarization gratings and high-speed refresh rate of liquid crystal display can be used to realize autostereoscopic 3D effect. By placing a twisted nematic liquid crystal layer on the emergent light side of the LCD, the polarization of the light can be changed,
which depends on whether there is an electric field in the liquid crystal layer. The quarter wave plate (QWP) is placed after the liquid crystal box to change the linear polarized light into circularly polarized light. When the emergent light from the LCD, whose linear polarization direction is the vertical, passes through the twisted nematic liquid crystal layer, its polarization direction rotates 90° and becomes horizontal. Then it passes through the QWP and becomes the right-handed circularly polarized light. When the right-handed circularly polarized light is incident on the polarization gratings, the left-handed circularly polarized light generates in the +1st order diffraction direction. Therefore the image on the LCD propagates in this direction and finally enters the person’s left eye. Then add an electric field which is perpendicular to the liquid crystal layer is added to the liquid crystal box, and the liquid crystal laser lose the ability to change the polarization of light, so after the emergent light from the LCD passes through the liquid crystal box, its polarization direction still is vertical. It becomes the left-handed circularly polarized light through the QWP. When the left-handed circularly polarized light is incident on the polarization gratings, the right-handed circularly polarized light generates in the -1st order diffraction direction. Therefore the image on the LCD propagates in this direction and finally enters the person’s right eye. The image which enters the person’s right eye and the image which enters the person’s left eye are two pictures with parallax, so user can perceive depth of the image. This system is based on the unique diffraction characteristics of the polarization grating. Circularly polarized light can be diffracted by the polarization gratings, and the diffraction direction is only +1st or -1st order, which totally depends on its handedness. Because the system has a very thin thickness, and it also does not affect the original structure of the LCD display, this system can be easily integrated into the LCD display.

2. The structure of the system

In this system, the output light from LCD is linearly polarized and every three monochromatic pixels comprise an image pixel. Every monochromatic pixel, liquid crystal box, corresponding QWP, and the corresponding polarization gratings comprise the unit of the system. The orientation of the liquid crystal molecules in the incident plane of liquid crystal box is parallel to the polarization direction of the output light. The orientation of the molecules gradually rotate 90° in the box if without the electric field. The polarization of light is rotated 90° along with the liquid crystal molecules. If the polarization of incident light is vertical and then rotates to the horizontal direction when light passed through the liquid crystal box. After the horizontal polarized light passes through the QWP, and because of the birefringence of QWP, the horizontal polarized light transforms into the right-handed circularly polarized light. Right-handed circularly polarized light is incident on the polarization gratings, and the diffraction direction is only +1st or -1st order, which totally depends on its handedness. If adding an electric field, which is perpendicular to the liquid crystal layer, to the liquid crystal box, the orientation of the molecules all are forced to rotate to be in line with the direction of the electric field. The liquid crystal box can not change the polarization of the incident light in this case, so the polarization direction of the emergent light from liquid crystal box is still vertical. The vertical polarized light passes through the QWP and transforms into the left-handed circularly polarized light. Left-handed circularly polarized light is incident on the polarization gratings and produces the -1st order diffraction light. As shown in figure 1, it is the schematic diagram of the system.

Due to the wavelength of every monochromatic light is not the same, the thickness of corresponding QWP is different.

$$\delta = \frac{2\pi h(n_e - n_o)}{\lambda} = \frac{2\pi \delta n}{\lambda}$$
δ is the phase delay between ordinary light and unusual light when polarized light transmit through the QWP. λ is the wavelength of the polarized light and h is the thickness of QWP. The n is the birefringence of QWP for λ. Due to δ for QWP is always equal to \( \pm \pi \) or \( \pm 2\pi \) odd times, h vary accordingly to the wavelength and the thickness of QWPs for different monochromatic pixels is not the same. Take the polarization direction of the linear polarized light for the x-axis. The QWP is placed perpendicular to the z-axis and the angle between its fast axes and x-axis is θ degrees. According to the Jones matrix formula:

\[
E = \begin{bmatrix} \cos^2 \theta + i \sin^2 \theta & \cos \theta \sin \theta (1 - i) \\ \cos \theta \sin \theta (1 - i) & i \cos^2 \theta + \sin^2 \theta \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

\[
E = (\cos^2 \theta + i \sin^2 \theta) \begin{bmatrix} \cos \theta \sin \theta (1 - i) \\ 1 \end{bmatrix} 
\]

\[
E = (\cos^2 \theta + i \sin^2 \theta) \begin{bmatrix} 1 \\ b e^{i\phi} \end{bmatrix}
\]

Among them, \( b = \frac{1}{\sqrt{1 + \cos^2 \theta}} \), which is the amplitude ratio of the y component and x component. When taking θ for 45°, b is equal to 1, and the emergent light of QWP is circularly polarized light.

The polarization gratings is the core component to determine the direction of the emergent light, and the propagation matrix of the diffraction in +1st or −1st order of polarization gratings is shown in the following formula:

\[
T_{\pm 1} = \sin \Delta \varphi \frac{i \exp(\pm i\phi)}{2} \begin{bmatrix} i & \pm 1 \\ \pm 1 & i \end{bmatrix}
\]

When the incident light is linearly polarized, the formula for the light field of diffraction in +1st or −1st order is:

\[
E_{\pm 1} = \frac{\sin \Delta \varphi}{2} \begin{bmatrix} \pm \sin \alpha & +i \cos \alpha \\ \pm \cos \alpha & -i \sin \alpha \end{bmatrix}
\]

When the incident light is right-handed circularly polarized, there is only the existence of the diffraction in +1st order. While there is only the existence of the diffraction in −1st order when the incident light is left-handed circularly polarized. The diffraction efficiency can reach 100% when the thickness of the material of polarization gratings film L and its optical anisotropy Δn meet the half wave condition: \( L \Delta n = \frac{\lambda}{2} \). Among them, the λ represents the wavelength of the incident light. The schematic diagram is shown in figure 2.

The red spiral line represents the incident light and emergent light, gray flat panel represents the polarization gratings. The optical axis orientation is in cycloidal manner in the polarization gratings plate (a). A circularly polarized light penetrates to the polarization gratings and generates diffraction in +1st or −1st order, which totally depends on its handedness (b) and (c), and both +1st and −1st orders are present for a linearly polarized light (d).
3. Simulation, experiments and results

3.1. The ray tracing of system simulated by software
In order to find the viewing zone where we can watch stereoscopic image, we used the software to simulate the system and carried on the ray tracing and the consequences are as shown below.

In figures 3(a) and (b), the two red point light sources represent two pixels at both ends of the LCD and red lines indicate the distribution of the light from point light sources due to the diffraction of the polarization gratings. Short heavy line represents the polarization gratings and long thin line represents the position which has 20 cm distance from the polarization gratings.

As we can see, in figure 3(c), the short gray line represents the system and long gray line represents the position which has 20 cm distance from the system. The red line represents the slide and the blue lines represent the parallel white incident light generated by surface light source, which is diffracted by the polarization gratings and the diffraction angle is $-8^\circ$. The picture in figure 3(d) indicates the colorful image forming on the detector, the detector is located at the position where the blue lines and long gray line overlap in figure 3(c). The image is of high quality and has no deformation. The luminance distribution of the image is uniform and there is no obvious dispersion.

3.2. The fabrication and detection of polarization gratings
A polarization gratings is fabricated and the experimental light path as shown in the figure 4. Among them, the 532 nm laser is used as the recording light to write polarization gratings in the azo liquid crystal layer. Firstly, 532 nm laser is divided into two beams after it transmitted through a beam splitter prism. They both are linearly polarized light which have same polarization direction. Then let one travels through the QWP and it is converted to the left-handed circularly polarized light, another one travels through the HWP and QWP, which is converted to the right-handed circularly polarized light. These two beams of light interfere in the azo liquid crystal layer and finally form the polarization gratings.
The 632.8 nm laser is used as the detecting light which is converted to right-handed circularly polarized light with the help of QWP, and the energy of diffraction light is mainly concentrated on $+1$st order. Then the QWP is adjusted and left-handed circularly polarized incident light is acquired, and the energy of diffraction light is mainly concentrated on $-1$st order. If the thickness of the polarization gratings meet the half wave condition, the diffraction efficiency will be 100%, and the energy of diffraction light will absolutely concentrate on $+1$st or $-1$st order. The polarization and intensity of the $+1$st or $-1$st order diffraction light have been detected, and the consequence as shown in figures 5 and 6.

When the incident light was right-handed circularly polarized (a), the polarization of the $+1$st order diffraction light has been measured by polarization detector, which is left-handed circularly polarized (b). When the incident light was converted to left-handed circularly polarized (c), the polarization of the $-1$st order diffraction light is right-handed circularly polarized (d).

As shown in figure 6, because the recording of polarization gratings and the diffraction experiment were conducted simultaneously, the intensity of diffraction light gradually increased over time and reached the
maximum since opened the recording light for 31 min, the intensity basically remained unchanged after the recording light had been closed.

3.3. The construction of simplified model of the system
A simplified model of the system is constructed to verify the working principle. The schematic diagram of the structure is shown in the figure 7.

The laser generates a light whose wavelength is 632.8 nm and the polarization direction is perpendicular to the plane of incidence. A square wave signal generated by signal generator is added to the transparent electrode layer covering the front and back surface of the liquid crystal layer, whose duty ratio is 1:1 and frequency is 48 Hz. When the high voltage is added to the transparent electrode layer, there will be a vertical electric field in the liquid crystal layer. The long axis of all the liquid crystal molecules are parallel to the electric field direction and perpendicular to the electrode plate. The polarization of the light remains the same through the liquid crystal layer (light 1). When no voltage is added to the transparent electrode layer, there will not be electric field in the liquid crystal layer. The polarization direction of the light rotates 90° after it passed through the liquid crystal layer and the polarization direction is parallel to the plane of incidence (light 2). The linearly polarized light changes into circularly polarized light through the QWP. It is incident on the polarization gratings, the diffraction light generates and the direction depends on the polarization of the incident light. The diffraction light has been found mainly in the −1st order when the high voltage is added to the transparent electrode layer, and mainly in the +1st order when no voltage is added to the transparent electrode layer, which has verified the basic principle of the system.

3.4. Solution for multiple viewpoints
In order to let 3D images with high quality could be seen in more than one viewing zone, the system have been further designed.

As shown in figure 8, the vertical linearly polarized light from LCD firstly passes through the liquid crystal box1 (LCB1), two orthogonal linearly polarized light can respectively be acquired, which depends on whether there is an electric field in LCB1. Then the linearly polarized light converts into the right-handed or left-handed circular polarized light through the QWP1. The circularly polarized light is incident on the PG1 and produce the −1st order or +1st order diffraction light, which depends on the handedness of the incident light. The diffraction light passes through QWP2 and respectively converts into two orthogonal linearly polarized light,
and then passes through the LCB2, two sets of orthogonal linearly polarized light can respectively be acquired, which depends on whether there is an electric field in LCB2. The emergent light converts into circularly polarized light through the QWP3. The circularly polarized light is respectively incident on the PG1 and produces diffraction light in four different directions. In general, the diffraction angle deviating from the normal direction of PG2 for the four directions are $-20^\circ$, $-6^\circ$, $6^\circ$ and $20^\circ$. The reduction of light intensity can be ignored because the diffraction efficiency can theoretically reach 100% if the half wave condition is met and the absorption of energy by material of polarization gratings is small due to the thin thickness of the material, generally about 10 $\mu$m. The LCD panel is loaded with corresponding image provided by four video sources when the light transmit in different directions. The images from the four directions can provide three viewpoints where people can acquire 3D images with high quality.

The transparent electrode layer can be covered on the front and back side of the polarization grating, and can control whether there is a electric field in polarization gratings to realize the conversion between 2D and 3D model.

4. Conclusions

In this paper, a new design of autostereoscopic 3D display with full resolution is proposed. This design is based on the unique diffraction characteristics of the polarization gratings, which is different with the previous solutions. An optical system, which is specially designed, is placed at the emergent light side of the LCD. The optical system consists of liquid crystal box, QWP, and polarization grating. By controlling whether add the voltage to the electrode plate of liquid crystal box to decide whether there is electric field in liquid crystal layer, the polarization of light can be changed after it passed through the liquid crystal layer, and the direction of the output light of the system can be changed rapidly and alternately.

A simplified model of the system has been designed to verify the basic principle of the new system. Moreover, we have discussed the display effect by stimulating the system and the results indicate the system work well. We have also discussed the solution for multiple viewpoints and theoretically explore the feasibility of it. The prototype of this system and specific results of experiment will be given in further work.

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References

[1] Wan W-Q, Qiao W, Huang W-B, Zhu M, Ye Y, Chen X-Y and Chen L-S 2017 Multiview holographic 3D dynamic display by combining a nano-grating patterned phase plate and LCD Opt. Express 25 1114–22
[2] Kim S-K, Yoon K-H, Yoon S K and Ju H 2015 Parallax barrier engineering for image quality improvement in an autostereoscopic 3D display Opt. Express 23 13230–44
[3] Lv G-J, Wang J, Zhao W-X and Wang Q-H 2013 Three-dimensional display based on dual parallax barriers with uniform resolution Appl. Opt. 52 6011–5
[4] Luo J-Y, Wang Q-H, Zhao W-X and Li D-H 2011 Autostereoscopic three-dimensional display based on two parallax barriers Appl. Opt. 50 2911–5
[5] Takaki Y and Nago N 2010 Multi-projection of lenticular displays to construct a 256-view super multi-view display Opt. Express 18 8824–35
[6] Kim H, Kim J, Kim J, Lee B and Lee S-D 2015 Liquid crystal-based lenticular lens array with laterally shifting capability of the focusing effect for autostereoscopic displays Opt. Commun. 357 52–7
[7] Zhao W-X, Wang Q-H, Wang A-H and Li D-H 2010 Autostereoscopic display based on two-layer lenticular lenses Opt. Lett. 35 4127–9
[8] Chang Y-C, Jen T-H, Ting C-H and Huang Y-P 2014 High-resistance liquid-crystal lens array for rotatable 2D/3D autostereoscopic display Opt. Express 22 2714–24
[9] Fattal D, Peng Z, Tran T, Vo S, Fiorentino M, Brug J and Beausoleil R G 2013 A multi-directional backlight for a wide-angle, glasses-free three-dimensional display Nature 495 348–51
[10] Chien K-W and Shieh H-P D 2006 Time-multiplexed three-dimensional displays based on directional backlights with fast-switching liquid-crystal displays Appl. Opt. 45 3106–10
[11] Eldes O, Akşit K and Urey H 2013 Multi-view autostereoscopic projection display using rotating screen Opt. Express 21 29043–54
[12] Yamamoto K, Ichihashi Y, Senoh T, Chihara K and Kurita T 2012 3D objects enlargement technique using an optical system and multiple SLMs for electronic holography Opt. Express 20 21137–44
[13] Sasaki H, Yamamoto K, Wakunami K, Ichihashi Y, Oi R and Senoh T 2014 Large size three-dimensional video by electronic holography using multiple spatial light modulators Sci. Rep. 4 6177

[14] Guo M, Xu Z and Wang X 2008 Photoinduced polarization gratings in molecular glass containing azobenzene and chiral isosorbide moieties Opt. Mater. 31 412–7

[15] Zhou J, Shen J, Yang J, Ke Y, Wang K and Zhang Q 2006 Fabrication of a pure polarization grating in a cross-linked azopolymer by polarization-modulated holography Opt. Lett. 31 1370–2