High optical-efficiency integral imaging display with a gradient-aperture parallax barrier

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We propose a one-dimensional integral imaging (1DII) display that consists of a display panel and a gradient-aperture parallax barrier. The gradient-aperture parallax barrier is symmetrical, and its slit widths gradually increase from both sides to the middle. The leftmost and rightmost slits are used to fix the viewing angle, whereas the other slits are used to increase the optical efficiency. A prototype of the proposed 1DII display is developed. Its optical efficiency is higher than that of the conventional display, but the viewing angles are the same.

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Integral imaging (II) is a promising display that presents true three-dimensional (3D) images with full parallax and continuous viewpoints[1]. However, high resolution, wide viewing angle, and large depth display are difficult to obtain[2−4]. To overcome these disadvantages, numerous methods have been proposed[5−7]. Conventional one-dimensional (1D) II reduces ray information by removing vertical parallax and displays 3D images with high resolution in the vertical direction[8]. Despite the resemblance, 1DII displays significantly differ from multiview autostereoscopic displays in terms of the position and interval of beam condensing points. Predetermination of the observer's viewpoints is not required in 1DII displays. By contrast, the observer's viewpoints are light ray converging points and an important design parameter in multiview autostereoscopic displays. Parallax barriers or lenticular lens arrays have been used for 1DII displays. 1DII displays based on a parallax barrier have less space and lower cost than those based on a lenticular lens array. However, low optical efficiency is still one of the problems in conventional 1DII displays using a parallax barrier. The optical efficiency can be increased by increasing the aperture width of the parallax barrier. However, the viewing angle of a 1DII display is inversely proportional to the aperture width of the parallax barrier. In this letter, we propose a 1DII display using a gradient-aperture parallax barrier to obtain high optical efficiency.

Figure 1 illustrates the structure of the proposed 1DII display consisting of a display panel and a symmetrical gradient-aperture parallax barrier. The aperture centers of the gradient-aperture parallax barrier are located at the centers of the corresponding element images on the display panel. Lights from the elemental image array (EIA) displayed on the display panel are modulated by the gradient-aperture parallax barrier, which reconstructs the angular distribution of the rays and hence displays the 3D images.

The structure of the gradient-aperture parallax barrier is shown in Fig. 2. The slit widths of the gradient-aperture parallax barrier gradually increase from both sides to the middle.

The principle of the proposed 1DII display is shown in Fig. 3. We assume that L is the viewing distance between the gradient-aperture parallax barrier and the observers, g is the gap between the gradient-aperture parallax barrier and the display panel, p is the pitch of the gradient-aperture parallax barrier, D is the width of the primary viewing zone, N is the number of elemental images, and P_i denotes the width of the ith slit, where i is a positive integer greater than or equal to 1 and less than or equal to N.

When L is constant, the viewing angle θ of the proposed 1DII display is only determined by D(Fig. 3). When the

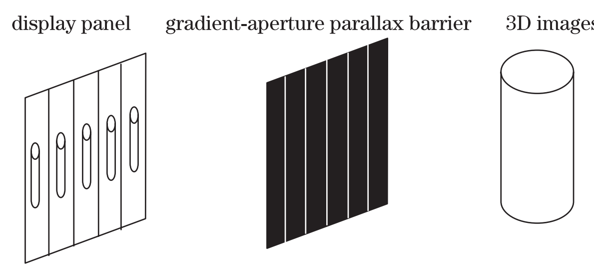

Fig. 1. Structure of the proposed 1DII display.

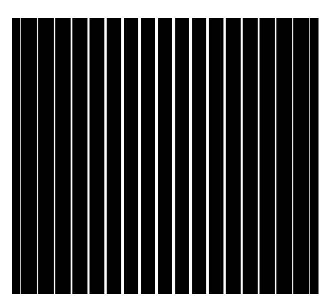

Fig. 2. Structure of the gradient-aperture parallax barrier.

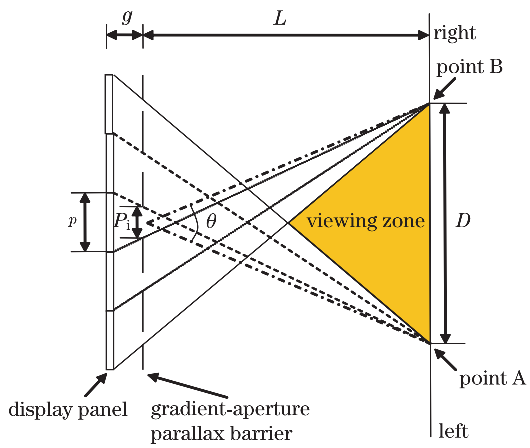

Fig. 3. Principle of the proposed 1DII display.

gradient-aperture parallax barrier and the display panel are fixed, D is only determined by the solid lines emitted from the leftmost and rightmost slits. Therefore, the viewing angle θ of the proposed 1DII display is only determined by the solid lines emitted from the leftmost and rightmost slits. The leftmost and rightmost slits in the gradient-aperture parallax barrier are denoted as special slits. The other slits in the gradient-aperture parallax barrier are denoted as general slits.

We assume that P_{E} is the width of each special slit and P_{C} is the aperture width of the conventional parallax barrier. When the viewing angle of the proposed 1DII display is equal to that of the conventional 1DII display, the relationship between P_{E} and P_{C} can be obtained as

$$P_{\mathrm{E}} = P_{\mathrm{C}}. \tag{1}$$

Points A and B are the points on the left and right edges of the primary viewing zone, respectively. The dotted lines emitted from the general slits in the left half of the gradient-aperture parallax barrier converge on point B, whereas the dashed lines emitted from the general slits in the right half of the gradient-aperture parallax barrier converge on point A. Depending on the position in the gradient-aperture parallax barrier, the width of each general slit is increased to increase the optical efficiency of the proposed 1DII display. P_i is given by a simple geometric calculation as

$$\begin{cases} P_i = P_{\mathrm{E}} + \dfrac{2gp}{L+g}(i-1) & 1 \leqslant i \leqslant \dfrac{N}{2} \\ P_i = P_{\mathrm{E}} + \dfrac{2gp}{L+g}(N-i) & \dfrac{N}{2} < i \leqslant N \end{cases}. \tag{2}$$

The viewing angle of the proposed 1DII display θ can also be obtained as[9]

$$\theta = 2\arctan\left[\frac{p-P_{\mathrm{E}}}{2g} - \frac{(N-1)p}{2L}\right]. \tag{3}$$

When the viewing distance between the gradient-aperture parallax barrier and the observers is larger than L, the viewing angle of the proposed 1DII display decreases (Fig. 3). The viewing distance recommended by television manufacturers is three times larger than the screen height. However, L is more than three times larger than the screen height. For example, in our experiment, the height of the EIA is 49.5 mm, whereas L is 930 mm. Therefore, the proposed 1DII satisfies this requirement.

The optical efficiency of the conventional 1DII display φ_1 is[10]

$$\varphi_1 = \frac{P_{\mathrm{C}}}{p}. \tag{4}$$

The optical efficiency of the proposed 1DII display φ_2 can be obtained as

$$\varphi_2 = \sum_{i=1}^{N} \frac{P_i}{Np}. \tag{5}$$

Equations (2) and (3) show that P_{C} is less than or equal to P_i. Therefore, the optical efficiency of the proposed 1DII display is obviously higher than that of the conventional one (Eqs. (4) and (5)). The horizontal and vertical gradient-aperture parallax barriers can be used in II to increase the optical efficiency.

We developed a prototype of the proposed and conventional 1DII displays. For accuracy, a 22 inch in liquid crystal display (used as the back light unit) and a film were combined as a display panel. The display panel was used to generate the EIAs of the proposed and conventional 1DII displays. Another film was used as the gradient-aperture and conventional parallax barriers. The EIA and gradient-aperture barrier of the proposed 1DII display are in the top half of the films. The EIA and parallax barrier of the conventional 1DII display are in the bottom half of the films. The parameters of the prototype are shown in Table 1.

Table 1. Parameters of the Prototype

Specification	Value
p (mm)	1.5
P_{C} (mm)	0.1
P_{E} (mm)	0.1
g (mm)	3.3
L (mm)	930.0
N	46

The EIAs of the proposed and conventional 1DII displays were generated by using a computer[11,12]. The images of the letters "S" and "C" are located at 60 mm in front of and behind the display panel, respectively. In other words, "S" is a real image, and "C" is a virtual one.

The top and bottom EIAs, which are simultaneously displayed on the display panel, are behind the gradient-aperture and conventional parallax barriers, respectively. Based on the slit widths of the gradient-aperture and conventional parallax barriers, the viewing angles of the proposed and conventional 1DII displays are both 20°. The 3D images reconstructed by the proposed and conventional 1DII displays viewed from different angles are shown in Figs. 4(a)–(c). The relative positions of the letters "S" and "C" in the proposed display are the same as those in the conventional display. The optical efficiencies of the proposed and conventional displays obtained from Eqs. (4) and (5) are 14.4% and 6.67%, respectively. For the prototype, the full white luminance of the

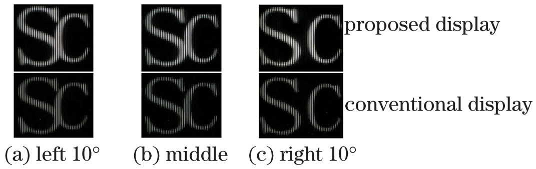

Fig. 4. 3D images reconstructed by the proposed and conventional 1DII displays.

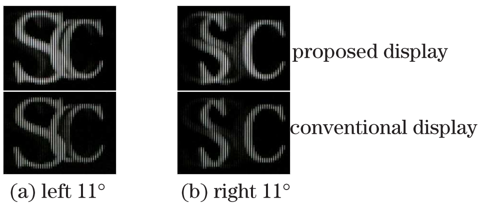

Fig. 5. Flipping images reconstructed by the proposed and conventional 1DII displays.

proposed display is 43 cd/m^2, and that of the conventional display is 20 cd/m^2. Therefore, the optical efficiency of the proposed 1DII display is 215% of the conventional 1DII display. Thus, the experimental results agree well with the theoretical values.

When the viewing angle is 11° to the left, the flipping images of the letter "C" in the proposed and conventional displays are shown in Fig. 5(a). When the viewing angle is 11° to the right, the letter "S" reconstructed by the proposed and conventional displays is also distorted, as shown in Fig. 5(b). Although the 3D image in the proposed display is brighter than that in the conventional one, the relative positions of the distorted letters "S" and "C" in the proposed display are the same as those in the conventional one. Moreover, the vertical strips are observed in both displays.

The experimental results prove that the optical efficiency of the proposed 1DII display is higher than that of the conventional one. The viewing angle of the proposed 1DII display is equal to that of the conventional one.

In conclusion, a 1DII display using a gradient-aperture parallax barrier is proposed. The gradient-aperture parallax barrier consists of special parallax barriers used to fix the viewing angle and general parallax barriers used to increase the optical efficiency. A prototype of the proposed 1DII display is developed. The optical efficiency of the proposed display is higher than that of the conventional one, and its viewing angle is the same as that of the conventional one. Therefore, the proposed high-luminance 3D display may be a practical solution.

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