REAL-TIME SYNTHESIS AND MANIPULATION OF PHOTOPOLYMERIZED MICROSTRUCTURES USING OPTOFLUIDIC MASKLESS LITHOGRAPHY AND OPTICAL TWEEZERS

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ABSTRACT

We report on a microfluidic platform for real-time synthesis, manipulation, and assembly of free-floating heterogeneous polymeric microstructures. We generate polymeric microparticles with various sizes, shapes, and composition using in-situ photopolymerization process with a dynamic spatial light modulator, and manipulate their relative positions and orientations using an optical tweezer for particle transportation, sorting, assembly, and reordering. Rapid prototyping of composite polymeric structures by assembling smaller microstructures with different shapes and materials is experimentally demonstrated. The integration of optical tweezers and maskless lithography with the microfluidic channels enables dynamic particle generation and manipulation in a single compact platform.

INTRODUCTION

Microscopic structures made of multiple polymeric materials with different physical and/or chemical properties have important applications in the various disciplines of microsystems engineering, including photonic devices [1], self-assembly process [2], and biocompatible materials [3, 4]. Rapid lab-on-a-chip prototyping of such composite microstructures can provide a number of advantages in terms of time, cost, and portability over conventional fabrication technologies with mask-based lithography [3-6]. However, in previous in-situ photopolymerization techniques for multi-faced microparticle generation, the number of materials and their boundary shapes within one microparticle are generally limited by microfluidic streams inside the channel [4-6]. In this paper, we demonstrate that an optical tweezer can manipulate polymerized microstructures inside the microfluidic channel [7], and can be used for in-situ fabrication of complicated composite microstructures.

EXPERIMENTAL SETUP

Figure 1: Schematic diagram of the experimental setup. The inset shows a microscope photograph of a polymeric two-dimensional lattice structure synthesized by the setup.

Figure 1a schematically shows our experimental setup based on an inverted microscope. Extruded polymeric microparticles with various shapes and sizes can be synthesized inside the microfluidic channel by selectively solidifying the liquid-phase photocurable

oligomer stream with the ultraviolet (UV) light exposure [3-6]. A high magnification microscope objective lens demagnifies computer-controlled image patterns from a two-dimensional spatial light modulator (SLM) [8] onto the microfluidic channel placed on the object plane of the microscope [6]. The illumination source for the SLM is a UV light source with the center wavelength of 365 nm.

The objective lens also focuses the high-intensity infrared (IR) optical beam from a continuous-wave 1060 nm Ytterbium fiber laser source for optical manipulation. The optical tweezing IR beam is spatially combined with the UV exposure pattern using a dichroic mirror as shown in Fig. 1. The beam spot size at the object plane is approximately 2 μm with a 60 $\times$ objective lens (numerical aperture: 0.65). The fiber laser output is mounted on a translational stage as shown in Fig. 1a, and, therefore, the beam spot position can be controlled independently from the UV exposure pattern. Since the optical tweezer wavelength is far from the UV photopolymerization wavelength, the IR beam does not solidify the photocurable oligomer, but only exerts force on the polymerized microparticles. The particle synthesis and manipulation processes are monitored and analyzed in real-time by a charge coupled device camera and a computer machine vision system.

The microfluidic channel is fabricated using a standard soft lithography technique with polydimethylsiloxane (PDMS) material as described in Fig. 2 [9]. Since the inhibition layer near the PDMS channel surface prevents the photopolymerization process [5], the cured microstructures can be made either free-flowing or adhered on the surface of the microfluidic channel depending on the UV exposure time. The photocurable oligomer used in our experiments is polyethylene glycol diacrylate (PEG-DA) with 10% UV photoinitiator (2, 2-dimethoxy-2-phenylacetophenone).

Figure 2: Fabrication process for the PDMS microfluidic channel. The channel height and the inhibition layer thickness are 12 μm and 1.5 μm , respectively.

An optical microscope photograph of a two-dimensional polymeric lattice structure synthesized by our experimental setup is shown in the inset of Fig. 1. All UV curing processes in this paper are performed with a 60 $\times$ objective lens. Since the SLM pixel size is 13.68 μm , one pixel corresponds to 0.228 μm at the object plane. However, the spatial resolution of our maskless lithography is currently $\sim 1 \mu\text{m}$, and limited by the diffraction, non-ideal transfer modulation function, and the depth of focus.

EXPERIMENTS AND RESULTS

Figure 3: Maximum drag speed as a function of the synthesized particle size for the optical tweezer beam power of 70, 140, and 210 mW. The experiments are performed with the cylindrical microparticles shown in the inset.

The trapping force of an optical tweezer depends on the IR beam intensity and the refractive indices of prepolymer solution and polymerized structures. Figure 3 shows the relationship between the maximum dragging speed, polymer particle size, and optical power. Higher optical power increases the tweezer force, and can compensate for larger friction force.

Figure 4: Synthesis of heterogeneous polymeric microstructures using in-situ photopolymerization and photocurable resin solution exchange. Microparticle synthesis with (a) Rhodamine B and (b) fluorescein. (c) Fluorescent image of nine polymeric microparticles. (d) Assembly of microparticles using the IR optical tweezer. Brightfield and fluorescent image of the assembled microparticle array (e) before and (f) after photocuring.

Figure 4 shows our proof-of-concept experiment, which generates a composite polymeric structure by assembling nine smaller microstructures with different shapes and materials. A

ring-shaped cage structure is first generated with long UV exposure time of 5 seconds (Fig. 4a). The fixed ring-shaped border passes the liquid-phase prepolymer material through its small openings when the microfluidic channel is pressurized by a syringe pump, but keeps the solidified polymeric particles inside the cage.

Using several solution exchanges, we then create nine different particles with two different material properties as shown in Fig. 4abc (red and green fluorescent for odd- and even-numbered particles, respectively). Five free-flowing microparticles (Particle: 1, 3, 5, 7, 9) are first synthesized inside the cage area after Rhodamine B (red) is added to the photocurable oligomer stream (Fig. 4a). The particle size is approximately $19 \mu\text{m} \times 19 \mu\text{m}$ (86 pixels by 86 pixels on the SLM), and the UV exposure time is 0.2 second. Due to short exposure time, the inhibition layer is not completely depleted, and therefore, the particles are free-floating inside the PDMS microfluidic channel [5-6]. The unpolymerized material is then washed away, and the oligomer stream with fluorescein (green) is injected into the channel for subsequent photocuring of four additional microparticles (Particle: 2, 4, 6, 8, Fig. 4b). Next, we wash away the unpolymerized material and fill the channel with the original oligomer stream again (Fig. 4c).

The optical tweezer moves and rotates these microparticles to form a 3×3 array pattern as shown in Fig. 4de. The last UV exposure combines the assembled heterogeneous particles, and creates a bigger structure composed of nine different regions (Fig. 4f). Figure 4f shows that the fluorescent property of each microparticle is preserved. Synthesizing such a structure using conventional fabrication techniques would require at least several deposition and etching steps with multiple masking patterns.

In summary, we have demonstrated a compact optofluidic platform for real-time synthesis, manipulation, and assembly of free-floating heterogeneous polymeric microstructures using in-situ photopolymerization and optical tweezer. Our technique provides flexible and interactive environments in the fabrication and manipulation of microstructures inside the microfluidic channels.

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