Biconcave micro-optofluidic lens with low-refractive-index liquids

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One of the current problems of micro-optofluidics is the choice of a suitable liquid with a high refractive index (RI). We report the use of a low-RI liquid in a biconcave liquid-core liquid-cladding lens for focusing light. For the characterization of the lens, a telescope system was constructed from polydimethylsiloxane lenses to collimate and expand a light beam emitted from an optical fiber. The tunable optofluidic biconcave lens focuses the parallel beam. Fluorescent dye diluted in an index-matching liquid was used for the visualization of the light rays in a beam-tracing chamber. The focused beam is tuned by adjusting the flow rate ratio between core and cladding streams. © 2009 Optical Society of America

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The integration of microlenses into microfluidic systems to improve fluorescence detection has been widely investigated recently. Camou *et al.* increased the excitation intensity using a polydimethylsiloxane (PDMS) lens [1]. Wenger *et al.* used a latex microsphere as a lens to detect single molecules by fluorescence correlation spectroscopy [2]. To overcome the drawbacks of the fixed focal length of the above mentioned solid-based lenses, several groups proposed tunable optofluidic lenses, which allow in-plane light focusing [3–7]. These optofluidic lenses take advantages of the hydrodynamically formed interface between two liquids with different refractive indices (RIs). The focal length is tuned by adjusting the flow rate ratio. Rosenauer and Vellekoop realized a micro-optofluidic lens based on a 90° bend of a microchannel [8]. All the above devices were fabricated in the PDMS. However, the relatively high RI of the PDMS ($n = 1.412$) requires these lenses to be shaped with liquids of higher RIs. The liquid forming the optofluidic lens should have an RI of the order of 1.60 to achieve a strong focusing ability. Currently used liquids for forming optofluidic lenses such as benzothiazole ($n = 1.64$) [3] are irritant and toxic to human.

In this Letter, we demonstrate an optofluidic biconcave lens, which can perform light focusing with a low-RI liquid. The liquids to form the lens are ethanol ($n = 1.36$, $\rho = 0.789$ g/ml, $\mu = 1.074 \times 10^{-3}$ Pa s) and benzyl alcohol ($n = 1.54$, $\rho = 1.044$ g/ml, $\mu = 8.0 \times 10^{-3}$ Pa s), which are relatively safe to use. Figure 1 depicts the concept of the liquid-core liquid-cladding optofluidic biconcave lens in a circular chamber. In traditional geometric optics, lenses are fabricated with glass, which has a higher RI than the surrounding medium. Thus a concave lens cannot be used to focus light. However in optofluidic systems, the properties of optical components can be adjusted by simply changing the liquids inside the system. In our micro-optofluidic lens depicted in Fig. 1(a), ethanol and benzyl alcohol were used as the core and

cladding liquids, respectively. The lower RI of the core enables the concave lens to have light focusing ability.

To shape a parallel beam for the characterization of the micro-optofluidic lens, we used a telescope system consisting of two solid lenses made of the PDMS to collimate and expand the divergent green beam (532 nm) emitted from an optical fiber. This parallel beam with a relatively large width incidents on the optofluidic biconcave lens formed in the circular chamber. A ray-visualization chamber is located behind the lens chamber along the light propagation direction. Rhodamine B diluted in a mixture of glycerol
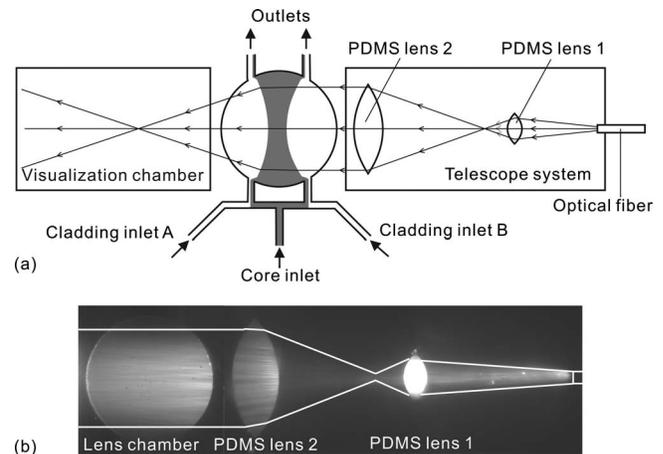

Fig. 1. (a) Schematic of an optofluidic system with a tunable biconcave lens. The system includes a telescope system, which collimates and expands the light beam, and an optofluidic biconcave lens to focus the rays. The multimode optical fiber has an NA of 0.22 and a diameter of 125 μm. The radii of the interface of the PDMS solid lenses are 700 and 400 μm. The diameter of the circular lens chamber is 1 mm. (b) Telescope system consisting of two PDMS lenses that collimate and expand the divergent beam from the multimode optical fiber (NA=0.22). The outline depicts the ray propagation.

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(60% by weight) and water (40% by weight), which has a matching RI with the PDMS, was used to visualized the beam. The incident light excites the fluorescent dye and so visualizes the ray path. The cladding flow rates were kept constant at 1 ml/h each, while the flow rate of the core stream is adjusted to get the different flow rate ratios ($\Phi = Q_{core}/Q_{cladding}$). Adjusting the flow rate ratio allows a tuning of the focused beam.

Our device was fabricated in the PDMS using soft lithography technique. The micro-optofluidic system including the PDMS lenses was designed and printed on a transparency film with a resolution of 8000 dpi. The transparency mask was subsequently used for defining the negative mold of the lens in a 150-μm-thick SU-8 layer. The PDMS was mixed in a weight ratio of 10:1 and poured onto the SU-8 mold working as a master. Thereafter, the PDMS was vacuumed for 2 h to remove the gas bubbles. After the degassing process, the PDMS was heated at 80°C for 2 h. The PDMS was then peeled off from the master mold, and 0.75 mm diameter access holes were punched using the Harris unicore puncher. The PDMS with the lens structure was subsequently bonded to another flat PDMS part after treating both surfaces with oxygen plasma. The bonded PDMS was then placed in an oven at 150°C for 2 h to ensure good bonding between both surfaces. Needles with an inner diameter of 0.33 mm and an outer diameter of 0.64 mm were press fit into the access holes and worked as fluidic interconnects.

A preliminary experiment was carried out to verify the function of the telescope system consisting of two symmetric biconvex lenses [Fig. 1(b)]. The radii of the interface of the lenses are 700 and 400 μm. The rear focal point of the first lens and the front focal point of the second lens are designed to coincide. Before the experiment, the PDMS chip was immersed in the fluorescence dye solution (Rhodamine B in a mixture of glycerol and water with an RI matched to the PDMS) for 1 week. The fluorescence dye diffused into the chip allowing ray tracing inside the PDMS substrate. During the experiment, the same fluorescence dye solution was injected into the circular chamber and fully filled it. Figure 1(b) shows the visualized parallel rays in the circular chamber demonstrating the competence of our telescope system as a collimator and a beam expander.

The liquid-core liquid-cladding concave lens was developed in a circular chamber (Fig. 2) to demonstrate its light focusing ability. The fluorescence dye solution with an RI matched to the PDMS was introduced into the visualization chamber to trace the rays coming out from the concave lens. Figure 2 shows that the parallel beam was focused to the optical axis after passing the concave lens at flow rate ratios of $\Phi = 2.0$ and 3.0. The variable Φ is defined as the ratio between the flow rates of the core stream and one cladding stream. As a comparison we stopped pumping the benzyl alcohol and let ethanol fully fill the circular chamber. Since the chamber represents a biconvex lens with a lower RI, we observed in the ray-visualization chamber that the light beam
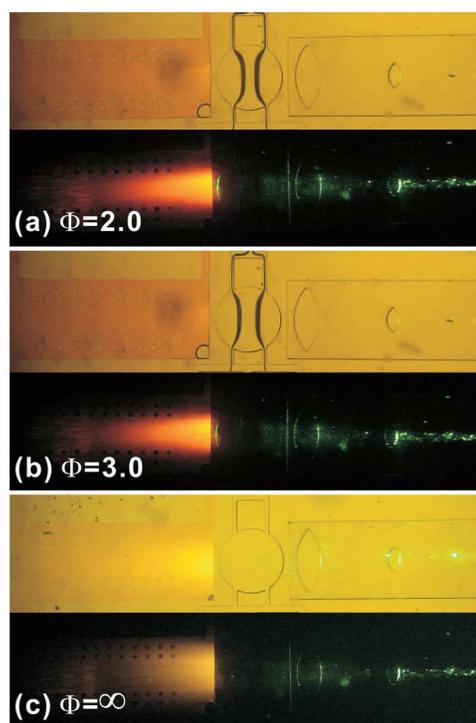

Fig. 2. (Color online) Liquid-core liquid-cladding biconcave lens formed in the circular chamber at different flow rate ratios: (a) $\Phi = 2.0$; (b) $\Phi = 3.0$. Ethanol ($n = 1.36$) works as core stream and benzyl alcohol ($n = 1.54$) serves as cladding steams. The parallel beam leaving the telescope system passes through the biconcave lens and is focused to the optical axis. (c) For comparison, the circular chamber was fully filled with ethanol, which causes the parallel beam to diverge.

become divergent [Fig. 2(c)]. For $\Phi = 3.0$, the intensity profiles at different lines (Fig. 3) were extracted and fitted with Gaussian curves. All the intensity values were normalized by the peak value of intensity along curve A. We measured the intensity distributions at curves located 810, 1100, and 1330 μm away from the biconcave lens. The beam width is defined as the FWHM of the fitting curves. Figure 3 shows that the beam width decreases along the light propagation direction, which verifies that the light beam is focused by the optofluidic biconcave lens. We found that the narrowest beam width of 370 μm is at curve C. After passing curve C, the beam width remained almost constant. This phenomenon may be caused by the uneven curvature distribution along the interface of the concave lens. Owing to the limit of the streamline inside the chamber and the surface tension between the two fluids, the curvature at the paraxial region is very small, and therefore the bundle of rays passing this paraxial region will not be bent but propagate straightforwardly. On the other hand, the non-paraxial rays will be bent owing to the large curvature at the off-axis region. After the beam waist, we observed that the light became parallel. This is because the mount of paraxial rays is larger than that of the off-axis rays, which are bent unevenly and finally scattered and absorbed by the fluorescence. So after the long optical path of propagation, we can only observe the unbent paraxial rays, which look
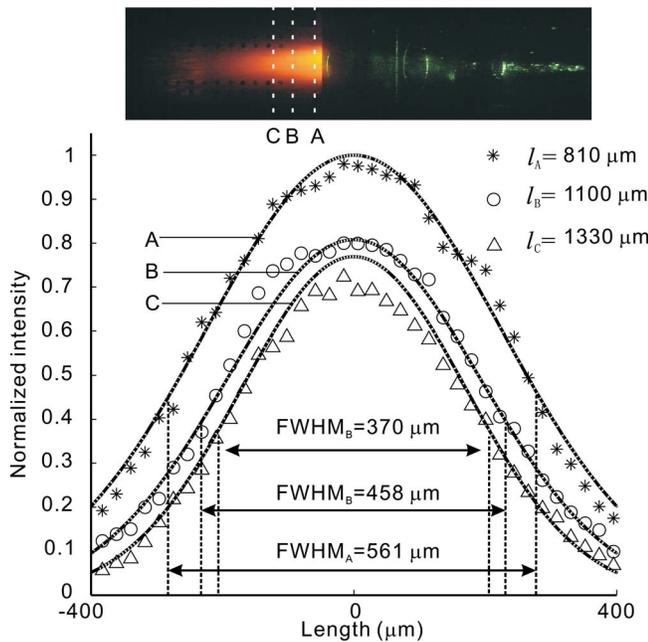
Fig. 3.   (Color online) Under a flow rate ratio of 3.0, the intensity profiles along different curves (dashed curves in the inset) were measured and fitted with Gaussian curves. All the intensity values are normalized by the peak value of intensity along curve A. l_A, l_B, and l_C are the distances from the dashed curves to the concave lens.
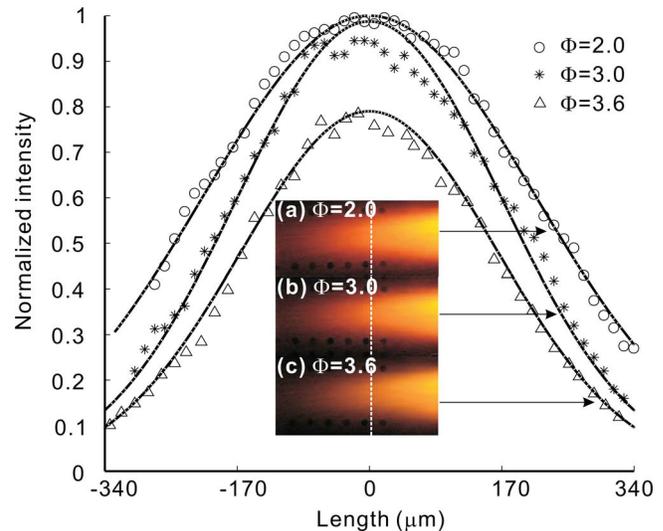

Fig. 4.   (Color online) Characteristics of the beam formed by the optofluidic lens at different flow rate ratios. The intensity profiles were measured along the dashed curves in the insets. Gaussian curves are fitted to intensity profiles. All the intensity values are normalized by the peak value of intensity profile in inset (a). The FWHMs for the cases depicted in insets (a), (b), and (c) are 430, 370, and 370 μm, respectively.

like collimated. The light beam waist was found to be located at curve C in the inset of Fig. 3. From this experiment, we verified that our optofluidic biconcave lens can perform light focusing

To demonstrate the tunability of the optofluidic biconcave lens, we measured the fluorescence intensity profile along curve C in Fig. 3 at different flow rate ratios Φ. The results are shown in Fig. 4. Insets (a), (b), and (c) in Fig. 4 illustrate the intensity distributions generated with flow rate ratios of 2.0, 3.0, and 3.6, respectively. The peak values of the intensity profiles of $\Phi = 2$ [Fig. 4(a)] and $\Phi = 3$ [Fig. 4(b)] are approximately the same, but the beam width of $\Phi = 2$ is larger than that of $\Phi = 3$. The light beam of $\Phi = 3.6$ [Fig. 4(c)] was measured to have the same width as the one of $\Phi = 3$, but the peak of the intensity value is lower. The comparison shows that the beam waist of $\Phi = 2$ is further away from the micro-optofluidic lens as that of $\Phi = 3.6$. These results show that the beam characteristics can be tuned by adjusting the flow rate ratio between the core and the cladding streams.

In conclusion, this Letter proposes what we believe to be a new concept of focusing light by a liquid-core liquid-cladding biconcave lens using a low-RI liquid as the core. A telescope system consisting of two

PDMS lenses was used to collimate and to expand the light beam emitted from an optical fiber. We demonstrated that our micro-optofluidic biconcave lens is able to focus the light. These characteristics can be used to enhance the fluorescence excitation intensity in laboratories on a chip with nonhazardous liquids. The characteristics of the light beam can be changed by adjusting the flow rate ratio between the core and the cladding streams.

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