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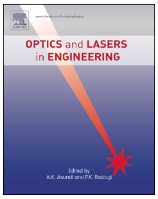

Parallel direct laser writing of micro-optical and photonic structures using spatial light modulator

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ABSTRACT

Two-photon polymerization (2PP) is a powerful tool for direct laser writing of micro-optical and photonic structures due to its flexibility in 3D structuring and sub-micrometer resolution. However, it can be time consuming to fabricate arrays of micro-optical devices and complex photonic structures. In this study, we propose to use predefined patterns (PPs) for parallel 2PP processing. A PP contains a multiple focal spot pattern optimized for the fabrication of certain microstructures. PP can be created by holographic laser beam modulation with a spatial light modulator (SLM). The quantity and position of the multiple foci can be flexibly and precisely controlled by predesigned computer generated holograms (CGHs). With these specially designed PPs, parallel fabrication of arbitrary distributed microlens arrays and 3D photonic structures is demonstrated. This method significantly improves throughput and flexibility of the 2PP technique and can be used for mass production of functional devices in micro-optics and photonics.

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1. Introduction

Two-photon polymerization has become a versatile tool for mask-free fabrication of functional micro- and nanodevices [1]. This technique is particularly appealing for the fabrication of micro-optical and photonic devices [2–6] complying its several properties, such as (a) the resolution of polymerized voxels can be beyond the diffraction limit down to sub-100 nm due to the nonlinear nature of 2PP [7], (b) the surface roughness of microstructures fabricated by 2PP can be less than 2.5 nm [8], and (c) arbitrary shaped 3D microstructures can be fabricated by precisely overlapped voxels [9].

However, a drawback of 2PP technique is the scaling characteristic of processing time. Micro and nano structures are fabricated by serially writing their contours and volume, and thus the processing time scales with the third power of the object size. It may take hours or even more time to fabricate a single micro or nano device [9,10], which is unacceptable for practical applications. This greatly hinders the development of this technology. Several approaches were investigated to reduce the processing time by establishing parallel processing, such as introducing mircolens arrays or diffractive optical elements (DOEs) into the 2PP fabrication system [11,12]. With microlens arrays or DOEs, femtosecond laser beam can be split into tens or even hundreds of spots, thus increasing the 2PP throughput. However, microlens arrays or DOEs create fixed patterns of laser spots, which makes this method less flexible. This technology is only suitable for the fabrication of structures with a constant period. Other attempts involve holographic lithography [13,14] and the use of shaped beams [15]. However, with these methods, only microstructures with specific profiles can be fabricated. A digital mirror device (DMD) based lithography technique has also been recently demonstrated [16,17]. DMDs modulate laser beam by controlling micro-mirror arrays to switch the light on and off on each individual pixel. This principle of operation may seriously affect the overall efficiency of the 2PP setup, since much of the laser power will be lost at the DMD if only a small percentage of the mirrors is switched on. In fact, the usable power is especially important in parallel 2PP processing since there exists a 2PP threshold power. It is necessary to guarantee that the power of every laser spot is above the threshold for 2PP. The more laser power can be used, the more laser spots can be achieved by laser beam modulation for 2PP processing. A recently developed multi-foci fabrication technique splits femtosecond laser beam into multiple beams by phase modulation with SLM [18–21]. However,

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the flexibility of SLM based 2PP was not fully investigated, as in these experiments microstructures were replicated by scanning of individual laser spots.

In this study, a multi-foci 2PP system based on an SLM is built. A femtosecond laser beam is modulated to a predesigned 2D multi-foci pattern. The quantity and positions of the multiple foci can be precisely controlled by CGHs. Parallel fabrication of micro-optical and photonic structures is realized by using the designed multi-foci pattern. Arrays of hemispherical microlens with a size of several tens of micrometers are fabricated in parallel. In addition, rapid fabrication of 3D photonic structures is also achieved by direct laser writing using PPs. Using this multi-foci 2PP technique, repetitive 3D scanning will not be necessary when complex functional microstructures are fabricated. Besides, by changing CGHs loaded to SLM, positions of multiple foci can be dynamically adjusted without optical or mechanical motion.

2. Experiment

The experimental setup is shown in Fig. 1. A high repetition rate femtosecond laser source (Coherent Chameleon with a pulse width of 75 fs, repetition rate of 80 MHz and center wavelength of 800 nm) is used with an average power of 2.2 W. The laser power is controlled by a half wave plate and a Glan polarizing beamsplitter. After passing through a beam expander, the laser beam illuminates a phase only SLM (Holoeye Pluto NIRII). The polarization of the incident laser beam should be set parallel to the orientation of the liquid crystal molecules in the SLM to ensure phase-only modulation. The expanded laser beam fully illuminates the SLM display. In fact it is even larger than the display to ensure an even light distribution over the active pixels in the SLM and to achieve better modulation. When a CGH is loaded to the SLM, the laser beam reflected from the SLM is modulated into a predesigned pattern of multiple beams. Only the first diffraction order is used in the experiment and the unwanted diffraction orders, created by the SLM, are blocked off by a spatial filter at the Fourier plane P of Lens1. Lens1 and Lens2 form a $4f$ optical system. Finally, the light is directed into a high numerical aperture microscope objective, which is used to tightly focus the first-order laser pattern on the sample. The sample consists of a photoresist layer on a cover glass, which is anchored to a 3D piezo stage. The process of fabrication is monitored in situ with a CCD camera. Two photoresists were used: SU-8 2075 (MicroChem) and Ormosil. SU-8 is colorless and transparent, which is suitable for the fabrication of microlens arrays. Ormosil is used for fabricating 3D photonic structures because of its good mechanical stability, high optical quality and good post-processing inertness. More importantly, it shows low shrinkage that makes it suitable for the fabrication of structures which are sensitive to deformation [22].

The SLM is a core component of the multi-foci 2PP system. It is used to control an LCOS display (Liquid Crystal-on-Silicon), active matrix in reflective mode, phase only modulation with 1920×1080 pixels and 8 μm pixel pitch. Fig. 2(a) shows a desired laser pattern representing the positions of multiple foci, a monochrome 1-bit bitmap image with 1080×1080 pixels, which matches the height of SLM. This black-and-white bitmap is converted into an 8-bit grayscale pattern that acts as a CGH (Fig. 2(b)). The CGH is generated with the Gerchberg–Saxton (GS) algorithm, an iterative 2-D Fourier transform algorithm [23]. Fig. 2(c) shows computer reconstruction of the designed pattern on Fourier plane P. When the CGH is loaded to the SLM with a computer, the gray levels on the CGH modulate a corresponding 0–2π phase shift of the laser beam. Thus, the femtosecond laser beam is modulated into multiple foci with a specific distribution as designed in Fig. 2(a). To avoid interference with the zero order, the foci patterns are not placed at the center. Optical reconstruction of the desired seven laser spots with hexagonal distribution is achieved at the focal plane of the objective lens, as shown in Fig. 2(d).

3. Results and discussion

3.1. Micro-optical structures

To demonstrate the ability of this multi-foci 2PP technique to fabricate micro-optical devices, arrays of hemispherical microlenses with a diameter of 20 μm, as shown in Fig. 3, were fabricated in photoresist SU-8 using a 100 × objective (NA = 1.25). A hemispherical microlens is designed with CAD software. The 3D model is sliced into layers (distance 0.3 μm) and raster scanned (0.2 μm) to fill the contour of each layer. Several microlenses are produced simultaneously with multiple foci by moving the 3D stage. Fig. 3(a) shows an SEM image of microlenses fabricated in three foci process. The multi-foci pattern used in Fig. 3(a) is designed to be in triangular distribution with a distance of 25 μm and that is the final period of the fabricated microlenses. These microlenses have a surface quality comparable to that fabricated with a single laser spot (Fig. 3(b)). The measured diameter of the microlenses is 19.5 μm, only 2.5% deviating from the designed 20 μm, which is attributed to the shrinkage of SU-8 resist after development [24]. The remarkable merit of multi-foci 2PP technique is that the foci quantity and their distribution are adjustable, which makes this technology very flexible. By modulating femtosecond laser beam with different CGHs, microlenses with 7 foci in hexagonal distribution and 4 × 4 foci pattern are also fabricated, as shown in Fig. 3(c) and (d), respectively. The multi-foci patterns used

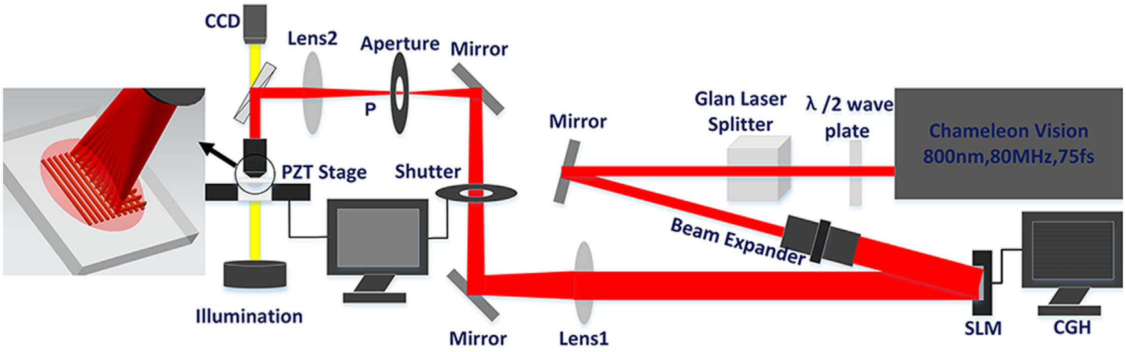

Fig. 1. Schematic illustration of the experiment setup: a femtosecond laser is modulated to multiple beams by the SLM, only the +1 order is used, unwanted diffraction orders are spatially blocked. Finally, the light is tightly focused into a sample with photoresist fixed on a 3D piezo stage.

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