

## THREE DIMENSIONAL CO-AXIAL DEFOCUSING FLOW-ASSISTED MICRO-MIXING FOR ENHANCED MOLECULAR DIFFUSION

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We proposed a passive micro-mixer using three dimensional co-axial defocusing flows. A computer-aid simulation was performed to optimize the design of the micro-mixer. Based on the simulated results, the micro-mixer was fabricated with two glass capillaries which could provide a true three dimensional geometry. The micro-mixer was tested with Rhodamine B dye for visualization. The results showed that defocusing flow was gradually developed below 3,000  $\mu\text{l/h}$  at low concentration ( $0.5 \text{ mol/m}^3$ ) of Rhodamine B and below 6,000  $\mu\text{l/h}$  at high concentration ( $2.0 \text{ mol/m}^3$ ). Molecular diffusion could be enhanced with high concentration and defocusing flow at low water flow rate, resulting in a possible passive micro-mixing.

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### 1. Introduction

Microfluidics, as a technology to manipulate micro-scaled fluids, has been successfully utilized for a variety of applications in physics, chemistry, biology, engineering, and medicine. This success seems to be attributed to many favorable advantages such as reduced reagent consumption, low costs, portability, rapid heat transfer, fast diffusive mixing, and integration of multiple components with different functionalities [1]. Currently, microfluidics incorporated with MEMS (Micro Electro-Mechanical Systems) technology is rapidly expanding their application areas to Lab-On-Chips and micro Total Analysis Systems for automation of chemical analysis and miniaturization [2, 3].

One of major microfluidic applications is to mix fluids at micro- and nano-scales. Microfluidic mixing is a key element for biochemical analysis, pharmaceuticals, analytical chemistry, and high-throughput synthesis [4]. Micro-mixers are categorized as either active or passive devices according to the existence of external forces. Different molecules can be homogeneously mixed in active devices using ultrasonic, dielectrophoretic, electrohydrodynamic, and magnetic-hydrodynamic forces [5-9]. However, these active devices to achieve high mixing performance require integration with external sources which place a limit to broad applications. In contrast, passive micro-mixers which require no energy input can perform micro-mixing based on schemes such as lamination, zigzag or twist channels, and 3D serpentine structure [10-13]. Therefore, passive micro-mixing which manipulates laminar flow in the microchannels to enhance molecular diffusion, can provide more advantages of disposability, ease fabrication, and lower cost.

In this study, we proposed a passive micro-mixer using three dimensional co-axial defocusing flows for the enhanced diffusion of molecules. This mixer could provide several benefits, such as a true three dimensional geometry, a convenient co-axial flow-defocusing

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control; a precise diffusion control, and a high chemical stability. A computer-aided simulation was conducted to predict the performance of the mixer designed for generation of defocusing flows. The glass capillary-based micro-mixer could generate three dimensional co-axial defocusing flows as well as focusing flows. The effect of defocusing flow-assisted diffusion on micro-mixing as a function of flow rate was investigated using two concentrations of a red dye in deionized water for visualization.

## 2. Experimental

### 2.1 Materials

A three dimensional co-axial micro-mixing was investigated using Rhodamine B (> 95%; MW = 479.01 g/mol; Sigma Aldrich, MO, USA) for visualization of diffusion. For 2.0 mol/m<sup>3</sup> concentration of Rhodamine B (RB), 20.0 mg of RB was dissolved in 20 ml of deionized (DI) water. For 0.5 mol/m<sup>3</sup> concentration of RB, 5.0 mg of RB was dissolved in 20 ml of deionized (DI) water.

### 2.2 Computer simulation for the design of the micro-mixer

A two-dimensional axial symmetry model using Comsol Multiphysics software was prepared to design the micro-mixer for generation of defocusing flows. The model was the glass capillary-based microfluidic geometry, as shown in Fig. 2. This geometry consists of three dimensional core (RB solution) and shell (DI water) regions with two inlets and one outlet. Assuming incompressible, laminar, and steady state, both the continuity and Navier-Stokes equations were applied as follows:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{F} \quad (2)$$

where  $\rho$  is the density (1,000 kg/m<sup>3</sup>),  $\mathbf{u}$  is the velocity vector,  $p$  is pressure,  $\mathbf{F}$  is the volume force vector, and  $\mu$  is dynamic viscosity of water (0.001 Pa·s). The viscosity of RB solution was assumed to be equivalent to that of water. The applied boundary conditions were a flow rate of RB (1,000  $\mu$ l/h) at the inlet, a flow rate of DI water (from 500 to 10,000  $\mu$ l/h) at the inlet, zero pressure at the outlet, and no slip on the wall.

In order to analyze the transport of diluted RB via diffusion, the following balance equation was considered:

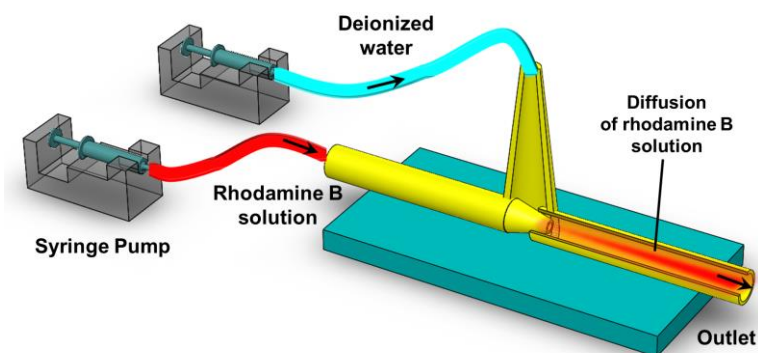
$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \nabla \cdot (D \nabla c) + R \quad (3)$$

where  $c$  is the concentration of RB,  $\mathbf{u}$  is the velocity vector,  $D$  is the diffusion coefficient of RB into water at 21.5 °C ( $3.6 \times 10^{-10}$  m<sup>2</sup>/s), and  $R$  is a reaction rate [14]. The boundary conditions were the concentration of RB (0.5 and 2.0 mol/m<sup>3</sup>) at the inlet, the concentration of DI water (0.0 mol/m<sup>3</sup>) at the inlet, symmetry and insulation at the wall, and convective flux at the outlet. Optimally meshed geometry was solved for the coupled multiphysics equations. The calculated results were post-processed and visualized in terms of concentration of RB solution.

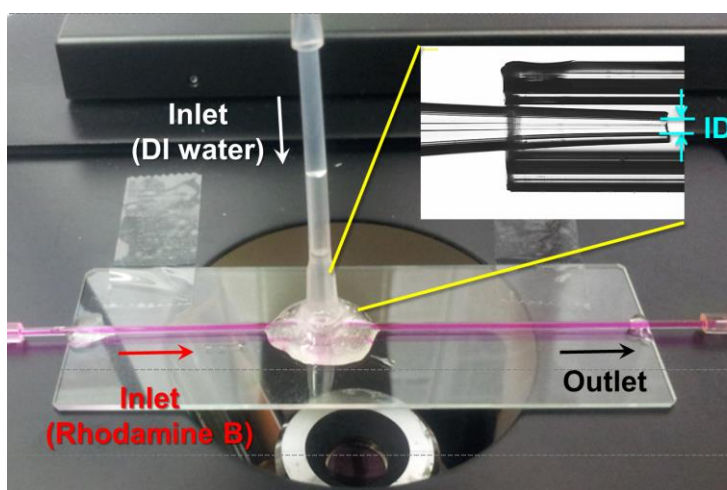
### 2.3 Co-axial flow defocusing micro-mixer

The co-axial flow defocusing micro-mixer was designed and fabricated to perform micro-mixing. Fig. 1a and b show a schematic illustration and an image of the flow-defocusing micro-mixer which consists of two inlets, a main channel, and one outlet. One inlet was made using glass capillary [100  $\mu$ m inner diameter (ID)] to infuse RB solution, and the other one using a micropipette tip (10 – 100  $\mu$ l) to introduce DI water. The main channel was connected with two inlets and one outlet. A 100- $\mu$ m-ID glass capillary, which was drawn under thermal treatment, was inserted into main glass capillary with 580  $\mu$ m ID (World Precision Instruments, Inc., FL, USA) to

form the three-dimensional co-axial geometry. The micropipette tip was cut, placed, and bonded on the connection of the inlet and outlet channels. All the prepared components were permanently glued on a glass slide ( $25 \times 75$  mm). Two inlets were then connected to syringe pumps (Genie Touch, Kent Scientific, Inc., CT, USA) via Tygontubings.



(a)



(b)

Fig. 1.(a) Schematic of micro- and nano-mixing system; (b) the image of the fabricated micro-mixer for generation of three dimensional co-axial defocusing flow. ID = 100  $\mu\text{m}$ .

#### 2.4 Micro-mixing analysis

Two glass syringes (5 ml and 3 ml) were filled with DI water and RB solution, and loaded in the syringe pumps, respectively. DI water was introduced into the main channel at flow rates ranging from 500 to 10,000  $\mu\text{l/h}$ . RB solution was perfused into the micro-mixer at a constant flow rate of 1,000  $\mu\text{l/h}$ . To avoid the effect of temperature variation on the diffusion, the temperature was maintained at  $21 \pm 1.5^\circ\text{C}$ . Defocusing flow and diffusion were monitored using an inverted optical microscope (Olympus, Tokyo, Japan). To characterize defocusing flows as a function of water flow rate, the flow width of RB solution along  $z$ -direction was measured five times at each distance of 200, 1,000, and 5,000  $\mu\text{m}$  at the end of the tip of the 100- $\mu\text{m}$ -ID glass capillary.

### 3. Results and discussion

In order to optimize the design of a micro-mixer, a computer-aided simulation was performed. As shown in Fig. 2, the designed micro-mixer could generate defocusing and focusing flows according to the change of water flow rate. Figs. 2a and b show defocusing flows at an identical flow rate of DI water and RB (1,000  $\mu\text{l/h}$ ) with two different concentrations of RB (0.5 and 2.0  $\text{mol/m}^3$ ). Figs 2c and d show focusing flows at the flow rates of DI water (8,000  $\mu\text{l/h}$ ) and

RB (1,000  $\mu\text{l/h}$ ) at two different concentrations of RB. Figs 2e and f show the effect of defocusing flow on diffusion at two different water flow rates (1,000  $\mu\text{l/h}$  and 8,000  $\mu\text{l/h}$ ). Comparing Area 1 and Area 2, low water flow rate enhanced molecular diffusion, resulting in expeditious micro-mixing. And higher diffusion was induced in Area 2 with higher concentration of RB solution than Area 4. Based on the simulated data, micro-mixing could be enhanced with higher concentration of RB and lower flow rate of DI water.

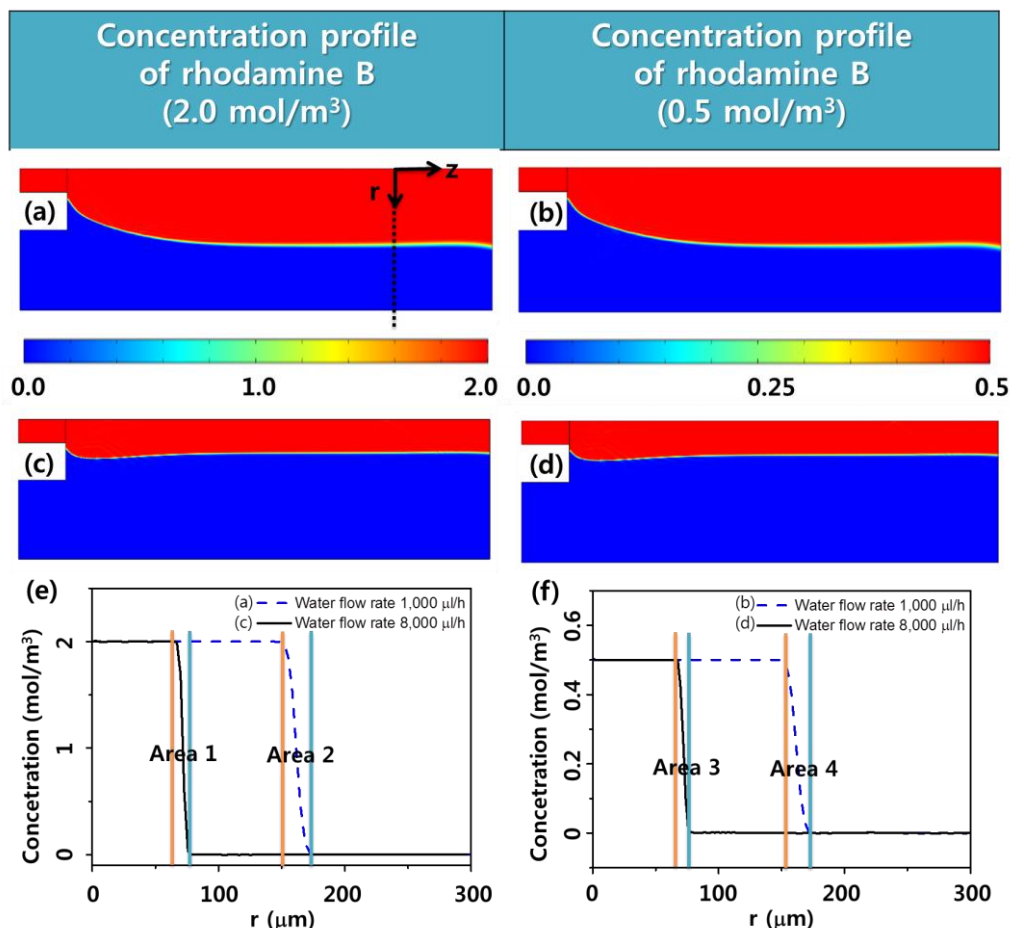


Fig. 2. Concentration profiles of Rhodamine B (RB) as a function of different flow rates of DI water. The flow rate of RB solution is fixed at 1,000  $\mu\text{l/h}$ . (a) Surface concentration of RB (2.0  $\text{mol/m}^3$ ) at water flow rate of 1,000  $\mu\text{l/h}$ ; (b) Surface concentration of RB (2.0  $\text{mol/m}^3$ ) at water flow rate of 8,000  $\mu\text{l/h}$ ; (c) Surface concentration of RB (0.5  $\text{mol/m}^3$ ) at water flow rate of 1,000  $\mu\text{l/h}$ ; (d) Surface concentration of RB (0.5  $\text{mol/m}^3$ ) at water flow rate of 8,000  $\mu\text{l/h}$ ; (e) Comparison of diffusion range between focusing and defocusing flows at a distance of 800  $\mu\text{m}$  from the entrance (RB = 2.0  $\text{mol/m}^3$ ); (f) Comparison of diffusion range between focusing and defocusing flows at a distance of 800  $\mu\text{m}$  from the entrance (RB = 0.5  $\text{mol/m}^3$ ). Areas 1, 2, 3, and 4 indicate diffusion range at different flow conditions.

A co-axial micro-mixer was fabricated and tested to generate defocusing flow, as shown in Fig. 3. As the two miscible fluids (RB solution and DI water) were introduced into the glass capillary channels, RB solution could be located in the core region of the co-axial flow, while DI water could be focused in the shell region. Changing the flow rates of DI water from 500 to 10,000  $\mu\text{l/h}$  at a fixed flow of RB (1,000  $\mu\text{l/h}$ ), defocusing and focusing flows were observed, as expected from the simulation. Especially, at water flow rates of 1,000 and 8,000  $\mu\text{l/h}$ , the concentration profiles observed by experiments appeared identical to those predicted by the simulation.

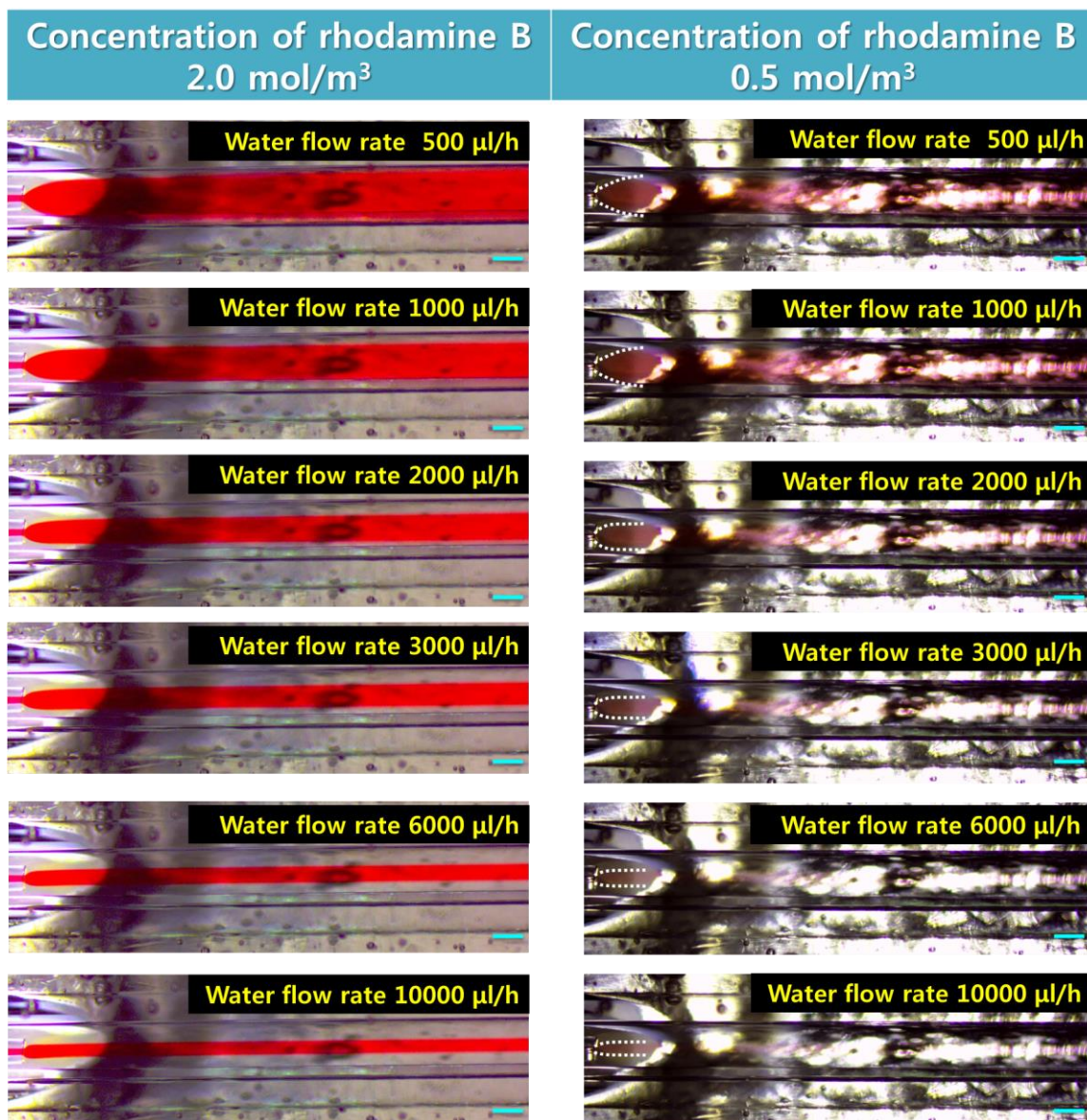


Fig. 3. Diffusion characterization as a function of water flow rate at two different concentrations (0.5 and 2.0 mol/m<sup>3</sup>) of RB (Scale bar = 300 µm).

In the left column (2.0 mol/m<sup>3</sup>) of Fig. 3, defocusing flow was apparently developed as the water flow rate was reduced, which enhanced the diffusive micro-mixing of RB solution and DI water. To investigate the effect of concentration on defocusing flow, the two different concentrations of RB (0.5 and 2.0 mol/m<sup>3</sup>) were applied. At high concentration of RB, defocusing flow was developed faster and covered the whole channel. These results indicated that higher concentrations could contribute to the enhancement of molecular diffusion.



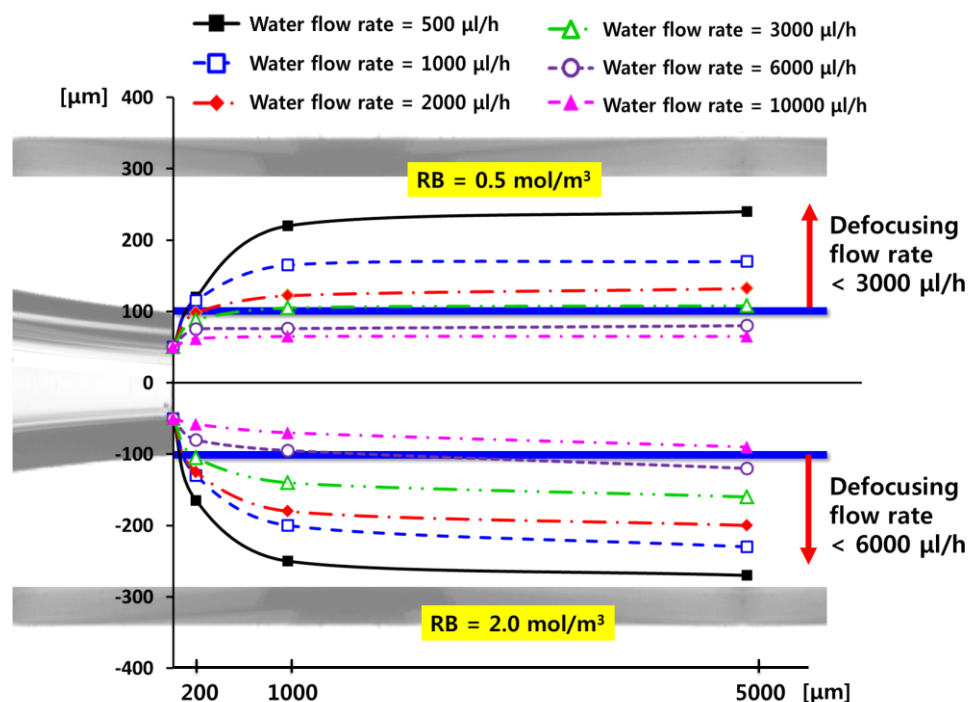


Fig. 4. Characterization of defocusing flow according to different flow rates of DI water at two different concentrations of RB ( $0.5$  and  $2.0 \text{ mol/m}^3$ ). At  $0.5 \text{ mol/m}^3$ , defocusing flow was developed with decrease of water flow rate below  $3,000 \text{ } \mu\text{l/h}$  (top). At  $2.0 \text{ mol/m}^3$ , defocusing flow was developed with decrease of water flow rate below  $6,000 \text{ } \mu\text{l/h}$  (bottom).

Based on Fig. 3, defocusing flow was characterized according to flow rates of DI water at two different concentrations of RB ( $0.5$  and  $2.0 \text{ mol/m}^3$ ). Fig. 4 shows comprehensive analysis of the characterized defocusing flows according to concentration, flow rate, and distance. Top and bottom represent the analyzed profiles at low and high RB concentrations of  $0.5$  and  $2.0 \text{ mol/m}^3$ , respectively. In terms of flow rates, at low concentration of RB, defocusing flow was generated when the water flow rate was less than  $3,000 \text{ } \mu\text{l/h}$ . At high concentration of RB, the critical flow rate to cause defocusing flow was observed at water flow rate of  $6,000 \text{ } \mu\text{l/h}$ . Below the critical flow rate, defocusing flow began to propagate. The shapes of the generated defocusing flows were laterally expanded along the flow direction. Especially, the expansion of concentration profile was much greater and faster at high concentration of RB. The width of the concentration profiles was inversely proportional to the change of the water flow rates.

From the aforementioned results, molecular diffusion for micro-mixing was correlated with concentration and defocusing flow in three dimensional co-axial micro-mixer. High concentration and low water flow rate for defocusing flow enabled molecular diffusion to be enhanced for micro-mixing. The proposed defocusing-assisted micro-mixing can be a suitable candidate for a passive micro-mixer in the applications of Lab-On-Chips and micro Total Analysis Systems.

#### 4. Conclusion

A micro-mixer was successfully designed, fabricated, and tested. Three dimensional co-axial micro-mixer generated defocusing and focusing flows, identical to the simulated results. From the characterized results, it was confirmed that diffusion could be enhanced with high concentration of RB and defocusing flow at low flow rate. The enhancement of diffusion led to the promising micro-mixing, which could be used as a possible platform for a passive micro-mixer.

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