An Integrated Optofluidic System for Two-Dimensional Focus Point Control

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ABSTRACT

In this paper, we described the design, fabrication and characterization of a tunable optofluidic biconcave microlens and tunable optofluidic microprism, which can perform both light focusing and deviation. This optofluidic microlens changed the curvature, and therefore the focal distance, in a biconvex manner using the flow rate ratio of the core and cladding. In addition, the use of different flow rate ratios resulted in the formation of a different apex angle of the microprism. The light path changed with the different refractive indices of the liquids and the apex angles. In this experimental setup, the focal position can be controlled on a two-dimensional plane.

Keywords: Optofluidic, focal point, tunable, microlens, microprism

1 INTRODUCTION

Recently, optical methods have been widely used for biological and chemical detection in microfluidic or lab-on-a-chip systems. Precise adjustment of the optical path among multiple integrated components, such as flow cytometers, optical tweezers, and molecule detectors, is important. However, traditional optical elements have a fixed refractive index and geometrical shape, and cannot change continuously with variation of the focal length and deviation angle. Optofluidics refers to the combination of optics and fluidics, which is a new discipline of microfluidics. Among the various micro-optofluidic devices, micro-optofluidic lenses are novel and possess potential commercial applications.

Microlenses can be categorized into fixed focal and tunable lenses [1]. This is because these lenses are capable of tunability, which serves as an advantage over traditional optical devices [2-3]. Although tunable lenses require an additional driving force, they have better sensitivity and flexible integration. Tunable lenses modulate the propagation of light by changing the refractive index and geometry [4-8].In this study, we demonstrate the liquid-core liquid-cladding lens using a hydrodynamic force. The lens was formed in an expanded chamber with three streams of fluids. A higher refractive index stream was sandwiched between two streams having lower refractive index. When three streams of liquid entered the expanded chamber, they widened and became biconvex. This tunable lens changed the focal length using the flow rate ratio of the core and cladding [5-6].

Prisms play many different roles in optics; there are

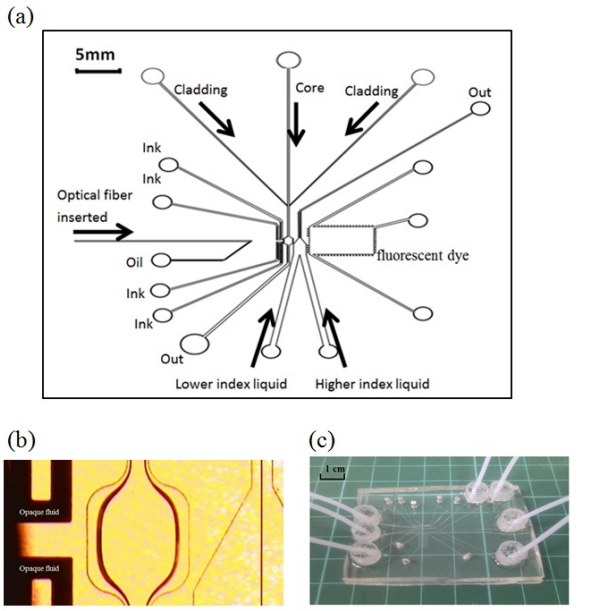

Figure 1: (a) The components of the optofluidic chip (from left to right) are light source (fiber inserted), aperture, microlens, microprism, and sample chamber. All circles are reservoirs. (c) Image of the optofluidic chip.

prism combinations that serve as beam splitters, polarizing devices and interferometers. When light comes into contact with the face of a prism, it either refracts at different angle or experiences total internal reflection, depending on the difference in the refractive indices of the two interfacial material [9-11]. In this study, we designed a two-fluid-combined microprism, which is a fast switching and provide a larger controllable deviation angle range. The use of different flow rate ratios results in the formation of a different flow solution and apex angle. The deviation angle of the output light beam can be tuned continuously using the flow rate ratio of two refractive index solutions.

In comparison with previous studies, the experimental setup of a microlens group describes only the single-axis focal position. However, this optofluidic device changes the light path by integration with a tunable lens and a tunable prism. In this paper, we discuss the different refractive and demonstrate that the angle of the prism apex can achieve a tuning range, in order to obtain a larger range and an accurate focal position. In addition, we analyzed the accuracy of the tuning range with different refractive liquids by using the simulation software "LightTools." The tuning of light is critical for realizing a broad range of LOC applications. By the combination of tunable microlens and tunable microprism, we can control the focal point on a two-dimensional plane.

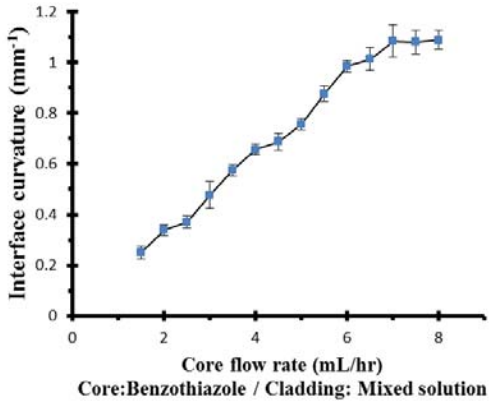

Figure 2: The relationship between the curvature of the tunable microlens and different flow rate ratios.

2 FABRICATION AND EXPERIMENTAL SETUP

2.1 Fabrication

We fabricated the microfluidic channels in PDMS (Poly (dimethyl) Siloxane) using the standard soft lithography [12-14]. The PDMS material is well known to perfectly replicate the SU-8 mold, with an accuracy of around a few tens of nanometers. Using commercial services, the CAD-generated patterns were printed on the transparency. The transparency mask was subsequently used for defining the negative mold of the microfluidic network in a 100-µm thick SU-8 layer. The PDMS was mixed from a silicone elastomer and an elastomer curing agent (Sil-More Industrial Ltd, USA Sylgard 184A and Sylgard184B) with a weight ratio of 10:1, and then poured into the SU-8 mold. The PDMS was cured at 70°C for 1 h, and the replica was then peeled from the master. PDMS consists of repeating −OSi(CH3)2− units, and the CH3 groups make its surface hydrophobic. The surface can be made hydrophilic by exposure to O2 plasma (O2 Plasma Cleaner, PCD150, All Real Tech., Taiwan). After exposing a replica and flat PDMS to O2 plasma, we placed the two surfaces in conformal contact to make a tight, irreversible seal.

2.2 Experimental setup

The optofluidic chip design is shown in Figure 1. The components of the optofluidic chip (from left to right) are light source, aperture, lens, prism, and sample chamber. The depth of channels and chamber is 100 µm. The green laser (532 nm, 40 mW) was coupled into a single-mode optical fiber (nominal numerical aperture, NA = 0.12) that was inserted into a pre-fabricated microchannel with a width of 140 µm to act as a point light source. The aperture, which is 334 µm, is formed by channels filled with ink and is based on the design [5-6].

Channels filled with ink primarily exclude redundant light. Three connected channel chambers form a tunable lens. In the tunable lens, benzothiazole (n = 1.641) was used as the core liquid, and a mixture of 73.5% ethylene glycol (n = 1.429) and 26.5% ethanol (n = 1.360) with the effective refractive index matching PDMS (n=1.412) worked as the cladding liquid. The curvatures of the tunable lens depend on the flow rate ratio of the core stream and the cladding stream. Two connected channels form a tunable prism. The direction of angle modulation deviation is determined by the two injected liquids, one with a refractive index greater than PDMS and the other with a refractive index less than the refractive index of PDMS.

The sample chamber is filled with a fluorescent dye Rhodamine B (Sigma-Aldrich, excitation wavelength of 540 nm, emission wavelength of 625 nm). Fluorescent dye mixture with 73.5% ethylene glycol and 26.5% ethanol, that makes the optical path visible. The solution is used to prevent the light beam from refracting at the inter In the experiment, all liquids were kept in 10-ml plastic syringes (TERUMO®), which were driven by syringe pumps (Syringe Pump KDS200, Kd Scientific, U.S.A.) to attain the required flow rate. The images recorded using a charge coupled device (CCD SSC-DC50A, Sony, Japan) attached to an optical microscope (Eclipse 50I, Nikon, Japan) with 2x magnification objective lenses. The fluorescence intensity was analyzed using ImagePro Plus® software. All fluorescence images were converted to 8-bit grayscale (256 gray levels).face between the sample chamber and the PDMS.

3 RESULTS AND DISCUSSION

The tunable lens reconfigures the shape and the focal distance by manipulating the flow rate ratio of the core and cladding. In the focusing mode of the biconvex lens, a low refractive index liquid is used as the core stream and a higher refractive index liquid is used as the cladding stream. Following this principle, we choose benzothiazole (n =1.642) and silicone oil (n = 1.52) for the core liquid. The cladding liquid was DI water (n = 1.33) and a solution (73.5% ethylene glycol and 26.5% ethanol, n = 1.412)

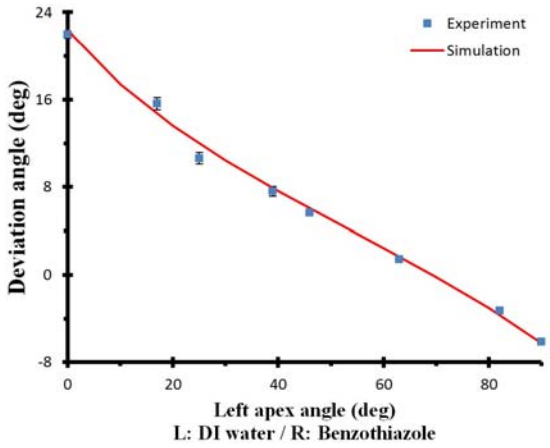

Figure 3: The relationship between the deviation angle and apex angle with a chamber of 90°.

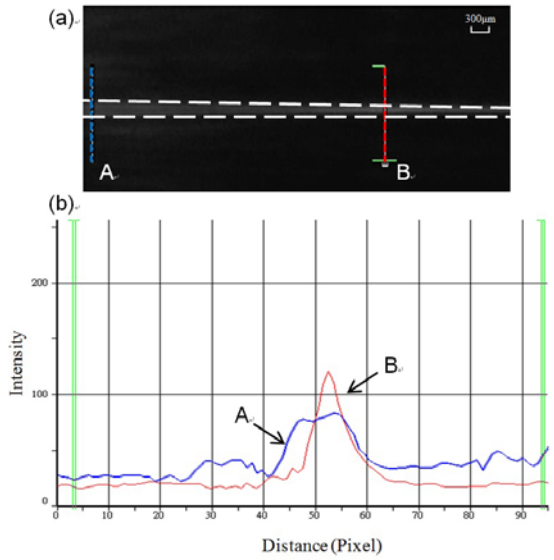

Figure 4: (a) Light propagated from the left side of the image to the right side of the image. (b) The intensity of light is obtained by subtracting the background intensities from the fluorescence excitation.

with a refractive index that matched PDMS. Furthermore, the cladding liquid with a refractive index that matches PDMS can effectively reduce light scattering. Light passing through the interface between the core and the cladding is a high quality optical interface, rather than a rough surface of the chamber wall.

From Snell's law, the focal distance and the curvature are relative. The lower curvature lens focuses light beams at a longer distance than the higher curvature lens. By increasing the flow rate ratio of core stream, the interface becomes more curved, which results in a shorter focal engath. When the interface approaches the side-wall of the chamber, the curvature of the interface begins to decrease (Figure 2), thus elongating the focal length. In addition, it is possible to achieve a shorter focal distance by using a high contrast refractive index between the core and cladding liquid. Therefore, the light emitted from an optical fiber can be well focused and the focal length can be tuned by adjusting the flow rate ratio between core and cladding streams. The data of curvature is the fitted radius of the curvature at the interface between the core and the cladding, and the effective range is 334 μm. Each image has two curvature values for each flow rate ratio.

The tunable prism is first filled with a solution (Benzothiazole or silicone oil) having higher refractive index greater than PDMS, making the output light beam is refracted clockwise. When the second solution (DI water) is injected, the light will once more refract at the liquid - liquid interface. During this period, the deviation angle began to counter-clockwise deviate. Finally, the first solution is completely replaced by the second solution and the direction of angle deviation has completely changed. In addition to used different liquid of refractive index, we found the tuning range of the deviation angle was not expanded much in the chamber with the smaller apex angle. The use of DI water and benzothiazole results the deviation angle from -6.28° to 22.3°for the 90° chamber (Figure 3) for the 60°chamber. It is possible to achieve larger deviation angles using a larger apex angle, but excessively large angles will result in total internal reflection.

Figure 4 shows the variation in the intensity of fluorescence dye (Rhodamine B) in the sample chamber at two different distances. The fluorescence intensity was measured using ImagePro Plus software. All fluorescence images were converted to 8-bit grayscale (256 gray levels). From the relationship between intensity and distance(Figure 4 (b)), we found the location of the intensity of the peak value and the minimum beam width on the hyperbola, which is the focal point. The focal distance is the distance between the focal point and the center of the lens. However, we found that using a sample chamber with a fluorescent dye for the beam tracing has several consequences. First, the optical fiber-emitted light is three-dimensional; however, the aperture only blocks the light in the x-y direction. The fluorescent dye is therefore excited with the light in the z-direction, because the substrate (PDMS) contains nanoparticles of silica that scatter light. Second, if the concentration of the fluorescent dye is too high, the excitation light will cover the sample chamber and the light path. In this experimental set up, the light path is in obvious contrast with the brightness at a concentration of 50 μM.

Figure 5 is shown the relationship between curvature and focal distance. The experimental results indicate that the profile of the interface between the core and the cladding is not an ideal lens shape. Therefore, such profiles cause aberration, and it is difficult to correctly determine the focal point when there is increased aberration. The light path change continuously with variation of the focal lengthand deviation angle are shown in Figure 6. The tunable lens, benzothiazole (n = 1.641) was used as the core liquid, and a mixture of 73.5% ethylene glycol (n = 1.429) and 26.5% ethanol (n = 1.360) as the cladding liquid. When the curvature of lens increased, the light beam began

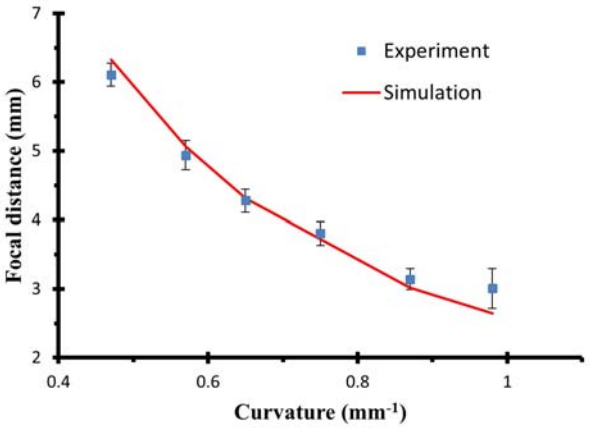

Figure 5: The core liquid is benzothiazole and the cladding liquid is a solution of 73.5% ethylene glycol and 26.5% ethanol. The liquid of microprism are DI water and benzothiazole in the microprism chamber of 90°.

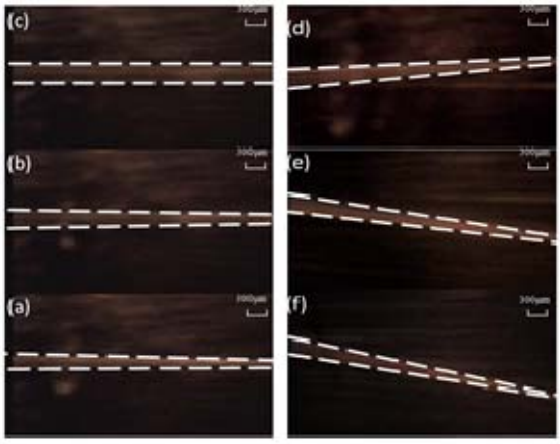

Figure 6: The focused beam recorded with a CCD. Light beam propagated from the left side of the image to the right side.

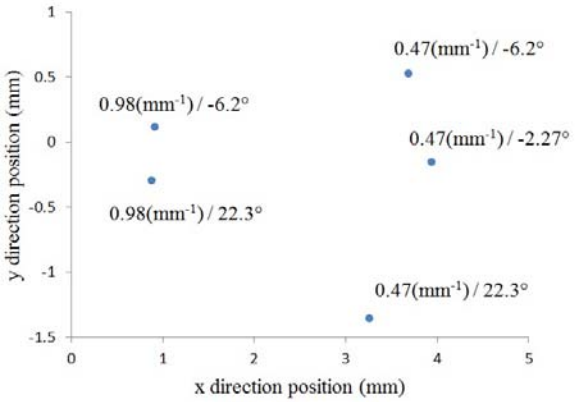

Figure 7: The location of focal point on the sample chamber. The lens axis intersects with the sample chamber at (0, 0).

focusing (from Figure 6 (a) to (c)). Furthermore, the use of DI water and benzothiazole with a chamber of 90° results the maximum deviation angle from -6.28° to 22.3° (From 6 (d) to (f)). The experimental results indicate that the focal point can be adjusted on a 2-D plane, as shown in Figure 7.

4 CONCLUSIONS

In this paper, we demonstrate a hydrodynamically tunable optofluidic microlens and optofluidic microprism, which can be conveniently fabricated by the standard soft lithography technique and allows variable focusing and deviation within an optofluidic device. By the combination of tunable lens and tunable prism, we can control the focal point on a two-dimensional plane. The tunable lens was formed in an expanded chamber with three streams of fluids. A higher refractive index stream was sandwiched between two streams having lower refractive index. This tunable lens changed the focal length using the flow rate ratio of the core and cladding.

In addition, the tunable prism changes the light path by two different index of the solution and apex angle. The deviation angle of the output light beam can be tuned continuously using the flow rate ratio of higher and lower refractive index solutions. In this optofluidic chip, we can adjust efficiently the focal length between 3 mm and 6.1 mm with benzothiazole (n = 1.642) and a solution (73.5% ethylene glycol and 26.5% ethanol, n = 1.412). By using different apex angles, the optimum deviation angle ranged from −6° to 22°. In addition, the distance between the sample chamber and the prism determines the light intensity and the effective working range. The chosen relative position and apex angle should be based on the specific requirements for the light output. Therefore, the concept of deviation and focusing can be further applied to other optofluidic designs, in which the light may focus on different sample chambers. Realizing tunable optofluidic elements that can adjust the optical path in an integrated optofluidic system is one of the developments of lab-on-a-chip systems.

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