Article

Computer-Generated Hologram Based on Reference Light Multiplexing for Holographic Display

Dapu Pi and Juan Liu *

Beijing Engineering Research Center for Mixed Reality and Advanced Display, School of Optics and Photonics, Beijing Institution of Technology, Beijing 100081, China; pidapu@bit.edu.cn

* Correspondence: juanliu@bit.edu.cn

Abstract: In this article, we propose a reference light wave multiplexing scheme to increase the information capacity of computer-generated holograms. The holograms were generated by different reference light waves and superimposed together as a multiplexed hologram. A modified Gerchberg–Saxton algorithm was used to improve image quality, and different images could be reconstructed when the multiplexed hologram was illuminated by corresponding reference light waves. We performed both numerical simulations and optical experiments to demonstrate the feasibility of the proposed scheme. Numerical simulations showed that the proposed method could reconstruct multiple images successfully by a single multiplexed hologram and optical experiments are consistently good with numerical simulations. It is expected that the proposed method has great potential to be widely applied in holographic displays in the future.

Keywords: holography; computer-generated hologram; holographic display

1. Introduction

Holographic display is regarded as the ideal three-dimensional (3D) display technology because it offers all the visual information human eyes require [1,2]. Computer-generated hologram (CGH) is a key method to realize holographic display by recording holograms digitally and has attracted attention in recent years [3–6]. However, limited information capacity and the quality of reconstructed images are two main problems that restrict the development of holographic display.

Multiplexing technology is widely applied to increase information capacity. In previous decades, various multiplexing methods for multiple-image encryption were proposed, such as angular multiplexing [7], wavelength multiplexing [8], and position multiplexing [9]. In recent years, metasurface holograms have attracted great interest because metasurface can overcome the challenges faced by traditional holography, such as wide viewing angles, and the elimination of unwanted diffraction orders. So far, different physical parameters, such as polarization [10], helicity [11], wavelength [12], incidence angle [13], and orbital angular momentum [14], have been utilized to increase information capacity in metasurface. In CGH, the time-multiplexing method [15–17] and spatial-multiplexing method [18–20] are widely applied to realize color holographic display or increase the field of view. Additionally, various multiplexing coding methods are also proposed to realize color holographic display, where three color sub-holograms are encoded into one hologram, such as depth-division multiplexing [21], space-division multiplexing [22,23], frequency-division multiplexing [24–26], and so on. Currently, position multiplexing has also been used in CGH, where different images can be reconstructed at different positions by a multiplexed CGH (MCGH) [27,28]. Furthermore, curvature multiplexing [29,30] has been utilized to increase information capacity, where different images can be reconstructed at the same or different positions by changing the curvature of a MCGH. However, this method exhibits strong crosstalk noise in reconstructed images. Therefore,
multiplexing methods that can increase information capacity further and reconstruct multiple images are strongly required in the development of holographic display.

In CGH, phase-only SLM, where the complex amplitude distribution is encoded into phase-only information by considering the amplitude distribution as constant, is widely utilized because of its high diffraction efficiency. Furthermore, the addition of an initial random phase is also widely used to diffuse object information in a calculation, which causes speckle noise and decays the reconstructed image quality [31,32]. There are two methods to solve this problem; one is complex amplitude modulation methods, and the other is iteration algorithms. The complex amplitude modulation method encodes target complex amplitude distribution into amplitude-only or phase-only holograms by encoding specific algorithms or through optical devices. Scholars have presented many complex amplitude modulation methods, such as double-phase method [33–36], superpixel method [37,38], iteration method [39], and so on [40,41]. However, it is known that the amount of information for complex amplitude holograms is double that for amplitude-only or phase-only holograms. Hence, complex amplitude modulation has been realized with the reduction of space bandwidth product. The iteration algorithm optimizes phase distribution in the hologram plane after an iterations calculation by controlling the amplitude distribution of the hologram plane and imaging plane [42,43]. In general, the iteration algorithm is the most widely used method for phase-only CGH calculation and has achieved considerable success in less convergence time and clear reconstruction.

In this article, we propose a multiplexing scheme to increase information capacity. CGHs of different images are generated by different reference light waves and encoded into one MCGH. We used a modified Gerchberg–Saxton (GS) algorithm to improve the quality of reconstructed images; different images can be reconstructed when MCGH is illuminated by corresponding reference light waves. Numerical simulations and optical experiments were performed to validate the proposed method.

2. Principles and Methods

The calculation for the proposed method contains eight steps, and the detailed description is as follows:

1. Acquire target complex amplitude distribution

The complex amplitude distribution of each image is initialized as follows:

$$E_i(\xi, \eta) = A_i(\xi, \eta) \exp[i \varphi(\xi, \eta)]$$

(1)

where $A_i(\xi, \eta)$ is the target amplitude of the $i$th image, and $\varphi(\xi, \eta)$ is random phase, which is distributed between 0 and $2\pi$.

2. Propagate to CGH plane

The object light wave propagates toward the CGH plane using angular spectrum diffraction, which divides the optical wavefront into several plane waves with different spatial frequencies and superimposes them after propagating distance $z$, as shown in Equation (2):

$$O_i(x, y) = \text{IFFT} \{ \text{FFT} \{ E_i(\xi, \eta) \} \cdot T(f_x, f_y) \}$$

(2)

where $T(f_x, f_y)$ is the angular spectrum transfer function and can be described as:

$$T(f_x, f_y) = \exp(jkz \sqrt{f_x^2 + \lambda^2 f_y^2})$$

(3)

where $f_x$ and $f_y$ are spatial frequencies. $\lambda$ is wavelength and $k = 2\pi/\lambda$ is wave number.

3. Define reference light wave

Usually, the reference light of the CGH is a parallel light wave. However, in the proposed method, cylindrical and spherical light waves are used as reference light waves to
reduce crosstalk among different images and increase information capacity. The reference light wave can be provided by:

\[
R_c(x, y) = \exp(jk\sqrt{x^2 + r^2}) \\
R_s(x, y) = \exp(jk\sqrt{y^2 + r^2})
\]  \hspace{1cm} (4)

where \(R_c(x, y)\) and \(R_s(x, y)\) are cylindrical and spherical reference light waves, respectively. \(x\) and \(y\) are horizontal and vertical horizontal coordinates in the CGH plane, respectively. \(r\) is the distance between the light source and CGH plane. In numerical simulations, the light sources of different reference light waves locate at different positions along \(z\)-direction, which creates a more compact system in practical application.

4. Record CGH

The process of recording is shown in Figure 1. \(E(x, y)\) indicates the complex amplitude distribution of the image. \(H(x, y)\) is the complex amplitude distribution of CGH. \(R(x, y)\) represents the reference light waves.

\[E(x, y) \times H(x, y) = R(x, y)\]  \hspace{1cm} (5)

5. Generate MCGH

The complex amplitude distribution of MCGH is generated by adding the complex amplitude distribution of all sub-CGHs, and is provided by

\[H(x, y) = \sum_{i=1}^{N} H_i(x, y)\]  \hspace{1cm} (6)

Then the amplitude of MCGH is normalized and the phase is retained, which is provided by:

\[H'(x, y) = \exp[j\text{angle}(H(x, y))]\]  \hspace{1cm} (7)

6. Reconstruct image

The process of reconstruction is shown in Figure 2. \(H'(x, y)\) is the complex amplitude distribution of MCGH. \(R'(x, y)\) represents the conjugate light waves of reference light waves.
In the reconstruction process, the conjugate light waves of reference light waves are used as reconstructed light waves. MCGH under the illumination of reconstructed light waves propagates backward to the object plane using inverse angular spectrum diffraction to obtain the corresponding reconstructed images as shown in Equation (8):

$$E_i(\xi, \eta) = \text{IFFT}\{\text{FFT}[H(x, y) \cdot R^*(x, y)] \cdot T^*(f', f_i)]\}$$  \hspace{1cm} (8)

7. Decide to stop the iteration process

The iteration algorithm uses forward and backward propagation of the light field between the object plane and CGH plane. The iteration operation aims to produce an appropriate MCGH and obtain the target images. Therefore, it is essential to evaluate the quality of reconstructed images and determine whether to stop the iteration process. We preset the threshold value $\epsilon$, and the average differences between target amplitude distributions and the reconstructed amplitude distributions must be less than $\epsilon$, as shown in Equation (9). If the quality of image agrees with the requirements, the iteration stops. If not, we execute the next step, and the iteration continues.

$$\sum_{\xi=1}^{p} \sum_{\eta=1}^{q} |A(\xi, \eta) - |E_i(\xi, \eta)||^2 \, d\xi \, d\eta < \epsilon$$  \hspace{1cm} (9)

8. Modify target distribution

In our proposed method, if the image quality does not satisfy the requirements shown in Equation (9), the reconstructed amplitude will be replaced by a target amplitude and the phase will be retained. The modified target complex amplitude distribution is written in Equation (10):

$$E_i(\xi, \eta) = A(\xi, \eta) \exp\{\text{angle}[E_i(\xi, \eta)]\}$$  \hspace{1cm} (10)

Steps 2–7 are repeated until the image quality meets the requirements. The flowchart of proposed technique is shown in Figure 3.
Figure 3. Flowchart of proposed method.

In order to evaluate the quality of reconstructed images from MCGH, the root-mean-square error (RMSE) and speckle contrast (SC) are utilized.

RMSE is defined as:

$$\text{RMSE} = \left( \frac{1}{p \times q} \sum_{m=1}^{p} \sum_{n=1}^{q} (f(m,n) - g(m,n))^2 \right)^{1/2}$$

(11)

where the intensity distribution of reconstructed images and target images are $f(m,n)$ and $g(m,n)$, respectively. The horizontal and vertical number of pixels in the reconstructed images are $p$ and $q$, respectively. Generally, the higher quality reconstruction can be indicated by a lower RMSE.

SC can be expressed as:

$$\text{SC} = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (I_j - I)^2}$$

(12)

where the total number of pixels in reconstructed images are $N$, $I$ is the average intensity of reconstructed images and $I_j$ is the intensity of the $j$th pixel in reconstructed images. Generally, the higher quality reconstruction can be indicated by a lower SC.

3. Numerical Simulation and Emulation

In order to prove the viability of proposed method, we conducted numerical simulations. The parameters used in the computation included a 1080 × 1920 resolution for the CGH, and a pixel size of 8 μm × 8 μm. The simulations were performed by a computer with MATLAB on Core i7-7700, 3.6 GHz, and 8G RAM.

In the numerical simulations, we first used different cylindrical light waves as reference light waves and reconstructed four independent images at the same position, as shown in Figure 4. The numerical reconstructions without iterations are shown in Figure 4e–h, which demonstrates how the proposed method can reconstruct different images successfully; although, there is some crosstalk and speckle noise in the reconstructed images. RMSE and SC of reconstructed images are shown in Table 1. In numerical simulations, a total of 20 iterations is enough to guarantee that images will be reconstructed accurately; the reconstructed results with 20 iterations are presented in Figure 4i–l. The results show that the reconstructed images created after these iterations are more accurate and clearer to the naked eye. The RMSE decreases by 51.1%, 50.1%, 56.5%, and 52.1%, and SC decreases by 43.8%, 41.9%, 37.3%, and 37.8%, respectively, compared with the results of the non-iteration process. It is apparent that crosstalk and speckle noise is small in reconstructed images obtained from 20 iterations. Hence, the proposed method can increase
information capacity. It is noteworthy that the RMSE and SC increase by 60.9% and 51.4% when nine independent images are reconstructed at the same position, indicating that the quality of reconstructed images under these circumstances is not satisfactory enough.

![Figure 4. Numerical reconstructions; (a) ‘pepper’, (b) ‘cameraman’, (c) ‘baboon’, (d) ‘woman’ are target images, (e–h) are reconstructed images without iterations, and (i–l) are reconstructed images with 20 iterations.](image)

| Iteration | Image     | RMSE | SC  |
|-----------|-----------|------|-----|
| 0         | pepper    | 0.325| 0.513|
|           | cameraman | 0.337| 0.518|
|           | baboon    | 0.352| 0.536|
|           | woman     | 0.303| 0.516|
| 20        | pepper    | 0.159| 0.288|
|           | cameraman | 0.168| 0.301|
|           | baboon    | 0.153| 0.336|
|           | woman     | 0.145| 0.321|

In order to improve information capacity further, we reconstructed different images at different positions. We chose different spherical light waves as reference light waves. Images shown in Figure 5a–d were located at 200 mm from the CGH plane, whereas the images shown in Figure 5e–h were located at 210 mm. The reconstructed results with 20 iterations are shown in Figure 5i–p. It is apparent that all images were reconstructed successfully. RMSE and SC of the reconstructed images are shown in Table 2. From these results, we can conclude that information capacity can be multiplied by the proposed method with position multiplexing.
Figure 5. Numerical reconstructions; (a) ‘pepper’, (b) ‘cameraman’, (c) ‘baboon’, (d) ‘woman’, (e) ‘man’, (f) ‘girl’, (g) ‘sailboat’, (h) ‘bridge’ are target images, and (i–p) are corresponding reconstructed images with 20 iterations.

Table 2. RMSE and SC of numerical reconstructions.

| Image     | RMSE | SC  |
|-----------|------|-----|
| pepper    | 0.232| 0.367|
| cameraman | 0.244| 0.292|
| baboon    | 0.254| 0.369|
| woman     | 0.221| 0.345|
| man       | 0.234| 0.353|
| girl      | 0.238| 0.300|
| sailboat  | 0.248| 0.351|
| bridge    | 0.236| 0.322|

4. Optical Experiments

In order to verify the viability of the proposed method, we executed optical experiments. The resolution of the CGH was 1080 × 1920 and the pixel size was 8 μm × 8 μm. The schematic of the experimental setup for reconstruction is shown in Figure 6. The zero order beam introduced by a SLM on the reconstructed images was eliminated by the 4f system, which consists of two lens and a filter [44]. In the optical experiments, a flat reflection-type SLM and plane reference wave with a wavelength of 532 nm was used. The reconstructed images were captured by a CCD.
In order to reconstruct different images, the phase distribution $\Phi_{\text{MCGH}}$ of the MCGH must be precompensated before loading on the SLM. The phase distribution $\Phi_R$ of reference light wave is added to the MCGH, which is the equivalent of changing the plane reference wave to a cylindrical or spherical reference light wave. After compensation, the phase distribution $\Phi_{\text{SLM}}$ can be written as:

$$\Phi_{\text{SLM}} = \Phi_{\text{MCGH}} + \Phi_R$$  \hspace{1cm} (13)

In optical experiments, we first reconstructed four independent images at the same position. Different cylindrical precompensated phases were added to the MCGH before loading on the SLM. In this way, different images, including ‘pepper’, ‘cameraman’, ‘baboon’, and ‘woman’, were all reconstructed successfully, as shown in Figure 7; the corresponding evaluation parameters are shown in Table 3. It can be observed that the optical reconstructions were in good agreement with the numerical reconstructions and there is little crosstalk in the reconstructed images.

![Figure 7. Optical reconstructions from (a) ‘pepper’, (b) ‘cameraman’, (c) ‘baboon’, (d) ‘woman’.](image)

| Image   | RMSE | SC  |
|---------|------|-----|
| pepper  | 0.293| 0.258 |
| cameraman | 0.322 | 0.296 |
| baboon  | 0.294 | 0.244 |
| woman   | 0.257 | 0.278 |

We also reconstructed eight independent images at different positions. Different spherical precompensated phases were added to MCGH. The reconstructed images are presented in Figure 8, where Figure 8a–d are located at 200 mm and Figure 8e–h are located at 210 mm. The corresponding evaluation parameters of the reconstructed images are shown in Table 4. It can be remarked that the proposed method achieves high reconstruction quality and the optical reconstructions agree with the numerical reconstructions perfectly. With the knowledge gained from these results, the proposed method can further...
realize multiplexed information capacity with other multiplexing methods, indicating that the proposed method is flexible and has great potential for dynamic holographic display.

Figure 8. Optical reconstructions from (a) ‘pepper’, (b) ‘cameraman’, (c) ‘baboon’, (d) ‘woman’, (e) ‘man’, (f) ‘girl’, (g) ‘sailboat’, (h) ‘bridge’.

| Image  | RMSE  | SC   |
|--------|-------|------|
| pepper | 0.337 | 0.244|
| cameraman | 0.319 | 0.322|
| baboon | 0.354 | 0.273|
| woman  | 0.292 | 0.317|
| man    | 0.349 | 0.249|
| girl   | 0.363 | 0.249|
| sailboat | 0.364 | 0.314|
| bridge | 0.317 | 0.298|

5. Conclusions

In conclusion, we propose a multiplexing scheme to increase information capacity in a holographic display, with the MCGH generated by a modified GS algorithm with different reference light waves. We performed numerical simulations and optical experiments to validate the proposed method. The numerical simulations indicated that different images could be reconstructed by MCGH correctly, and the optical experiments followed the numerical simulations perfectly. Moreover, the information capacity can be increased further with position multiplexing, which shows great potential for the proposed method. It can be anticipated that our method is promising for future applications in holographic display, optical encryption, optical pattern recognition, holographic data storage, and many other fields.

Author Contributions: Conceptualization, D.P. and J.L.; methodology, D.P. and J.L.; software, D.P.; validation, J.L.; writing—original draft preparation, D.P.; writing—review and editing, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: National Natural Science Foundation of China (NSFC) (62035003, 61975014).

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Pan, Y.; Liu, J.; Li, X.; Wang, Y. A review of dynamic holographic 3D display: Algorithms, devices, and systems. *IEEE Trans. Ind. Inform.* **2015**, *12*, 1599–1610.
2. Shi, L.; Li, B.; Kim, C.; Kelthofer, P.; Matusiket, W. Towards real-time photorealistic 3D holography with deep neural networks. *Nature* **2021**, *591*, 234–239.
3. Pi, D.; Liu, J.; Kang, R.; Zhang, Z.; Han, Y. Reducing the memory usage of computer-generated hologram calculation using accurate high-compressed look-up-table method in color 3D holographic display. *Opt. Express* **2019**, *27*, 28410–28422.
4. Zhang, H.; Zhao, Y.; Cao, L.; Jin, G. Fully computed holographic stereogram based algorithm for computergenerated holograms with accurate depth cues. Opt. Express 2015, 23, 3901–3913.
5. Zhang, H.; Cao, L.; Jin, G. Three-dimensional computer-generated hologram with Fourier domain segmentation. Opt. Express 2019, 27, 11689–11697.
6. Pi, D.; Liu, J.; Kang, R.; Han, Y.; Yu, S. Accelerating calculation method for curved computer-generated hologram using look-up table in holographic display. Opt. Commun. 2021, 485, 126750.
7. Matoba, O.; Javidi, B. Encrypted optical memory system using three-dimensional keys in the Fresnel domain. Opt. Lett. 1999, 24, 762–764.
8. Situ, G.; Zhang, J. Multiple-image encryption by wavelength multiplexing. Opt. Lett. 2005, 30, 1306–1308.
9. Situ, G.; Zhang, J. Position multiplexing for multiple-image encryption. J. Opt. A Pure Appl. Opt. 2006, 8, 391–397.
10. Mueller, J.P.B.; Rubin, N.A.; Devlin, R.C.; Groeves, B.; Capasso, F. Metasurface polarization optics: Independent phase control of arbitrary orthogonal states of polarization. Phys. Rev. Lett. 2017, 118, 113901.
11. Wen, D.; Yue, F.; Li, G.; Zheng, G.; Chan, K.; Chen, S.; Chen, M.; Li, K.F.; Wong, P.W.H.; Cheah, K.W.; et al. Helicity multiplexed broadband metasurface holograms. Nat. Commun. 2015, 6, 8241.
12. Li, X.; Chen, L.; Li, Y.; Zhang, X.; Pu, M.; Zhao, Z.; Ma, X.; Wang, Y.; Hong, M.; Luo, X. Multicolor 3D meta-holography by broadband plasmonic modulation. Sci. Adv. 2016, 2, e1601102.
13. Kamali, S.M.; Arbabi, E.; Arbabi, A.; Horie, Y.; Faraji-Dana, M.; Faraon, A. Angle-multiplexed metasurfaces: Encoding independent wavefronts in a single metasurface under different illumination angles. Phys. Rev. X 2017, 7, 041056.
14. Fang, X.; Ren, H.; Gu, M. Orbital angular momentum holography for high-security encryption. Nat. Photonics 2020, 14, 102–108.
15. Pi, D.; Liu, J.; Han, Y.; Khalid, A.U.R.; Yu, S. Simple and effective calculation method for computer-generated hologram based on non-uniform sampling using look-up-table. Opt. Express 2019, 27, 37337–37348.
16. Pi, D.; Liu, J.; Han, Y.; Yu, S.; Xiang, N. Acceleration of computer-generated hologram using wavefront-recording plane and look-up table in three-dimensional holographic display. Opt. Express 2020, 28, 9833–9841.
17. Mishina, T.; Okano, F.; Yuyama, I. Time-alternating method based on single-sideband holography with half-zone-plate processing for the enlargement of viewing zones. Appl. Opt. 1999, 38, 3703–3713.
18. Jia, J.; Wang, Y.; Liu, J.; Li, X.; Pan, Y.; Sun, Z.; Zhang, B.; Zhao, Q.; Jiang, W. Reducing the memory usage for effective computer-generated hologram calculation using compressed look-up table in full-color holographic display. Appl. Opt. 2013, 52, 1404–1412.
19. Hahn, J.; Kim, H.; Lim, Y.; Park, G.; Lee, B. Wide viewing angle dynamic holographic stereogram with a curved array of spatial light modulators. Opt. Express 2008, 16, 12372–12386.
20. Kozacki, T.; Kujawińska, M.; Finke, G.; Hennelly, B.; Pandey, N. Extended viewing angle holographic display system with tilted SLMs in a circular configuration. Appl. Opt. 2012, 51, 1771–1780.
21. Makowski, M.; Sypek, M.; Kołodzieczyk, A. Colorful reconstructions from a thin multi-plane phase hologram. Opt. Express 2008, 16, 11616–11623.
22. Shimobaba, T.; Takahashi, T.; Masuda, N.; Ito, T. Numerical study of color holographic projection using space-division method. Opt. Express 2011, 19, 10287–10292.
23. Ito, T.; Okano, K. Color electroholography by three colored reference lights simultaneously incident upon one hologram panel. Opt. Express 2004, 12, 4320–4325.
24. Kozacki, T.; Chlipala, M. Color holographic display with white light LED source and single phase only SLM. Opt. Express 2016, 24, 2189–2199.
25. Lin, S.; Kim, E. Single SLM full-color holographic 3-D display based on sampling and selective frequency-filtering methods. Opt. Express 2017, 25, 11389–11404.
26. Lin, S.; Cao, H.; Kim, E. Single SLM full-color holographic three-dimensional video display based on image and frequency-shift multiplexing. Opt. Express 2019, 27, 15926–15942.
27. Makey, G.; Yavuz, O.; Kesim, D.K.; Turmali, A.; Elahi, P.; Ilday, S.; Tokel, O.; Ilday, F.O. Breaking crosstalk limits to dynamic holography using orthogonality of high-dimensional random vectors. Nat. Photonics 2019, 13, 251–256.
28. Velez-Zea, A.; Torroba, R. Mixed constraint in global and sequential hologram generation. Appl. Opt. 2021, 60, 1888–1895.
29. Kang, R.; Liu, J.; Xue, G.; Li, X.; Pi, D. Curved multiplexing computer-generated hologram for 3D holographic display. Opt. Express 2019, 27, 14369–14380.
30. Liu, C.; Jin, F.; Wu, Y.; Wang, J.; Chen, C. Two-dimensional angle multiplexing by segmented spherical holography. Appl. Opt. 2021, 60, 155–161.
31. Pi, D.; Liu, J.; Duan, X.; Han, Y.; He, P. Design methods to generate a computer hologram for improving image quality. Appl. Opt. 2018, 57, 2720–2726.
32. Chen, L.; Zhang, H.; Cao, L.; Jin, G. Non-iterative phase hologram generation with optimized phase modulation. Opt. Express 2020, 28, 11380–11392.
33. Mendoza-Yero, O.; Mínguez-Vega, G.; Lancis, J. Encoding complex fields by using a phase-only optical element. Opt. Lett. 2014, 39, 1740–1743.
34. Qi, Y.J.; Chang, C.L.; Xia, J. Speckleless holographic display by complex modulation based on double-phase method. Opt. Express 2016, 24, 30368.
35. Sui, X.M.; He, Z.H.; Zhang, H.; Cao, L.C.; Chu, D.P.; Jin, G.F. Spatiotemporal double-phase hologram for complex-amplitude holographic displays. Chin. Opt. Lett. 2020, 18, 100901.

36. Sui, X.; He, Z.; Jin, G.; Chu, D.; Cao, L. Band-limited double-phase method for enhancing image sharpness in complex modulated computer-generated holograms. Opt. Express 2021, 29, 2597–2612.

37. Reichelt, S.; Häussler, R.; Füttner, G.; Leister, N.; Kato, H.; Usukura, N.; Kanbayashi, Y. Full-range, complex spatial light modulator for real-time holography. Opt. Lett. 2012, 37, 1955–1957.

38. Goorden, S.A.; Bertolotti, J.; Mosk, A.P. Superpixel-based spatial amplitude and phase modulation using a digital micromirror device. Opt. Express 2014, 22, 17999–18009.

39. Chang, C.; Xia, J.; Yang, L.; Lei, W.; Yang, Z.; Chen, J. Speckle-suppressed phase-only holographic threedimensional display based on double-constraint Gerchberg-Saxton algorithm. Appl. Opt. 2015, 54, 6994–7001.

40. Liu, J.P.; Hsieh, W.Y.; Poon, T.C.; Tsang, P. Complex Fresnel hologram display using a single SLM. Appl. Opt. 2011, 50, H128–H135.

41. Li, X.; Liu, J.; Jia, J.; Pan, Y.; Wang, Y. 3D dynamic holographic display by modulating complex amplitude experimentally. Opt. Express 2013, 21, 20577–20587.

42. Gerchberg, R.W.; Saxton, W.O. A practical algorithm for the determination of phase from image and diffraction plane pictures. Optik 1972, 35, 237–246.

43. Fienup, J.R. Reconstruction of an object from the modulus of its Fourier transform. Opt. Lett. 1978, 3, 27–29.

44. Zhang, H.; Xie, J.; Liu, J.; Wang, Y. Elimination of a zero-order beam induced by a pixelated spatial light modulator for holographic projection. Appl. Opt. 2009, 48, 5834–5841.