Compact auto-stereoscopic display based on directional backlight using side-glowing polymer optical fiber array*

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A compact directional backlight module of time-multiplexed auto-stereoscopic display based on side-glowing polymer optical fiber (SGPOF) is proposed. The optical system is mainly composed of SGPOF array and cylindrical lens array. Spatial crosstalk is reduced by inserting a grating film as multi-slit diaphragm between the SGPOF array and the cylindrical lens array. A theoretical model is constructed based on the imaging optics principle of the off-axis ray. In the experiments, the cylindrical lens array concentrates a small number of views on three different view zones, the display can provide high luminance. The measurement results show that the luminance uniformity of the backlight module is up to 89.6%, and in the viewing zone the crosstalk is lower than 10%. The backlight module is compacted that the thickness being only 7 mm. The full-resolution and low-crosstalk 3D images are realized by using SGPOF backlight.

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Auto-stereoscopic display technology can achieve stereoscopic effects without wearable devices such as glasses or helmets and is regarded as the future main-stream three-dimensional display technology. The method is mainly divided into two types of space and time multiplexing[1-7]. In the spatial multiplexing, a switch liquid crystal screen, polarizing coating, and a high-molecular liquid crystal layers are used, and the vertical fringe is manufactured by using the liquid crystal layer and the polarizing coat to form a parallax barrier. In stereoscopic display mode, the opaque stripes occluded the right eye when the left eye image was displayed, and the viewer could see the 3D images by separating the visual images of the left eye and the right eye. However, it has many disadvantages, such as low resolution, low optical efficiency and narrow-angle of view, and it is necessary to align the LCD pixels accurately with the fringe panel. Most importantly, the image resolution is reduced, and the spatial multiplexing display technology cannot provide a full-resolution stereoscopic images[8].

In order to overcome these disadvantages, the auto-stereoscopic display based on time-multiplexing directional backlight technology has advantages such as keeping the original resolution of liquid crystal display unchanged. And it has become a research hotspot of stereoscopic display technology. At present, there are two main methods to use time-multiplexing directional backlight: One is a time-multiplexing directional backlight scheme consisting of a multi-pointing backlight unit and a liquid crystal display as a time-multiplexing switch[9,10]. The other is a mixed space-time directional backlight scheme by controlling the switch of the light source and changing the projection angle of the light source[11]. The first type of time-multiplexing directional backlight scheme needs to add another LCD panel to the original liquid crystal display. The structure is more complex, the display module is thicker and the cost is higher. The light source projection system of the second type of time-multiplexing directional backlight scheme has complex structure, high precision of machining and installation, and the light source projection system takes up a large amount of space.

In past decades, various new technologies of directional backlight were proposed, such as a multidirectional diffraction backlight technique[12]. This technique is to produce a layer of silicon nitride on a glass surface using a chemical weather deposition method to allow high resolution, full-parallax three-dimensional images to be drawn on a very wide viewing area. The key is a guided wave illumination technology based on LEDs, which generates wide-angle and multi-angle color images from thin plane transparent light guide. The multi-directional backlight provides the basis for a very efficient display and can use multiple passes of the incident light, such as in a standard

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LCD. However, the pixel modulation method requires polarized light, and low efficiency makes the multi-directional backlight not directly apply to a 3D display product. Another technology is a three-dimensional display method of directional backlight timing based on cylindrical optical elements (COE) density LED array[13]. It is suitable for viewing under ambient lighting conditions. And full-resolution of the display images can be provided with time-division multiplexing technology. However, the display has complex structure and large volume.

As reported in our last paper[14-18], previous research has established that manufacture and application of side-glowing polymer optical fiber (SGPOF) in display filed. In this paper, a directional backlight module based on SGPOF is presented and it has been verified by experiments. A set of black-and-white grating films are introduced into the SGPOF backlight plate to filter out the stray light. The directional backlight with uniform luminance distribution is obtained through the cylindrical lens array. Our directional backlight module achieves two main goals: highly uniform lighting on the display screen and viewing positions insensitive to observed uniformity, which are necessary for naked-eye 3D display.

The directional backlight module is designed based on the uniform SGPOF. As shown in Fig.1, the focal length of the cylindrical lens array is on its focal plane. A grating film sheet is between the cylindrical lens array and the SGPOF, which is used to filter the stray light and reduce the crosstalk, for the sake of ensuring the uniformity of the directional backlight source. The SGPOF is fixed on the film, in which the grating constant on the film is consistent with that of the SGPOF array. All the devices are fixed on the black backplane, and there is a reflective film between the black backplane and the SGPOF array to recover stray light and improve the utilization rate of light energy. In order to verify the design theory, a 3D backlight system is established. The system layout diagram is shown in Fig.2, and the detailed parameters of the system design are shown in Tab.1. Each column of the cylindrical lens array has two SGPOFs, one for the left viewing zone and the other for the right viewing zone. All the directional light beams from different SGPOF numbered 1 converge in the right eye, and the light beams from different SGPOF numbered 2 converge in the left eye. The two light beams have electronic controllers and processors independently to control?>: the on or off synchronization with the display of the LCD screen. In the process of machining the backlight module, the high precision grating film is pasted on the cylindrical lens array firstly. The SGPOF is then fixed to the transparent slit of the grating film to ensure the correct layout of the SGPOF.

In the directional backlight 3D display based on the SGPOF, the optical system is mainly composed of SGPOF and cylindrical lens. The light source is the SGPOF array. As shown in Fig.2, The diameter of the SGPOF is d. The cylindrical lens array is a conventional cylindrical lens with a cross section of circular arc, and let the curvature radius be R.

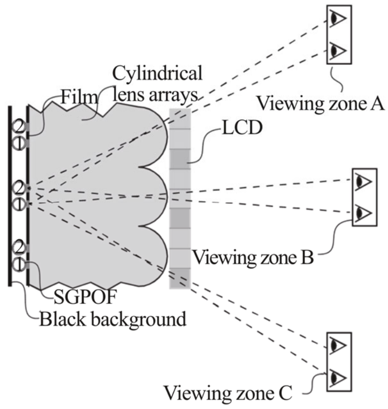

Fig.1 Structure and principle of directional backlight 3D display with an SGPOF array as a backlight

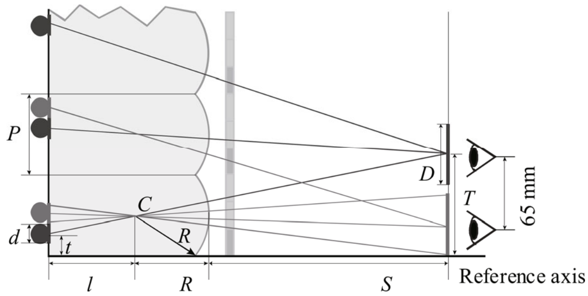

Fig.2 Schematic diagram of the light path in the optical system composed of SGPOF array and cylindrical lens

Tab.1 Designed parameter

Parameter	Value	Parameter	Value
d (mm)	0.5	σ (mm)	1.421 85
P (mm)	1.411 1	n_0	1.595
R (mm)	2.238 2	l (mm)	3.761 8
f (mm)	6	S (mm)	486.8

In Fig.2, it is a schematic diagram of the light path in the optical system composed of SGPOF array and cylindrical lens array. The reference axis is placed at the junction of the two cylindrical lenses. Where P denotes the cylindrical lens width, l denotes the distance from the SGPOF to the center of the cylindrical lens, S is the distance from the arc surface of the cylindrical lens to the observation surface. T and t denote, respectively, the offset of one edge of the object relative to the reference optical axis. According to geometry knowledge, Eqs.(1) and (2) can be obtained as

$$\frac{\frac{P}{2}-t}{T-t}=\frac{l}{R+S+l}, \tag{1}$$

$$\frac{d+\omega}{65}=\frac{l}{R+S}. \tag{2}$$

After simplification, T can be obtained from Eq.(1) as

$$T=(\frac{1}{2}+\frac{R+S}{2l})P-\frac{R+S}{l}t, \tag{3}$$

where ω represents the distance between the numbered 1 and the numbered 2 fibers. The focal length in the object space of the cylindrical lens element is calculated as

$$f=\frac{nR}{n-n_0}, \tag{4}$$

where n denotes the air refractive index and n_0 denotes the medium refractive index. The next periodic position of the side-glowing fiber from the same viewpoint is σ+t. The distance 3/2P between the center of curvature and the reference axis is adjacent cylindrical lens imaging. And also the light beam is projected to the same point of view. According to Eq.(3),

$$T=(\frac{1}{2}+\frac{R+S}{2l})(\frac{3}{2}P)-\frac{R+S}{l}(t+\sigma). \tag{5}$$

Apparently, from Eq. (2) and Eq. (3), the distance σ between two SGPOFs from the same viewpoint is calculated as

$$\sigma=\frac{1+\frac{R+S}{l}}{\frac{R+S}{l}}P=\frac{l+R+S}{R+S}P. \tag{6}$$

For the m column of the cylindrical lens array, the SGPOF coordinates $\sum$ of the same viewpoint is:

$$\sum=m\sigma+t. \tag{7}$$

For an auto-stereoscopic display, theoretical values of structure parameters of optical system are listed in Tab.1.

The SGPOF backlight module enables us to control luminance uniformity and reduce crosstalk. We measure the luminance distribution of different angles by using an imaging luminance meter. The luminance distribution is located at the front 486.8 mm optimum viewing distance of the SGPOF backlight, and the viewing angle can be converted to a parallel moving distance $X_{position}$ through Eq.(8):

$$X_{position}=\frac{\theta\pi S_L}{180}. \tag{8}$$

The measuring device is shown in Fig.3, when placing the SGPOF directional backlight on an angled rotatable disc, attention should be paid to making the center vertical line of the backlight coincide with the rotation axis of the rotatable disc when placing the SGPOF directional backlight. The CX-2B imaging luminance meter is placed at the distance of the SGPOF directional backlight 486.8 mm. When the rotating disc is used to measure the luminance of the backlight at different angles at 0.5° intervals.

As shown in Fig.4(a)-(c) and Fig.4(d)-(f) respectively show the backlight luminance distribution and the crosstalk for right eye and left eye at A, B, and C viewing zones. Fig.4(a) shows that the luminance for right eye at viewing zone A is slightly higher than the luminance for left eye. At symmetry position of right, the luminance for left eye at viewing zone C is slightly higher than the luminance for right eye, as shown in Fig.4(c). This is due to the difference in the incident angle of the light rays in the cylindrical lens array. Since the off-axis source (viewing zone A and C) results in a large aberration, such a factor is inevitable. The general nature of the decentering aberration function have been analyzed in some fundamental papers[19].

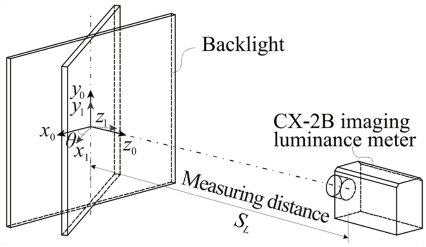

Fig.3 Configuration for measurement of crosstalk

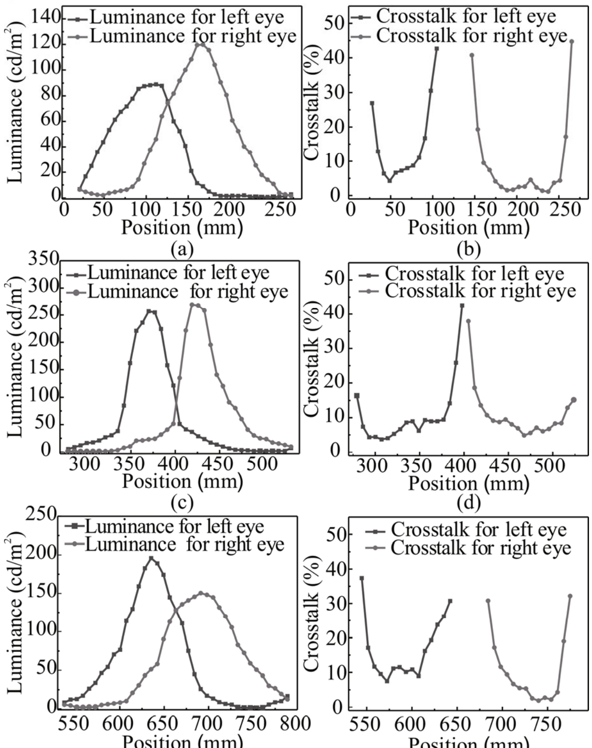

Fig.4 Illustrations of the crosstalk measurement of the directional backlight based on SGPOF: (a)-(c) Luminance distribution of binocular; (d)-(f) Crosstalk right eye and left eye at A, B, and C viewing zones

The crosstalk could be caused principally by the internal reflection and scattering of the optical lens existing in our current prototype. In our system, scattering is mainly due to two factors, that is, in an ideal cylindrical lens array structure, each cylindrical lens element is seamlessly connected. However, in the actual processing process, the joint of the two lens elements has a limited gap[20]. Outside the defect region, the transmission of light through the optical system obeys Snell's law. In fact, there are defects in the cylindrical lens array, such as material impurity, machining precision or tool radius limit, etc., which causes stray light in the linked slit region relative to the other parts of the lens, and thus increases crosstalk. The diffraction of light through LCD sub-pixels is inevitable[13]. Fig.4(b) shows that the luminance for left and right eyes at the viewing zone B is basically the same, and there is no luminance deviation.

The crosstalk is calculated by:

$$Crosstalk = \frac{L_{\text{noise}}}{L_{\text{signal}}} \times 100\% \cdot \tag{9}$$

It is basically consistent with our expected results. The calculated crosstalk is slightly larger than that of the expected result because of the error in the fabrication of optical fiber array in the experiments. However, in the viewing zone the crosstalk is lower than 10%, as show in Fig.4(d)-(f).

As shown in Fig.5(a), the thickness of the backlight source of the 3D display is only 7 mm based on the SGPOF, and in Fig.5(b), the overall thickness including the LCD screen is only 18 mm, which reduces the space occupied by the 3D display.

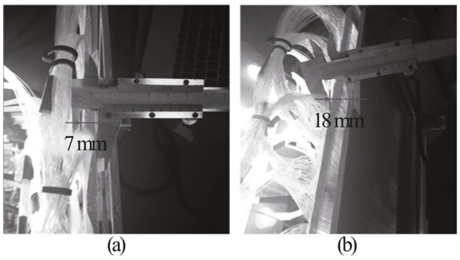

Fig.5 The thicknesses of (a) backlight source and (b) 3D display screen

The photographs of the displayed dolphins captured at different times within the viewing distance are demonstrated in Fig.6. The *x*-axis denotes time sequence, while the y-axis corresponds to the different images received by the observer's left and right eyes. At time t_1, in the case of right eye, a bright image appears, while the left eye image appears dark due to the backlight in the direction of the time sequence principle. Similarly, at time t_2, a bright image can be observed in the left eye, while a bright image cannot be seen in the right eye. This indicates a clear separation between the left eye and the right eye, although there is a small crosstalk that the observer can tolerate. At time t_3, the image was restored to t_1 so that can form a periodic display.

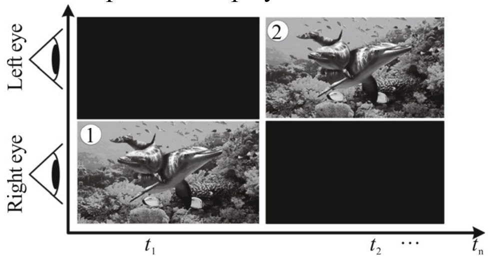

Fig.6 Photos of images displayed by each viewpoint at different time

For purposes of evaluating the luminance uniformity of the directional backlight, we measure the luminance of the middle points on the backlight and four points at its corners, which is called 5-point method[21]. The sampling location as shown in Fig.7, and the experiment setup as shown in Fig.8. The luminance measurement is carried out by using CX-2B imaging luminance meter, the light source used in the directional backlight modular is the CREE-XPL-HI-3535-LED. In order to reduce the measurement error, the sampling points are measured three times, and the measurement results are shown in Tab.2. The average luminance uniformity M is calculated by Eq.(10):

$$M = \frac{L(P_i)_{\min}}{L(P_j)_{\max}} \times 100\% , \tag{10}$$

where $L(P_i)_{\min}$ denotes the minimum luminance value of the i point and $L(P_j)_{\min}$ denotes the maximum luminance value of the point. According to the values in Tab.2, the luminance uniformity of the SGPOF directional backlight is 89.6%.

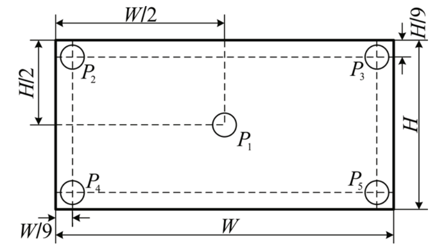

Fig.7 Sampling position of five-point measurement method

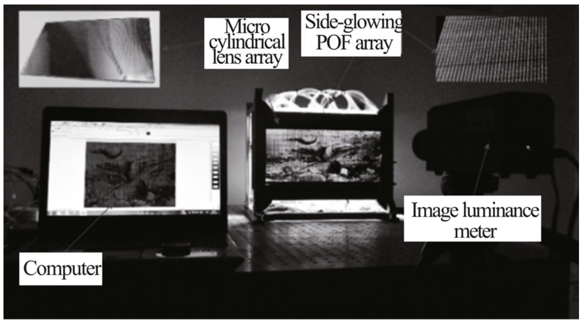

Fig.8 Photos of the experimental setup

The cylindrical lens array concentrates a small number of views on three different viewing zones A, B and C, as shown in Fig.1, so that this autostereoscopic 3D display can provide high luminance (as shown in Tab.2).

The experimental results show that the luminance of the whole backlight can reach a high level of uniformity. Finally, when the 3D images is displayed on it, the display quality is shown in Fig.9. The details of the display in 3D mode can be observed with the equipment of a magnifier in both the left and the right eyes, the resolution maintains the 1 366×768 and has a high uniformity. The compact autostereoscopic system is 15.6 inch with 60 Hz refreshing rate. Detailed data of the system is listed in Tab.3. Crosstalk are almost invisible across the screen, except for overlaps in certain parts (e.g. magnify Fig.9). Therefore, the technology we propose can provide high-quality 3D image display.

Tab.2 Measurement results of the luminance of the directional backlight

Option		Value				
Sampling point coordinates (mm)		P_1	P_2	P_3	P_4	P_5
The luminance ($cd \cdot m^{-2}$)	1	304.88	320.77	337.43	326.11	318.53
	2	296.93	327.68	332.16	317.32	319.29
	3	298.13	314.04	334.15	323.75	321.94
Average luminance ($cd \cdot m^{-2}$)		299.98	320.83	334.58	322.39	319.92

Tab.3 Performance of compact auto-stereoscopic display system

Name	Data
Panel size	15.6 inch
Resolution in 3D	1 366×768
Luminance	≤340 $cd \cdot m^{-2}$
Crosstalk	≤10%
Color temperature	6 107 K
Thickness of auto-stereoscopic display	18 mm

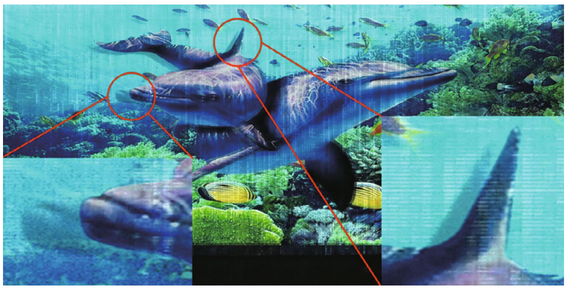

Fig.9 Image display quality magnification

A compact directional backlight based on SGPOF array for 3D display is proposed and demonstrated and its experimental verification is carried out in this paper. A sheet of grating film is introduced into the backlight modular to filter the stray light and create a uniform backlight. The cylindrical lens array concentrates a small number of views on three different view zones, so that this autostereoscopic 3D display can provide high luminance. The measurement results show that the luminance uniformity of the backlight module is up to 89.6%, and in the viewing zone, the crosstalk is lower than 10%, which can provide comfortable 3D visions. And the backlight module is compact that the thickness being only 7 mm. Therefore, this design provides an effective autostereoscopic 3D display design scheme.

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