

Three-Dimensional Passive Micromixer Fabricated by Two-Photon Polymerization for Microfluidic Mixing

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Flow mixing is an important process for many microfluidic applications. Efficient mixing is difficult in microscale channels owing to laminar flow. Disturbing the flow stream by modifying channel geometries or embedding barriers improves the mixing rate. In this study, a three-dimensional (3-D) passive micromixer with propeller blades fabricated by two-photon polymerization (TPP) technology is embedded in the channel for fluid mixing. The propeller blades are designed to disturb the laminar flow in three dimensions to improve the mixing rate. Screw-shaped and flat blades are compared. The experimental results indicate that the screw-shaped propeller provides additional streamlines in the *Z* direction, which enhances the mixing efficiency. Finally, this phenomenon was verified through simulation.

1. Introduction

In recent years, the lab-on-a-chip or microfluidic chip has been attracting attention because of its convenience, rapid operation, low-consumable reagents, and accuracy. This technology has given rise to an important trend in the biological industry.^(1,2) For the successful performance of biological operations, such as drug delivery, DNA

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hybridization, polymerase chain reaction (PCR) amplification, and biochemical reactions,⁽³⁾ rapid mixing of multiple fluid species becomes important and the design of the chip structure becomes complicated. Because flow is laminar under the low-Reynolds-number condition, fluid mixing in microscale channels is mainly governed by molecular diffusion. Unfortunately, the mixing rate is severely limited. In efforts to enhance the mixing rate, previous works have been dedicated to increasing the contact area between two fluids, and two mixing methods, active and passive, have been proposed.⁽⁴⁾

Active mixing is accomplished using external devices in an integrated system composed of several independent components. In general, such a system provides high mixing efficiency. However the external driving powers generated by, for example, acoustic waves, thermal convection, and magnetic force, require complex control and might cause damage to biological samples.^(5,6)

Passive mixing, which is typically accomplished by driving fluids through channels with delicate and fixed geometries, is reported to achieve fluid mixing. In this case, a longer channel or embedded barriers increase the fluid contact area or disturb the flow stream, which enhances the mixing rate. Such methods provide a simple operation and avoid damaging biological samples. Unfortunately, the mixing rate is still unsatisfactory.^(7,8) Recent works are focused on enhancing the mixing efficiency by modifying the channel geometries⁽⁹⁾ or using 3-D channels.⁽¹⁰⁾ On the other hand, an array of barriers of various shapes, such as diamond, fishbone, and circle,^(11,12) are proposed for disturbing the stream. However, complex channels or array barriers might cause the flow to be blocked.

In this paper, 3-D microstructures fabricated by two-photon polymerization (TPP) are proposed to be embedded in the channel to enhance the stream disturbance. TPP is a convenient technique for fabricating 3-D microstructures of arbitrary shapes.⁽¹³⁻¹⁵⁾ Structures with complex shapes can be directly obtained by scanning a laser-focusing point along predetermined trajectories. This technology promises a convenient method to fabricate an embedded 3-D structure in a microchannel.

2. Materials and Methods

2.1 TPP 3-D fabrication system

The microstructures were fabricated using a commercial TPP 3-D microfabrication module (Teem Photonics Inc.) with a passively Q-switched Nd:YAG microchip laser (532 nm). The laser beam was expanded using a telescope coupled to an inverted microscope (Olympus IX51) and focused using a microscope objective lens (100 \times , $NA=1.3$). Figure 1 shows the diagram of the TPP 3-D fabrication system.

2.2 Fabrication of microfluidic channel

The microfluidic devices were fabricated using PDMS bonded on a glass microscope slide, by the soft lithography and replica molding techniques previously described by Yang *et al.*⁽¹⁶⁾ The fabrication steps of the PDMS microchannel follow the valuable illustration presented by Iosin *et al.*⁽¹⁷⁾ The design of the microfluidic Y-shaped channel is shown in Fig. 2. The main channel is 80 μm wide and 25 μm deep. The branches at an angle of 120 $^\circ$ are 35 μm wide and the same depth as the main channel. The apertures at the two ends of the channel allow entry and exit of the fluid. The PDMS and glass

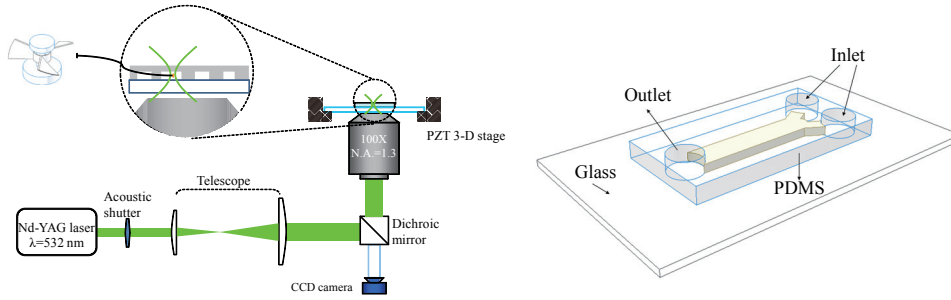


Fig. 1 (left). (Color online) Schematic of two-photon polymerization 3-D fabrication system.

Fig. 2 (right). (Color online) 3-D schematic illustration showing microchannel design.

surfaces were treated with a plasma cleaner and immediately brought into contact to create a permanent bond.

2.3 Fabrication of 3-D micromixer

To demonstrate fluid mixing, three-blade propellers with flat and screw-shaped blades were designed for fabrication in microchannels. The dimensions of the propellers are shown in Fig. 3. A commercially available resin (Photomer 3015, Henkel Inc.) with a photoinitiator was injected into the microchannel for TPP fabrication, as shown in Fig. 1. Afterward, the unpolymerized resin was dissolved with ethanol (95%). The SEM micrographs of the 3-D propellers are shown in Fig. 4.

3. Results and Discussion

3.1 Demonstration of fluid mixing

The micromixers were set at 400 μm and the sampling area was measured at 700 μm from the merging point of the two branch channels, as shown in Fig. 5. Ethanol and ink were injected into the Y-shaped microchannel from inlets to demonstrate the mixing. The experimental parameters are listed in Table 1.

The mixing index (I), as shown in eq. (1),⁽¹⁸⁾ is used to verify the efficiency of the mixer. The term c_k is the color index at pixel k and \bar{c} is the average over N pixels in the sampling area. The more uniform the mixture, the smaller the mixing index.

$$I = \left(1 - \sqrt{\frac{1}{N} \sum_{k=1}^N \left(\frac{c_k - \bar{c}}{\bar{c}} \right)^2} \right) \times 100\% \quad (1)$$

3.2 Mixing efficiency

A series of barriers of different shapes, such as circular pillars, diamond pillars, flat propellers, and screw-shaped propellers, were embedded in the microchannel to demonstrate the mixing efficiencies. The result (Fig. 6) indicates that the propeller-type

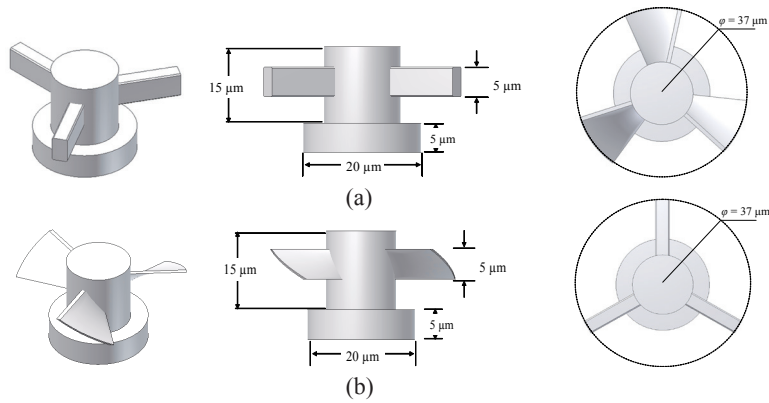


Fig. 3. Dimensions of micromixers: (a) flat and (b) screw-shaped blades.

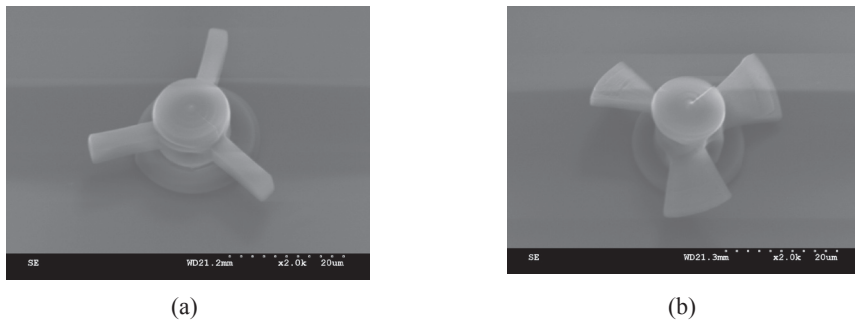


Fig. 4. SEM images of the 3-D propellers: (a) flat and (b) screw-shaped blades.

Table 1
Experimental parameters for two-fluid mixing.

	Fluid A: ethanol	Fluid B: black ink
Inlet flow rate	12 $\mu\text{l}/\text{min}$	12 $\mu\text{l}/\text{min}$
Molarity	16.7 mol/m^3	55.6 mol/m^3
Diffusion coefficient	$1 \times 10^{-9} \text{ m}^2/\text{s}$	

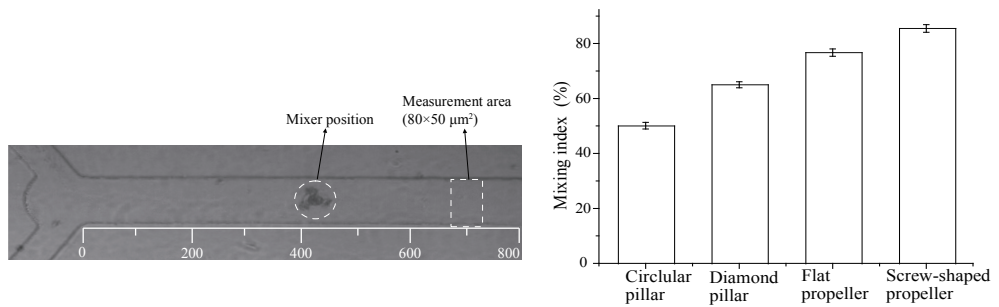


Fig. 5 (left). Mixer position and measurement area in Y-shaped microchannel.
Fig. 6 (right). Mixing indexes of different types of mixers.

barriers lead to higher mixing efficiency than pillar barriers. Even just one screw-shaped propeller results in a mixing efficiency of over $\sim 80\%$. The flows in the microchannel were visualized using commercial software (COMSOL Multiphysics, COMSOL Inc., USA). For the simulation, a Y-shaped channel with an embedded micromixer was designed as previously described. The simulation results (Fig. 7) show that the screw-shaped propeller generates streamlines in the Z direction. This phenomenon indicates that Z-direction stream generation increases flow disturbance and hence enhances the mixing efficiency.

4. Conclusions

We proposed a 3-D passive micromixer with propeller blades fabricated by TPP technology, which is convenient for fabricating structures of arbitrary 3-D shapes. The results indicated that the screw-shaped propeller generates streamlines in the Z direction and enhances the mixing efficiency. On the basis of this result, even just one mixer can promise a mixing index above 80% at a flow rate of $12 \mu\text{l}/\text{min}$.

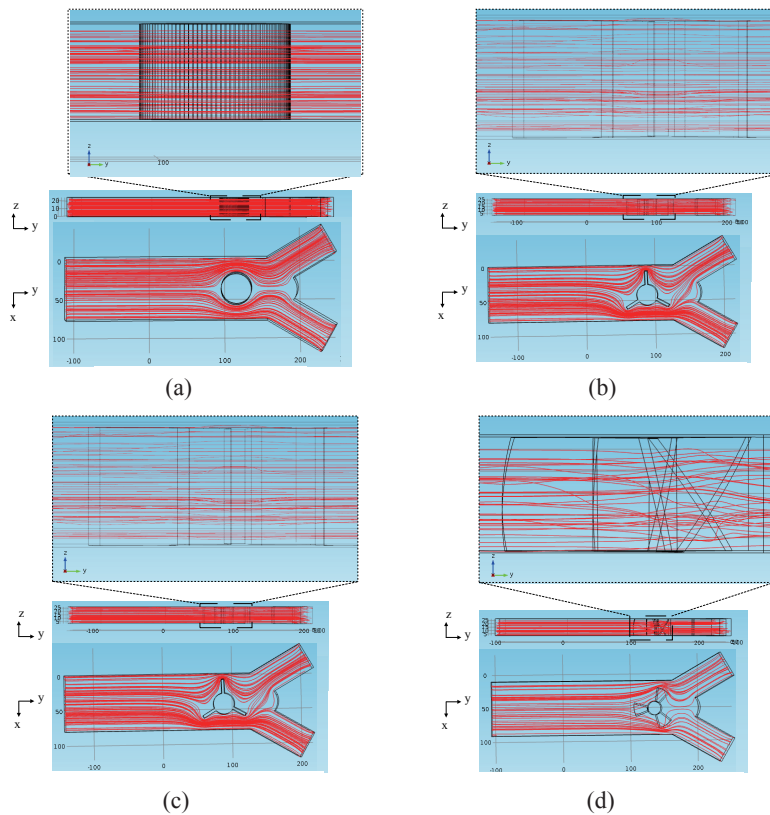


Fig. 7. (Color online) Simulation results of streamlines: (a) circular pillar, (b) diamond pillar, (c) flat propeller, and (d) screw-shaped propeller.

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