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Speckle reduction using phase plate array and lens array

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In this paper, a solution for speckle reduction using phase plate array (PPA) and lens array (LA) in a motionless way is proposed. The specially designed PPA is composed of sub-phase plates, which are constituted by phase patterns formed by Hadamard sub-matrices. Each component of the proposed optical system should satisfy the stated relationships. The incident laser beam will be incoherent after passing through PPA, and superpose on the screen under the action of LA and main lens. Speckle reduction can be achieved by the averaging of the incoherent speckle patterns. Because of abandoning the mechanical movement, it will be suitable for laser displays and images.

Keywords: laser display; speckle reduction; lens array; Hadamard

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Introduction

Laser display has attracted lots of attentions for its advantages of longer lifetime, higher luminance, lower power consumption and wider color gamut¹. However, when an optical rough surface is illuminated by a coherent laser, speckle will appear². Speckle is a drawback of laser display for it can downgrade the image quality greatly. To solve this problem, numerous methods have been proposed, such as: using a deformable mirror³ or a scanning mirror^{4,5} to realize angle diversity; using a broad-area vertical-cavity surface-emitting laser⁶ or random lasers⁷ to realize wavelength diversity; using a staircase element⁸ or a refractive steppers⁹ to realize optical path difference; rotating independent speckle patterns¹⁰ or a magneto-optical disk¹¹ to realize polarization diversity; using a light pipe¹² or a multimode optical fiber bundle¹³ to realize time averaging and so on.

J. I. Trisnadi firstly proposed the speckle reduction method using Hadamard phase diffuser^{14,15}. Later, more researches about this topic^{16,17} and its extensions^{18,19} were presented. However, most of these methods need either a

vibration system or a line scan system, which is cumbersome for laser display system. For example, in Ref.¹⁴, sub-matrices are produced by each row of Hadamard matrix to form phase patterns through vibrating the Hadamard phase diffuser in cooperation with grating light valve (GLV). Therefore, how to reduce the speckle effect in a static way is an open research topic.

Lens array (LA) is the most commonly used device in 3D display, which can integrate elemental images into 3D images²⁰⁻²². Inspired by this, we hope that the LA can also be integrated with the phase plate array (PPA) for speckle reduction. Thus, we propose a motionless method for speckle reduction using LA and PPA. A 4-f system includes PPA, LA and main lens will be described in Section 3. A special PPA will be designed, and the relationships among each component will be discussed. The results are explained in our experiments in Section 4. Speckle reduction can be realized in a static way without any moving mechanism.

Theory

Hadamard matrices $H(n)$ are matrices of 1's and -1's

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whose columns are orthogonal, which satisfy:

$$H' \times H = n \times I(n) \quad (1)$$

where, H' is the transpose of H , n is the order of Hadamard matrix, and $I(n)$ is identity matrix. For example, $H(4)$ has the following expression:

$$H(4) = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \quad (2)$$

According to Trisnadi's theory¹⁴, a diffuser based on Hadamard binary phase matrix can be used for speckle reduction. Supposing a detector resolution spot is divided into $M=N_1 \times N_2$ cells, as shown in Fig. 1(a).

If the amplitude of each cell is E_{ij} , and each cell is assigned with a phase φ_{ij} where $i=1, 2, \dots, N_1$ and $j=1, 2, \dots, N_2$. Then, these cells will constitute a phase pattern, and the intensity I of the resolution spot will be:

$$I = \left| \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} E_{ij} \exp(i\varphi_{ij}) \right|^2 \quad (3)$$

When N different phase patterns are presented in one resolution spot during the integration time, which have the equal duration, the intensity I can be expressed as:

$$I = \frac{1}{N} \sum_{n=1}^N \left| \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} h_{ij}^n E_{ij} \right|^2 \quad (4)$$

where, $h_{ij}^n = \exp(i\varphi_{ij}^n)$.

If the summation of h_{ij}^n over all the N phase patterns satisfies:

$$\sum_{n=1}^N (h_{ij}^n)^* h_{kl}^n = N \delta_{ik} \delta_{jl} \quad (5)$$

Then, we will get the following equation:

$$I = \frac{1}{N} \sum_{n=1}^N \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} \sum_{k=1}^{N_1} \sum_{l=1}^{N_2} (h_{ij}^n)^* (E_{ij})^* h_{kl}^n E_{kl} = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} |E_{ij}|^2 \quad (6)$$

Comparing equation (3) and equation (6), we could find that the cross terms vanished due to the averaging.

Most importantly, ' N different phase patterns' can be formed by the rows or columns of the Hadamard matrix. They are also named sub-matrices of Hadamard matrix (SH). For example, in Fig. 1(b), SH_2 is one sub-matrix of Hadamard matrix, which is formed by the second row of $H(4)$. If the elements of '1' and '-1' in Hadamard matrix are assigned with phase '0' and ' π ' respectively, each SH will represent a phase pattern. Moreover, the amplitudes of each cell E_{ij} usually have the same value.

At the same time, according to Goodman's theory²³, supposing we have N incoherent speckle configurations that have equal mean intensities added on an intensity basis, then speckle contrast will decrease to $N^{-1/2}$ of the previous level. Therefore, for an n -order Hadamard matrix $H(n)$, n incoherent SH can be generated, which correspond to n incoherent speckle configurations. Averaging SH in one resolution spot during the integration time of detector, the speckle contrast will reduce by the factor of $n^{-1/2}$.

System design

Optical system

A sketch diagram of the optical system for our method is shown in Fig. 2. 632 nm light is generated by a He-Ne laser. A 10× beam expander (BE) (Thorlabs, BE05-10-A) is used to expand the incident light. A phase only spatial light modulator (SLM) is used to generate the sequentially changing PPA, and the n -order PPA contains $n \times n$ sub-phase plates. When using the 2-order PPA, the PPA, LA, main lens and screen constitute a 4-f system. When using the 4-order PPA, another beam expander (BE 2) is added, and the whole system contains two seamlessly connected 4-f systems. More details will be described in the following paragraphs. A rough paper is used as screen and is placed on the focal plane of main lens. Speckle

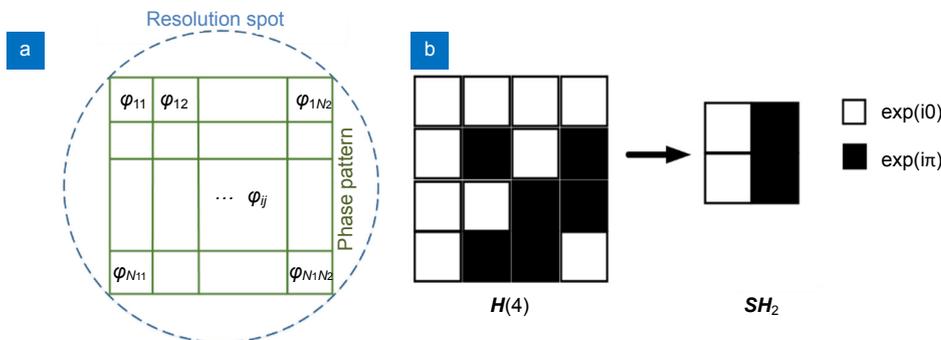


Fig. 1 | (a) A detector resolution spot contains a phase pattern, which consist of $M=N_1 \times N_2$ cells. (b) As an example of sub-matrix, SH_2 is formed by the second row of a 4-order Hadamard matrix $H(4)$.

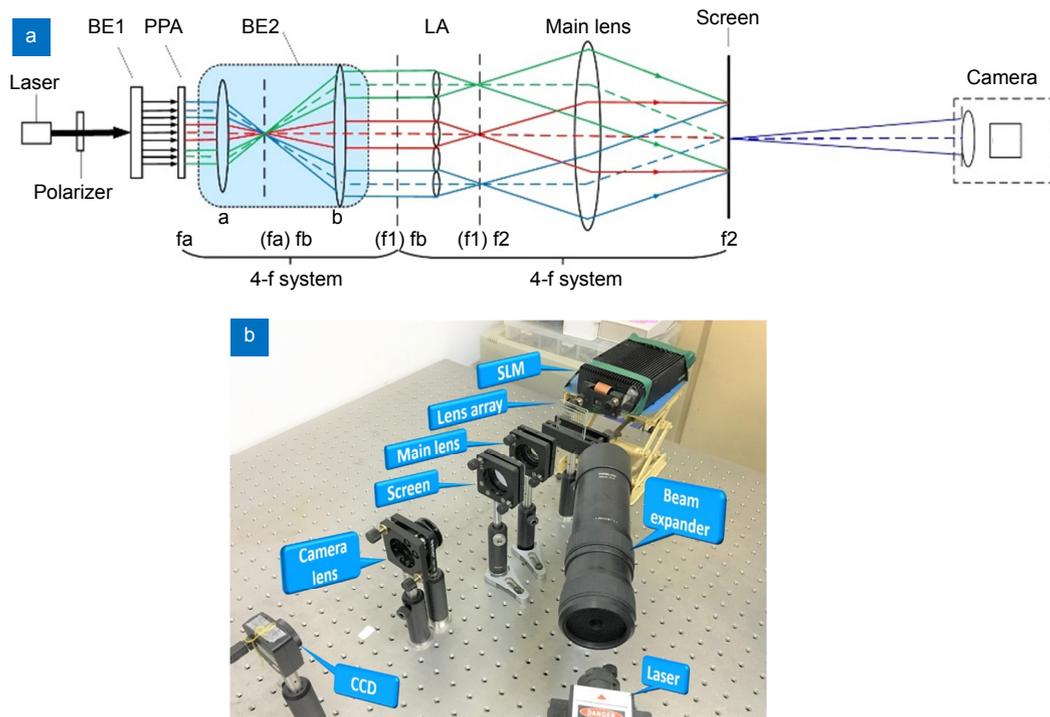


Fig. 2 | (a) The sketch diagram of our optical system: the PPA, LA, main lens and screen constitute a 4-f system. For a higher-order PPA, another beam expander (BE2) is added. Incoherent speckle patterns will superpose on the screen under the action of LA and main lens. (b) The experimental setup of the proposed system.

patterns on the screen will be captured by CCD camera.

Speckle reduction will be achieved by the averaging of the incoherent speckle patterns with the following process: paralleled laser light comes across the PPA, beams in different position will carry sequentially changing phase patterns SH ; under the action of LA and main lens, incoherent speckle patterns will superpose on the screen and then be averaged.

Phase plate array

Specially designed PPA is used for speckle reduction. One

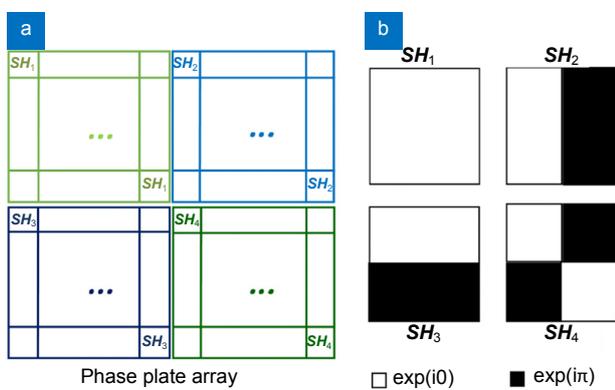


Fig. 3 | (a) An example for PPA: the 2-order PPA is composed of 4 sub-phase plates, which are constituted by four phase patterns SH_1 , SH_2 , SH_3 and SH_4 respectively. (b) The four phase patterns are formed by the first, second, third and fourth rows of $H(4)$ respectively.

example is shown in Fig. 3(a). The PPA contains four sub-phase plates. These sub-phase plates are constituted by repeating the four phase patterns SH_1 , SH_2 , SH_3 and SH_4 , which are formed by the first, second, third and fourth row of a $H(4)$ phase matrix respectively, as shown in Fig. 3(b).

The phase patterns in each sub-phase plate will change in a cycle mode to reveal all the SH formed by $H(4)$. However, the same SH will not be revealed in more than one sub-phase plate in any moment. In other words, the 2-order PPA is always constituted by four different SH . To understand the corresponding relationships among SH , sub-phase plate, PPA, lens unit of LA and LA, an example is shown in Fig. 4(a). Resolution spot A is on the focal plane of the main lens, and corresponds to four phase patterns SH (A_1 , A_2 , A_3 , and A_4) in four sub-phase plates respectively, which constitute the whole PPA. To achieve speckle reduction, A_1 – A_4 must be incoherent from one another. However, in the same sub-phase plate, SH could be the same. In other words, A_1 can be the same with B_1 , and this principle can also be applied to A_2 – A_4 with B_2 – B_4 equally. This is because for a standard 4-f system, the same SH (A and B) will not overlap. Conversely, the position dislocation that may cause the same SH to superimpose must be avoided, which would reduce the incoherence of beams.

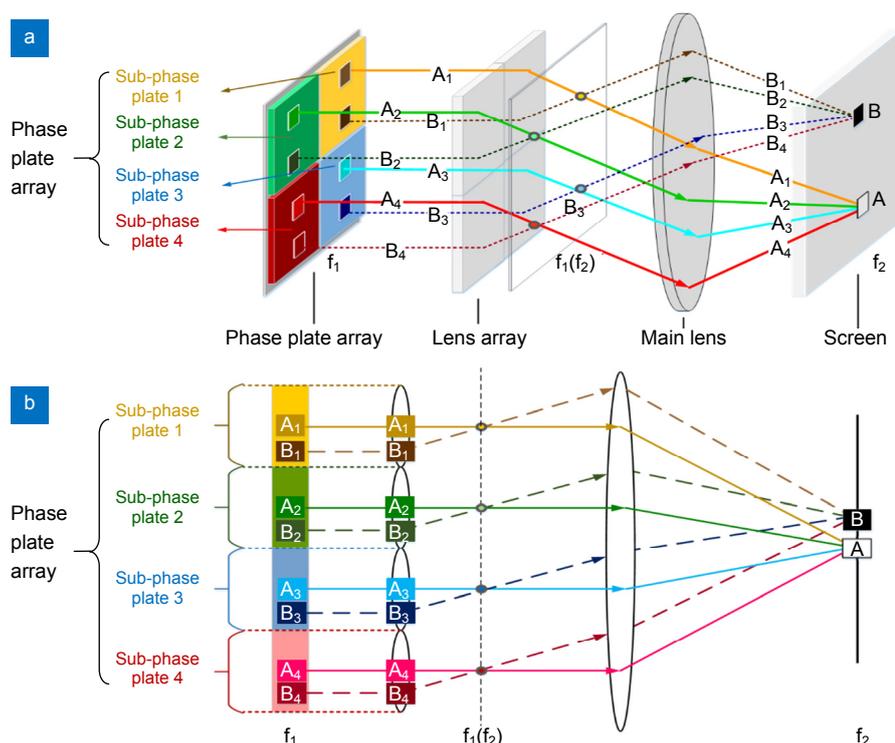


Fig. 4 | (a) The incoherent speckles that correspond to different SH should superpose in the same position. Each sub-phase plate should correspond to lens unit of LA both in size and position. (b) To further understand the stated relationships, the 2×2 PPA is converted into a 1×4 PPA and its side view is given.

Therefore, not only the number and the size of the sub-phase plate should correspond to the lens unit of LA, but also every sub-phase plate should match with the lens unit of LA in position. To further understand the stated relationships, the 2×2 PPA is converted into a 1×4 PPA and its side view is given, as shown in Fig. 4(b). The following requirements need to be satisfied: The size of sub-phase plate should be equal to the lens unit; Along the principal axis, the position of PPA, LA, main lens and screen should satisfy a standard of $4-f$ system; Perpendicular to the principal axis, each sub-phase plate should satisfy the positional correspondence with the lens unit.

Experiments and results

In this optical system, the unit of LA (Edmund, #63230) is $4 \text{ mm} \times 3 \text{ mm}$ with a focal length of 38.1 mm . The working area of SLM is 0.55 inch with a length-width ratio of $16:9$, which means the length and width are about 12.2 mm and 6.9 mm , respectively. Thus, to match the work-

ing area of SLM and LA, the 2×2 PPA is used. That means the sizes of sub-phase plate and PPA are $4 \text{ mm} \times 3 \text{ mm}$ and $8 \text{ mm} \times 6 \text{ mm}$, respectively. The control unit of SLM is $6.4 \mu\text{m} \times 6.4 \mu\text{m}$, and we use the 2-order phase patterns SH formed by $H(4)$ as described in Fig. 3. Therefore, the size of one phase pattern SH will be $12.8 \mu\text{m} \times 12.8 \mu\text{m}$. A rough paper is used as screen. The focal length of the main lens is set as 40.0 mm , and then SH will be $13.4 \mu\text{m} \times 13.4 \mu\text{m}$ on the screen.

A CCD (Thorlabs, DCC1545M) with pixel size of $8.5 \mu\text{m} \times 8.5 \mu\text{m}$ is used to capture the speckle patterns. The integration time, focal length, pupil size and F-number ($F/\#$) of CCD are set as 30 ms , 60 mm , 3 mm and 20 , respectively. The speckle size on CCD will be $2.44\lambda(F/\#) = 31 \mu\text{m}$, which is greater than the CCD unit cell's size of $8.5 \mu\text{m} \times 8.5 \mu\text{m}$. Hence, the CCD can digitize the speckle pattern without any significant spatial averaging effects making the measurement accurate¹⁶. The size of CCD resolution spot on the screen is $2.44\lambda(F/\#) = 30.8 \mu\text{m}$,

Table 1 | The experimental setup parameters of LA, main lens, camera and PPA.

Lens array		Main lens	CCD		Phase plate array		
Focal length	The size of lens unit	Focal length	Integration time	Focal length	Pupil size	The size of phase unit	The size of sub-phase plate
38.1 mm	$4 \text{ mm} \times 3 \text{ mm}$	40 mm	30 ms	60 mm	3 mm	$6.4 \mu\text{m} \times 6.4 \mu\text{m}$	$4 \text{ mm} \times 3 \text{ mm}$

which means that on the screen the 2×2 phase cells belonging to one picture pixel fall in one resolution area of the camera lens. Thus, a phase pattern SH can be contained in one resolution spot¹⁷.

Our experimental results using 2-order PPA are shown in Fig. 5. The speckle contrast ratio C is defined as the ratio of standard deviation to mean value of a speckle image. Before loading the designed 2-order PPA, the speckle contrast is $C_1=0.57$. After loading the designed 2-order PPA, the speckle contrast reduces to $C_2=0.30$. Here, we define the relative ratio of speckle contrast as $\gamma=C_2/C_1$. Thus $\gamma=52.63\%$, which is close to the theoretical value 50%. Further, as we have mentioned above, if a larger number of different SH are used, speckle will be reduced further. Therefore, we study a more complicated PPA, which consists of 16 sub-phase plates. Obviously, this 4-order PPA contains 16 4-order SH , which are formed by the 16-order Hadamard matrix $H(16)$. Theoretically, the speckle contrast will reduce to $1/4$ of the previous level. Considering the limited size of SLM, the sub-phase plates are set as $2 \text{ mm} \times 1.5 \text{ mm}$, making sure that the 4×4 PPA can be contained in the working area. However, the unite size of LA is still $4 \text{ mm} \times 3 \text{ mm}$. Therefore, the PPA formed by SLM need to be magnified twice. In such way, the sub-phase plate can match with the size of lens unit.

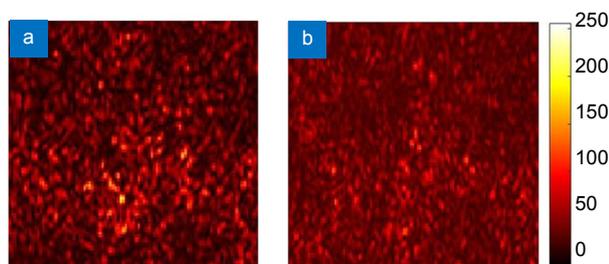


Fig. 5 | Speckle patterns (a) before and (b) after loading the designed 2-order PPA. The speckle contrast is reduced from 0.57 to 0.30, and a relative ratio $\gamma=52.63\%$ is realized.

As shown in Fig. 2, another beam expander (BE 2) is added on the basis of original optical system, so that sub-phase plates and lens units are corresponding one by one. The PPA, lens 'a' and lens 'b' constitute a 4-f system, as well as the LA, main lens and screen. Moreover, these two 4-f systems are seamlessly connected. The focal lengths of lens 'a' and 'b' are set as 3 cm and 6 cm, respectively, which enlarge the phase patterns with a $2 \times$ magnification. A 4-order phase pattern on SLM is $25.6 \mu\text{m} \times 25.6 \mu\text{m}$. After the first 4-f system, the size changes to $51.2 \mu\text{m} \times 51.2 \mu\text{m}$. After the second 4-f system, its size changes

to $53.8 \mu\text{m} \times 53.8 \mu\text{m}$. The camera's parameters are reset as: the integration time 30 ms, focal length 120 mm, pupil size 3 mm and $(F/\#)=40$. Therefore, the size of CCD resolution spot on the screen is $2.44\lambda(F/\#)=61.8 \mu\text{m}$, which is larger than a phase pattern. Thus, one SH can be contained in one resolution spot on the screen, and the 4×4 phase cells belonging to one picture pixel fall in one resolution area of the camera lens.

The experimental results using 4-order PPA are shown in Fig. 6. Before loading the PPA, the speckle contrast is $C_1=0.45$. After loading the PPA, the speckle contrast reduces to $C_2=0.12$. Thus, the relative ratio of speckle contrast $\gamma=26.67\%$, which is close to the theoretical value 25%.

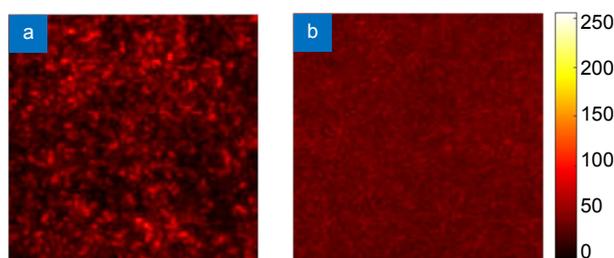


Fig. 6 | The speckle patterns before (a) and after (b) loading the 4-order PPA. The speckle contrast is reduced from 0.45 to 0.12, and a relative ratio $\gamma=26.67\%$ is realized.

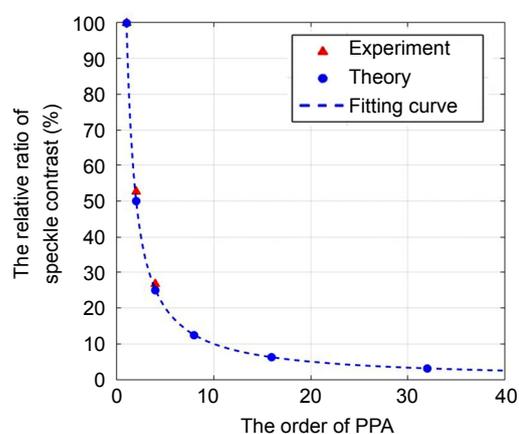


Fig. 7 | The relative ratio of speckle contrast is inversely proportional to the order of PPA.

Therefore, as shown in Fig. 7, the higher order the PPA, the lower the speckle contrast. When using an n -order PPA, speckle contrast will decrease to $1/n$ of its original value, which means the relative speckle contrast is inversely proportional to the order of PPA. The experimental results coincide with the theoretical values. Although speckle can be further eliminated by using a higher-order PPA, the restricted size of SLM and LA and the requirements for precise alignment of optical elements

are two main obstacles.

Conclusions

In this paper, a solution for speckle reduction using PPA and LA in a motionless way is proposed. The PPA, LA, main lens and screen constitute a 4-f system. For the 2-order PPA, sub-phase plates are constituted by four phase patterns formed by a 4-order Hadamard matrix. Incident light will be incoherent after passing through PPA and superpose on the screen under the action of LA and main lens. Speckle reduction will be achieved by the averaging of incoherent speckle patterns. We also analyze the size and positional relationships among each component. Experiments show that a relative ratio of 52.63% is achieved, which is close to the theoretical value 50%. For the 4-order PPA, sub-phase plates are constituted by sixteen different phase patterns, which are formed by a 16-order Hadamard matrix. In order to match the working area of SLM with the size of lens unit, another beam expander is added, which also satisfies a 4-f system standard. Thus, the whole system contains two seamlessly connected 4-f systems. Experiments show that a relative ratio of 26.67% is achieved, which is close to the theoretical value 25%. The results prove that using an n -order PPA will decrease the speckle contrast to $1/n$ of its original value. Speckle can be further suppressed by using a higher-order PPA. However, the light loss is inevitable due to the existence of diffraction. How to improve the light efficiency is our next work.

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Competing interests

The authors declare no competing financial interests.