AN OPTOFLUIDIC TUNABLE PRISM VIA CONTROL OF FLOW RATE RATIO
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ABSTRACT
This paper reports an optofluidic tunable prism which is realized with two laminar flows in a microfluidic chip. By controlling the flow rate ratio between the two flows, the apex angle of the prism can be tuned continuously and therefore the deviation angle can be changed accordingly. A model for the hydrodynamic control is established for the prism. The optical deviation caused by the prism is theoretically analyzed and experimentally proved. The optofluidic prism can be used for building up the on-chip optical circuits and promising for the optical detection and biochemical analysis.

KEYWORDS: Liquid prism, Optofluidics and Micro-opto-fluidic-systems (MOFS)

INTRODUCTION
Prism is an important optical component which can be used to break light into its constituent spectral colors, as well as reflect light and split light into different paths. The last decades has seen rapid growth in developing the multiple functions in the microfluidic systems. It is highly desired to fabricate various optical components in integrated microfluidic systems. Prisms are not exception. To meet the demands of miniaturized devices and sensing operations on liquid, the prisms need to be much smaller and more flexible than the current solid ones.

This paper reports an tunable optofluidic prism which is hydrodynamically formed by two laminar flows in a triangular chamber. The apex angle of this optofluidic prism can be tuned by controlling the flow rate ratio between the two flows. As a consequence, the propagation direction of the light beam which passes through the prism can be adjusted continuously.

THEORY
As shown in Fig. 1, when a light beam goes through a prism, the light will be refracted. The deviation angle can be deduced by using Snell’s law [1] and the geometric optical analysis. The deviation angle $\delta$ can be expressed as

$$\delta = i_1 + \arcsin \left( \sin(\phi) \sqrt{n^2 - \sin^2(i_1)} - \cos(\phi) \sin(i_1) \right) - \phi$$  \hspace{1cm} (1)

where $n$ is the refractive index, $i_1$ is the incident angle, $\phi$ is the apex angle of the prism.

From the above equation, it can be found that when the incident angle and the emergence angle are the same, the prism is said to be in the position of minimum deviation, for a given wavelength [2]. It is given by the equation

$$n = \frac{\sin(\phi + \delta_m)}{\sin(\phi/2)}$$  \hspace{1cm} (2)

where $\delta_m$ is the minimum deviation angle. Since $n$ varies with wavelength, the angle of minimum deviation also varies, but it is constant for any particular wavelength.

Assuming that a light beam is incident on the prism with an angle of $\alpha$ to the horizontal direction, then $i_1 = \frac{\phi}{2} + \alpha$. Take that into Eq. (1), one obtained

$$\delta = \arcsin \left( \sin(\phi) \sqrt{n^2 - \sin^2\left(\frac{\phi}{2} + \alpha\right)} - \cos(\phi) \sin\left(\frac{\phi}{2} + \alpha\right) \right) - \frac{\phi}{2} + \alpha$$  \hspace{1cm} (3)

DESIGN AND THEORETICAL ANALYSIS

Figure 2 shows the design of the triangular chamber in which the liquid prism is configured when the two flow streams merged in the chamber. Conducting a theoretical estimation of the prism tuning would be helpful as a guidance in forming the prism with desired shape. A model of minimal complexity was therefore employed to predict the angle changing with the flow rate ratio. The position of the interface of two laminar flows can be estimated as $\gamma = \frac{W_w}{W} = \frac{1}{1 + \mu \nu}$.
where $\varphi = \frac{v_2}{v_1}$ is the ratio of flow rates and $\mu = \frac{\eta_2}{\eta_1}$ is the ratio of viscosity of the two flows. Since the liquid prism is symmetrical regarding the middle axis of the triangular cavity, only half of the model needs to be considered. Because the cavity is an isosceles righttriangle, the base angle $\beta$ can be approximately expressed by the height of the channel wall ($h$) and the height of the flow $h_2$ as

$$\beta = \arctan \frac{h_2}{h}$$

(4)

Define $h_1 = h - h_2$, considering the angular difference between the axis of the inlet channel and that of the triangle cavity, we get

$$\beta = \arctan \left(1 - \frac{h}{h_1}\right) = \arctan \left(1 - \frac{\gamma}{\cos 22.5^\circ}\right)$$

(5)

The apex angle of the optofluidic prism is

$$\phi = 180^\circ - 2\beta = 180^\circ - 2\arctan \left(\frac{1}{1 + \mu \varphi \cos 22.5^\circ}\right)$$

(6)

**EXPERIMENTAL RESULTS AND DISCUSSIONS**

In the experiments, the microfluidic chip is fabricated by standard soft lithography technique using polydimethylsiloxane (PDMS). DI water (viscosity $\eta_1 = 0.89$ mPa S at 25°C) with a refractive index of 1.332 is employed as the outside flow stream (flow 1), ethyl glycol (viscosity $\eta_2 = 16.1$ mPa S at 25°C) with a refractive index of 1.430 is employed as the inside flow stream (flow 2), which constructd the optofluidic prism. Ethylene glycol and DI water are doped with Rhodamine 6G (Sigma-Aldrich, 0.01 mg/ml) are injected from the inlets. Light is coupled into the microchannel through a single mode fiber. Argon ion laser (488 nm) is used as the light source for exciting the Rhodamine 6G. The fluorescent images are captured by using a charge coupled device (CCD) camera (DS-Fil, Nikon) mounted on an inverted system optical microscope (TS 100 Eclipse, Nikon).

![Figure 2: model of the optofluidic prism](image)

Figure 3 shows the shape of the streamlines inside the triangular chamber is similar with the shape of the boundary. Thus, the interface between the two laminar flows can form a prism shape. In addition, the refractive index of the flow 2 is higher than that of flow 1, and the refractive index is wavelength dependent. That gives out the basic properties of a prism. In the experiment, the total flow rate is set as 50 μl/min, the flow rate ratio is changed from 0.01 to 9. When the flow rate ratio is decreased, the interface between the two flows becomes lower, the apex angle increases. Although the top of the prism is curved, the two sides of the prism are straight lines. If we only used the lower parts of the prism, it won’t affect the optical deviation or the dispersion. So the incident light is required to avoid the 1/4 part on the top of the prism.

![Figure 3: Symmetric optofluidic prism with different flow rate ratio: (a) 2.33, (b) 0.43, and (c) 0.25.](image)

As discussed above, the relationship between the apex angle $\phi$ and the flow rate ratio can be estimated from Eq. (6), as depicted as the solid curve in Fig. 4. This is confirmed by the experimental results. In our experiments, the apex

![Figure 4: Relation between the apex angle and the flow rate ratio.](image)
angle $\phi$ is tuned from 90° to 150°. Although the apex angle can be larger, the available straight side of the prism becomes shorter. Considering the requirement of the optical applications, we will not discuss the situations when the apex angle larger than 150°.

To demonstrate the tunability of the light beam refracted by the optofluidic prism, an optical fiber is inserted into the microchannel. The light with a wavelength of 488 nm is injected into the chamber though the fiber. In order to verify the theory of minimum deviation angle, the fiber is put with an angle of 7.5° to the horizontal direction. Another fiber is set at the opposite direction on the other side of the chamber. Theoretically, only when the light beam get a minimum deviation angle of 15°, the output fiber will detect a maximum light intensity. The output signal can be monitored by a spectrometer.

Figure 5 shows the light beam deviation caused by the optofluidic prism. When there is only DI water in the chamber, the light is propagating straight. The light beam has an angle of 7.5° to the horizontal direction as shown in Fig. 5(a). When the prism is realized in the chamber, the propagation direction of the beam is changed, and the deviation angle is increased with the increasing apex angle of the prism as shown in Fig. 5(b) and (c).

As we discussed in the previous part, the apex angle of the optofluidic prism can be tuned by adjusting the flow rate ratio between the two laminar flows. The relation between the deviation angle and the flow rate ratio is depicted in Fig. 6. The theoretical estimate is deduced from the Eq. (3) and (6), which agrees well with the experiment results. During the process of tuning the flow rate ratio, the deviation angle can be changed continuously from 9° to 17°.

CONCLUSIONS

In conclusion, an on-chip tunable prism is designed, fabricated and demonstrated using optofluidic system. This optofluidic prism is only using two flow streams to control the apex angle tuning from 90° to 150°. An optical fiber was induced as a light source, whose beam is refracted by the prism. The deviation angle can be changed continuously from 9° to 17°. Compared with other proposed on-chip prism, it is simpler and has larger tenability. It can be integrated on a microchip with other optical components and used to develop a miniaturized spectrometer system for chemical and biochemical analysis applications.

REFERENCES


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