Optics Communications 361 (2016) 47–54

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High brightness three-dimensional light field display based on the aspheric substrate Fresnel-lens-array with eccentric pupils

Xin Gao [a], Xinzhu Sang [a,*], Xunbo Yu [a], Xuemei Cao [a], Zhidong Chen [a], Binbin Yan [a], Jinhui Yuan [a], Kuiru Wang [a], Chongxiu Yu [a], Wenhua Dou [b], Liquan Xiao [b]

[a] State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), 100876 Beijing, China
[b] School of Computer Science, National University of Defense Technology, Changsha, Hunan 410073, China

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
16 October 2015
Accepted 16 October 2015
Available online 23 October 2015

Keywords:
Light field display
Eccentric pupil
Aberration
Illuminance

ABSTRACT

The brightness and viewing field of the reproductive three-dimensional (3D) image are crucial factors to realize a comfortable 3D perception for the light field display based on the liquid crystal device (LCD). To improve the illuminance of 3D image with sub-image-units with small aperture angles and enlarge the viewing field, the illuminance of the Fresnel-lens combining with the sub-images on LCD is analyzed and designed. Theoretical and experimental results show that the Fresnel-lens-array with eccentric pupil (FAEP) can address above problems. A 3D light field display based on LCD with FAEP and directional diffuser screen are used to reconstruct the target 3D field. 25 parallax sub-images are projected to the directional diffuser screen to verify the improvement of illuminance and viewing field. To reduce eccentric aberration introduced by eccentric pupil, a novel structure of Fresnel-lens-array is presented to reduce the aberration. The illuminance and viewing field are well promoted at the same time. 3D image with the high quality can be achieved.

1. Introduction

Three-dimensional (3D) displays based on lenticular lenses or parallax barriers with the image of flat panel displays or projectors can realize several types of multi-view auto-stereoscopic displays [1–10]. However, these 3D displays cannot provide continuous and smooth motion parallax due to the limited number of viewpoints. High density-view systems [11,12] can solve the problem but in the small viewing field. A large viewing field is essential condition for comfortable 3D viewing experience. The light field display reconstructs the light field of 3D scene in pixels-based rather than views-based. It brings the real physical depth to the viewer, which can create smooth motion parallax in a large viewing field. The holographic displays can reproduce the real light field [13,14]. However, current holography is still hard to realize real time, large format, full-color 3D display for practical application. The 360° light field of 3D scene can be achieved by the spatial scanning system including a high-speed video projector, a spinning table and a directional diffuser screen [15,16]. While, complex equipment and small display area are undesirable. A large multi-projector light field display is proposed by Sang et al. [17], and a special holographic functional screen is used to the target 3D object. In addition, several systems using LCD-based projection with Fresnel-lens-array and directional diffuser screen are presented [18–20]. LCD display region is divided into a series of sub-images. Each sub-image and corresponding Fresnel-lens-unit make up a so-called projector. All of sub-images are projected to the designed position to reconstruct the target 3D light field.

Large viewing field, high image resolutions, smooth motion parallax, and suitable image plane illumination are definitely required to develop an excellent natural 3D displays. In previous LCD-based light field displays, the self-calibration method is investigated to solve the distortion problem of projected images. The curve directional diffuser screen is applied to enlarge the viewing field. However, some drawbacks are still existed including unclear reproductive image and low efficiency of light source, which severely affects the 3D visual perception. The aberration of lens results in a low resolution and a decreasing of 3D depth [21,22]. Several factors cause the decrease of illuminance of image plane (IOIP), such as the clear aperture, absorbance, magnification, luminous flux and brightness of light source.

In order to address these issues, the Seidel aberration and Radiosity theory are used to analyze the relationship among aberration, illumination and the parameters of Fresnel-lens. Theoretical and experimental results show that aspheric substrate

* Corresponding author.
E-mail address: xzsang@bupt.edu.cn (X. Sang).

http://dx.doi.org/10.1016/j.optcom.2015.10.040
0030-4018/

FAEP can suppress the aberration and improve the IOIP. The 3D image with a high quality is demonstrated in the proposed system.

2. Fresnel-lens-array with eccentric pupil

2.1. The previous and proposed structure

In the previous LCD-based light field display, the system is consists of a LCD, Fresnel-lens-array, diaphragm array and directional diffuser screen. The LCD device is divided into numerous sub-images regions, each sub-image and corresponding lens-unit make up a so-called projector. The directional diffuser screen provides the continuous brightness in horizontal and large viewing angle in vertical. All the parallax images projected by these so-called projectors converge at the center of the directional diffuser screen as shown in Fig. 1(a). d_1, y_1 is the horizontal and vertical distance between the sub-image and corresponding lens-unit respectively. Each image pixel on the directional diffuser screen is the overlapped pixels which come from different parallax images. As shown in Fig. 1(b), the different direction information of the overlapped pixels can be viewed along the horizontal direction. Thus, the reconstructed 3D scene can be viewed in front of the directional diffuser screen.

In order to suppress aberration, the diaphragm-array is attached on the Fresnel-lens-array to decrease the clear aperture. However, the small-size aperture reduce the practical efficiency of emitting rays from LCD. The illumination of 3D image is reduced, which may aggravate visual fatigue. For the center sub-image on LCD, it still keep a higher IOIP. However, due to some sub-images deviate from the corresponding lens, IOIP is deteriorated seriously and some sub-images cannot be viewed completely because of the low illuminance. Depth perception and viewing field are also affected. In order to improve IOIP, the FAEP is proposed as shown in Fig. 2.

Fig. 2 shows the basic structure of the proposed 3D display, which consists of $4k \times 2k$ LCD, FAEP, diaphragm array and directional diffuser screen. The display region of LCD is divided into 25 sub-images, setting stagger vertically with 5 rows. The stagger distance equals to the diameter of clear aperture, and there is not dark space on the reproductive image. In every so-called projector, the Fresnel-lens-unit with the eccentric pupil(FUEP) is directly in front of the corresponding sub-image. The utilization rate of the light source can be improved.

The top left corner sub-image as shown in Fig. 1(a) is as an example to demonstrate how to achieve the corresponding FUEP. As shown in Fig. 3, the corresponding FUEP marked red can be

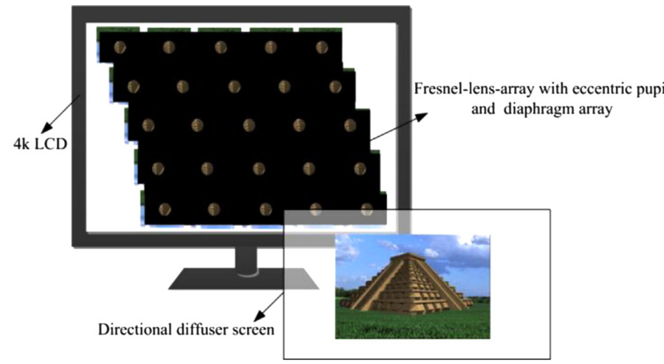

Fig. 2. The proposed LCD-based light field display structure.

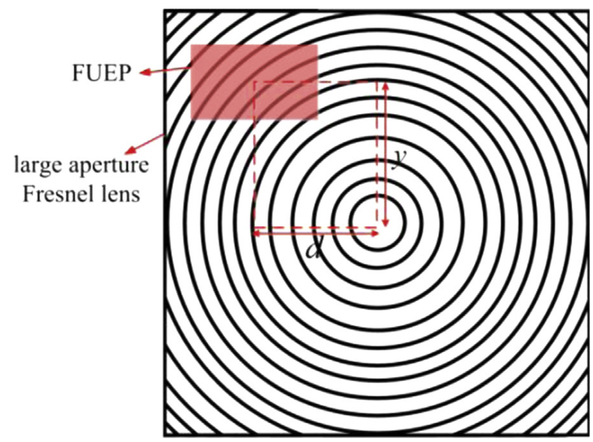

Fig. 3. The Fresnel-lens-unit with eccentric pupil.

achieved by cutting out a part of the large aperture Fresnel lens. d, y is the horizontal and vertical deflected distance of eccentric pupil respectively, which is equal to the d_1, y_1 in Fig. 1(a) respectively. They can be calculated according to Eq. (1),

$$d = d_1 = \frac{D_1}{D_1 + D_2}X$$
$$y = y_1 = \frac{D_1}{D_1 + D_2}Y \qquad (1)$$

where D_1 is the distance between the LCD and FAEP, and D_2 is the distance between the directional diffuser screen and FAEP. In the following discussion, D_1 and D_2 have the same meaning. X and Y are the horizontal and vertical deflected distance from the sub-

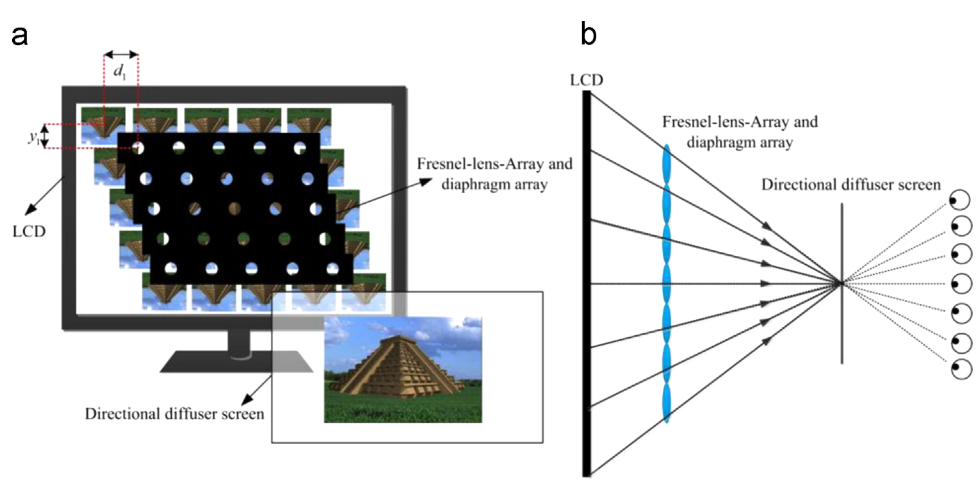

Fig. 1. The previous LCD-based light field display structure, (a) The system structure, (b) The optical ray schematic.