

Tunable micro-optofluidic prism based on liquid-core liquid-cladding configuration

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The integration of optical components into microfluidic systems has the potential to reduce the amount of bulky external devices and thus reduce the cost. However, one of the challenges of this concept is the accurate alignment of the optical path among multiple optical components inside a chip. We propose a tunable micro-optofluidic prism based on the liquid-core liquid-cladding structure formed in a sector-shape chamber. The optical interface of the prism is maintained in a straight line shape by distributing a row of pressure barriers in the chamber. By adjusting the flow rate ratio between core and cladding streams, the apex angle of the prism can be tuned accordingly. As a consequence, the deviation angle of the light beam refracted by the prism can be changed continuously. This tunability of our optofluidic prism can be utilized for the alignment of the optical path inside a chip or for the development of optical switches. © 2010 Optical Society of America

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The combination of microfluidics and optics has enabled the miniaturization and tunability of optofluidic devices for lab-on-chip systems. The miniaturization and integration of optical components promise the potential of reducing the amount of bulky external devices and the alignment of multiple components in a single chip. One challenging problem is the alignment of the optical path among multiple integrated components. Moreover, precise adjustment of the optical path is critically important for interferometer sensors [1] and multiple-prism laser pulse compressors [2], especially when they are integrated into a chip. The laminar flow-based liquid-core liquid-cladding configuration has been widely applied to configure optical components in versatile ways. On the one hand, the interface between two immiscible fluids is atomically smooth, which can be utilized in reflection or refraction of light. On the other hand, two miscible fluids can create an index-gradient distribution, which can modulate the propagation of light inside the fluids. Recently, optical waveguides [3,4], reconfigurable lenses [5–9], and optical switches [10] based on this configuration have been demonstrated.

In this Letter, we propose a tunable micro-optofluidic prism, which is hydrodynamically formed by one core and two cladding streams inside a sector-shape chamber (Fig. 1). Benzyl alcohol (viscosity $\mu = 5 \times 10^{-3}$ Pa s at 25 °C) with a refractive index of 1.536 is employed as the core stream, which forms the geometry of a triangular prism. A mixture (viscosity $\mu = 9 \times 10^{-3}$ Pa s at 25 °C) of glycerol (60% by weight) and water (40% by weight) with a refractive index of $n = 1.412$ matching that of polydimethylsiloxane (PDMS) serves as cladding streams. Owing to the higher refractive index of the core stream, this configuration can perform a prism function. The apex angle of this optofluidic prism can be tuned by adjusting the flow rate ratio between core and cladding

streams, and therefore the deviation angle of an incident light beam can be changed accordingly. Since the propagation direction of a refracted light beam can be accurately controlled by choosing a proper flow rate ratio, this tunable prism can continuously scan the light beam and therefore can be engaged in the alignment of the optical path or in the development of optical switches.

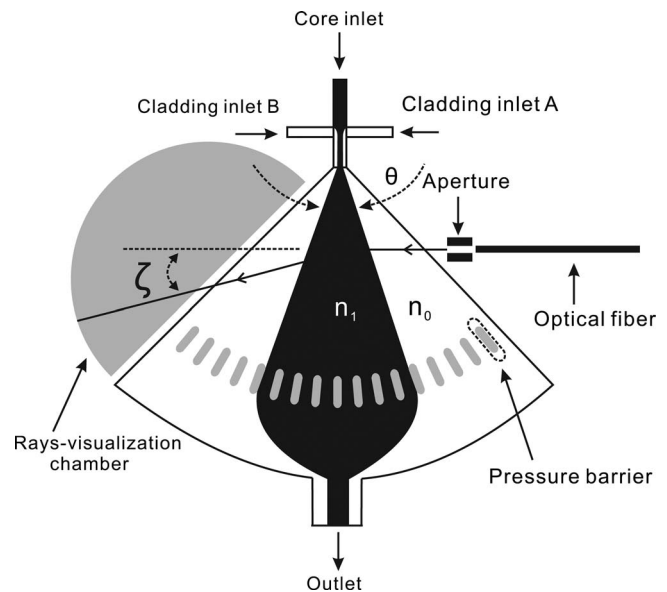


Fig. 1. Schematic configuration of the optofluidic prism. The core and cladding streams are driven by syringe pumps into a sector-shape chamber. The arc-shape distributed pillars work as a pressure barrier to make the interface between streams extend as a straight line. An optical fiber is inserted to guide the laser beam into the device. The divergence of the emitting light beam is reduced by a built-in aperture. The refracted light beam is traced by the ray-visualization chamber locating beside the prism chamber.

Our device was fabricated in PDMS by using a standard soft lithography technique. The configuration of our tunable prism is based on three streams of laminar flows in a sector-shape chamber, which has a 90° opening angle (Fig. 1) and a channel depth of $150\ \mu\text{m}$. In the chamber, an array of pillars distributed in an arc and located at a distance of $3.5\ \text{mm}$ from the inlet serves as pressure barriers. The angular interval between each pillar is 1.5° . The entrance of the sector-shape chamber with a width of $300\ \mu\text{m}$ is much smaller than the radius of the chamber. The small gaps between the pillars are supposed to make the pressure drop equally distributed along the arc where the pillars stand. Therefore, the entrance of the chamber and the arc consisting of the gaps act approximately as a source–sink pair bounded within a divergent boundary with a 90° opening angle. The streamlines inside a source–sink pair domain have a similarity in shape with the boundary [7]. Thus the interfaces between the core and the cladding streams are theoretically radiating lines from the source. This fact was confirmed experimentally (insets in Fig. 2). Because of the even distribution of the pressure at the pillars, the flow flux through the gaps is assumed to be equally distributed. Therefore, the apex angle can be derived as a function of the flow rate ratio based on the theory of the liquid-core liquid-cladding system reported in [10]:

$$\theta = 90^\circ \times \frac{\varphi}{\varphi + 2\beta}, \quad (1)$$

where φ and β are the flow rate ratio and viscosity ratio between core and cladding streams, respectively. The relationship between the angle θ and flow rate ratio φ is depicted as the solid curve in Fig. 2. In the experiment, the flow rate of cladding streams was fixed at $1\ \text{ml/h}$, while the flow rate of core stream varied from 1 to $11\ \text{ml/h}$. Increasing the flow rate ratio between core and cladding streams can tune the apex angle of our optofluidic prism accordingly.

To demonstrate the tunability of the light beam refracted by our optofluidic prism, we inserted an opti-

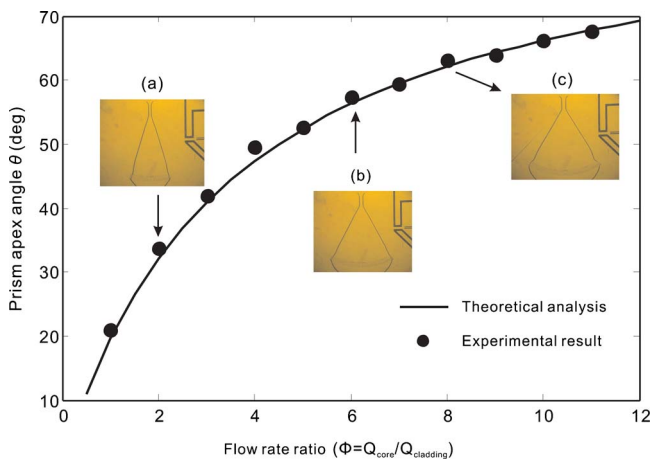


Fig. 2. (Color online) Relationship between the apex angle of the prism and the flow rate ratio between core and cladding streams. The apex angle of the prism can be tuned by adjusting the flow rate ratio.

cal fiber (multimode, $\text{NA}=0.22$) into a predefined microchannel with a width of $130\ \mu\text{m}$. An aperture was built by filling black ink into two channels with a width of $50\ \mu\text{m}$, and the size of the aperture is $130\ \mu\text{m}$. To trace the light beam refracted by the prism, a visualization chamber was placed beside the prism chamber. Rhodamine B diluted in a mixture of glycerol (60% by weight) and water (40% by weight) was injected into the visualization chamber to trace the rays. When the prism chamber was filled with only the mixture of glycerol and water, the rays emitted from the optical fiber propagated horizontally without refraction, which is shown by inset (a) of Fig. 3. If the chamber is fully occupied by the core liquid (benzyl alcohol), the total deviation angle can achieve a maximum value of 11.4° , which is depicted as inset (c) in Fig. 3. During the process of tuning the flow rate ratio, the total deviation angle can be adjusted continuously from 0° to 11.4° .

Assuming that a light beam is horizontally incident on a prism with an apex angle of θ (Fig. 1), the total deviation angle can be calculated based on Snell's law, which is expressed in Eq. (2):

$$\zeta = \arcsin[n_1/n_0 \cdot \sin(\theta - \alpha)] - \theta/2, \quad (2)$$

where n_1 and n_0 are the refractive indices of core and cladding streams, respectively, and the angle α is as calculated as

$$\alpha = \arcsin[n_0/n_1 \cdot \sin(\theta/2)]. \quad (3)$$

Substituting Eq. (1) into Eq. (2) yields the relationship between the total deviation angle and the flow rate ratio:

$$\zeta = \arcsin\left[\frac{n_1}{n_0} \sin\left(\frac{90^\circ \times \varphi}{\varphi + 2\beta} - \alpha\right)\right] - \frac{45^\circ \times \varphi}{\varphi + 2\beta}, \quad (4)$$

which is represented by the solid curve in Fig. 3. The

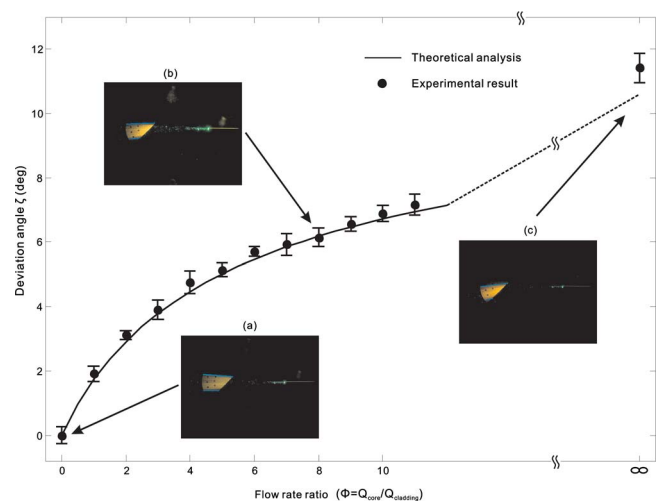


Fig. 3. (Color online) Relationship between the deviation angle of the light beam refracted by the prism and the flow rate ratio between core and cladding streams. The blue lines in the insets depict the boundaries of refracted light beams. By adjusting the flow rate ratio, the refracted light beam can be changed in a scanning mode ($n_1=1.536$, $n_0=1.412$ at the wavelength of $\lambda=532\ \text{nm}$).

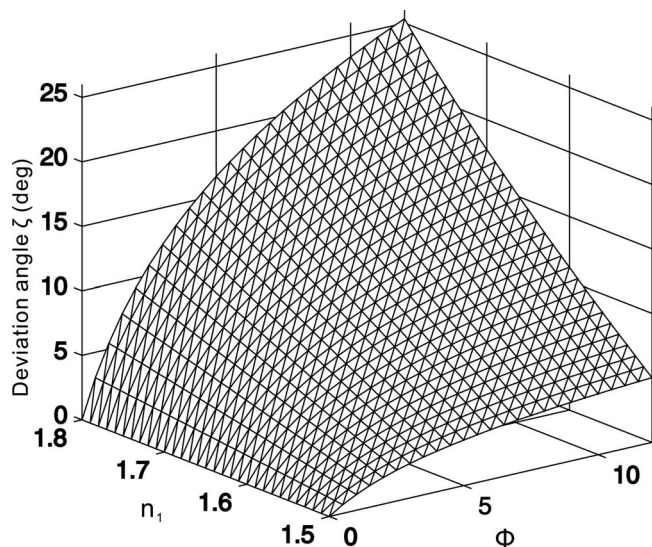


Fig. 4. Deviation angle of the refracted light beam as a function of the refractive index of the core liquid and the flow rate ratio between core and cladding streams, provided the light beam is horizontally incident on the prism. It is assumed that the refractive index of the surrounding medium is 1.412, which matches the PDMS.

experimental result agrees well with the theoretical analysis, which indicates that the control of the light beam refracted by our optofluidic prism can be mathematically predicted. Equation (4) indicates that the flow rate ratio and the refractive index of the core liquid are the two main parameters to influence the performance of the prism. Figure 4 shows the effect of these two parameters on the deviation angle. It is found that the deviation angle is highly dependent on the refractive index of the prism material. A higher refractive index of the prism material can ensure a larger deviation angle and broaden the beam scanning range.

In conclusion, we proposed a reconfigurable micro-optofluidic prism based on the liquid-core liquid-

cladding configuration in a sector-shape chamber. The arc-shape distributed pillars were built to ensure the streamlines inside the chamber to be along the radial direction and therefore to shape a straight optical interface. An optical fiber was induced as a light source, whose beam divergence was reduced by a built-in aperture. The apex angle of the prism can be tuned and predicted mathematically by adjusting the flow rate ratio between core and cladding streams. As a consequence, the deviation angle of light refracted by the prism can be controlled accurately. This beam scanning function of our optofluidic prism can be utilized in the alignment of the optical path among integrated optical components inside a lab-on-a-chip system or for optical switches.

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