High-Throughput Volumetric Microfabrication with Structured Light

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***Abstract* — This paper describes a volumetric fabrication method developed for multiphoton polymerization (MPP) with orders-of-magnitude higher throughput than conventional approaches. Microstructures are fabricated using 3D sculpted light-fields. This advance moves us closer to MPP-based mass production of devices for photonics, microfluidics, and medicine.**

Keywords* — *Multiphoton lithography, spatial beam shaping, volumetric fabrication, Bessel beam.

I. Introduction

Multiphoton polymerization (MPP) as one of the direct laser writing techniques is capable of manufacturing three-dimensional (3D) micro-structures with complex shapes and novel functionalities [1–3]. However, current MPP methods rely on point-by-point or layer-by-layer scanning and therefore are time-consuming. The low fabrication throughput of conventional MPP is the key factor that limits its wider adoption for industrial manufacturing over large surface area. One way to increase the fabrication speed is to turn layer-by-layer process into a volumetric process. An ideal volumetric printing method can fabricate structures with complex 3D geometry by single exposure and should be easy to implement.

As a step towards this goal, our paper discusses a volumetric fabrication method based on 3D structured light-fields. The present work first explores the potential of using zero-order Bessel beams for fabricating high-aspect-ratio structures volumetrically[4]. Two modes of fabrication using Bessel beams are investigated. First, high-aspect-ratio fibers are fabricated with stationary exposure to characterize the shape and morphology of structures formed by the Bessel beam (Fig. 1). Using single exposure of few laser pulses, thin fibers with diameter around 400 nm and length around 200 µm are obtained. We show that the fabrication throughput has been significantly improved compared to tradition multiphoton lithography. In the second mode of fabrication, the sample is translated in the plane perpendicular to the direction of beam propagation. Mesh-like structures are fabricated by synchronizing the movement of the sample with shuttering of the beam. Removing unpolymerized material after exposure yields free-standing, high-aspect-ratio structures.

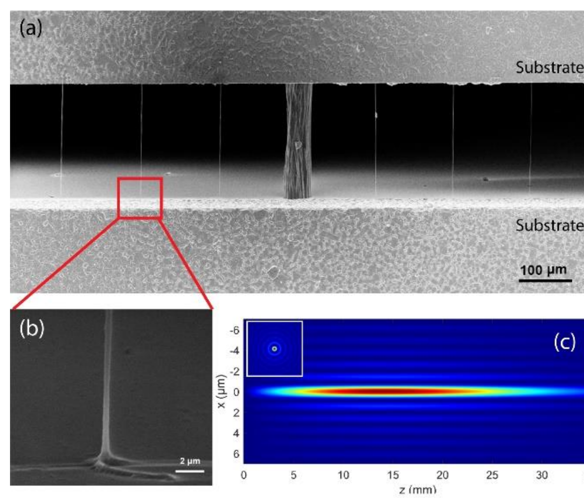

Fig. 1. (a) SEM images of fibers fabricated with stationary exposure using zero-order Bessel beam. (b) zoom-in view of the fiber with diameter around 400 nm. (c) zero-order Bessel beam intensity distribution.

To further increase the fabrication throughput, we demonstrate the generation of superposed high-order Bessel beams using a spatial light modulator (SLM) [5]. These beams have tightly packed foci whose patterns can be flexibly designed using a proper choice of fundamental Bessel modes, so they could be a good candidate for fabricating high-aspect-ratio micro-pillar array structures in parallel. We develop an analytical expression for the superposed high-order Bessel beams generated by displaying holo- grams on a spatial light modulator (SLM) and relaying them by a 4f system. We confirm the validity of the model by comparing with simulation results and experimental results.

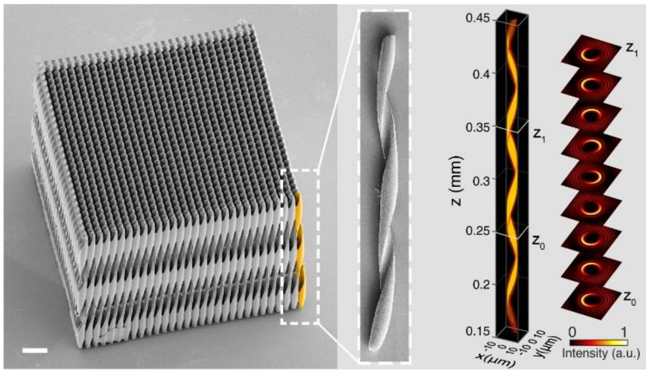

Fig. 2. Fabrication of a 30 by 30 helix array. Each helix is fabricated volumetrically using a three-dimensionally structured, “twisting” beam. Scale bar corresponds to 30 µm. White-boxed inset shows a high-magnification view of a single helix. Image on the right shows the simulation of iso-intensity and x-y intensity distribution of the “spiral” beam that was used for the fabrication.

Finally, we develop the theory of “spiral” beams, whose transverse intensity distribution rotates while propagating along the optical axis , and forms a stationary helical shape in space [6]. These beams are generated as a superposition of high-order Bessel modes and have a closed-form expression relating the design of the phase mask to the rotation rate of the beam. These beams can be generated with independently adjustable transverse width and rotational pitch. Using the concept of *r-z* mapping, the pitch of the helix can be made to vary with propagation distance *z*. We demonstrate rapid fabrication of helical microstructures with tunable shape in polymer by single exposure using these beams (Fig. 2). By performing a series of single exposures with lateral translation, helical matrices can be fabricated. Fig. 2 shows one helix array consisting of 30 × 30 helices. The fabrication time for each matrix is approximately 15 min, and most of the time is spent on translating the sample. In terms of fabrication volume per unit time, our method is more than 100 times higher than point-by-point scanning for similar structures reported in Ref. [7]. This volumetric fabrication technique increases the throughput by orders of magnitude compared to conventional MPP, paving the way for adopting MPP in many industrial applications. Such helical structures could have applications in metamaterials, microfluidics, and biomaterials. As MPP is maturing towards industrial applications, our method addresses the issue of throughput, and is a step forward for mass microfabrication over large surface areas.

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References

1. S. Kawata, H. B. Sun, T. Tanaka, and K. Takada, "Finer features for functional microdevices," Nature **412**(6848), 697–698 (2001).

2. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," Opt. Lett. **21**(21), 1729 (1996).

3. J. Lv, Y. Cheng, W. Yuan, X. Hao, and F. Chen, "Three-dimensional femtosecond laser fabrication of waveguide beam splitters in LiNbO_3 crystal," Opt. Mater. Express **5**(6), 1274 (2015).

4. H. Cheng, C. Xia, M. Zhang, S. M. Kuebler, and X. Yu, "Fabrication of high-aspect-ratio structures using Bessel-beam-activated photopolymerization," Appl. Opt. **58**(13), D91 (2019).

5. H. Cheng, C. Xia, S. M. Kuebler, P. Golvari, M. Sun, M. Zhang, and X. Yu, "Generation of Bessel-beam arrays for parallel fabrication in two-photon polymerization," J. Laser Appl. **33**(1), 012040 (2021).

6. H. Cheng, P. Golvari, C. Xia, M. Sun, M. Zhang, S. M. Kuebler, and X. Yu, "High-throughput microfabrication of axially tunable helices," Photonics Res. **10**(2), 303 (2022).

7. M. Thiel, M. Decker, M. Deubel, M. Wegener, S. Linden, and G. von Freymann, "Polarization Stop Bands in Chiral Polymeric Three-Dimensional Photonic Crystals," Adv. Mater. **19**(2), 207–210 (2007).