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Generation and application of petal-like structured light based on spatial light modulator

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Abstract: The phase hologram of petal-like structured light is realized by the circular arrangement of the sector phase mask obtained from the one-dimensional Airy beam. Femtosecond laser is reflected by the spatial light modulator encoded with the designed phase hologram, and then passes through a lens. In this way, petal-like light is formed in the focal plane of the lens. With the proposed phase generation method, one can conveniently adjust the number of lobes of the light field. By introducing the vortex phase in the central region of the phase hologram, the intensity of the structured light can be freely tuned. The microstructures array is prepared by two-photon polymerization with generated structured light. The particle capture experiment enabled by the microstructure array is carried out, and the experimental result unfolds the potential application of the structured light in microfluidic chips.

Keywords: Airy beam; structured light; spatial light modulator; two-photon polymerization; particle capture

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1 Introduction

In 1979, Berry and Balazs theoretically demonstrated that the Schrödinger equation describing a free particle can exhibit a nonspreading Airy wave packet solution[1], which possesses the ability to freely accelerate even in the absence of external potential. In 2007, Siviloglou et al[2,3] experimentally generated and observed the diffraction-free 1D and 2D Airy beams with finite energy for the first time. Since then Airy beams have attracted considerable attention of multidisciplinary researchers due to their unique properties such as self-acceleration, self-healing, and non-diffraction. In 2007, Zhang et al[4] explored the trapping and guiding of microparticles with autofocusing Airy beams. In 2012, Mathis et al[5] studied the micromachining of curved profiles in diamond and silicon using the accelerating beams. Recently, our group[6] realized the high-efficiency dynamic Airy imaging with broadband phase microelements fabricated by direct femtosecond laser writing.

Holding the tremendous advantages like high spatial resolution, arbitrary 3D structure construction, femtosecond laser two-photon polymerization (fs-TPP) has been applied in many fields such as microfluidics[7,8], micro-optics[9-11] and biological scaffold[12-14]. The traditional fs-TPP is time-consuming due to the single focus scanning strategy, which hinders its application in preparing structures with large areas or large volumes. Several methods have been adopted to improve the efficiency of fs-TPP, for example, multifoci parallel fabrication based on the spatial light modulator (SLM)[15,16] and 3D focal field engineering[17]. The 3D focal field engineering can be realized by superimposing specific light fields or computing the target light pattern using special iterative algorithms. Particularly, the former method is efficient and low-cost compared to the last one. Herein, we propose a strategy to generate petal-like structured light by superimposing the phase plates of 1D Airy beam and vortex beam based on SLM. The number of the petals of the generated structured light can be flexibly adjusted with the method. Moreover, microstructures arrays are constructed in photoresist by fs-TPP using the formed petal-like beam and are applied formicroparticles trapping to demonstrate the potential application of these arrays in microfluidics.

2 Method

The wave function of 1D Airy beam can be formulated as[2]

$$\varphi(\xi,s) = A_i[s-(\xi/2)^2]\exp[i(s\xi/2)-i(\xi^3/12)] \quad (1)$$

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where $\xi = z/kx_0^2$ is a normalized propagation distance, and $k = 2\pi n/\lambda$ is the wave number, $s = x/x_0$ represents a dimensionless transverse coordinate, x_0 is an arbitrary transverse scale. At the origin $\xi = 0$, Equation. (1) is simplified as $\varphi(0,s) = A_i(s)$. For the experimental generation of finite-energy Airy beams, an exponential aperture function is introduced, i. e., let

$$\varphi(0,s) = A_i(s)\exp(as) \tag{2}$$

where a is a positive parameter and $a \ll 1$ to ensure the realization of finite-energy Airy beams. The Fourier transform of Equation. (2) is:

$$\Phi_0(k) \propto \exp(-ak^2)\exp(ik^3/3) \tag{3}$$

from this equation one can easily conclude that the Airy beam with finite energy is Gaussian beam with a cubic phase in the spectrum. The top of Figure 1(a) shows the phase mask of the 1D Airy beam.

Researchers have produced an array of Airy beams in experiments by combining several 2D Airy phase masks[18]. Here, we introduce a new method to generate petal-like beams by combining the phase masks of the 1D Airy beam. The main process of this method is as follows: a sector phase mask with the angle θ is cut from the phase mask of the 1D Airy beam, as shown in Figure 1(a). The angle θ meets the condition $0 < \theta <= \pi/2$. We introduce a positive integer n to regulate angle θ:

$$\theta = 2\pi/n,\ n = 4,5,6\cdots \tag{4}$$

in this letter n is referred petal number. Figure 1(b) shows phase mask (top) formed by combining $n = 6$ sector phase masks and the corresponding simulated intensity distribution of the petal-like structured light (down). The case of $n = 8$ is shown in Figure 1(c). From the simulation results demonstrated in Figure 1(b), (c), one can see that the petal number of the structured light equals the parameter n, which means that the petal number of the generated beam can be flexibly adjusted by changing the parameter n. The central region of the phase masks shown in Figure 1(b) and (c) is almost black (i. e., the phase equals 0), which has neglectable modulation on the phase of the light and results in a bright spot in the center of the light field. Inspired by the research carried out in Reference [19], we introduced the phase of vortex beam into the center region of the generated phase mask to enhance the phase modulation ability of the central region:

$$\varphi(r,\varphi) = (l\varphi + 2\pi r/R) \tag{5}$$

where r,φ are polar coordinates, R is the radial shift value, which determines the shift angle of the vortex beam, l represents the topological charge. The phase mask ($n = 6$) and the corresponding simulation of light intensity are shown in Figure 1(d). It can be seen from the simulation results that the light field is in the shape of a "windmill", and the number of blades in the windmill is consistent with the petal number $n = 6$.

3 Experiment result and discussion

Figure 2(a) sketches the experimental setup for the fs-TPP with the petal-like structured light. A predesigned computer-generated hologram (CGH) is loaded on a reflective liquid-crystal SLM (Pluto NIR-II, Holoeye, 1920 × 1080 pixels, 256 gray levels, pixel pitch of 8 μm). A blazed grating (BG) is superimposed on the CGH for shifting the desired petal-like structured light away from the zero-order diffraction light, as illustrated in Figure 2(b). The phase profile of BG can be expressed by $2\pi x/\Delta$, where Δ represents the period of the BG. After beam expanding and collimation, a femtosecond laser (central wavelength, 800 nm; repetition rate, 80 MHz; pulse width, 75 fs) is reflected by the SLM, and then focused by a 60×oil objective

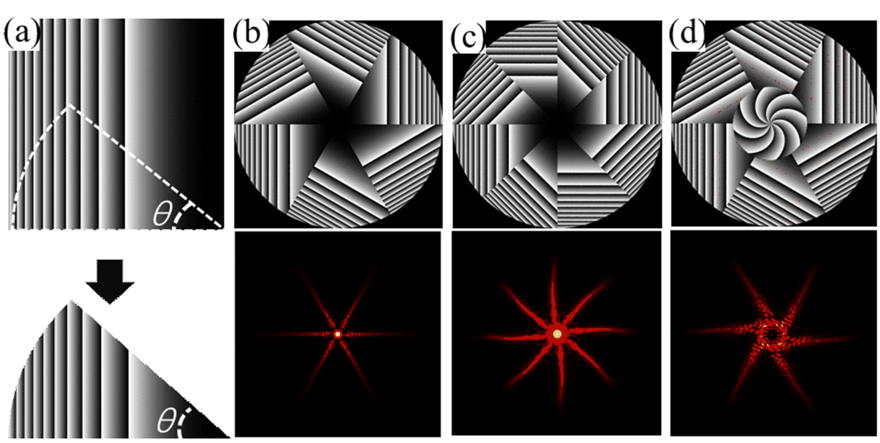

Figure 1. The generation of the phase mask of 'petal-like' structured light. (a) Top: The phase mask of 1D Airy beam; down: thefan-shaped phase mask cut from the 1D Airy beam phase mask; (b) Top: the phase mask for $n = 6$; down: transverse intensity distribution of the simulated beams; (c) Top: the phase mask for $n = 8$; down: transverse intensity distribution of the simulated beams; (d) Top: the central area of the phase mask was replaced by the phase mask of vortex beam, down: the corresponding simulated intensity distribution.

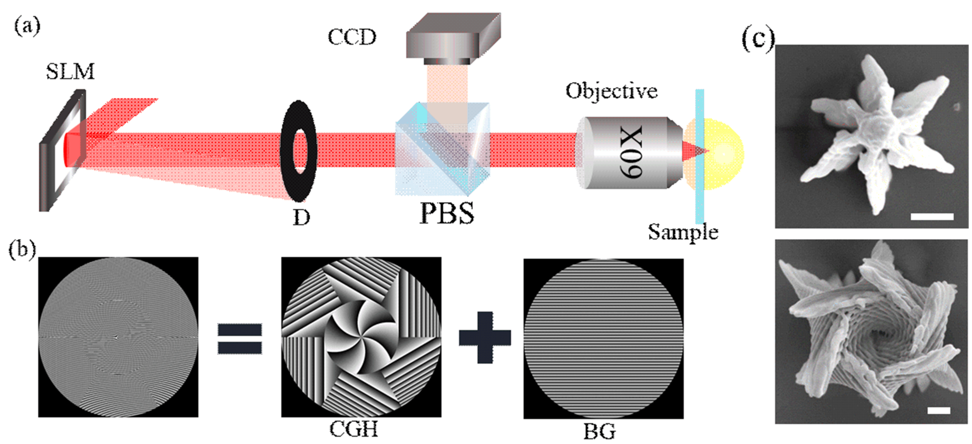

Figure 2. The generation of the petal-like beam and fabrication result. (a) Sketch of the experimental setup, SLM: spatial light modulator; D: diaphragm; CCD: charge-coupled device; (b) Design of the hologram loaded on the SLM; CGH: computer generated hologram; BG: blazed grating; (c) Top: the SEM image of the fabricated structure by the petal-like structured light without the phase of vortex beam; down: the SEM image of the fabricated structure by a single exposure with the petal-like structured light possessing the phase of vortex beam, scale bar: 2 μm.

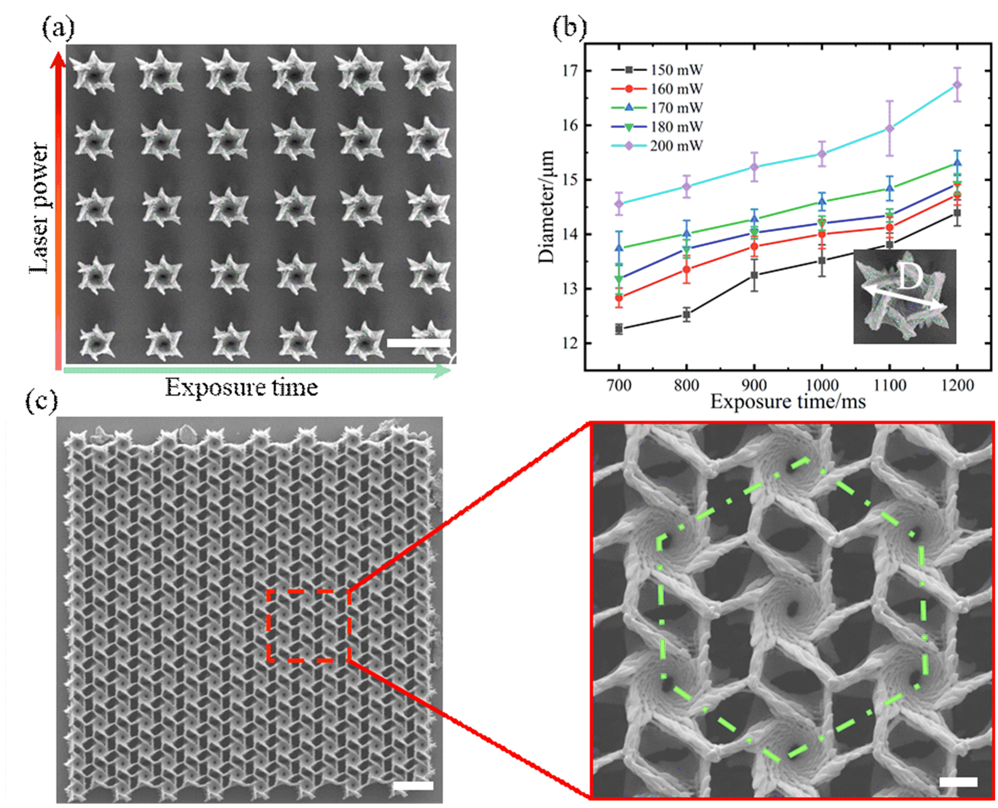

Figure 3. Fabrication of the microstructures array. (a) Top-view SEM image of the structures prepared with various exposure time and laser power. Scale bar: 20 μm; (b) The line chart demonstrates the influence of exposure time and lase power on the diameter of the micro-structures; Inset presents the definition of the diameter of a microstructure; (c) Top-view SEM image shows the fabricated array (right). Scale bar: 20 μm; The zoomed-in SEM image shows the distribution of the formed structures (left). Scale bar: 4 μm.

lens (Olympus, NA: 1.35). The undesired zero-order diffraction light is blocked out by a diaphragm and the petal-like structured light can be observed in the focal plane of the objective lens. The top panel of Figure 2 (c) shows the petal-like structured light intensity distribution captured by a CCD camera. 10 μL photoresist (SZ2080, IESL-FORTH, Greece) is dropped on a glass slide by pipette and then baked on a hot plate for 1 hour for fabrication. The prepared sample is inversely mounted on a 3D piezoelectric stage (P545, Physik

Instrumente, traveling range: 200 μm × 200 μm × 200 μm) and the exposure time is controlled by a mechanical shutter. After processing, the sample is put into a developer (1-propanol) for about 30 min to dissolve the unpolymerized photo resist and subsequently taken out for the evaporation of the liquid. The top panel of Figure 2(c) presents the structure fabricated by the petal-like structured light ($n = 6$) without the introduction of the phase of vortex beam. Figure 2(c) (down) shows the microstructure fabricated by single exposure with the petal-like structured light possessing the phase of vortex beam.

In order to produce microstructures with intact morphology and facilitate further application research, we first study the effects of exposure time and laser power on the morphology of the structure. Figure 3(a) shows the fabricated microstructures under different exposure times and different laser power. In order to facilitate the quantitative analysis, the longest distance in the horizontal direction between two ends of the microstructure is referred to as the diameter D of the structure, as depicted in the inset of Figure 3(b). Figure 3(b) reveals the relationship between structure diameter D and exposure time under different laser power. The increase of either laser power or exposure time will make the diameter D of the processed structure longer because more photoresist is exposed. In order to avoid overexposure and produce the structure stably, we set the exposure time of 700 ms and the power of 160 mW for array processing. Figure 3(c) shows a regular, uniform and periodic array of microstructures fabricated with petal-like light with the number of lobes is 6. The processed microstructures are arranged at the vertices of the regular hexagon, as shown by the dotted green line in the enlarged image on the right of Figure 3(c). By regulating the spacing between the microstructures, the microstructures can contact each other. Since the processing of a single structure only takes 700 ms, the entire processing time of the array can be controlled in 3 min.

The accurate capture of targeted particles is of great significance in a wide range of research fields. For instance, single-cell analysis in bioengineering requires the capture of a single cell[20]. Although optical tweezers have been successfully developed to trap tiny objects and cells with different sizes ranging from tens of nanometers to micrometers[21,22], in some special scenario, mechanical capture methods are needed[23,24] when the size of the target particle is large or the laser may cause damage to the sample or chemical reactions. Previous studies have realized microparticles trapping by combining femtosecond laser processing with capillary force guided self-assembly[25-27], these trapping methods are sensitive to the structure size and surface tension of

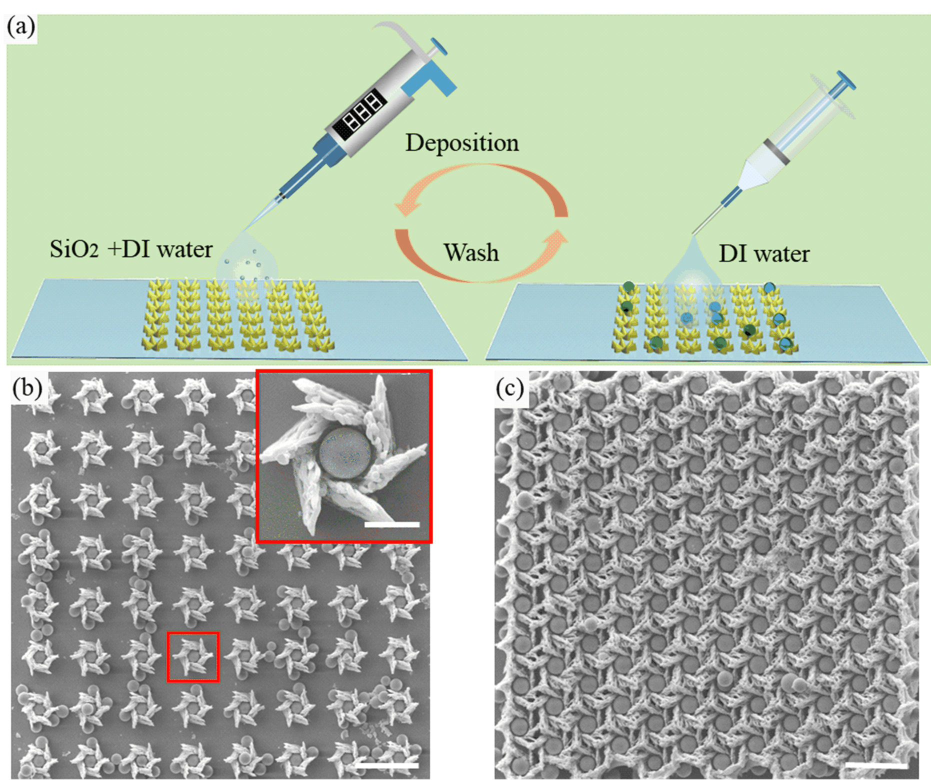

Figure 4. The trap of microparticles by the fabricated structures. (a) Schematicillustration for the trapping of SiO_2particles; (b), (c) SEM images of SiO_2 particles trapped in the square and hexagonal arrays. Scale bar: 20 μm; Inset is the magnified view. Scale bar: 5 μm.

the solution. Here we experimentally demonstrate the potential application of microstructures array constructed by petal-like light in microparticle trapping.

The experimental process of particle trapping based on the microstructured array is depicted in Figure 4(a). 5 μm SiO_2 microparticles are uniformly dispersed in deionized water and subsequently transferred on the prepared sample by pipette. The particles are left standing until they deposit into the center of microstructures. Finally, the uncaptured SiO_2 particles are rinsed by a syringe. By repeating the above experimental steps for several times, microparticles can be captured in the whole array. Figure 4(b) shows the experimental result of captured particles in the microstructures arranged in a square. Each single microstructure successfully captures a SiO_2 particle and high capture efficiency is achieved. Some microstructures have multiple particles surrounding them that can't be washed out due to the gaps between the microstructures that allow some particles to deposit on the substrate. In order to avoid particles being trapped by the gaps between the microstructures, we arranged the microstructures closely into a hexagonal array, as shown in Figure 4(c). From the scanning electron microscope (SEM) image, we can clearly see that the array captures particles in a honeycomb shape with a high capture rate. In this case, the gaps between the microstructures are very small to prevent particles from depositing on substrate.

4 Conclusions

In conclusion, a strategy to generate petal-like structured light based on SLM by combining the phase mask of 1D Airy beam and vortex beam is proposed. The number of petals in the structured light field can be flexibly adjusted. Compared with the traditional direct laser writing technology, the periodic microstructures array can be prepared in a very short time by using the generated petal-like light for fs-TPP. Based on these arrays, high efficiency trapping of SiO_2 particles is readily achieved, indicating that our method is of great application potential in the fields of microfluidics and biological scaffold engineering.

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Conflict of interest

The authors declare no conflict of interest.

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基于空间光调制器的瓣状结构光生成及应用

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摘要：在一维艾里光相位模板中截取扇形相位模板，通过对扇形相位模板的圆周排列，实现了一种“瓣状”空间结构光场的相位全息图．激光经加载该相位全息图的空间光调制器反射后，在透镜焦平面形成瓣状光场．本文提出的相位生成方法可以对光场的瓣数进行自由调控，并在全息图中心区域引入涡旋光相位实现了对结构光场中心光强的调控．基于该光场通过双光子聚合方式制备出复杂微结构阵列．利用这些微结构阵列进行的微粒捕获实验证明了该结构光场在微流控等领域的潜在应用价值．

关键词：艾里光；结构光；空间光调制器；双光子聚合；微粒捕获