MOVING MASK LITHOGRAPHY FOR REAL-TIME SYNTHESIS OF PHOTOPOLYMERIZED MICROSTRUCTURES IN MICROFLUIDIC CHANNELS

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ABSTRACT

This paper describes a high-throughput moving mask lithography technique to fabricate high-precision photopolymerized microstructures inside microfluidic channels using a computer-controlled ultraviolet (UV) optical projector. We demonstrate that resolution of optofluidic lithography can be significantly improved by synchronously shifting the UV exposure pattern with the prepolymer solution flow.

KEYWORDS: Moving mask, Optofluidic, Maskless Lithography, Microfluidic

INTRODUCTION

Continuous-flow lithography can synthesize extruded polymeric microparticles of various shapes and sizes inside the microfluidic channel by selectively solidifying the liquid-phase photocurable oligomer stream with the UV light exposure using a high-magnification objective lens [1]. However, when the photomask pattern is fixed, there exist inevitable tradeoffs between the lithography resolution, exposure dose/time, prepolymer flow speed, and fabrication throughput. For example, when microstructures are synthesized under fast flow speed for higher fabrication throughput, the lithography resolution decreases proportionally to the flow speed because of motion blur during the UV exposure time [1, 2]. The stop-flow lithography technique overcomes such tradeoffs by stopping the flow during the exposure [2]. However, it cannot be used for some applications where the active flow control in the microfluidic channel is difficult. In this paper, we demonstrate high resolution continuous-flow lithography without motion blurring eliminating need for stopping the flow.

EXPERIMENTAL METHODS

As schematically shown in Fig. 1a, our experimental setup replaces a fixed photomask of conventional continuous-flow lithography with a programmable two-dimensional spatial light modulator (SLM) for dynamic UV exposure [3]. The UV light is projected onto the microfluidic channel filled with photocurable oligomer (polyethylene glycol diacrylate (MW=258) containing 10% of UV photoinitiator (2,2-dimethoxy-2-phenylacetophenone)). The particle synthesis is monitored and analyzed in real-time by a computer-controlled machine vision system. The microfluidic channel is fabricated using a standard soft lithography technique with polydimethylsiloxane (PDMS) material, and its height is 12 µm.
First, we measured the flow speed by generating a test particle and measuring its speed in the microfluidic channel. The machine vision system captures multiple microscope images (15 frames per second), and calculates the moving direction and speed of the test particle using an image processing algorithm. Due to the limitations in the field of view and computational speed, the maximum measurable flow speed is \( \sim 300 \text{ } \mu\text{m/s} \) with a 40x objective. Second, we selected the appropriate exposure time. Exposure time is inversely proportional to both the height of the channels and the size of the mask feature [1].

Figure 1. (a) Schematic diagram of the experimental setup. (b) Conceptual diagram of the moving mask lithography for real-time in-flow microparticle synthesis.

Figure 2. Screen shot of our computer control program for the moving mask lithography system. Flow speed and direction are automatically calculated by analyzing multiple frames captured by the image sensor shown in Fig. 1a.

With known flow speed and exposure time, control program automatically calculated number of entire masks, moving step and time interval of each mask (shown on Fig. 1b). If we assume the particle speed is not changed during exposure, then we can get those parameters from following equations.

\[
T_{\text{dose}} = N_{\text{mask}} \cdot T_{\text{delay}} \quad V_{\text{particle}} = \frac{P_{\text{step}} \cdot C_{\text{scale}}}{T_{\text{delay}}} \quad (1)
\]

Where \( N_{\text{mask}} \) is the total number of masks, \( T_{\text{delay}} \) the time interval of each mask, and \( T_{\text{dose}} \) is total exposure time. \( V_{\text{particle}} \) is the speed of test particle, \( P_{\text{step}} \) the pixel shift of each mask and \( C_{\text{scale}} \) is the scaling factor. \( C_{\text{scale}} \) is 0.33 um/pixel when 40x objective is used. When the photomask pattern moves at the same direction and speed of the photocurable solution flow, and the microstructures are exposed multiple times, we can effectively increase the exposure time/dose without sacrificing the flow speed and microstructure generation throughput.
RESULTS AND DISCUSSION

When the photomask pattern is not dynamically updated during 100 ms exposure time, the fabricated polymeric structure is significantly blurred and we could not reliably generate 10 µm features (Fig. 3a). Figure 3b demonstrates that our dynamic moving mask lithography technique effectively compensates for the lateral offset between the exposure pattern and the synthesized microstructures, and, thus, improves the lithography resolution and throughput simultaneously. As shown in Fig. 3c, the overall spatial resolution of moving mask lithography closely matches with that of stop-flow lithography.

![Figure 3](image)

*Figure 3. Optical microscope photographs of polymeric lattice structures. A 40X objective is used. (a) The SLM is not updated for 100 ms except the particle in dotted box. Particle in dotted box was fabricated by moving mask exposure. (b) The SLM image pattern exactly follows the synthesized microstructure, and get exposed for 6.6 ms 15 times during 100 ms. Particle at right side was synthesized without using moving mask exposure. (d) For comparison, we stopped the flow and synthesized the same polymeric lattice structure with 100 ms exposure time.*

CONCLUSIONS

Without stopping the flow, moving mask lithography technique can significantly improve the resolution of optofluidic lithography by synchronously shifting the UV exposure pattern with the prepolymer solution flow.

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REFERENCES

