Aberration Compensated Point Light Source Display With High-Resolution

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A high-resolution enhanced point light source integral imaging display is proposed. Using additional light sources to create extra point light sources in the point light source plane, the point light sources appeared on the plane that deviated from the expected values because of aberrations in the lens. Previously, only the lens array aberration was corrected and the distance along the horizontal and vertical axes was corrected too. The objective of this paper is to simultaneously correct the aberration between the lens array and the collimating lens, plus the horizontal and vertical axes, and correct the error along the *z*-axis. So, we determined the distance between the central light source and the additional light source to compensate for lens aberrations. From the experimental results, our technique precisely increased the resolution 3 times in both vertical and horizontal dimensions when compared to a traditional point light source display. Our method is applicable to 3D displays and compensates for the lens array and collimating lens aberrations.

Keywords: integral imaging, 3D display, point light source, high-resolution, lens aberration

INTRODUCTION

We can see three-dimensional (3D) images in many different technologies (Hong et al., 2011; Geng, 2013). The point light source (PLS) (Park et al., 2004; Kim et al., 2007) display is one of the integral imaging (InIm) (Okano et al., 1997; Lee et al., 2006) displays. The PLS display has certain advantages, such as without the need for special glasses (Lippmann, 1908), 3-D color, full parallax horizontal and vertical, and the wide depth range of 3-D images (Jang and Javidi, 2003; Park et al., 2004; Hong et al., 2004; Luo et al., 2012; Zhang et al., 2012; Oh et al., 2014). However, limited viewing angle (Lee et al., 2002; Kim et al., 2004) and low resolution (Kim et al., 2008) make PLS display unable to be widely used in life. Therefore, the resolution needs to be improved. The researchers studied the limitations of 3-D displays and tried to improve them.

Park et al. used an additional lens array between the collimating lens and the lens array to double the resolution (Park et al., 2005). However, the disadvantage is that the more lens arrays, the more expensive, the screen is thick, and the additional PLS is not precisely aligned with the boundary, and this method cannot compensate for lens aberrations.

Wang et al. nine light sources on the one board are being used to generate 4 times more point light sources than elemental lenses, and the resolution was enhanced two times (Fenghua et al., 2017). However, the additional PLS is not precisely aligned with the boundary due to aberrations in the lens array.

Choimaa et al. analyzed the effect of Petzval curvature in InIm display (Choimaa et al., 2015). Due to aberration of the elemental lens, the depth plane of the InIm display becomes an array curvature, reduces the depth range, changes the viewing direction, and increases the black stripe. Therefore, they suggested that the lens array on the InIm display should be customized. Although the Petzval
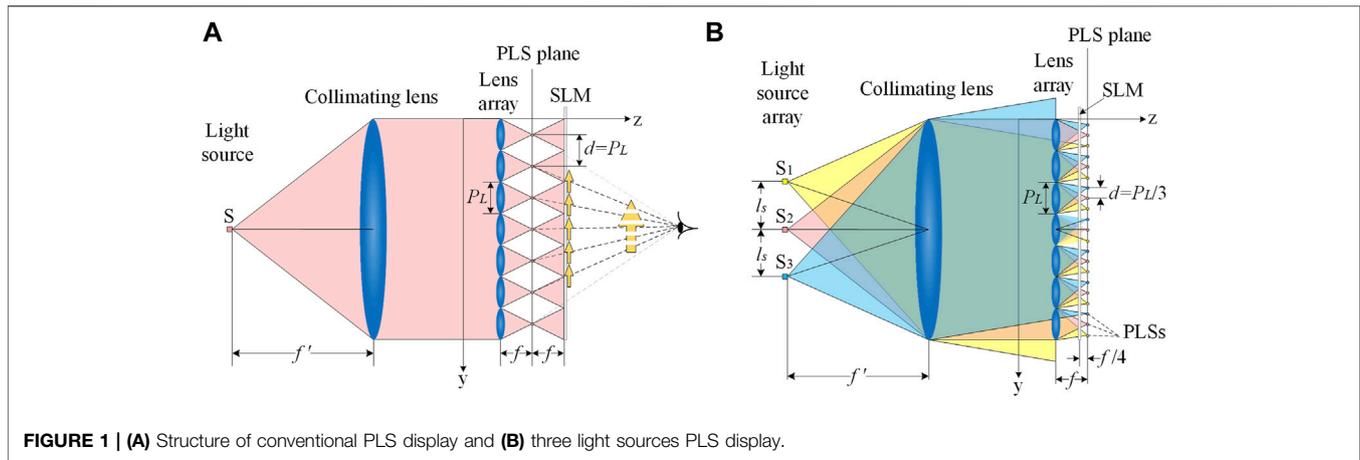
FIGURE 1 | (A) Structure of conventional PLS display and **(B)** three light sources PLS display.

double-lens can compensate Petzval curvature, however, it is difficult to apply to element lenses, and Petzval curvature becomes a mirror curve in the PLS display.

Our previous study compensated for lens aberrations on PLS displays by configuring the distance between additional light sources by design (Baasantseren et al., 2021). We changed the distance between the light sources along the x and y axes, the distance between the PLSs became uniform, and the resolution increased four times. However, the lens aberrations in which PLSs appear in different planes are not corrected.

In this paper, we first explained the effect of Petzval curvature in PLS display. The plane in front of the lens array is curved due to the Petzval curvature on the InIm display (Choimaa et al., 2015). Our experimental results that the effect of the Petzval curvature in the PLS display is mirror curvature. Then we also introduce a new method to compensate for lens aberrations with moving parts. We all know that enhancing the resolution uses an additional light source. Our new method is moving the additional light source along the z-axis to compensate for lens aberrations. So easily resolved problems due to lens aberrations that initially appear in a different plane than the theoretical value. This high-resolution PLS display is suitable for 3D display.

Figure 1A shows the structure of a conventional PLS display. Many small elemental lenses make up the lens array. The light source is placed at the focal point of a collimating lens. The collimating lens collimates the light emitted by the light source (one Surface-Mount-Device Light-Emitting-Diode (SMD LED)). The collimated light rays are imaged into an array of point light sources at the focal plane of the lens array. The corresponding elemental image pixels modulated the light rays from each point light source, which are then integrated into 3D images. The 3D resolution is determined by the number of PLS equal to the elemental lens number. In addition, **Figure 1B** shows enhanced 3D resolution, using an additional light source. According to the principle that light beams passing through the optical center of the lens do not change the propagation direction, and the collimated light rays converge at the focal points of elemental lenses on the PLS plane. The resolution of a PLS display is determined by the distance between two adjacent PLSs

(Lippmann, 1908). The resolution of PLS display is calculated as follows:

$$R = \frac{1}{d} \qquad (1)$$

where d is the distance between two adjacent PLSs. The resolution and distance between two PLSs are inversely proportional. The resolution improves as the distance between two PLSs is lowered, as shown in **Eq 1**.

For the (3 × 3) light source PLS display, the light sources array is used to generate more PLSs as shown in **Figure 1B**. The SLM position is on the back of the PLS plane, distance from PLS plane 1/4f, and the illumination area size on SLM of each PLS is equal, therefore avoid crosstalk. The distance between two light sources determines the distance between adjacent PLSs (Baasantseren et al., 2021). When the distances between adjacent PLSs are equal, the distance between two light sources is as follows:

$$l_s = \frac{f' \cdot P_L}{n \cdot f} \qquad (2)$$

where f' is the focal length of the collimating lens, P_L is the pitch of the elemental lens, f is the focal length of the elemental lens, and n is the times resolution enhancement. When n is 3, the resolution of the display is three times that of a conventional PLS display.

The parallel rays are converged into PLSs on the PLS plane by the lens array. Due to aberrations of the lens array, additional light sources in a flat of normal to the main optical axis cannot be properly brought into focus on a PLS plane and call it the Petzval curvature.

PETZVAL CURVATURE

Petzval curvature describes the optical aberration in which a flat object normal to the optical axis cannot be properly brought into focus on a flat image plane. It appeared in an arc of radius R_C as shown in **Figure 2**. A radius of the Petzval curvature of a thin lens can be obtained by

$$R_C = n_L \cdot f \qquad (3)$$

where n_L is the refractive index of the lens and f is the focal length of the lens (Choimaa et al., 2015). The PLS of the central light

FIGURE 2 | Green color shows (A) Petzval curvature and (B) the mirror Petzval curvature.
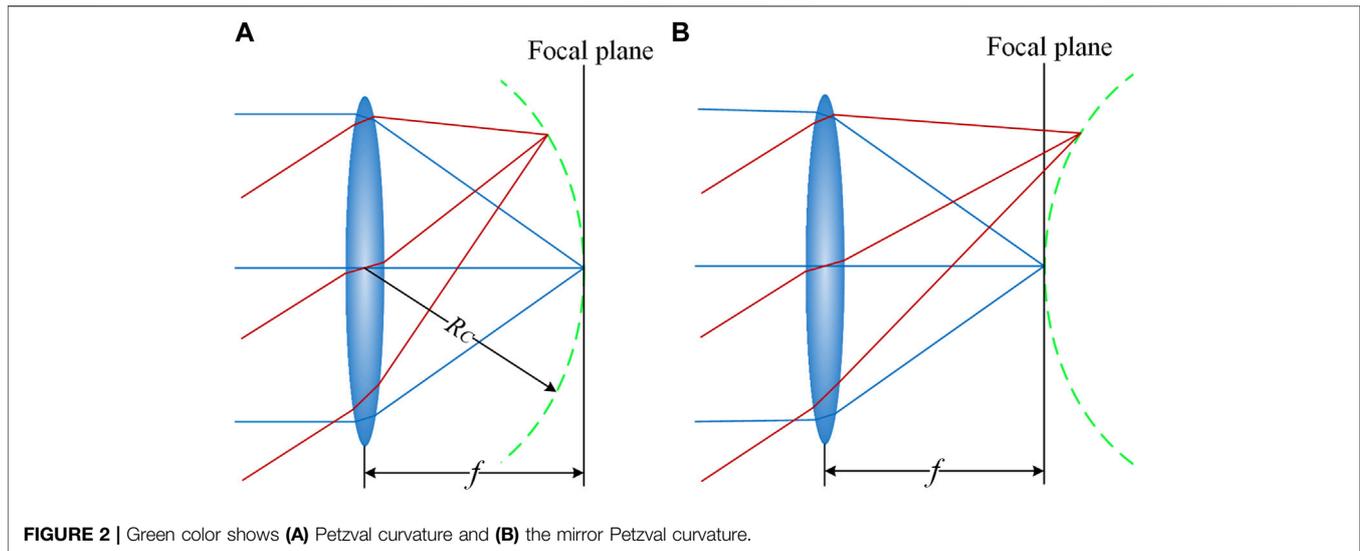
source is focused at the focal plane, and the PLSs of additional light sources are focused behind the focal plane, as shown by the green curve. If the lens array and the collimating lens are ideal lenses, the addition of additional light sources can enhance the resolution by a factor of n. Unfortunately, both the lens array and the collimating lens have aberrations, which enlarges the size of the PLS.

In our previous study, experimental results based on theoretical values showed that the distances between point light sources are close and appear on different planes (Baasantseren et al., 2021), which is believed to be the result of Petzval curvature. Therefore, we speculate that by moving the position of the additional light source, the Petzval curvature can be corrected. The experimental results show that the distance between the PLSs is modified, but the PLSs appear in different planes. The opposite of the Petzval curvature was found by measuring the distance between the lens array and the extra PLS, as shown in **Figure 2B**. Therefore, we recommend not placing the additional light source close to the collimating lens, but away from it, as shown in **Figure 4**. Moving distance Δz of the additional light source can only be obtained experimentally because both the lens array and the collimating lens have aberrations. After determined the distance Δz through experiments, we performed experiments with the newly proposed method. This part is written in the experimental results section, and we should do the experiment.

NEW METHOD

The Additional Light Sources Placed in Front of the Focal Plane of the Collimating Lens

Two light sources O and A′ are focused on the PLS plane through a collimating lens and lens array, the distance between

FIGURE 3 | Additional light sources placed in front of the focal plane of the collimating lens.
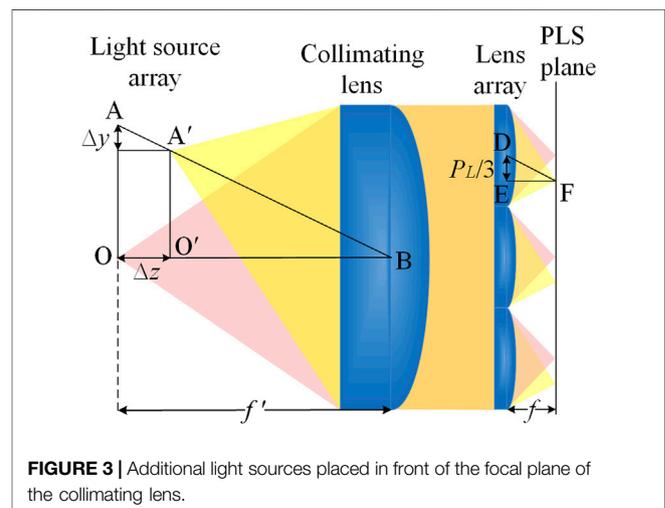
the PLSs is adjusted to $P_L/3$, as shown in **Figure 3**. According to the principle that a light beam passing through the optical center of the collimating and elemental lenses does not change direction, place the PLS generated by the additional light source at point F, connect point F with the center point D of the element lens with a straight line, and then draw a right triangle DEF. In the same way, the light beam passing through the center of the collimating lens does not change its propagation direction and draws a line AB parallel to the line DF move the A light source Δz distance to the right along the AB line and Δy distance down, and placed a new additional light source at point A'. Previously, as shown in **Figure 2A**, peripheral rays were thought to radiate close to the lens array due to Petzval curvature. Then, as shown in **Figure 3**, we experimented with the idea that the lens aberration could be corrected by moving the additional light source far to the collimating lens from the center light source at a distance of Δz.
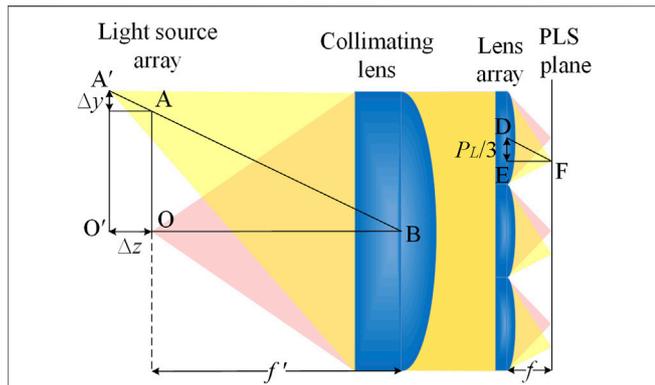
FIGURE 4 | Additional light sources placed behind the focal plane of the collimating lens.

TABLE 1 | Experimental specification.

Setup	Parameter	Value
SLM	Pitch	0.036 mm (V) × 0.036 mm (H)
	Resolution	1,024 × 768
Collimating lens	Type	Achromatic
	Focal length	75 mm
	Diameter	50 mm
Lens array	Focal length	3.3 mm
	Diameter	1 mm × 1 mm
Light source	Type	SMD LED
	Color	White
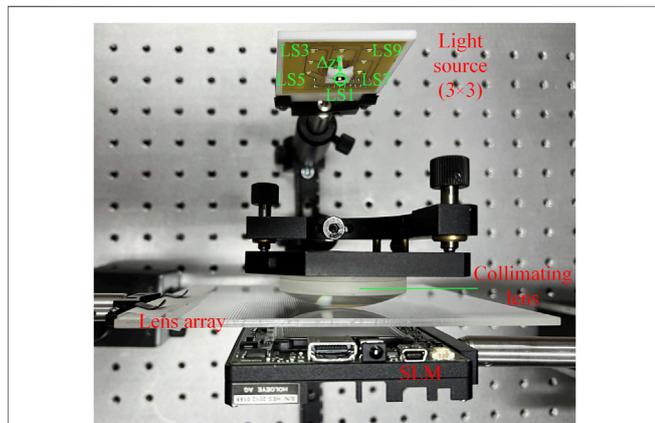
FIGURE 5 | Experimental setup of the PLS display.

FIGURE 6 | When the nine light sources are placed in the focal plane of the collimating lens (A) three light sources lit and (B) 3 PLS sizes.

TABLE 2 | Relationship between the size of the PLS and z.

Δz (mm)	4	6	8	10	12
Central PLS (mm)	0.23	0.25	**0.266**	0.277	0.28
Edge PLS (mm)	0.249	0.241	**0.231**	0.25	0.266
Diagonal PLS (mm)	0.3	0.28	**0.26**	0.302	0.31

FIGURE 7 | A board that additional light source placed 8 mm in front of the central light source.

Our Method

The additional light source A' is placed behind the focal plane of the collimating lens, as shown in **Figure 4**. Finding the new position of the additional light source A' is the same as the previous method. Move the A light source Δz distance to the left along the AB line and Δy distance up, and placed a new additional light source at point A'. The exact location of the new additional light source A' and the distance Δz were experimentally determined. The experimental results show the opposite as shown in **Figure 2B**. We have previously considered an aberration of the lens array. However, it was assumed that the parallel rays were not generated because of the aberration of the collimating lens. In other words, the aberration of the lens array and the collimating lens had to be corrected at the same time. The proposed method is to move the additional light sources away from the center light source with
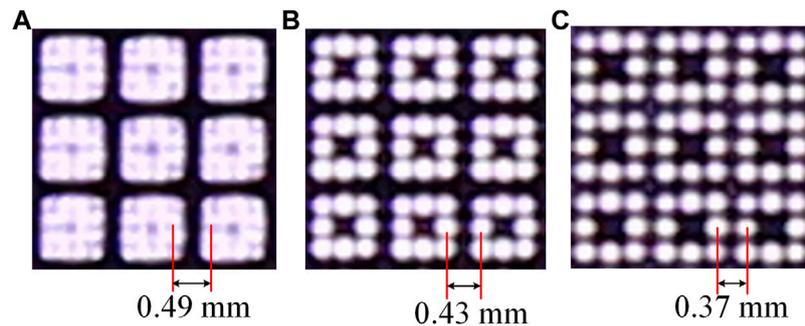
FIGURE 8 | Experimental results show, at Δz **(A)** 2 mm **(B)** 2.5 mm, and **(C)** 3 mm respectively when eight additional light sources.
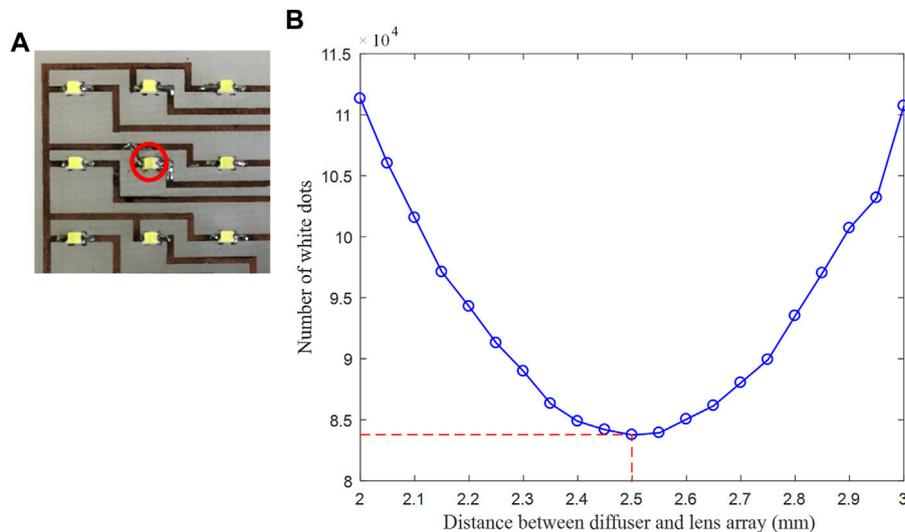
FIGURE 9 | When only the central light source lit **(A)** the red circle refers to the lit light source and **(B)** the result in 2.5 mm.

the Δz distance, as shown in **Figure 4**. There is no other way than to determine this Δz distance experimentally. The experimental section explains how to find and configure the Δz distance and the Δy distance experimentally and create a 3D image.

EXPERIMENTAL RESULTS

The light source array of the PLS display is placed close to the collimating lens to compensate for the aberration caused by the Petzval curvature so that the point light sources all appear on the PLS plane. The moving distance Δz of the additional light source cannot be found theoretically, so it is found experimentally. We performed three experiments. In the first experiment, we attempted to move the additional light source forward along the z-axis, which compensated for the elemental lens aberration. In the second experiment, we determined the Petzval surface in the PLS display. In the third experiment, we moved the additional light source back along the z-axis, compensated for lens aberrations, and enhanced the resolution threefold compared to that of the conventional method. **Table 1** shows the system

parameters. **Figure 5** shows the experimental setup of a PLS display that triples resolution by compensating for lens aberrations. We soldered nine surface-mount LEDs (SMLEDs) to different boards. The central LED LS1 is placed at the focal point of the collimating lens. LS2-LS9 are placed at Δz back the focal point of the collimating lens, respectively, and used to increase the number of PLSs.

Move the Additional Light Source Closer to the Collimating Lens

When the nine light sources are placed at the focal plane of the collimating lens, we only lit the three light sources of center, edge, and diagonal as shown in **Figure 6A**. Because the light sources of the PLS display are symmetrical. **Figure 6B** shows the result of taking a picture from the front using a camera, 3 PLS of different sizes when the diffuser is placed at the focal plane of the lens array.

Given the edge and diagonal PLS are minimal on the PLS plane, the correct distance Δz is found when moving the light source closer to the collimating lens, as shown in **Figure 3**; **Table 2** shows the change in PLS size with Δz. As Δz longer,

FIGURE 10 | When two edge light sources are lit **(A)** red circle refers to the lit light sources and **(B)** result.

FIGURE 11 | When two diagonal light sources are lit **(A)** the red circle refers to the lit light sources and **(B)** the result.
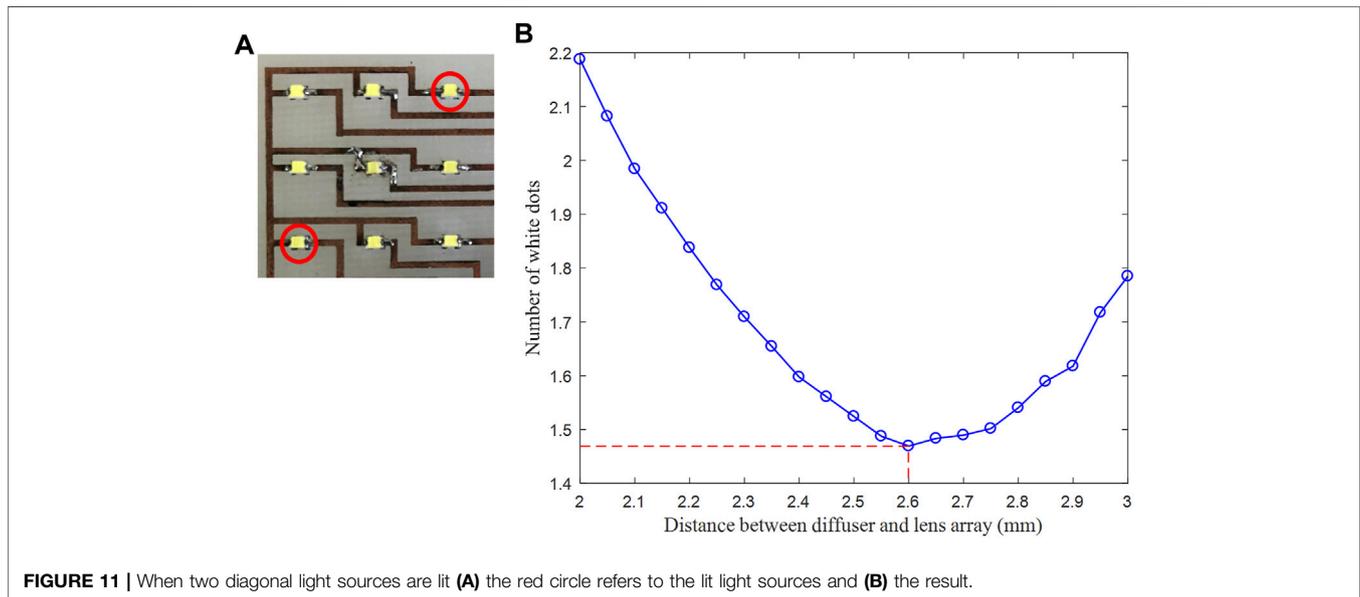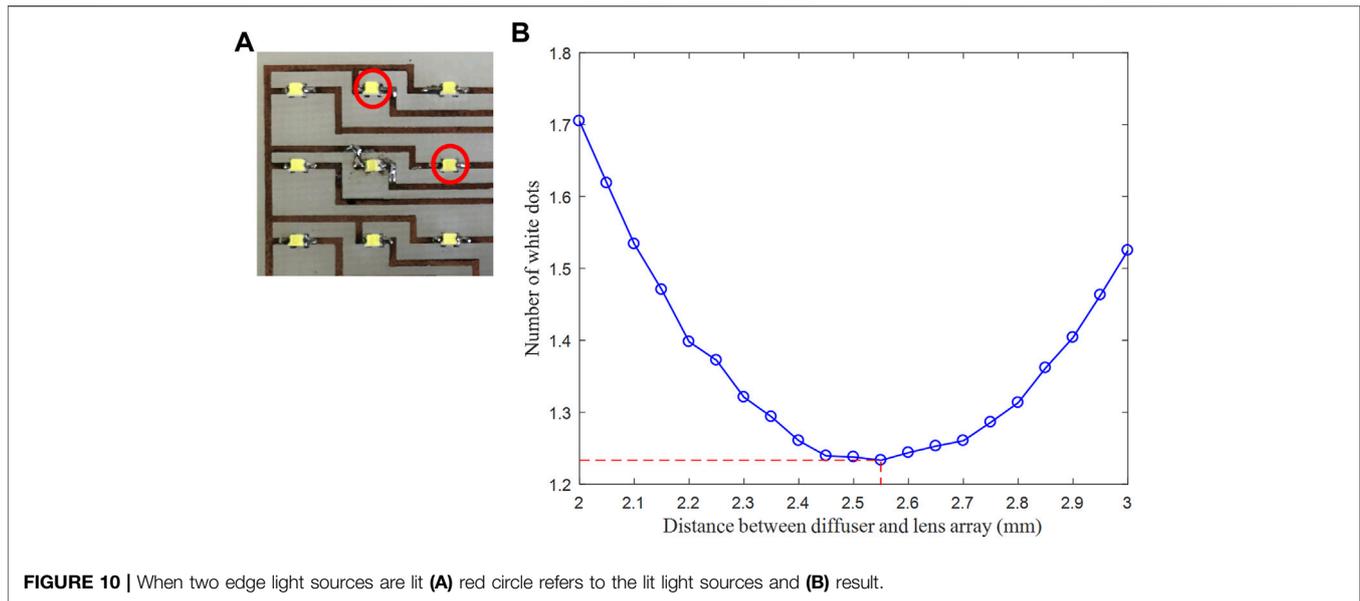
the size of the central PLS is increasing. The size of the additional edge and diagonal PLS first decreases next to the increase. Experimental results show when Δz = 8 mm same size of the edge and diagonal PLS. According to the experimental results of our proposed method, the limit of Δz is 8 mm.

Figure 7 shows a board corresponding to **Figure 3**, on which an additional light source is placed 8 mm in front of the central light source. At this time, eight additional light sources are lit. The experimental results are shown in **Figure 8**. When Δz = 2 mm, the distance between adjacent PLSs is not uniform, as shown in **Figure 8A**. When Δz = 2.5 mm, the size of the adjacent PLSs is uniform but the distance between the adjacent PLSs is not uniform, as shown in **Figure 8B**. When Δz = 3 mm, the distance between adjacent PLSs is uniform, but the size of adjacent PLSs is not uniform, as shown in **Figure 8C**. Therefore, this method cannot be

used. We initially considered that moving the additional light source closer to the collimating lens compensated for lens array aberrations due to the Petzval curvature. However, the experimental results were unexpected, so we tested the Petzval curvature.

Test Petzval Curvature
To find the exact location of the extra PLS, simply find the smallest corresponding extra PLS generated in front of the lens array. It should be noted that PLS is the smallest and sharpest when properly focused. First, the diffuser was placed 2 mm in front of the lens array, then the diffuser was moved from 2 to 3 mm in 0.05 mm steps and 21 images were taken from the diffuser. Because many high-resolution images are indistinguishable in size from the naked eye, we use Matlab to count the dots that are different from black. Consider the least white dots as the smallest dots. **Figure 9**
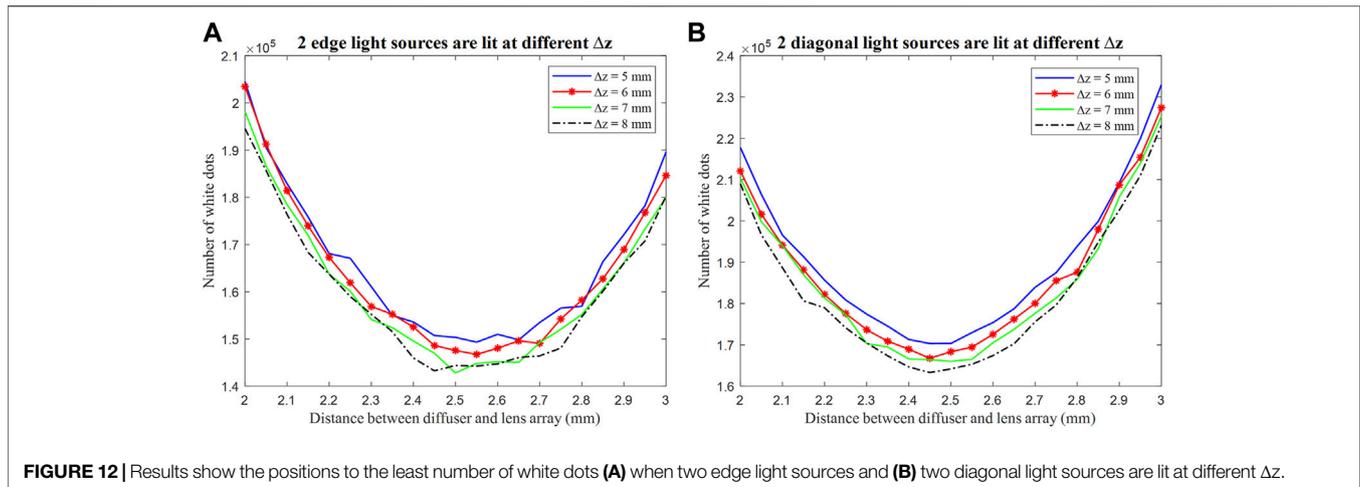
FIGURE 12 | Results show the positions to the least number of white dots **(A)** when two edge light sources and **(B)** two diagonal light sources are lit at different Δz.
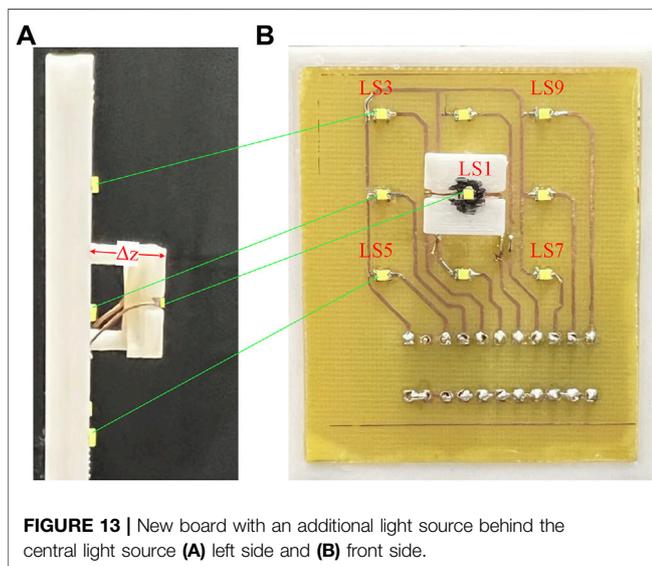
FIGURE 13 | New board with an additional light source behind the central light source **(A)** left side and **(B)** front side.

shows the result when only the central light source is lit. The central light source is colored red, as shown in **Figures 9A, B**, the vertical axis represents the sum of the number of white dots, and the horizontal axis represents the distance between the diffuser and the lens array. The least number of white dots at 2.5 mm, which we consider, is the focal length of the lens array. Therefore, we determine two conditions. The first condition that the distances of PLSs are 2.5 mm from the lens array. The second condition that the number of white dots is least at 2.5 mm from the lens array.

The same method can find the position of the smallest white dots in **Figures 10**, **11**, as shown by the red circle in **Figures 10, 11A**, when the two edge and two diagonal light sources are lit separately; the results are shown in **Figures 10**; **Figure 11B** repeat the previous experiment. The results show that when two edge light sources are lit, the least number of white dots at 2.55 mm. When two diagonal light sources are lit, the least number of white dots at 2.6 mm. From the test results, we obtain the opposite Petzval curvature, as shown in **Figure 2B**. On this opposite

Petzval surface, central PLS is the same size as adjacent PLS. Therefore, we consider that when nine light sources are placed on the focal plane of the collimator lens and lited (spherical wave), the light passing through the collimating lens appears as the erroneous parallel light beams (transverse wave).

Move the Additional Light Source Away From the Collimating Lens

Since the central PLS is focused on the focal point of the lens array, the central light source position does not move. The eight additional light sources are moved by Δz and Δy in the same way, as shown in **Figure 4**; **Figure 12A** shows that the results show the positions with the least number of white dots when two edge light sources are lit at different Δz. In contrast, the green curve (Δz = 7 mm) has the least number of white points at 2.5 mm. We can conclude that edge light sources at Δz = 7 mm satisfy two conditions.

Figure 12B shows that the results show the positions with the least number of white dots when two diagonal light sources are lit at different Δz. The black dash-dot curve (Δz = 8 mm) has the least number of white points at 2.45 mm. However, it satisfies only the first condition. **Figure 12B** shows that the results show the positions with the least number of white dots when two diagonal light sources are lit at different Δz. The green curve (Δz = 7 mm) has the least number of white points at 2.5 mm, so it satisfies two conditions. Therefore, the additional light source is moved back by 7 mm from the collimating lens.

Figure 13 shows a new board with eight additional light sources placed 7 mm back from the central light source. The experimental results are shown in **Figure 14A** shows the result for the conventional PLS display with one central light source. The resolution is low and the distance between adjacent PLSs is 1 mm. **Figure 14B** shows the result for the conventional (3 × 3) PLS display with one board. It is the resolution enhanced three times, but the distance between adjacent PLSs is not uniform. The distance between adjacent PLSs is about 0.28 and 0.43 mm respectively. **Figure 14C** shows the result of our previous method (Baasantseren et al., 2021) for the (3 × 3) PLS display with one board. The resolution is enhanced three times, and the
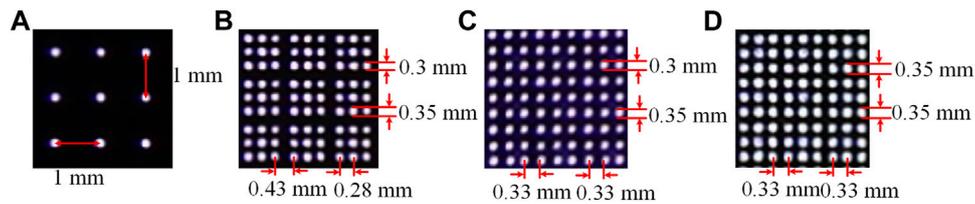
FIGURE 14 | Take photos of the PLS plane, using **(A)** conventional PLS display **(B)** conventional (3 × 3) PLS display with one board **(C)** previous method with one board and **(D)** New diffrent board.
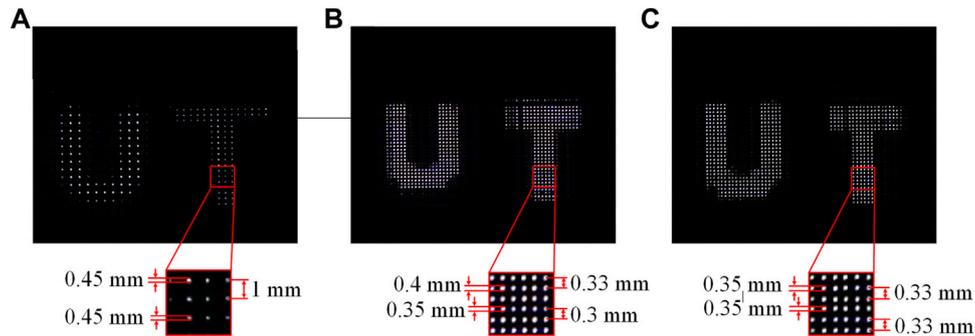
FIGURE 15 | Experimental results of **(A)** traditional PLS display with one light source **(B)** (3 × 3) light sources are on one board, and **(C)** the new PLS display.

distance between adjacent PLSs is uniform, but the size of adjacent PLSs is not uniform. The adjacent size PLSs are about 0.3 and 0.35 mm, respectively. **Figure 14D** shows new method results for the (3 × 3) PLS display with a different plane board. It is the resolution precisely enhanced threefold. The distance between adjacent PLSs is uniform, and the size of adjacent PLSs is uniform. The adjacent size PLSs are all 0.35 mm.

Our New PLS Display

The two objects 'U' and 'T' are 10 and 20 mm, respectively, in front of the SLM. We created two sets of EI and displayed them on the SLM. We photographed the two objects when the camera was focused on the PLS plane. The results are shown in **Figure 15A** shows the result of the traditional PLS display with one light source. It is difficult to identify 'U' and 'T' because the resolution is low. **Figure 15B** shows the result when (3 × 3) light sources are on one board. The resolution is three times higher than the traditional method. When the correct moving distance cannot be found, the distance between the PLS is not uniform, the PLS is not the same size. **Figure 15C** shows the result with (3 × 3) light sources on different plane boards. When the additional light source is placed back into the collimating lens at Δz = 7 mm, the distance between the PLS of 'U' and 'T' is uniform and the size of the PLS appears the same. The distance between adjacent PLSs is 0.35 mm and the adjacent size PLSs is 0.33 mm. Experimental results show that the new method of moving the position of the additional light source backward along the z-axis enhances the resolution threefold and compensates for lens aberrations more precisely.

CONCLUSION

In this paper, a new high-resolution PLS display has been proposed using a (3 × 3) light source. Moving back the additional light sources along the z-axis correcting aberration in the lens array and the collimating lens enhance the resolution precisely threefold. Experimental results show that our new method makes all PLS appear on the PLS plane, allowing viewers to watch better quality 3D images. Our simple method will be used to compensate for aberration of the lens array and collimating lens in the integral imaging display. We are currently working to enhance the resolution of the PLS display.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

CY developed a methodology, conducted data recording, and wrote the original draft. B-OC took experiment and validation. N-ED reviewed and edited the writing. GB developed the methodology, reviewed and edited the writing, and supervised the research project.

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