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Superposition of orbital angular momentum of photons by a combined computer-generated hologram fabricated in silica glass with femtosecond laser pulses*

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This paper introduces a novel method to realize the superposition of orbital angular momentum of photons by combined computer-generated hologram (CCGH) fabricated in silica glass with femtosecond laser pulses. Firstly, the two computer-generated holograms (CGH) of optical vortex were obtained and combined as a CCGH according to the design. Then the CCGH was directly written inside glass by femtosecond laser pulses induced microexplosion without any pre- or post-treatment of the material. The vortex beams with different vortex topological charges (including new topological charges) have been restructured using a collimated He–Ne laser beam incidence to the CCGH normally. A theoretical and experimental explanation has been presented for the generations of the new topological charges.

Keywords: femtosecond laser, micro-structure, optical vortices, CGH
PACC: 4240E, 4262A

1. Introduction

Optical vortex (OV) has been paid considerable attentions in the past two decades because of their special characteristics and potential applications.[1−3] OV has been described as a topological point defect (also known as a dislocation) on wavefront and manifests as a "null" within a light beam because the phase at the defect point is undetermined. As predicted[4] and observed,[5] OV beams carry an orbital angular momentum (OAM) distinct from the intrinsic angular momentum of photons associated with their polarizations. This external angular momentum of the photon states is coming from the helical phase structure on the wavefront. The OAM of photon states is the reason why they have been suggested for optical data storage[6,7] and gearing micromachines, such as optical tweezers[8] and optical manipulation for microelectromechanical systems (MEMS).[9] The superposition of OAM of photons by Mach–Zehnder interferometer[10−12] has also attracted great attention because of their potential applications in quantum computation and quantum information processing.

Recently, there is increasing interest in microfabrication and micromachining of various three-dimensional structures in dielectrics by femtosecond laser pulses for high-quality, damage-free processing. Multiphoton absorption can be induced in a region smaller than the diffraction limit in both the lateral and axial directions by a tightly focused femtosecond laser pulse. Up to now, various high-quality material processing schemes have been achieved by using femtosecond laser pulses, such as waveguides,[13] couplers,[14] micro-gratings,[15,16] photonic crystals[17,18] and three-dimensional channels.[19] Some special diffractive optical elements (DOEs)[20,21] have also been obtained via the interactions between the femtosecond laser pulses and the material by ablation on the surface and the inner structural changes of the materials.

In this article we report the observation of the superpositions of the photon OAM by using a combined computer generated hologram (CCGH) which is fabricated inside glass with a near infrared 800 nm femtosecond laser. The CCGH is combined by two special

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binary CGHs of OV which are recorded by the interference of OV beams with a planar beam simulating on the computer and directly written and recorded inside the glass by femtosecond laser pulses induced microexplosion because of multiphoton absorption. This process does not need any pre- or post-treatments of the material and hence can not cause surface damage of the material. The OV beams with new topological charges can be reconstructed in the diffraction field with a collimated He–Ne laser beam incidence to the CCGH normally, which reveals the superposition of OAM of photons successfully.

2. Experimental results

Nye and Berry[1] have analysed the phase dislocation within a monochromatic wave in detail in 1974. They have also analysed a number of optical wavefront dislocations including screw dislocations, edge dislocations and mixed screw-edge dislocations. A monochromatic beam propagating in the z-direction and containing a single vortex transversely centred at the origin ($r = 0$) can be expressed by the scalar envelope function:

$$u(r,\theta, z) = A_m(r, z)\exp(\mathrm{i}m\theta)\exp[\mathrm{i}\,\Phi_m(r, z)]. \quad (1)$$

Where $u(r, \theta, z)$ is the optical field expressed in cylindrical coordinates with the optical axis aligned along the z axis, $\exp(\mathrm{i}m\theta)$ is the characteristic expression of the OV, m is a signed integer called the topological charge, Φ_m is the phase.

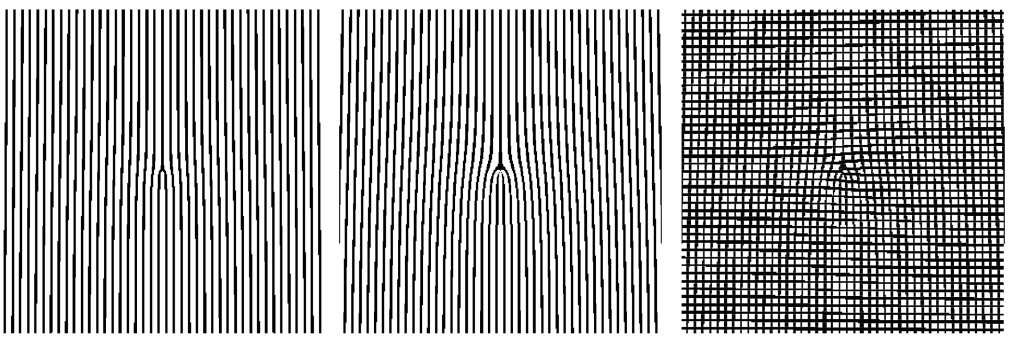
Ordinary beams carry only "spin angular momentum", encoded in the polarization of light. All possible spin states can be constructed with just two polarization states (vertical and horizontal, or clockwise and counterclockwise). In 1992, however, Allen and Beijersbergen[4] showed that OV beams carry a discrete OAM of $m\hbar$ units per photon along their propagation direction because of having an azimuthal phase dependence of the form $\exp(-\mathrm{i}m\theta)$. For the light with OAM, the energy spirals around the beam axis. Therefore there would be OAM transferring to materials while interacting with materials, which can make the particles in the beam spin around the beam axis.

To construct a CGH of an OV, we numerically calculate the interferogram of two waves: a planar reference wave and an object wave containing the desired OV. For simplicity, the interferogram can be given by the intensity of the interfering waves:

$$\begin{aligned} I_{z=0}(x,\theta) &= |E_\mathrm{o} + E_r|^2_{z=0} \\ &= 2C_\mathrm{o}\left[1 + \cos\left(2\pi x/\Lambda + m\theta\right)\right], \end{aligned} \quad (2)$$

where C_o is the amplitude of a reference wave and the OV beam, $\Lambda = \lambda/\sin\varphi$ is the spatial period of the plane wave in the transverse plane, λ is the wavelength of the waves, and φ is the angle between two interfered waves.

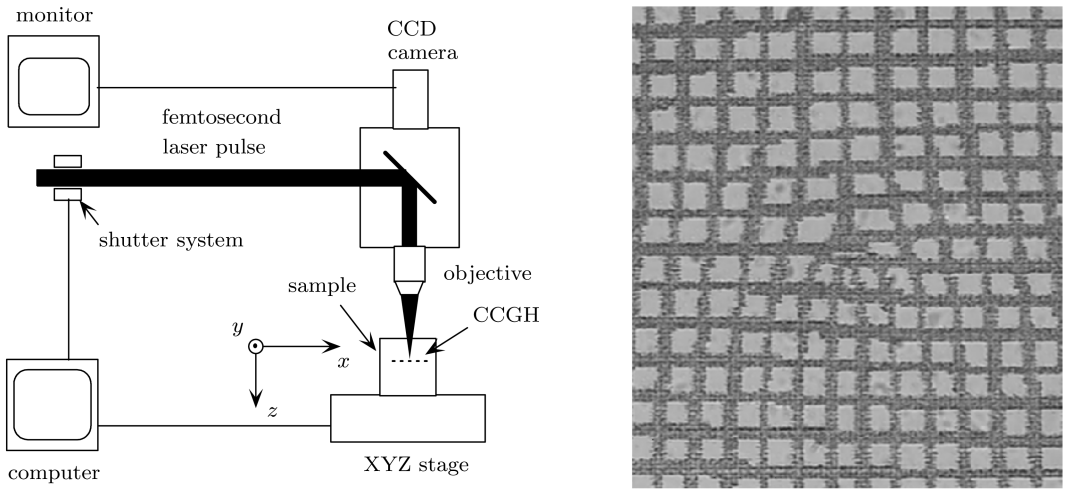
We can get two CGHs by choosing topological charges $m = 1$ and $m = 3$ with the same Λ for getting the same diffracting angle of the diffracting beams in the same diffracting order. The resulting binary interferograms, depicted in Figs.1(a) and 1(b), represent binary diffraction gratings besides a fork in the centre place. In order to get the CCGH, two CGHs were combined with an orthogonal style keeping one invariable and the other one rotated to vertical direction (depicted in Fig.1(c)).



(a) (b) (c)

Fig.1. The CGH $m = 1$, $m = 3$, and the CCGH combined with the two CGHs.

After getting the binary CCGH, we directly fabricated it inside glass with femtosecond laser pulses. A regeneratively amplified Ti:sapphire laser system (Coherent. Co.) was used, which delivered pulses with a duration of 120fs (full width at half maximum), with a centre wavelength at 800nm and a repetition rate of 1kHz. We applied a microscope objective lens with a numerical aperture of 0.45 (20X, Nikon. Co.) to focus the laser pulses, and mounted the sample on a computer-controlled XYZ translation micro-stage with 0.1 μm resolution. The schematic setup is shown in Fig.2(a).



(a) (b)

Fig.2. (a) Experimental scheme of femtosecond laser inducing microstructures. (b) The top view of the central part of the fabricated CCGH.

The refractive index change could be induced when the pulses were focused inside glass, depending on the pulse duration and the incident energy. The change of the refractive index is owing to either the formation of the colour centre or the damage in the sample. In our experiment, the internal damage caused by microexplosion is the dominant mechanism for the refractive index change.[22] Hence, we adjusted the incident energy to 0.5 μJ per pulse by an optical attenuator. Then the pulses were focused at a location of 500 μm beneath the surface of the sample. The intensity at focus would be approximate to 100 TW/cm^2. Such a high energy fluence within the focal volume would rapidly ionize the silica glass by the combined actions of avalanche and multiphoton processes[23] and thus induce microexplosion to create a void with a size of sub-micrometre. The void damage scattered light strongly, and hence resulting in an opaque spot inside the transparent glass.

To record the desired CCGH, the sample was moved step by step and irradiated selectively by the focused pulses according to the hologram pattern controlled by the personal computer (PC). When the area is blank in the hologram, the shutter system controlled by the PC will be closed. The irradiated dots became opaque and was shown as the 'black region' while the unirradiated dots remained transparent as the 'white region'. The size of the resulted CCGH is 256×256, and every pixel in the recorded CCGH is controlled as 2 μm. So the scale of the recorded CCGH is 512 μm $\times$ 512 μm in the silica glass. The top view of the central part of the fabricated hologram is presented in Fig.2(b) according to the CCGH depicted in Fig.1(c).

To reconstruct the OV beams from the fabricated CCGH, a collimated He–Ne laser beam was incident normally on the CCGH. In order to get an excellent diffraction result, we place a mask with a special aperture array in the diffraction beam path to block out the zero-order diffraction. Then, the diffraction pattern depicted in Fig.3(a) could be taken by a digital camera on the screen. The OV beams with topological charges $m = \pm 1$ and $m = \pm 3$ should be generated in the first order of the diffraction field respectively. However, the OV beams with $m = \pm 2$ and $m = \pm 4$ can also be attained in the first order diffraction modes. We also give an analytical result for the OV beams with new topological charges as shown in Fig.3(b), which shows high fidelity to OV beams.

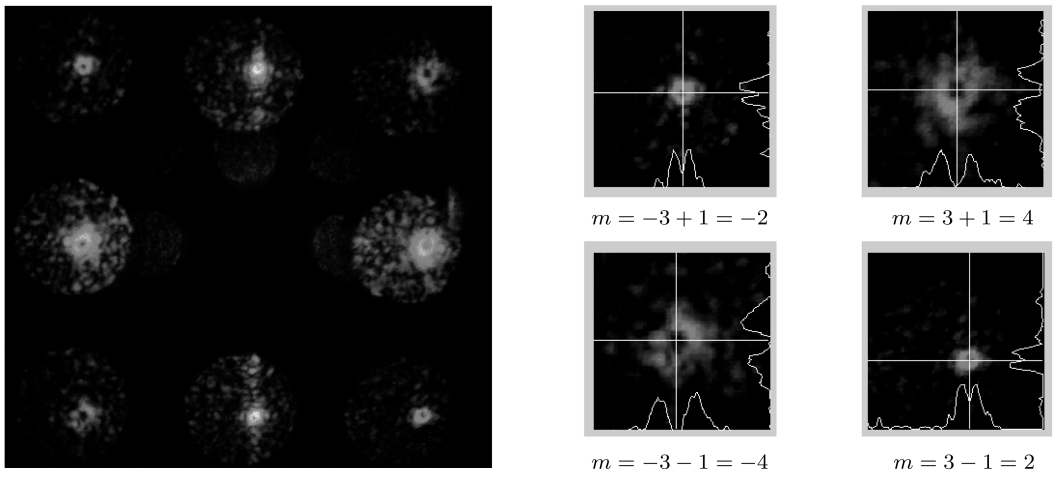


Fig.3. (a) The diffraction pattern. (b) The analytical result for the four superposed modes.

The OVs with new topological charges can be attributed to the superposition of the topological charges between ± 1 orders of the two CGHs. We give a sketch for the explanation of diffraction modes as shown in Fig.4. We can see that the topological charge is $m = 4$ in the position of the cross between $+1$ order for CGH with $m = 1$ and $+1$ order for CGH with $m = 3$ from the Fig.4. While the topological charge is $m = -2$ in the position of the cross between $+1$ order for CGH with $m = 1$ and -1 order for CGH with $m = 3$.

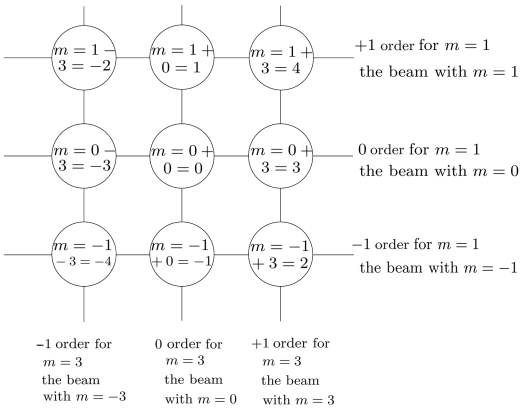
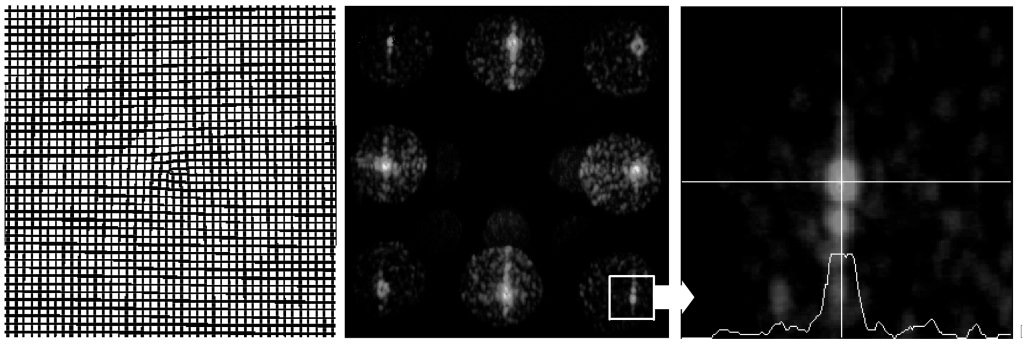


Fig.4. The sketch for explanation of diffraction mode.

In order to confirm the theoretical explanation about the superposition of the topological charges, we use another CCGH made by two CGHs with $m = 1$ depicted in Fig.5(a), and the diffraction pattern is shown in the Fig.5(b). From the Fig.5(b), we can find that the diffraction pattern in the position of the cross between the $+1$ order and the -1 order has become a Gaussian mode with the topological charge $m = 0$, and the analytical profile of the superposed beam is depicted in Fig.5(c). It can be seen that our explanation about the superposition of the topological charges is reasonable.

We also measured the diffraction efficiency by a power meter at the wavelength of 632.8 nm. Here, the diffraction efficiency is defined as the ratio of the intensity of each order diffraction beam to that of the incident beam. The efficiencies of diffraction beam with $m = \pm 1$ and $m = \pm 3$ were 2.2% respectively, and that of diffraction beam with $m = \pm 2$ and $m = \pm 4$ were 1.1% respectively. We can improve the diffraction efficiency by enhancing the thickness and decreasing the period of the fork grating of the CCGH according to the grating parameter $Q = 2\pi\lambda d/(n\Lambda^2)$ defined by Kogelnik,[24] where Λ is the period of the gratings, d is the thickness of the diffraction grating, n is the refractive index, λ is the wavelength of the incident beam.

The CCGH method would be an effective way to realize the superposition of the photon OAM. It would be significant for the micromachining, optical tweezer, quantum computation and quantum information processing to superpose the diffraction beams with the CCGH combined by two CGHs with the same spatial period Λ. Because it is much easier to generate the superposition of the OAM of the photons in comparison with it by the methods of Mach–Zehnder interferometer.



(a) (b) (c)

Fig.5. (a) The CCGH combined by two CGHs with $m = 1$, $m = 1$. (b) The diffraction pattern for the CCGH showed in (a). (c) The enlarged version for the superposed gaussian mode with $m = 0$.

3. Conclusions

We have realized the superposition of the OAM of photons with CCGH of OV fabricated in silica glass by femtosecond laser pulses. The CCGH was formed by combining two CGHs of OV in a special way and directly written inside glass by femtosecond laser pulses induced microexplosion without any pre- or post-treatment of the material. The OV beams with different photon OAM can be generated from different topological charges carried by the diffraction beams from the CCGH. Theoretical analysis and experimental demonstrations have been given to explain the generations of the superposition of the OAM. The efficiencies of the first order diffraction waves have been measured to be about 6.6% in total. Further researches and corresponding experimental work are in progress in our lab now.

References

[1] Nye J F and Berry M V 1974 *Proc. R. Soc.* A **336** 165
[2] Turnbull G A, Robertson D A, Smith G M, Allen L and Padgett M 1996 *Opt. Commun.* **127** 183
[3] Bazhenov V Y, Vasnetsov M V and Soskin M S 1990 *JETP Lett.* **52** 429
[4] Allen L and Beijersbergen M W 1992 *Phys. Rev.* A **45** 8185
[5] He H, Friese M E J and Heckenberg N R 1995 *Phys. Rev. Lett.* **75** 826
[6] Gibson G, Courtial J, Padgett M, Vasnetsov M, Pas'ko V, Barnett S and Franke-Arnold S 2004 *Opt. Express* **12** 5448
[7] Voogd R J, Singh M and Braat J J M 2004 *Proc. of SPIE* **5380** 387
[8] Simpson N B, Dholakia K and Allen L 1997 *Opt. Lett.* **22** 52
[9] Grier D G 2003 *Nature* **424** 810
[10] Leach J and Padgett M J 2002 *Phys. Rev. Lett.* **88** 257901
[11] Leach J and Courtial J 2004 *Phys. Rev. Lett.* **92** 013601
[12] Jiang W, Chen Q and Zhang Y 2006 *Phys. Rev.* A **74** 043811
[13] Schaffer C B, Brodeur A, Garcia J F and Mazur E 2001 *Opt. Lett.* **26** 93
[14] Watanabe W, Asano T, Yamada K, Itoh K and Nishii J 2003 *Opt. Lett.* **28** 2491
[15] Qu S, Qiu J, Zhao C, Jiang X, Zeng H, Zhu C and Hirao K 2005 *Appl. Phys. Lett.* **84** 2046
[16] Qu S, Zhao C, Zhao Q, Qiu J, Zhu C and Hirao K 2004 *Opt. Lett.* **29** 2058
[17] Kondo T, Matsuo S, Juodkazis S, Mizeikis V and Misawa H 2003 *Appl. Phys. Lett.* **82** 2758
[18] Zhao Q Z, Qiu J R, Zhao C J, Jiang X W and Zhu C S 2005 *Chin. Phys.* **14** 1181
[19] Cheng Y, Sugioka K and Midorikawa K 2004 *Opt. Lett.* **29** 2007
[20] Li Y, Dou Y, An R, Yang H and Gong Q 2005 *Opt. Express* **13** 2433
[21] Zhao Q, Qiu J, Jiang X, Dai E, Zhou C and Zhu C 2005 *Opt. Express* **13** 2089
[22] Guo Z, Qu S and Liu S 2007 *Opt. Commun.* **273** 286
[23] Juodkazis S, Misawa H, Hashimoto T, Gamaly E and Luther-Davies B 2006 *Appl. Phys. Lett.* **88** 201909
[24] Kogelnik H 1969 *Bell Syst. Tech. J.* **48** 2909