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Magnified holographic projection based on spatial light modulators

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In this paper, a magnified holographic projection based on spatial light modulators is proposed and implemented by combining four magnification methods, including similarity principle of Fourier transform, spatial division, digital lens, and image splicing methods. The Fourier holographic display system is constructed for the experimental verification of the proposed methods. With such four methods of holographic magnification, the reconstruction image can be magnified to 10×5 times in two-dimensional directions, which is verified by the experiments. Furthermore, the undesirable light of holographic projection is eliminated by encoding the linear phase onto the computer-generated holograms. The experimental results prove that the proposed system can realize magnified holographic projection with good reconstructed quality, which provides a promising potential for the dynamic holographic projector.

Keywords: holographic display, spatial light modulators, computer-generated holograms, magnified holographic projection.

1. Introduction

Holographic display is a promising wavefront reconstruction technology in the field of information display [1–3]. It can bring a vivid visual experience to the viewers, which has exhibited great potential for widespread applications, such as three-dimensional (3D) projection [4, 5], head-mounted display [6, 7] and augmented reality [8, 9]. In recent years, electronic holography based on spatial light modulator (SLM) has attracted much attention for realizing dynamic real-time display, and it has achieved rapid developments and advances because the SLMs have great flexibility of controlling optical wavefronts [10, 11]. However, there are still several difficult challenges hindering the practical applications of holographic display or holographic projection. One of the main problems is that the size of reconstructed image in electronic holography is small, which is caused by the overlarge pixel pitch of current commercial available SLM, and it greatly limits the observing experience of viewers.

To expand the size of holographic reconstructed image, several beneficial attempts have been performed [12–23]. The common way to achieve a large holographic reconstruction is using a zoom lens module composed of several lenses and mechanical parts in a holographic display configuration, which will contribute to the increase of system cost and complexity, and the inconvenience of manual operation. In addition, the active optical components such as liquid crystal lens [12–14] or liquid lens [15, 16] also have been widely used in holographic magnification systems. As the focal length of the liquid lens or liquid crystal lens can be continuously changed by a voltage, the magnification of the reconstruction image can be electrically controlled. But this method needs the additional devices, and the response time of the current liquid lens may not satisfy the frame requirement of holographic video applications. Furthermore, lensless zoomable holographic projection has been proposed and demonstrated by using scaled Fresnel diffraction [17]. The zoom function is realized only by changing the sampling rate on the projection image, whereas the magnification of this method is still limited by the adopted single SLM. Besides, some space-division [18–21] and time-division [22, 23] multiplexing methods also have been proposed to realize large holographic reconstruction. However, these systems may require an optical system containing lens arrays and other components, or a rapid refresh module, which is unfavorable for a compact dynamic holographic projector.

In this paper, we propose a magnified holographic projection system based on SLMs. Four different magnification methods, including similarity principle of Fourier transform (SPFT), spatial division (SD), digital lens (DL), and image splicing (IS) methods, are combined to enlarge the holographic reconstructed image. Firstly, the size of the reconstructed image can be magnified by using the SPFT method, and the undesirable light can be eliminated by loading linear phase onto the phase distribution of original hologram. Secondly, the holographic reconstruction can be enlarged further by image division and recombination with the SD method. Thirdly, the digital lens encoded onto the SLMs is used as a zoom lens for changing the magnification of holographic reconstructed image, which renders the system more compact. Last, the projection images reconstructed by different SLMs can be spliced without a tiling gap. By combining the four magnification methods mentioned above, the magnification factor can reach 10×5 in two-dimensional (2D) directions. In the following sections, the theoretical principles and system configurations will be described in detail, and the verification experimental results will be presented and analyzed.

2. Theoretical principles and system configurations

In the proposed method, the iterative Fourier transform algorithm (IFTA) [24] is used to calculate the phase-only hologram of original object, and the Fourier holographic

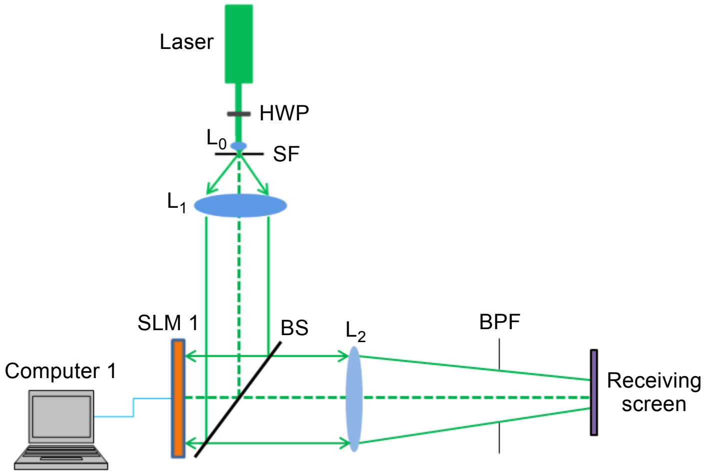

Fig. 1. Schematic diagram of the Fourier holographic display system for holographic projection. HWP is half-wave plate, L_0 – beam expander, SF – spatial filter, L_1 – collimating lens, BS – beam splitter, L_2 – the Fourier lens with a focal length of f, BPF – band-pass filter.

display system shown in Fig. 1 is adopted for holographic projection. The system is composed of a laser, a half-wave plate, a beam expander, a spatial filter, a collimating lens, a beam splitter, a phase-only SLM, a computer, a Fourier lens, a band-pass filter, and a receiving screen. The laser, beam expander, spatial filter, and collimating lens are used to generate a collimated light, the Fourier lens is placed behind the SLM, and the distance between them is just the focal length of the Fourier lens, then we can observe the holographic reconstructed image on the receiving screen when the beam uniformly illuminates the SLM. Suppose that the receiving screen is placed at the back focal plane of the Fourier lens, then the complex amplitude distribution on the receiving screen $g(x, y)$ can be calculated by

$$g(x, y) = \frac{\exp(jkf)}{j\lambda f}\iint G(\xi, \eta)\exp\left[\frac{-j2\pi}{\lambda f}(x\xi + y\eta)\right]\mathrm{d}\xi\mathrm{d}\eta \tag{1}$$

where f denotes the focal length of the Fourier lens, λ and k represent the wavelength of the incident light and the wave number, respectively, and $G(\xi, \eta)$ is the complex amplitude distribution on the hologram plane. When taking the field distribution on the receiving screen into consideration, Eq. (1) can be simplified as

$$g(x, y) \leftrightarrow G(\xi, \eta) \tag{2}$$

where $\leftrightarrow$ means the process of Fourier transform and inverse Fourier transform.

2.1. Magnification by the SPFT method

In order to adjust the size of the holographic reconstructed image, the similarity principle of Fourier transform (SPFT) is used in the proposed method as follows:

$$g(ax, by) \leftrightarrow \frac{1}{|ab|} G\left(\frac{\xi}{a}, \frac{\eta}{b}\right) \tag{3}$$

where a and b are scalar constants. From Eq. (3), we can see that compression in frequency domain gives rise to expansion in space domain and *vice versa*. In fact, the compression of the hologram is that the sampling interval in frequency domain decreases when calculating the phase-only hologram of original object. According the diffraction theory, the size of the holographic reconstructed image is inversely proportional to the sampling interval of the hologram. So the size of the reconstructed image will expand in space domain if the hologram is compressed in frequency domain. Furthermore, the scalar constants in Eq. (3) determine the scaling factor of the sampling interval and the reconstructed image. Thus, the size of the holographic reconstructed image can be adjusted conveniently by changing the values of a and b. If a hologram is generated with compression in frequency domain by a factor of $a \times b$, the holographic reconstructed image will be magnified to $a \times b$ times in x and y dimensions.

2.2. Magnification by the SD method

In order to enlarge the holographic reconstructed image further, the spatial division (SD) is used in the proposed method, which is illustrated in Fig. 2. When the hologram of an original image is loaded onto the SLM in Fig. 1, we assume the size of the holographic reconstructed image as $U \times V$.

Firstly, the original image is divided equally into $c \times d$ sub-images. For the sake of the illustration, we take 2×2 sub-images for example in Fig. 2. Secondly, $c \times d$ sub -holograms are generated by using the IFTA method. Thirdly, in order to realize the

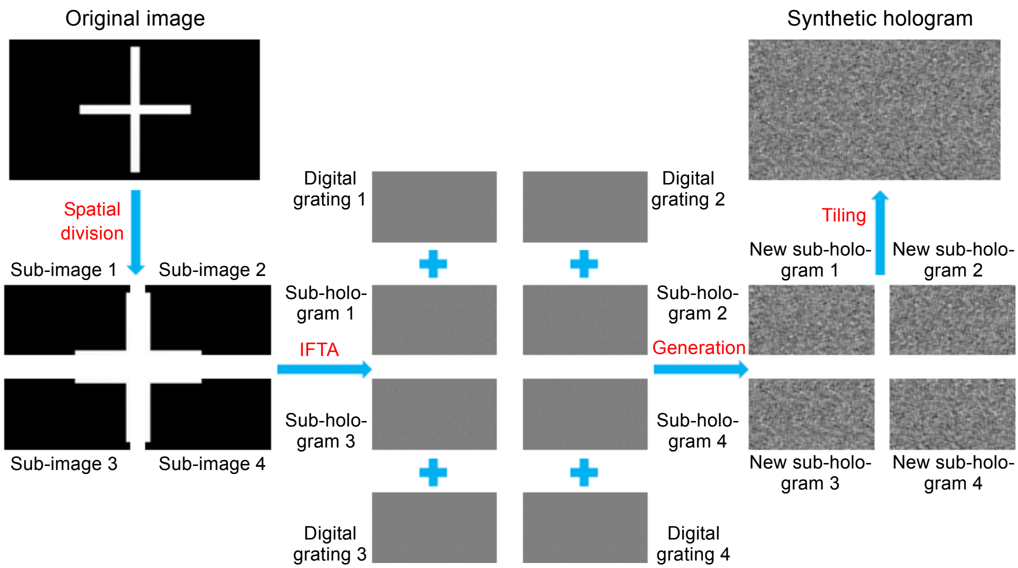

Fig. 2. Schematic diagram of the proposed spatial division method.

recombination of the $c \times d$ reconstructed images, $c \times d$ digital gratings are encoded onto the sub-holograms, which are used for controlling the locations of the $c \times d$ reconstructed images, and then the $c \times d$ new sub-holograms are generated. The phase distribution φ_{grating} of the digital grating can be expressed by [25]

$$\varphi_{\text{grating}} = \frac{2\pi}{T}\text{mod}(pm + qn, T) \tag{4}$$

where T represents the period of the digital grating, mod means the operation of taking remainder, m and n are the vertical and horizontal range of the digital grating, respectively, p and q represent the grating loaded onto m and n directions, and the orientation of the digital grating can be changed easily by adjusting p and q. Finally, a synthetic hologram is generated by tiling the $c \times d$ new sub-holograms, which is loaded onto the SLM and occupies the whole area of the SLM. Because the reconstructed sizes of the sub-holograms are equal to $U \times V$, the size of the reconstructed image after recombination is $cU \times dV$. That is to say, the holographic reconstructed image is magnified to $c \times d$ times in x and y dimensions.

2.3. Magnification by the DL method

The digital lens (DL) is used to expand the size of the holographic reconstructed image further more in the proposed method. By programming the digital lens, the focal length could be changed conveniently so that the encoded digital lens is able to be used as a zoom lens, which renders the system more compact in comparison with the traditional zoom lens modules. The phase distribution φ_{lens} of the digital lens can be written as [26]

$$\varphi_{\text{lens}} = \frac{\pi}{\lambda f_{\text{L}}}(\xi^2 + \eta^2) \tag{5}$$

where f_{L} represents the focal length of the digital lens. Assume that the phase distribution of original hologram is φ, then the new phase distribution φ' after adding the digital lens into the original hologram can be expressed as

$$\varphi' = \text{mod}(\varphi + \varphi_{\text{lens}}, 2\pi) \tag{6}$$

Therefore, the reconstructed image will be translated from the back focal plane of the Fourier lens into a new position, and we record the translated distance as z. According to the imaging formula of lens, the translated distance z can be calculated by

$$\frac{1}{f+f_{\text{L}}} + \frac{1}{f+z} = \frac{1}{f} \tag{7}$$

Thus, the magnification is

$$M = -\frac{f+z}{f+f_{\text{L}}} = -\frac{f}{f_{\text{L}}} \tag{8}$$

In other words, the holographic reconstructed image is magnified to $|f/f_L| \times |f/f_L|$ times in x and y dimensions by using the digital lens.

2.4. Magnification by the IS method

Multiple SLMs are used to realize the large-size holographic projection further by using the image splicing technology in the proposed method. Figure 3 is the schematic diagram of the holographic magnification system based on two SLMs. In order to control the locations of two reconstructed images, two digital gratings are encoded onto the two pre-calculated holograms, respectively. By programming the digital gratings, the final image displayed on the receiving screen is the combination of the reconstructed images from two SLMs. When the two images are spliced along the x dimension, the holographic reconstructed image is magnified to 2×1 times in x and y dimensions, and when the two images are spliced along the y dimension, the holographic reconstructed image is magnified to 1×2 times in x and y dimensions. Furthermore, the size of the holographic reconstructed image will continue to expand if the number of SLMs increases.

In addition, the vision perception of holographic projection could be disturbed by the undesirable light including multi-order reconstruction, zero-order and multi-order diffraction beams because of the pixelated structure of the current SLM [27, 28]. In the proposed methods mentioned above, the zero-order diffraction light can be separated with the projection image by adding the linear phase onto the pre-calculated hologram, and then the undesirable light can be removed by a single rectangular low-pass amplitude filter, where the filter represents the band-pass filter as shown in Figs. 1 and 3.

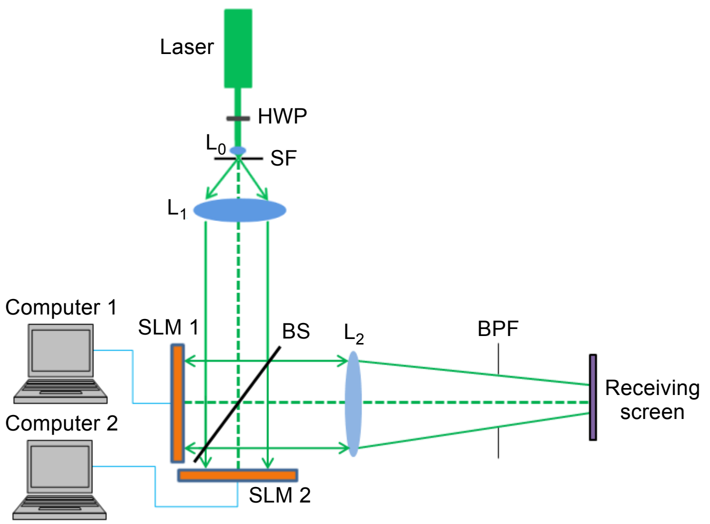

Fig. 3. Schematic diagram of the holographic magnification system based on two SLMs. HWP is half -wave plate, L_0 – beam expander, SF – spatial filter, L_1 – collimating lens, BS – beam splitter, L_2 – the Fourier lens with a focal length of f, BPF – band-pass filter.

3. Optical experiments and results

In order to verify the validity of the proposed methods, a series of experiments have been performed. In our experimental systems, a green laser with a wavelength of 532 nm is used as the light source to illuminate the reflective-type SLM. The pixel number of the SLM is 1920 × 1080, and the pixel pitch is 8 μm. The focal length of the Fourier lens is 400 mm, and the SLM locates in the front focal plane of the Fourier lens. Moreover, the cross logo is used as the original image for holographic projection with the experimental system shown in Fig. 1, and the corresponding original hologram is calculated by the IFTA. The experimental results are shown in Fig. 4, where Figs. 4**a** and 4**b** are the reconstructed images of the original hologram, the new hologram with compression in frequency domain by a factor of 2 × 2, respectively. Figure 4**c** is the magnified reconstructed image without the undesirable light, which attributes to the encoded linear phase onto the new hologram. From the results, we can see that the size of the reconstructed image can be magnified to 2 × 2 times conveniently by using the SPFT method.

According to the SD method mentioned in the above section, we first divide the original image equally into 2 × 2 sub-images, and then 2 × 2 sub-holograms are generated by using the IFTA and the SPFT method. After adding the digital gratings and tiling the 2 × 2 new sub-holograms, we can obtain the synthetic hologram whose reconstructed image is shown in Fig. 5. The experimental results of Figs. 4**c** and 5 demonstrate that the size of the reconstructed image can be enlarged to 2 × 2 times further by using the SD method.

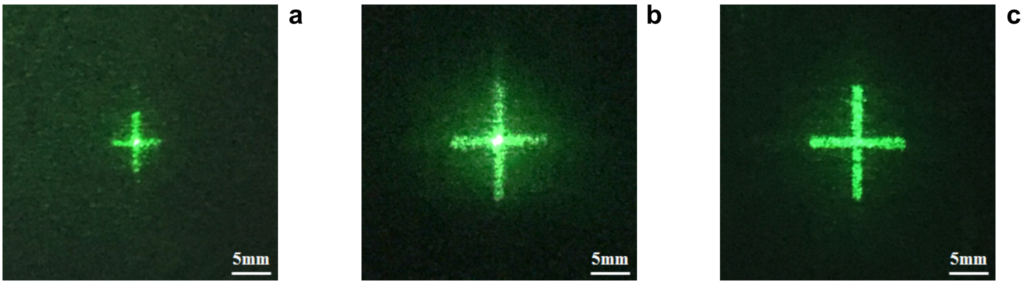

Fig. 4. Reconstructed image of the original hologram (**a**), reconstructed image of the new hologram with compression in frequency domain by a factor of 2 × 2 (**b**), and magnified reconstructed image without the undesirable light (**c**).

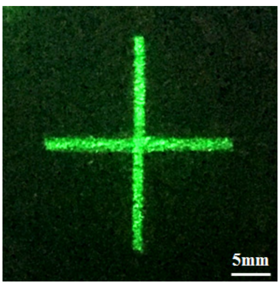

Fig. 5. Reconstructed image of the synthetic hologram generated by the SD method.

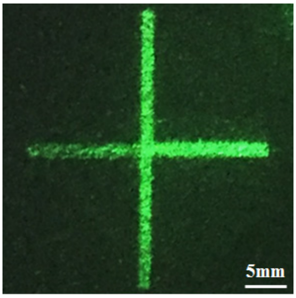

Fig. 6. Reconstructed image of the hologram after adding the phase of the digital lens to the phase distribution of the synthetic hologram.

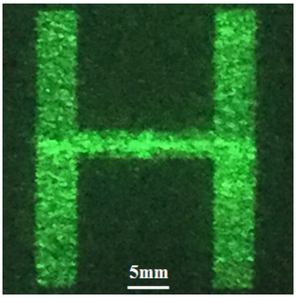

Fig. 7. Reconstructed image of the hologram after the SPFT, SD and DL magnification methods.

The digital lens with a focal length f_L of 320 mm is adopted to verify the DL method, the reconstructed image of the hologram after adding the phase of the digital lens to the phase distribution of the synthetic hologram is shown in Fig. 6. The experimental results of Figs. 5 and 6 show that the size of the reconstructed image can be enlarged to 1.25×1.25 times further more by using the DL method, which is in good consistency with the theoretical magnification.

In addition, the letter H is also chosen as the original image for holographic projection by using another SLM. The letter is processed according to the identical procedures of the cross logo, and corresponding experimental result after the SPFT, SD and DL magnification methods is shown in Fig. 7.

By constructing the experimental system shown in Fig. 2 and splicing the results in Figs. 6 and 7 horizontally, the final holographic reconstructed image is shown in Fig. 8**a**. Furthermore, we adopt two Chinese characters to demonstrate the vertical splicing result by using the same processing methods, and the final reconstructed image is shown in Fig. 8**b**. From the results, we can see that the size of the reconstructed image can be magnified to 2×1 or 1×2 times by using the IS method, the former represents horizontal image splicing and the latter represents vertical image splicing. In summary, the magnification factor of holographic reconstructed image can reach 10×5 in 2D directions by combining the four magnification methods mentioned above. Note that there exist valid images and invalid images in the adopted original images, where the valid images are used for holographic reconstruction to express object information while the invalid images are background, and the magnification factors of each magnification method mentioned above also work for the valid reconstructed images.

Therefore, the final valid reconstructed images shown in Fig. 8 are 10 × 5 times as large as the valid reconstructed image of the original hologram, which is shown in Fig. 4**a**.

We further use two complete letters to demonstrate magnified holographic projection. The letter W and Chinese characters firstly are equally divided into two parts for holographic reconstruction with two SLMs, respectively. Analogously, the reconstructed images could be enlarged by the proposed methods; corresponding experimental results are shown in Figs. 9**a** and 9**b**. The experimental results presented here demon-

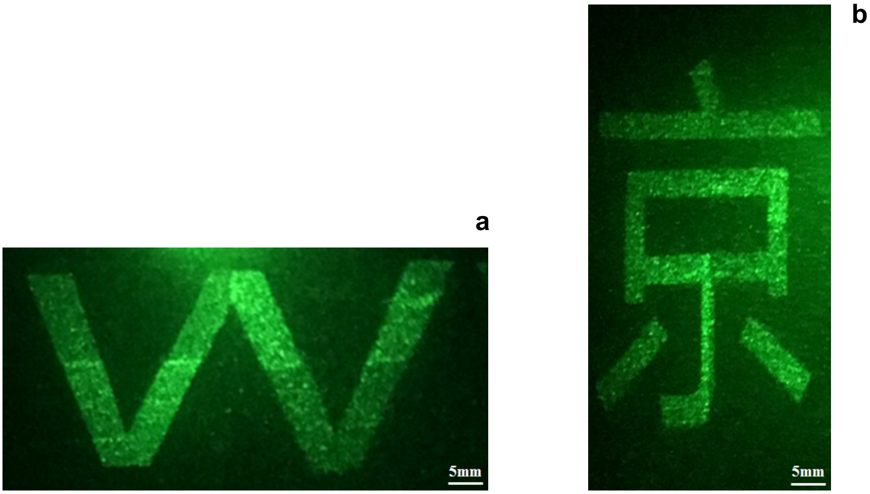

Fig. 8. Final magnified reconstructed image of a complete letter W (**a**), and final magnified reconstructed image of a complete Chinese characters (**b**).

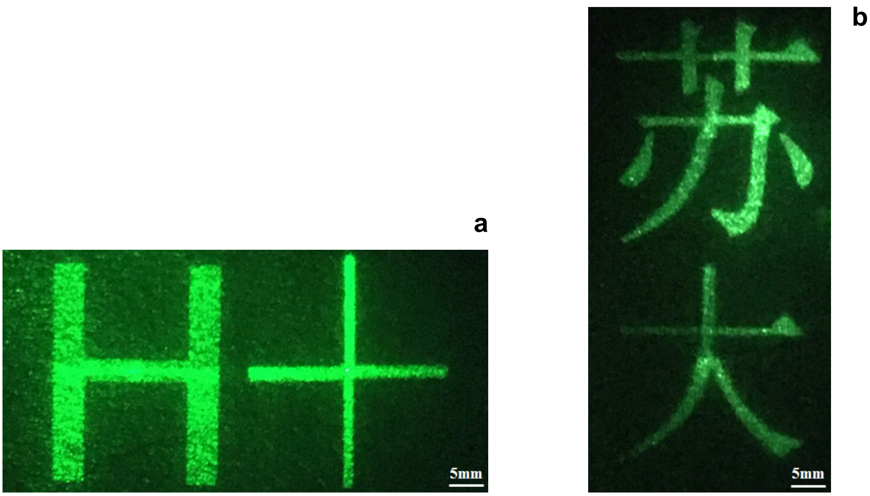

Fig. 9. Final reconstructed image of an letter H and a cross logo with horizontal image splicing method (**a**), and final reconstructed image of two Chinese characters with vertical image splicing method (**b**).

strate that the proposed methods can realize magnified holographic projection with good reconstructed quality.

4. Discussion and conclusions

In this paper, we propose a magnified holographic projection based on SLMs by combining four different magnification methods, including SPFT, SD, DL, and IS methods. The experimental results prove the feasibility of our methods because the reconstruction image can be magnified to 10×5 times in 2D directions by using such four methods. Furthermore, the undesirable light of holographic projection is eliminated by adding the linear phase onto the holograms for obtaining a good reconstructed quality. In addition, under the condition of not increasing the complexity of holographic projection system, the proposed methods are simpler, more compact, and easier to operate with low cost in comparison with traditional methods. The research work may have a certain value in holographic display or holographic projection. The refresh rate of a current commercial available SLM could reach more than 60 Hz, so the proposed system and method provide a promising potential for the dynamic holographic projector.

However, the proposed methods still face some problems. In the SPFT method, the decrease in the sampling interval means that the spatial frequency increases, but the maximum spatial frequency of the hologram loaded onto the SLM is limited by the pixel pitch of the SLM according to the Nyquist sampling theorem. So, the sampling interval of the hologram can only decrease to the minimum value that is the pixel pitch of the SLM. Thus, the size of the holographic reconstructed image is still limited by the overlarge pixel pitch of the SLM. In the DL method, the spatial frequency of the digital lens encoded onto the SLM is inversely proportional to its focal length. In other words, the spatial frequency of the digital lens increases when its focal length decreases. But the SLM can only carry limited spatial frequency because of the fixed pixel pitch. So, the focal length of the digital lens has minimum value under the circumstance that the adopted SLM is confirmed. Furthermore, the magnification factor is also inversely proportional to its focal length according to the derivation results depicted in Section 2.3. Therefore, the magnification factor has its upper limit so that the size of the reconstructed image is also limited by the pixel pitch of the SLM. Moreover, the speckle noises in experimental results are mostly caused by the coherence of the incident beam, and it can be reduced by using a light-emitting diode as the illuminating light source or using a rotating diffuser. To improve the reconstructed quality, more SLMs with better performance can be used instead. In the future, we will continue to improve the performance of this system with regard to image quality, real-time property and speckle noises. Chromatic magnified holographic projection will also be studied through reconstruction and integration of RGB color holograms.

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