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Hydrodynamically reconfigurable optofluidic microlens with continuous shape tuning from biconvex to biconcave

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Abstract: This paper presents an in-plane hydrodynamically reconfigurable optofluidic microlens, which is formed by the laminar flow of two streams of a low-refractive-index fluid and two streams of a high-refractive-index fluid in the two microchannels connecting to an expansion chamber where the microlens finally forms. In the expansion chamber, the stream of high-refractive-index fluid, acting as core, is sandwiched by the two streams of low-refractive-index fluid, acting as cladding. The interfaces between the streams can be flexibly manipulated by controlling the flow rate ratio between the two fluids in real time. Thus, the biconvex and biconcave microlens with different curvatures can be formed. By adjusting the microlens, the light beam can be continuously manipulated from focusing to collimation and then to divergence. In the experiment, a wide focus tuning range from 2.75 (focusing) to –1.21 mm (diverging) via collimation is achieved.

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References and links

1. Introduction

Microfluidic systems support optical components to realize and enrich optical functions in a compact, reconfigurable, and high-sensitive platform. Lots of optical components, including laser [1,2], grating [3,4], optical filter [5,6], micro lenses [7–11], saturable absorber [12], and optical attenuator [13], have been developed into an optofluidic system for various applications such as cell or molecule detection [14], optical signal manipulation, optical tweezer, and flow cytometry [15–19]. An in-plane microlens is a key component for light manipulation in the optofluidic system. Compared to the traditional optical lenses, which have a constant refractive index (RI) and a fixed geometrical shape, the microlenses integrated in the optofluidic systems can flexibly realize focal length tuning [20–23]. In-plane optofluidic microlenses with tunable focal length that perform as crucial components in the adaptive optical systems can flexibly adjust the focal point and reshape the beam profile inside a
microfluidic chip [24–28]. With the rapid development of optofluidic systems, lenses of wide focus tuning range are required for potential applications.

In-plane optofluidic lenses are usually formed by laminar flow of the streams of different fluids. While one fluid of high RI acts as core of the lens, another fluid of relative low RI is used as cladding. Since the optofluidic lenses operate in the low Reynolds number regime, turbulent mixing is avoided and the interface between the streams of the fluids is clear and smooth. The interface can be manipulated by controlling the flow rate of the fluids in real time so that the geometrical shape of the lens is changed and the focus tuning can be realized. The focus tuning is dynamically reconfigurable. Furthermore, since in-plane optofluidic lenses are integrated inside the microfluidic chip, the lenses can be designed and fabricated together with other functional components at the same time.

Dynamically reconfigurable liquid-core liquid-cladding lenses were demonstrated [29,30]. One fluid of high RI was sandwiched by another fluid of relative low RI in the microfluidic channel. When the fluids entered an expansion chamber, whatever it was a rectangular or circular chamber, the fluids hydrodynamically laterally spread in the chamber. The fluid of high RI sandwiched in the middle formed a lens. The curvature of the interface could be tuned by controlling the flow rate ratio of the streams of the fluids. By precisely adjusting the curvature, the fluid of high RI could form biconvex, plano-convex, and meniscus lenses. The optofluidic lenses achieved focusing of light with tunable focal length. However, collimation and diverging of light could not be realized by using these optofluidic lenses.

To enhance the function of optofluidic lenses, a hydrodynamically tunable optofluidic bi-concave lens using three fluids of different refractive indices was proposed for focusing and diverging of light [31]. In the focusing mode, the fluid of low RI, ethanol, was used as a core stream and the fluid of the highest RI, cinnamaldehyde, was used as a cladding stream. The third fluid, a mixture of ethylene glycol and ethanol, with a RI matching to that of the material for microfluidic chip worked as an auxiliary cladding stream to avoid light scattering. In the diverging mode, the injection of ethanol was stopped to allow the fluid of the highest RI to perform as a core stream. The auxiliary cladding fluid changed its role to being the low RI cladding of the lens. Focusing and diverging of light with tuneable focal length were achieved separately. Nevertheless, the mode switching was not continuous so that the focus tuning range was limited and collimation of light could not be realized.

In this paper, an in-plane hydrodynamically reconfigurable optofluidic microlens is proposed. The microlens can be produced at the two ends of the expansion chamber by laminar flow of four streams of two fluids. The interfaces between the core streams and the cladding streams can be flexibly adjusted by controlling the flow rate ratio of the two fluids. The microlens can be shaped into biconvex and biconcave. Thanks to the microlens shape tuning, the focus tuning has a wide range, continuously from focusing to diverging via collimation. Experiments are carried out to verify the concept. The shape change of the microlens is visualized and the light manipulation is demonstrated.

2. Operation principle

Figure 1 shows the concept of the proposed optofluidic microlens in an expansion chamber. The device operates in the low Reynolds number regime, so it promises that the streams of the fluids are laminar in the chamber. A fluid of high RI is used as core stream, and its RI is higher than that of the material used in the fabrication of the microfluidic chip. Another fluid of relative low RI is used as cladding stream, and its RI matches that of the material for microfluidic chip to avoid light scattering. Each fluid is firstly split into two streams and then joined together with the streams of the other fluid before entering the chamber through the two channels. The fluid of high RI is on the inner side. In the chamber, the streams of the fluid of high RI join and become a core stream. The stream of the fluid of high RI is thereby sandwiched by the streams of the fluid of low RI.

Two ends of the chamber are convex. Thus, there is enough space for the fluid of high RI to expand to form a biconvex lens. Manipulating the flow rate of the fluids allows tuning the
curvatures of the interfaces between the core and cladding streams. In the following explanation, it is assumed that the input light beam is divergent.

Fig. 1. The operation principle of the proposed micro lens. It is assumed that the input light is divergent. (a) The high RI fluid forms a biconvex microlens, and the curvature of the interface between high RI and low RI fluids is positive. The output light is focused. (b) The high RI fluid forms a biconvex microlens, and the curvature of the interface between high RI and low RI fluids is small. The output light is collimated. (c) The curvature of the interface between high RI and low RI fluids becomes negative. The output light is divergent. (d) The high RI fluids form a biconcave microlens. The output light severely diverges.

If the flow rate of the cladding stream is low, the two interfaces have positive curvatures and a biconvex microlens is formed. The input light beam is converged at every interface. As a result, the output light beam is focused. The focal distance can be tuned by adjusting the flow rate ratio between cladding and core streams. With the increase of the flow rate of the cladding stream, the curvatures of the interfaces become small and the focal distance extends. At a certain situation, the focal distance becomes infinite and the output light beam is collimated. Continuous increase in the flow rate ratio of the cladding and core streams makes the curvature of the interface smaller. Then, the interface becomes flat at a certain flow rate ratio. The output light beam becomes divergent. If the flow rate ratio of the cladding and core streams is further increased, the curvatures of the interfaces turn to negative and a biconcave microlens is formed. The output light beam further diverges.

3. Model of the optofluidic microlens

The flow inside the expansion chamber can be analyzed by using a two-dimensional quadrupolar flow model with two source-sink pairs. The height of the chamber is neglected. In this model, two sources of strength $Q$ located at $(-a, b)$ and $(-a, -b)$ in the Cartesian coordinates and two sinks of strength $-Q$ are placed at $(a, b)$ and $(a, -b)$, as shown in Fig. 2. The sources and the sinks are assumed as dimensionless points. According to the dispersion in planar multipole flow [30,32,33], the flow field can be expressed as

$$W(z) = \frac{Q}{2\pi} \left[ \ln(z + a + ib) + \ln(z + a - ib) - \ln(z + a + ib) - \ln(z - a - ib) + \ln(z + \frac{R^2}{a + ib}) + \ln(z + \frac{R^2}{a - ib}) - \ln(z - \frac{R^2}{a + ib}) - \ln(z - \frac{R^2}{a - ib}) \right], \quad (1)$$

where $x$ and $y$ are the coordinates in the two-dimensional Cartesian system, $z = x + iy$ with $i$ as the imaginary unit and $R$ as the radius of the two curved sides of the chamber. The real and imaginary parts of Eq. (1) are the velocity potential and the stream function, respectively. The boundaries of the expansion chamber can be expressed as follows.
In the analysis, only upper half of the chamber \((y > 0)\) is considered for modeling because the chamber is symmetric. The stream function for the upper half of the chamber \((y > 0)\) can be described by calculating the imaginary part of the flow field, yielding

\[
\begin{align*}
\phi &= \frac{Q}{2\pi} \left\{ \tan^{-1} \left( \frac{y + b}{x + a} \right) + \tan^{-1} \left( \frac{y - b}{x + a} \right) - \tan^{-1} \left( \frac{y - b}{x - a} \right) - \tan^{-1} \left( \frac{y + b}{x - a} \right) + \tan^{-1} \left( \frac{(a^2 + b^2)(y - bR^2)}{(a^2 + b^2)(x + aR^2)} \right) \right. \\
&\quad \left. + \tan^{-1} \left( \frac{(a^2 + b^2)(y + bR^2)}{(a^2 + b^2)(x + aR^2)} \right) - \tan^{-1} \left( \frac{(a^2 + b^2)(y - bR^2)}{(a^2 + b^2)(x - aR^2)} \right) - \tan^{-1} \left( \frac{(a^2 + b^2)(y + bR^2)}{(a^2 + b^2)(x - aR^2)} \right) \right\},
\end{align*}
\]

where \(c\) is a constant which is related to the region of the chamber. \(c = 0\) for \(0 \leq y < b\) and \(c = -4\pi\) for \(b \leq y \leq R\). The calculated streamlines are shown in Fig. 3. These streamlines indicate the potential interface position of the cladding and core streams. The curvature of the interface is tunable, and both concave and convex shapes can be realized by properly adjusting the flow rate ratio of the two streams.

Fig. 2. The coordinate of microlens model.

Fig. 3. The streamlines for two-dimensional quadrupolar flow. Two sources are located at \((-a, -b)\) and \((-a, b)\) and two sinks are located at \((a, -b)\) and \((a, b)\). \(S^+\): source. \(S^-\): sink.
The velocity components in x-axis, \( u \), and y-axis, \( v \), can be derived from the first derivative of the stream function, i.e.

\[
u = \frac{\partial \varphi}{\partial x}
\]

\[
= \frac{y+b}{(x+a)^2 + (y+b)^2} + \frac{y-b}{(x-a)^2 + (y-b)^2} - \frac{y-b}{(x-a)^2 + (y+b)^2} + \frac{y+b}{(x+a)^2 + (y-b)^2} + \frac{y+b}{(x-a)^2 + (y+b)^2} - \frac{y+b}{(x+a)^2 + (y+b)^2}
\]

\[
+ \frac{(a^2 + b^2)[(a^2 + b^2) y - b R^2]}{[(a^2 + b^2) x + a R^2]^2 + [(a^2 + b^2) y - b R^2]^2} + \frac{(a^2 + b^2)[(a^2 + b^2) y + b R^2]}{[(a^2 + b^2) x + a R^2]^2 + [(a^2 + b^2) y + b R^2]^2}
\]

\[
- \frac{(a^2 + b^2)[(a^2 + b^2) x - a R^2]}{[(a^2 + b^2) x - a R^2]^2 + [(a^2 + b^2) y - b R^2]^2} + \frac{(a^2 + b^2)[(a^2 + b^2) y - a R^2]}{[(a^2 + b^2) x - a R^2]^2 + [(a^2 + b^2) y - a R^2]^2}
\]

\[
= \frac{x+a}{(x+a)^2 + (y+b)^2} + \frac{x+a}{(x+a)^2 + (y-b)^2} - \frac{x-a}{(x-a)^2 + (y-b)^2} - \frac{x-a}{(x-a)^2 + (y+b)^2} + \frac{x-a}{(x+a)^2 + (y-b)^2} - \frac{x-a}{(x+a)^2 + (y+b)^2}
\]

\[
+ \frac{(a^2 + b^2)[(a^2 + b^2) x + a R^2]}{[(a^2 + b^2) x + a R^2]^2 + [(a^2 + b^2) y - b R^2]^2} + \frac{(a^2 + b^2)[(a^2 + b^2) y + b R^2]}{[(a^2 + b^2) x + a R^2]^2 + [(a^2 + b^2) y + b R^2]^2}
\]

\[
- \frac{(a^2 + b^2)[(a^2 + b^2) x - a R^2]}{[(a^2 + b^2) x - a R^2]^2 + [(a^2 + b^2) y - b R^2]^2} + \frac{(a^2 + b^2)[(a^2 + b^2) y - a R^2]}{[(a^2 + b^2) x - a R^2]^2 + [(a^2 + b^2) y - a R^2]^2}
\]

\[(4)\]

The velocity at the center of the streamlines (\( x = 0 \)) can be expressed as

\[
u = \frac{2a}{a^2 + (y+b)^2} + \frac{2a}{a^2 + (y-b)^2} + \frac{2a R^2 (a^2 + b^2)}{a^2 R^4 + [(a^2 + b^2) y - b R^2]^2} + \frac{2a R^2 (a^2 + b^2)}{a^2 R^4 + [(a^2 + b^2) y + b R^2]^2},
\]

\[(5)\]

It indicates that the velocity of each streamline only depends on the velocity component in x-axis. Thus, the flow rates for core and cladding streams can be determined from the integral of the velocity component in x-axis, \( u \), from \( B_2 \) to \( A_2 \), and from \( A_2 \) to \( A_1 \) (or from \( B_1 \) to \( B_2 \)), respectively. Then, the flow rate ratio between cladding and core streams can be written as follows

\[
\phi_{\text{Cladding}} = \frac{\tan^{-1}\left(\frac{a+2b}{a}\right) + \tan^{-1}\left(\frac{a}{a+b}\right) + \tan^{-1}\left(\frac{a+2b}{a+b}\right) + \tan^{-1}\left(\frac{a}{a+b}\right) + \pi}{4}
\]

\[
\phi_{\text{Core}} = \frac{1}{2} \left[ \frac{1}{2} \right] \left[ \frac{1}{2} \right]
\]

\[(6)\]

where \( s \) reflects the relationship of the curvature radius and the size of the chamber. If the curvature is positive, \( s \) equals to \( d \), where \( d = r - \sqrt{r^2 - a^2} \) and \( r \) is the radius of the interface. \( s \) equals to \( -d \) for the negative curvature of the interface. It indicates that the curvature of the interface can be adjusted by changing the flow rate ratio between cladding and core streams.

If the cladding stream has a low RI, \( n_0 \), and the core stream has a relatively higher RI, \( n_1 \), a biconvex or biconcave lens is formed. In addition, the curvature of the interface affects the focal length of the lens. The focal length can be derived based on the theory of a thick lens [34].
Thus, the flow rate ratio between cladding and core streams determines the type (biconvex or biconcave) and the focal length of the lens.

4. Experimental design and operation

The design of the optofluidic chip is shown in Fig. 4. A single-mode optical fiber is inserted into the chip, and it points to the center of the expansion chamber. The distance from the tip of the fiber to the chamber is 420 μm. The optical path is perpendicular to the flow direction of the fluids. An aperture is built in front of the chamber to make the light only illuminate the center of the chamber. The size of the aperture is 200 μm. The channels for the infusion of the fluids are symmetrically split into two after the two inlets. The split channels for the streams of the high RI fluid are combined to the channels for the streams of the low RI fluid from the outer sides. The combined channels are connected to the expansion chamber. The height and width of all the channels are 105 and 100 μm. The length and width of the chamber are 1.2 mm (including the two convex ends) and 800 μm, respectively. Both a and b are 400 μm. The curvature radius of the convex sidewalls of the chamber is 400 μm. Two outlets are on the opposite sides of the chamber. A beam-tracing chamber is behind the expansion chamber for monitoring the output light beam.

The optofluidic chip is fabricated on polydimethylsiloxane (PDMS) substrate using the standard soft lithography technique, which describes the procedure for design and fabrication of microfluidic systems in an elastomeric PDMS [35,36]. Firstly, a network of microfluidic components and channels is designed by using a commercial AutoCAD software and then converted into a transparent film by a high-resolution printer with 8000 dpi. Secondly, the transparent film is used as a mask in the photolithography to create a negative mold, which is composed of a relief of 105 μm SU-8 photoresist on a silicon wafer. PDMS is prepared by
mixing silicone elastomer and a curing agent (Sylgard 184, Dow Corning) in a weight ratio of 10:1 and poured onto the mold to develop an elastomeric replica. After the PDMS replica is heated for 2 hours in the vacuum oven at 80 °C, the microfluidic network of components and channels is formed on the surface. Subsequently, access holes for inlets and outlets are opened by a puncher. A single-mode optical fiber is buried into the corresponding groove on the PDMS replica. The numerical aperture of the optical fiber is 0.14. Thirdly, a flat slab of PDMS is covered on the surface of the PDMS replica to form a microfluidic chip. Then, the microfluidic chip is heated for 4 hours in the vacuum oven at 80 °C. The RI of cured PDMS, \( n_{\text{PDMS}} \), is 1.403. Finally, needles with an inner diameter of 330 μm and an outer diameter of 640 μm are pegged into the access holes and worked as fluidic interconnects.

5. Demonstration of focus tuning

In the experiment, silicone oil (RI \( n_{\text{Oil}} = 1.579 \), density \( \rho = 1.1 \text{ g/cm}^3 \), viscosity \( \mu = 170 \times 10^{-3} \text{ Pa}\cdot\text{s} \) [37]) is selected as the high-RI fluid and 28.9% calcium chloride solution is used as the low-RI fluid. The RI of the calcium chloride solution is matched to that of PDMS to avoid light scattering. The fluids are kept in two 10-ml syringes, which are driven by two syringe pumps (Harvard PHD 2000) for infusion into the microfluidic chip. The syringe pumps have high flow accuracy of ± 0.35%. Tubes and connectors are tightly fixed to avoid vibration. A 200-μm knife-edged aperture is produced by filling in the two corresponding channels with black ink. Furthermore, to visualize the output beam, fluorescent dye Rhodamine 6G (excitation wavelength of 526 nm and emission wavelength of 560 nm) is dissolved into the ethanol solvent and the fluorescent solution fills in the beam tracing chamber. A 532-nm semiconductor laser, whose maximum output power is 100 mW, is employed as the light source. To avoid heating the liquids in the chamber and the distortion of the interface, the power of the input light should not be extremely high. A charge-coupled device (CCD) camera mounted on a stereomicroscope with 20 × magnification is used to record the micrographs.

Fig. 5. Variation of microlenses. The interfaces of the microlenses are adjusted with the change of the flow rate ratio of calcium chloride solution and silicone oil. (a) and (b) Biconvex microlenses are formed when the flow rate ratios are 3:10 and 1:3, respectively. (b) Plano microlens is formed when the flow rate ratio is 9:20. (d) and (e) Biconcave microlenses are formed when the flow rate ratios are 1:2 and 7:13, respectively.

Figure 5 shows the variation of the microlens versus the flow rate ratio between calcium chloride solution and silicone oil. The interfaces between the fluids are changed with the adjustment of the flow rate of calcium chloride solution. When the flow rate ratio is low, e.g.,
0.30 and 0.34, the stream of silicone oil squeezes the streams of calcium chloride solution and forms a biconvex microlens. The curvatures of the interfaces between the fluids are symmetrical and positive and become small with the increase of the flow rate ratio. The interfaces turn to flat when the flow rate ratio is 0.45. If the flow rate ratio is kept increasing, the streams of calcium chloride solution expands and the stream of silicone oil shrinks. The interfaces become concave, resulting in negative curvatures. A biconcave microlens is formed. Figures 5(d) and 5(e) shows the two biconcave microlenses when the flow rate ratios are 0.48 and 0.54, respectively. The tuning of the microlenses from biconvex to plano and then to biconcave is continuous.

Figure 6 illustrates the calculated and measured focal length of the microlens. The solid lines represent the theoretically calculated results according to Eq. (6) and (7). The circles represent the measured results obtained by measuring the curvature of the interfaces. The curvature is evaluated by using a custom Matlab program, in which the fluid–fluid interfaces are assumed to be quadric curves. Then, the focal length is calculated by using commercial Zemax software (Zemax OpticStudio 15). In the calculation, the curvatures of the interfaces and the refractive indices of calcium chloride solution and silicone oil are taken into account. The error bars are standard deviation of the focal length for identical flow rate ratio in the different experimental runs. The green and yellow shadow areas indicate that the shape of the microlens is biconvex and biconcave, respectively. In between the shadow areas, it means the shape of microlens is plano. The corresponding Reynolds number ranges from 4.67 to 5.98, and the Peclet number for the silicone oil ranges from 113.3 to 145.1. In the experiment, the size of the sources and sinks and the height of the expansion chamber cannot be neglected, which leads to the disparity between the experimental and calculated results.

When the shape of the microlens is biconvex, the focal length is positive and keeps increasing with the flow rate ratio. The minimum focal length of the biconvex lens is 2.75 mm. The limitation of the positive focal length is related to the most significant convex curvature that is attributed to the constraint of expansion of silicone oil in the expansion chamber. After the flow rate ratio is larger than 0.46, the focal length becomes negative, indicating diverging of light. The focal length is shortened and tends asymptotically toward a limiting value, −1.21 mm. The limitation is determined by the highest achievable flow rate ratio. It is worth noting that the flow rate ratio cannot be too high, though a high flow rate ratio leads to a more negative curvature and a wide tuning range. If the flow rate ratio is too
high (>0.63), the two streams of calcium chloride solution merge and the flows in the expansion chamber becomes unstable.

In addition, in the measurement of the curvature of the interfaces, both the upper and lower interfaces have the same tendency owing to the symmetrical structure. The mean deviation between the upper and lower interfaces is 4.7%, which means the high uniformity of the channels.

The output light beam is observed in the beam-tracing chamber, as shown in Fig. 7. When the flow rate ratio is 2:5, the shape of the microlens is biconvex and a focused beam can be observed in the beam-tracing chamber. The convergent angle of the output beam is 13.2 degrees. With the increase of the flow rate ratio, the convergent angle shrinks. Afterward, the shape of the microlens gradually turns into biconcave and the output beam becomes divergent. Figure 7(b) shows a divergent beam when the flow rate ratio is 1:2. The divergent angle of the beam is 22.5 degrees. Furthermore, the divergent angle expands with the flow rate ratio. The light beam is stable and no fluctuation is observed.

![Fig. 7. Experimental results for the focal distance of the microlens versus the flow rate ratio between calcium chloride solution and silicone oil.](image)

6. Conclusion

In this study, an in-plane hydrodynamically reconfigurable optofluidic microlens is reported. The microlens is formed by injecting two streams of silicone oil as core together with two streams of calcium chloride solution as cladding separately through two entrances into an expansion chamber. The interfaces between the core stream and the cladding streams can be flexibly adjusted by controlling the flow rate ratio between calcium chloride solution and silicone oil. Thus, the microlens can be shaped into biconvex, plano, and biconcave. The microlens with different curvatures is demonstrated in the experiment. A wide focus tuning range can be achieved continuously from focusing to diverging. The minimum focal distances for focusing and diverging are 2.75 and –1.21 mm, respectively. The proposed tuneable microlens is a promising candidate for various microfluidic or lab-on-a-chip applications.

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