Optical Materials 135 (2023) 113228

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Research article

Fabrication of 3D computer-generated hologram inside glass by femtosecond laser direct writing☆

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ARTICLE INFO

Keywords:
Femtosecond laser
Computer-generated hologram
Three-dimensional holography

ABSTRACT

The three-dimensional holography technique offers a powerful method for storing the depth information of objects, and it provides more realistic scene reconstruction compared with the two-dimensional case, so it is widely used in beam shaping, holographic display, and image encryption. However, the fabrication of holograms is currently limited to complex and time-consuming traditional nanofabrication techniques. Here, we demonstrate the fabrication of a hologram containing depth information inside glass using femtosecond laser direct writing. The whole process is simple and flexible because there is no complex operation like mask preparation. Then the reconstruction of the three-dimensional object is demonstrated and evaluated, and the experimental optimization as well as the limitations are also discussed.

1. Introduction

Optical holography is a technique for wavefront reconstruction by recording the amplitude and phase of the wavefront. This technology was first discovered by Dennis Gabor in 1948 [1]. Due to its ability to record full information including the amplitude and phase, holography is considered to be one of the most potential technologies for achieving three-dimensional(3D) scene reconstruction. However, it was not until the invention of the first laser in 1960, which solved the problem of coherent light sources, that holography technology has been greatly developed and the first practical optical holograms capable of recording 3D objects were realized by Leith in 1962 [2]. With the advent of the information age, the functions of computer in information processing have been applied to holography, which led to the emergence of Computer-generated holograms(CGHs). The CGH technology can perform the interference process without an optical system. In addition, it can record virtual objects as long as the corresponding light wave information is known, which greatly expands its application. It has been widely used in 3D displays [3–5], beam shaping [6,7], ultrashort pulse laser parallel processing [8–10], optical encryption [11–13] and nonlinear holography [14–16]. Usually, CGHs are fabricated with standard nanofabrication technology including electron beam lithography, ultraviolet lithography and so on [17,18]. The processes of fabrication require mask preparation or dry etching, which are relatively complicated and time-consuming. They also need to be carried out in a strictly controlled experimental environment.

Compared with the above methods, femtosecond laser has attracted great interest as it has the advantages of high peak intensity and high machining precision, so it is widely used in micro/nanofabrication such as microlens arrays [19], gratings [20], photonic crystals [21,22] and optical waveguides [23,24]. Furthermore, it is the only method that can fabricate 3D structure inside transparent media, so it can effectively resist external mechanical damage compared to structures processed on the surface. It has been reported that femtosecond laser has fabricated CGH patterns on different materials such as metal film [25], glass [26–28], silicon [29], polymer [30,31] and lithium niobate crystal [15].

In this paper, we report a general approach to fabricating CGH pattern inside glass by femtosecond laser direct writing. This process does not require complex operations, so the proposed method is efficient and flexible. The fabricated CGH pattern is made of microstructure arrays with a special shape that can modulate the spatial distribution of the incident laser and then reconstruct the original 3D object. In previous researches, this method is always used for two-dimensional(2D) imaging which cannot show the advantages of holography in 3D imaging.

☆ This work was supported by the National Key R&D Program of China (Grant Nos. 2019YFB2203501 and 2017YFA0303701), the National Natural Science Foundation of China (Grant Nos. 12134009, and 91950107), Shanghai Municipal Science and Technology Major Project (2019SHZDZX01-ZX06), and SJTU No. 21X010200828.

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https://doi.org/10.1016/j.optmat.2022.113228
Received 23 September 2022; Received in revised form 3 November 2022; Accepted 9 November 2022
Available online 29 November 2022
0925-3467/

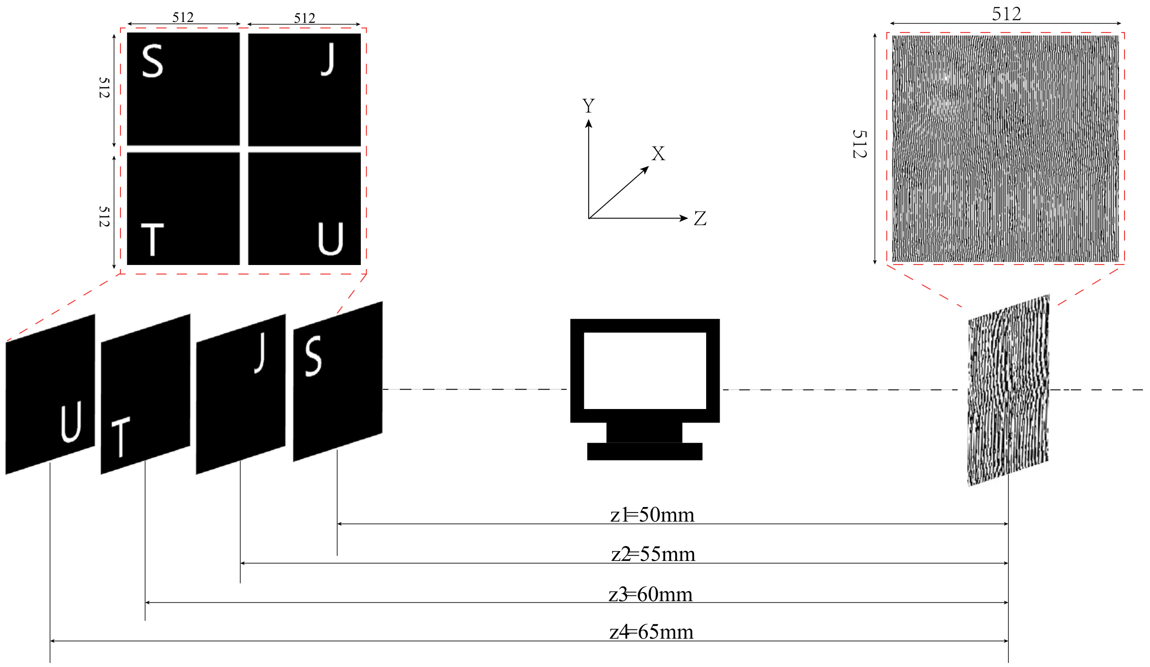

Fig. 1. Diagram of generating CGH from 3D source image comprising four letters "SJTU" at different depth planes.

2. Method

To begin with, we chose multi-plane images of the letters "SJTU" as our 3D object model. As is illustrated in Fig. 1, the four letters are divided into four layers which are positioned at different distances from the hologram ($z_1 = 50$ mm, $z_2 = 55$ mm, $z_3 = 60$ mm, $z_4 = 65$ mm), and each layer has 512 × 512 pixels. The calculation process of the CGH can be broken down into two steps. In the first step, we recorded the complex amplitude $U_j(x, y)$ of each layer of the virtual 3D object using the following diffraction equation [32]:

$$U_j(x, y) = \frac{e^{ikz_j}}{ikz_j} \iint u_j(x_j, y_j) e^{i\varphi_j(x_j, y_j)} e^{\frac{ik}{2z_j}[(x-x_j)^2+(y-y_j)^2]} dx_j dy_j \quad (1)$$

where $u_j(x_j, y_j)$ and $\varphi_j(x_j, y_j)$ represent the complex amplitude and phase of the jth layer respectively. $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength. z_j is the distance between the jth layer and the hologram plane. Then, the total complex amplitude on the hologram plane can be expressed as:

$$U(x, y) = \sum_{j}^{4} U_j(x, y) = A_0(x, y)\, e^{i\varphi_0(x,y)} \quad (2)$$

where $A_0(x, y)$ and $e^{i\varphi_0(x,y)}$ are the amplitude and phase term of the complex amplitude on the hologram plane, respectively.

Next, we chose a suitable way to encode the complex fields in the hologram plane. Because we use the femtosecond laser to modulate the glass with a high power which results in two states corresponding to the actual laser-nonirradiated area and laser-irradiated area, the binary Fresnel CGH was selected in our experiments. Through the interference of the object wave $U(x, y)$ and the planar reference wave $R(x, y) = Re^{i2\pi\alpha x}$, where R and α are the amplitude and the carrier frequency of the object wave respectively, we first obtain the transmittance function $h(x, y)$ of the hologram, it can be represented as:

$$\begin{aligned} h(x, y) &= |U(x, y) + R(x, y)|^2 \\ &= \frac{1}{2}\left\{1 + A_0(x, y) cos[\varphi_0(x, y) - 2\pi\alpha x]\right\} \end{aligned} \quad (3)$$

The bright fringes equation of the hologram can be obtained as:

$$\varphi_0(x, y) - 2\pi\alpha x = 2\pi n \quad (4)$$

where n represents the serial number of the bright fringes, $n = 0, \pm1, \pm2, \cdots$. By solving the position of each bright fringe and opening a thin slit, a binary transmission grating is formed, that is, the phase of the object light wave is encoded. The encoding of the amplitude is obtained by introducing an offset $cos\pi q(x, y)$ to modulate the width of the bright fringes [33], where $q(x, y) = arcsin[A_0(x, y)]/\pi$ and amplitude $A_0(x, y)$ takes the normalized value, this coding method is widely used in standard wavefront generation and interference detection [34,35]. Then, interferometric binary CGH is represented as follows:

$$H(x, y) = \begin{cases} 1, & cos[\varphi_0(x, y) - 2\pi\alpha x] \geq cos\pi q(x, y) \\ 0, & others \end{cases} \quad (5)$$

All calculations are carried out with the software MATLAB.

3. Experiment

The CGH was fabricated using a compact ytterbium-doped diode-pumped ultrafast amplified laser at the center wavelength of 1030 nm, which has a pulse width of 500 fs. The femtosecond laser direct writing system is shown in Fig. 2. A fused silica glass with a thickness of 1 mm was used as a sample which was mounted on the computer-controlled XYZ translation stage with a resolution of 0.1 μm. The laser beam was focused 50 μm below the sample surface by an objective lens with a numerical aperture of 0.50 (RMS20X-PF, Olympus). The moving speed was 800 μm/s and the moving direction was perpendicular to the laser beam. The Fabricating condition of CGH was detected in real-time through the charge-coupled device (CCD) attached to an optical microscope.

In order to obtain well-defined patterns, we must first determine the appropriate processing parameters. Adjusting the energy of a single pulse from small to large on an order of magnitude can lead to different results: no modulation, small refractive index changes that can be used for fabricating various optical devices such as waveguides, controlled modulation for optical data storage (formation of void-like structures), uncontrollable damage [36,37]. In our experiment, a single pulse energy of about 2.6 μJ is used to generate a microexplosion inside the glass. The material at the center of the focal spot is forced into the surrounding volume, leading to the formation of a void-like structure which is surrounded by densified material. In this case,

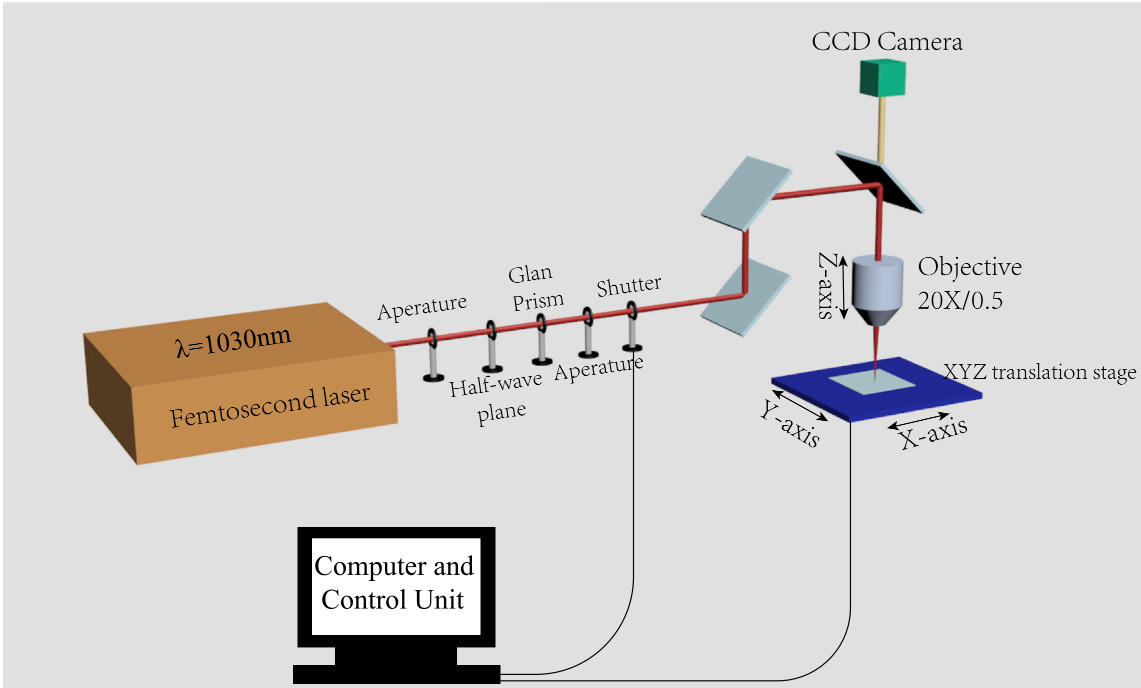

Fig. 2. Schematic illustration of the fs laser direct writing system for fabricating the CGH pattern.

the decrement of the refractive index is large enough, so that the structure can be approximately seen to be opaque [38]. In addition, the laser we use had a repetition rate of 300 kHz which ensured a satisfactory processing effect at a relatively high translation stage movement (800 μm/s). Under these parameters, the diameter of the irradiated spots was about 3 μm which makes the resolution up to 111 Kpixels/mm^2 (~8500 dpi). Through the control of the computer program, the translation stage changed the relative position of the focus point and the sample through step movement, and cooperated with the shutter to selectively illuminate the sample, the irradiated points became non-transparent, corresponding to the black pixels in the binary hologram, while the non-irradiated points remained in the original transparent state corresponding to the white pixels. The binary Fresnel CGH contains 512 × 512 pixels, as shown in Fig. 1. As can be seen, Fig. 3(a) and (b) show the CGH pattern fabricated by femtosecond laser which were imaged by 5X, 20X microscope objectives respectively. The fabricated hologram was written within an area of 1.5 × 1.5 mm^2 and the total processing time is 2.5 h.

4. Results and discussions

In order to characterize the 3D reconstruction performance of the fabricated CGH, we have built an optical holographic imaging system, as shown in Fig. 4. The system consists of a laser source with a wavelength of 785 nm, a standard beam expander, a sample with a CGH pattern and a CCD camera. The diameter of the beam was adjusted to 1500 μm to fit the size of the CGH. The CCD camera was fixed on a three-dimensional movable stand to capture the reconstruction results at different distances from the hologram pattern.

From the reconstructed image captured by the CCD, we can see that the letters have the clearest reconstruction when they are in the designed imaging plane, as shown in the red box, while the other three letters are relatively blurred, which can clearly prove the hologram contains the 3D depth information of the original object.

The numerical reconstructions of the CGH at four different depth planes are shown in Fig. 5(a–d) and the corresponding experimental reconstruction results are shown in Fig. 5(e–h). The distances between the reconstructed images and the hologram plane are 50 mm, 55 mm, 60 mm, and 65 mm, respectively. As we can see, the upper and lower pictures in the same column have the same characteristics of the corresponding letters, and the three-dimensional effect of optical reconstruction is in good agreement with numerical reconstruction.

Table 1
The results of MSE and MSE_r.

	S ($z_1 = 50$ mm)	J ($z_2 = 55$ mm)	T ($z_3 = 60$ mm)	U ($z_4 = 65$ mm)
MSE	0.0342	0.0337	0.0282	0.0290
MSE_r	0.2868	0.2990	0.3011	0.2874

In order to accurately evaluate the 3D reconstruction effect of the hologram, the mean square error (MSE) is usually introduced. It is the average of the squares of the corresponding pixel differences between the numerical and the experimental reconstructed images, which can be expressed as:

$$MSE = \frac{\sum_{mn}[I(m,n) - K(m,n)]^2}{m \times n} \quad (6)$$

where the $I(m,n)$ and $K(m,n)$ denote the optical intensity matrices of the experimental and numerically simulated images respectively, and m and n are the number pixels of matrices corresponding to horizontal and vertical directions. Generally speaking, a low MSE corresponds to a high-quality reconstruction. For comparison, we choose a random noise image generated by random numbers as a reference, and its root mean square error is denoted as MSE_r. Table 1 shows the results of MSE and MSE_r. As we can see, the MSE of the reconstructed images are an order of magnitude smaller than that of the random noise images, which indicates that the 3D object is well reconstructed by our method.

In fact, the quality of 3D reconstructed images based on our proposed method can be further improved. First, the pixel size can be further reduced by beam shaping, lowering the laser energy or using other transparent materials with higher damage threshold. As a result, the resolution of holograms can be efficiently increased if the fabricating area is fixed. According to the diffraction equation, the diffraction point spacing at small angles is inversely proportional to the grating period (corresponding to the hologram pixels spacing), so reducing

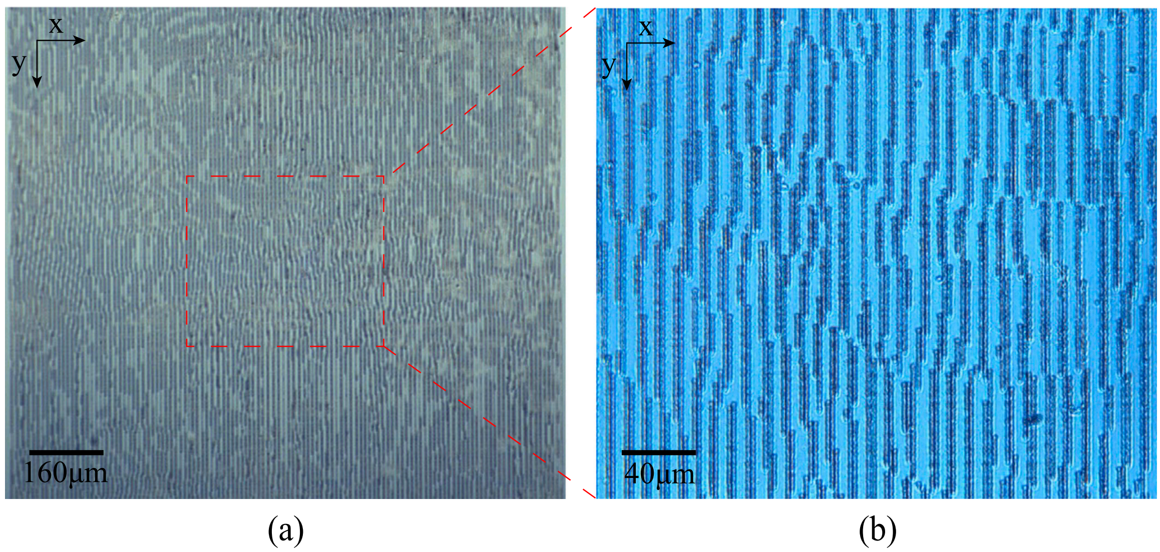

Fig. 3. Optical images of CGH pattern fabricated by femtosecond laser. (a) and (b) correspond to 5×, 20× microscope objective imaging respectively.

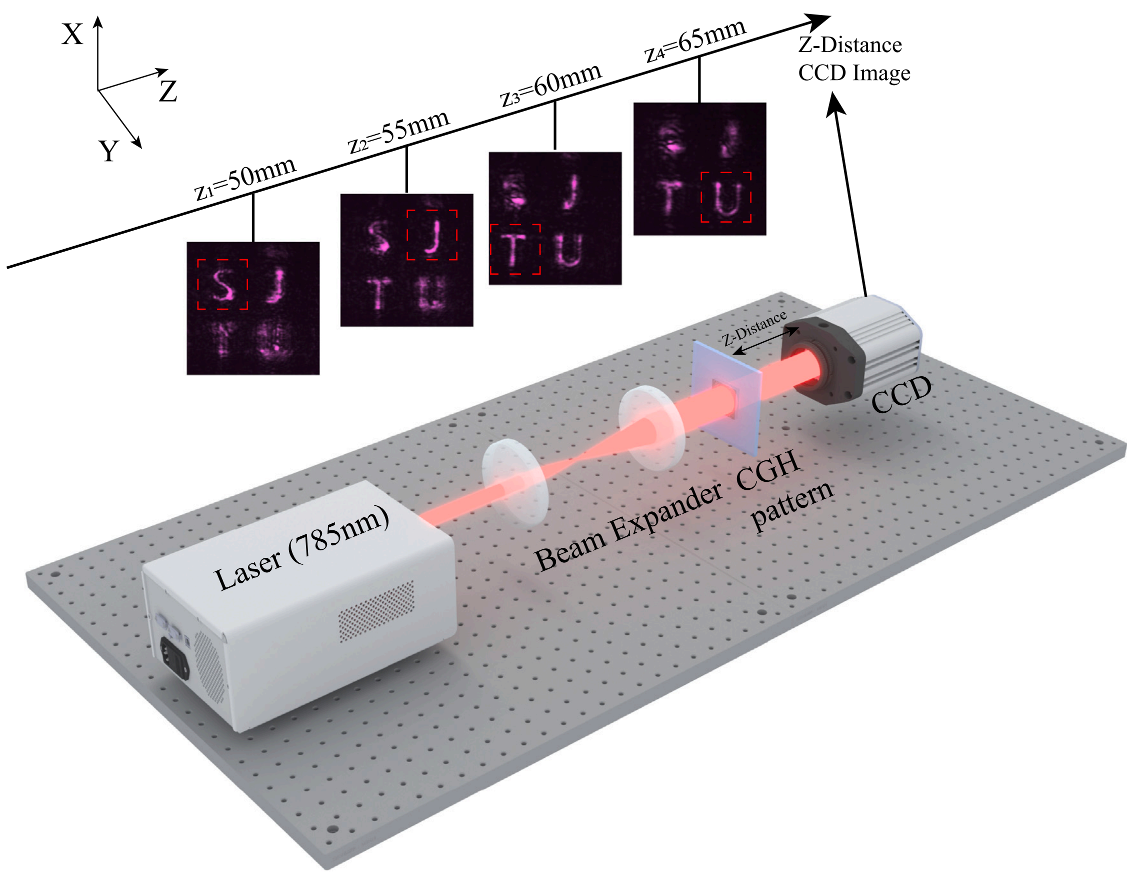

Fig. 4. Schematic illustration of the optical system for holographic image reconstruction.

the pixel size can be used to create a larger size reconstructed images without overlapping. Secondly, the femtosecond laser may affect the surrounding area due to power fluctuation when irradiating the modulated pixels, which can be solved by optimizing the fabricating parameters. Finally, due to the high efficiency of femtosecond laser direct writing, in principle, the pixels of the hologram can be increased to optimize the reconstructed image quality.

Certainly, this approach has its limitations. First of all, compared with traditional nanofabrication technology (A few hundred nanometers), the pixel size fabricated in our experiment is about 3 μm, so the hologram contains less information and lower resolution in an equal area. Although the pixel size can be reduced by some methods, the adjustment ability is limited. Secondly, considering the characteristic of femtosecond laser micromachining in our experiment, the fabricated

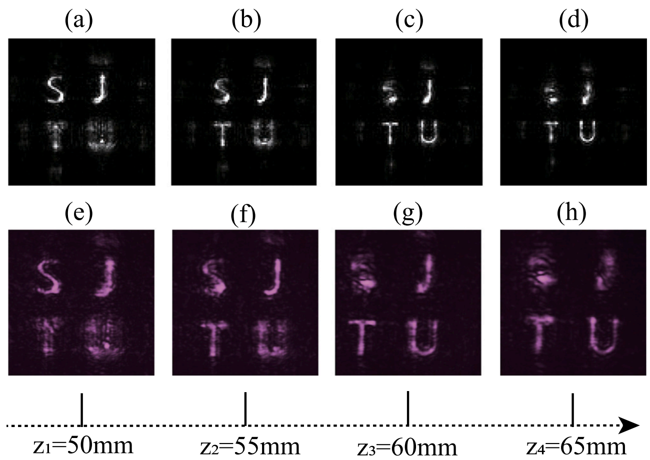

Fig. 5. (a)–(d) The numerical reconstructions of 3D model "SJTU" at distance of z_1, z_2, z_3 and z_4, respectively. (e)–(h) The experimentally reconstructed images in the corresponding planes along the z-axis directions.

hologram is an amplitude binary hologram, so the original image and its conjugate image will be reconstructed at the same time. How to eliminate the conjugate image and fabricate a multi-order hologram are also worth exploring.

5. Conclusion

In summary, we have demonstrated the realization of 3D holographic imaging in a fused silica by femtosecond laser direct writing. Based on the method of computational holographic interference, the hologram pattern is obtained by layering and encoding the 3D virtual object "SJTU". The original object is optical reconstructed at different depths. Both visual effects and numerical analysis verify the results of the experiment. Combined with the discussion of experimental optimization and future improvements in coding methods, the technique can be used in the fields of 3D display, beam shaping and diffractive optical element fabrication [39]. It is worth mentioning that this processing method is suitable for a variety of transparent materials, so we can explore the behavior on different materials, such as nonlinear holographic imaging in nonlinear crystals.

CRediT authorship contribution statement

Honghuan Tu: Term, Conceptualization, Methodology, Software, Validation, Writing – original draft. **Tingge Yuan:** Validation, Formal analysis, Writing – review & editing. **Zhiwei Wei:** Investigation, Data curation. **Yuping Chen:** Project administration, Funding acquisition, Supervision, Resources, Writing – review & editing. **Xianfeng Chen:** Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

All authors approved the version of the manuscript to be published.

References

[1] Dennis Gabor, A new microscopic principle, Nature 161 (1948) 777–778.
[2] Emmett N. Leith, Juris Upatnieks, Reconstructed wavefronts and communication theory, JOSA 52 (10) (1962) 1123–1130.
[3] Chenliang Chang, Dongchen Zhu, Jiamao Li, Di Wang, Jun Xia, Xiaolin Zhang, Fast calculation of computer generated hologram based on single Fourier transform for holographic three-dimensional display, Displays 69 (2021) 102064.
[4] Jung-Ping Liu, Ming-Hsuan Wu, Peter W.M. Tsang, 3D display by binary computer-generated holograms with localized random down-sampling and adaptive intensity accumulation, Opt. Express 28 (17) (2020) 24526–24537.
[5] Xuemei Cao, Xinzhu Sang, Zhidong Chen, Ying Zhang, Junmin Leng, Nan Guo, Binbin Yan, Jinhui Yuan, Kuiru Wang, Chongxiu Yu, Fresnel hologram reconstruction of complex three-dimensional object based on compressive sensing, Chinese Opt. Lett. 12 (8) (2014) 080901.
[6] Maria Manousidaki, Dimitrios G Papazoglou, Maria Farsari, Stelios Tzortzakis, 3D holographic light shaping for advanced multiphoton polymerization, Opt. Lett. 45 (1) (2020) 85–88.
[7] Bing Zhu, Haigang Liu, Yuping Chen, Xianfeng Chen, High conversion efficiency second-harmonic beam shaping via amplitude-type nonlinear photonic crystals, Opt. Lett. 45 (1) (2020) 220–223.
[8] Jin Wang, Yoshio Hayasaki, Fengyun Zhang, Xi Wang, Satoshi Hasegawa, Honghao Zhang, Pingping Wang, Yadi Wang, Shufeng Sun, Three-dimensional holographic femtosecond laser parallel processing method with the fractional Fourier transform for glass substrates, Ceram. Int. 48 (11) (2022) 16364–16373.
[9] Masahiro Yamaji, Hayato Kawashima, Jun'ichi Suzuki, Shuhei Tanaka, Three dimensional micromachining inside a transparent material by single pulse femtosecond laser through a hologram, Appl. Phys. Lett. 93 (4) (2008) 041116.
[10] Honghao Zhang, Satoshi Hasegawa, Haruyoshi Toyoda, Yoshio Hayasaki, Three-dimensional holographic laser reconstruction and processing with optimized computer-generated hologram, in: Holography, Diffractive Optics, and Applications XI. Vol. 11898, SPIE, 2021, pp. 59–66.
[11] Dezhao Kong, Liangcai Cao, Guofan Jin, Bahram Javidi, Three-dimensional scene encryption and display based on computer-generated holograms, Appl. Opt. 55 (29) (2016) 8296–8300.
[12] Junfeng Hou, Guohai Situ, Image encryption using spatial nonlinear optics, ELight 2 (1) (2022) 1–10.
[13] Zhenbo Ren, Ping Su, Jianshe Ma, Guofan Jin, Secure and noise-free holographic encryption with a quick-response code, Chin. Opt. Lett. 12 (1) (2014) 010601.
[14] Yujia Wu, Haigang Liu, Xianfeng Chen, Three-dimensional nonlinear optical holograms, Phys. Rev. A 102 (2020) 063505.
[15] Bing Zhu, Haigang Liu, Xiongshuo Yan, Yuping Chen, Xianfeng Chen, et al., Second-harmonic computer-generated holographic imaging through monolithic lithium niobate crystal by femtosecond laser micromachining, Opt. Lett. 45 (15) (2020) 4132–4135.
[16] Xinyuan Fang, Haocheng Yang, Wenzhe Yao, Tianxin Wang, Yong Zhang, Min Gu, Min Xiao, High-dimensional orbital angular momentum multiplexing nonlinear holography, Adv. Photonics 3 (1) (2021) 015001.
[17] Gun-Yeal Lee, Gwanho Yoon, Seung-Yeol Lee, Hansik Yun, Jaebum Cho, Kyookeun Lee, Hwi Kim, Junsuk Rho, Byoungho Lee, Complete amplitude and phase control of light using broadband holographic metasurfaces, Nanoscale 10 (9) (2018) 4237–4245.
[18] Wenqiang Wan, Wen Qiao, Wenbin Huang, Ming Zhu, Zongbao Fang, Donglin Pu, Yan Ye, Yanhua Liu, Linsen Chen, Efficient fabrication method of nano-grating for 3D holographic display with full parallax views, Opt. Express 24 (6) (2016) 6203–6212.
[19] An Pan, Tao Chen, Cunxia Li, Xun Hou, Parallel fabrication of silicon concave microlens array by femtosecond laser irradiation and mixed acid etching, Chinese Opt. Lett. 14 (5) (2016) 052201.
[20] Jun He, Yiping Wang, Changrui Liao, Qiaoni Wang, Kaiming Yang, Bing Sun, Guolu Yin, Shen Liu, Jiangtao Zhou, Jing Zhao, Highly birefringent phase-shifted fiber Bragg gratings inscribed with femtosecond laser, Opt. Lett. 40 (9) (2015) 2008–2011.
[21] Shan Liu, Krzysztof Switkowski, Chenglong Xu, Jie Tian, Bingxia Wang, Peixiang Lu, Wieslaw Krolikowski, Yan Sheng, Nonlinear wavefront shaping with optically induced three-dimensional nonlinear photonic crystals, Nature Commun. 10 (1) (2019) 1–7.
[22] Dunzhao Wei, Chaowei Wang, Huijun Wang, Xiaopeng Hu, Dan Wei, Xinyuan Fang, Yong Zhang, Dong Wu, Yanlei Hu, Jiawen Li, et al., Experimental demonstration of a three-dimensional lithium niobate nonlinear photonic crystal, Nat. Photonics 12 (10) (2018) 596–600.
[23] Mark Triplett, John Khaydarov, Xiaozhen Xu, Alireza Marandi, Gennady Imeshev, John Arntsen, Ajit Ninan, Gregory Miller, Carsten Langrock, Multi-watt, broadband second-harmonic-generation in MgO: PPSLT waveguides fabricated with femtosecond laser micromachining, Opt. Express 27 (15) (2019) 21102–21115.
[24] Bin Zhang, Lei Wang, Feng Chen, Recent advances in femtosecond laser processing of LiNbO3 crystals for photonic applications, Laser Photonics Rev. 14 (8) (2020) 1900407.
[25] Quan-Zhong Zhao, Jian-Rong Qiu, Xiong-Wei Jiang, En-Wen Dai, Chang-He Zhou, Cong-Shan Zhu, Direct writing computer-generated holograms on metal film by an infrared femtosecond laser, Opt. Express 13 (6) (2005) 2089–2092.

[26] Zhulin Yao, Xiaowei Li, Zhipeng Wang, Zhentao Xu, Andong Wang, Lingling Huang, Jiangang Lu, Honglei Wang, High-efficiency fabrication of computer-generated holograms in silica glass using a femtosecond bessel beam, Opt. Laser Technol. 135 (2021) 106729.

[27] René Berlich, Daniel Richter, Martin Richardson, Stefan Nolte, Fabrication of computer-generated holograms using femtosecond laser direct writing, Opt. Lett. 41 (8) (2016) 1752–1755.

[28] Carlos Gerardo Treviño-Palacios, Oscar Javier Zapata-Nava, Arturo Olivares-Pérez, Optical damage as a computer generated hologram recording mechanism, J. Appl. Res. Technol. 13 (6) (2015) 591–595.

[29] Kristian J. Wædegaard, Peter Balling, High-resolution computer-generated reflection holograms with three-dimensional effects written directly on a silicon surface by a femtosecond laser, Opt. Express 19 (4) (2011) 3434–3439.

[30] Tawfiq Alqurashi, Yunuen Montelongo, Pavel Penchev, Ali K Yetisen, Stefan Dimov, Haider Butt, Femtosecond laser ablation of transparent microphotonic devices and computer-generated holograms, Nanoscale 9 (36) (2017) 13808–13819.

[31] JM Versnel, Calum Williams, CAB Davidson, TD Wilkinson, CR Lowe, Signal intensity enhancement of laser ablated volume holograms, Opt. Mater. 73 (2017) 400–407.

[32] Yan Zhao, Liangcai Cao, Hao Zhang, Dezhao Kong, Guofan Jin, Accurate calculation of computer-generated holograms using angular-spectrum layer-oriented method, Opt. Express 23 (20) (2015) 25440–25449.

[33] Wai-Hon Lee, Binary synthetic holograms, Appl. Opt. 13 (7) (1974) 1677–1682.

[34] J.C. Wyant, V.P. Bennett, Using computer generated holograms to test aspheric wavefronts, Appl. Opt. 11 (12) (1972) 2833–2839.

[35] James H. Burge, Applications of computer-generated holograms for interferometric measurement of large aspheric optics, in: International Conference on Optical Fabrication and Testing. Vol. 2576, SPIE, 1995, pp. 258–269.

[36] D.M. Krol, Femtosecond laser modification of glass, J. Non-Crystalline Solids 354 (2–9) (2008) 416–424.

[37] James W. Chan, Thomas R. Huser, S.H. Risbud, D.M. Krol, Modification of the fused silica glass network associated with waveguide fabrication using femtosecond laser pulses, Appl. Phys. A 76 (3) (2003) 367–372.

[38] EN Glezer, M Milosavljevic, L Huang, RJ Finlay, T-H Her, J Paul Callan, Eric Mazur, Three-dimensional optical storage inside transparent materials, Opt. Lett. 21 (24) (1996) 2023–2025.

[39] Bing Zhu, Haigang Liu, Yuping Chen, Xianfeng Chen, High conversion efficiency second-harmonic beam shaping via amplitude-type nonlinear photonic crystals, Opt. Lett. 45 (1) (2020) 220–223.