Electrokinetically tunable optofluidic bi-concave lens

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This paper numerically and experimentally investigates and demonstrates the design of an optofluidic in-plane bi-concave lens to perform both light focusing and diverging using the combined effect of pressure driven flow and electroosmosis. The concave lens is formed in a rectangular chamber with liquid core liquid cladding (L^2) configuration. Under constant flowrates, the performance of the lens can be controlled by an external electric fields. The lens consists of a core stream (conducting fluid), cladding streams (non-conducting fluids), and auxiliary cladding streams (conducting fluids). In the focusing mode, the auxiliary cladding stream is introduced to sandwich the biconcave lens for protecting the light rays from scattering at the rough chamber wall. In the diverging mode, the auxiliary cladding liquid has a new role as the low refractive-index cladding of the lens. In the experiments, the test devices were fabricated in polydimethylsiloxane (PDMS) using the standard soft lithography technique. Ethanol, cinnamaldehyde, and a mixture of 73.5% ethylene glycol and 26.5% ethanol work as the core stream, cladding streams and auxiliary cladding streams. In the numerical simulation, the electric force acts as a body force. The governing equations are solved with finite volume method on a Cartesian fixed staggered grid. The evolution of the interface was captured by the level set method. The results show that the focal length in the focusing mode and the divergent angle of light beam in the diverging mode can be tuned by adjusting the external electric field at fixed flowrates. The numerical results have a reasonable agreement with the experimental results.

Introduction

One of the most popular micro optofluidic applications is the liquid core-liquid cladding (L^2) micro-lens, which improves the portability of optical components and potentially makes lab-on-a-chip systems cost-effective.¹⁻⁴ Prior to optofluidic L^2 micro-lenses, solid-interface lenses were integrated into microfluidic network to improve the light properties^{5, 6}. Compared to solid-interface lens, micro optofluidic L^2 lenses have a number of advantages, such as smooth interfaces, tuneable focal length, and a simple fabrication process.⁷⁻⁹ Following the concept of L^2 micro-lens, different types of optofluidic lenses were developed in the past¹⁰⁻¹⁹. These lenses can dynamically manipulate a light beam introduced from an optical fibre. Moreover, their L^2 configuration has an atomically smooth interface, in contrast to the rough interface of solid-base lenses. Nguyen²⁰ recently reviewed the different concepts of implementing micro optofluidic lens.

Currently, most of the L^2 lenses can only focus light along the optical axis. The single function of these micro-lenses cannot satisfy the requirement of fluorescence excitation and detection. Mao et al.¹⁹ designed a gradient refractive-index lens to swing a focused light beam based on the diffusion of interface between two miscible fluids. Song et al.² reported a liquid-core liquid-cladding prism to continuously deflect a light. Xiong et al.⁹ presented another prism to deflect light using only two laminar flow streams of mismatching refractive indices. These works provided different ways of modifying the in-plane light, by which the area out of the optical axis can also be selectively illuminated, thus exciting the local fluorescent sample. Song et al.⁸ integrated the focusing and diverging function into a single bi-concave lens, where the focal length or the divergent angle of the light beam can be tuned by adjusting the flow rate ratio between core and cladding streams.

The light properties of focused length, location of light beam or divergent degree depends on the interfacial shape between the streams. Most of previous micro optofluidic lenses tune the

interfacial shape by adjusting flowrates^{2, 3, 8, 11, 12, 19}. The results showed the relationship between the interfacial shape and flowrate ratio of the core stream and cladding streams are complex parabola.⁸ In order to achieve the ideal optical performance, the flowrate ratio has to be manually adjusted. Electroosmosis is another popular actuating method in microfluidic to control the interfacial shape and location.²¹⁻²⁵ When the electric field is used to adjust the interfacial shape, a direct relationship between the interfacial shape and the electric field can be established.^{4, 26, 27}

This paper presents the design and demonstration of an optofluidic bi-concave lens that can tune light beam from focused to divergent using the combined effect of pressure driven and electroosmosis. The functions are achieved by adjusting the applied external electric field under fixed flow rates. This lens consists of a core stream, cladding streams and auxiliary cladding streams. These streams have various roles in focusing mode and diverging mode. Figure 1(a) schematically describes the focusing mode of the lens. In this mode, the core stream is a conducting fluid with a low refractive index, and the cladding streams are non-conducting fluids with a high refractive index. The flow rates of the core stream and cladding stream are kept constant in the operation. The external electric field is added to the core stream. Following the concept reported by Song et al.,⁸ an auxiliary cladding stream with a very low flow rate and a refractive index matching that of PDMS can prevent the light beam from scattering. Although no external electric field is added to the auxiliary cladding stream, the auxiliary cladding streams are electrically conducting in order to tune the lens from focusing mode to diverging mode conveniently. The effect of auxiliary cladding stream is negligible due to the low flow rate and matched refractive index. The light emitted from the optical fibre can be well focused and the focal length can be tuned by adjusting the electric field applied to the conducting core stream. The diverging mode is described in Fig. 1(b). In the diverging mode, the roles of the streams are changed. Table 1 indicates these changes. The core stream in focusing mode is blocked; the cladding streams in focusing mode become the core stream, the

Fig. 1 Schematics: (a) Bi-concave lens in the focusing mode. The light beam in the ray-tracing chamber propagates through the bi-concave lens in the focusing mode. The liquids for the core, cladding, and auxiliary cladding streams are ethanol, cinnamaldehyde, and the mixture of 73.5% ethylene glycol and 26.5% ethanol, respectively. The voltage applied to the core stream is $V = -5000V$. (b) Bi-concave lens in the diverging mode. The light beam in the ray-tracing chamber propagates through the bi-concave lens in the diverging mode. The liquids for the core and cladding streams are cinnamaldehyde, and the mixture of 73.5% ethylene glycol and 26.5% ethanol, respectively.

auxiliary cladding streams work in focusing mode as cladding streams. In the diverging mode, the core stream is non-conducting and the cladding streams are conducting, the external electric field is applied to the cladding stream. Diverging of light beam is achieved by the higher refractive index of the core stream and the tuneable lens interface. The expansion of the light beam can be adjusted by the external electric field.

Table 1 The roles of liquid in different model

Liquids	Focusing	Diverging
Enthanol	Core stream	N.A
Cinnamaldehyde	Cladding stream	Core stream
Mixture of 73.5% ethylene glycol and 26.5% ethanol	Auxiliary cladding stream	Cladding stream

Comparing to the micro optofluidic lenses previously reported in the literature, our lens combines the functions of both focusing and diverging in a single design. The width of the light beam can be tuned across a larger range.

Numerical simulation

Physical model

The configuration of the devices is illustrated in Fig. 1. The rectangular chamber for forming the optofluidic lens measures $1\text{ mm} \times 1\text{ mm}$. The device includes five inlets, a core inlet, two pairs of cladding inlets and three outlets. The widths of the inlets

and outlets are $50\text{ }\mu\text{m}$. The light emitted from an optical fiber aligned by a pre-fabricated guide channel of a width of $130\text{ }\mu\text{m}$. The distance between the center of the rectangular chamber and the tip of the fiber is 4 mm . In order to fix the angle of coming light and filter the noise, an aperture with a size of $400\text{ }\mu\text{m}$ is formed by filling ink into the two aperture channels. The propagation of light rays is visualized by a ray-tracing chamber which is placed behind the rectangular lens chamber and filled with fluorescence dye. The whole device has uniform thickness of $120\text{ }\mu\text{m}$. Figure 2(a) shows the computational domain of the numerical model. The domain includes the rectangular chamber, the inlets and the outlets.

Governing equations

The electric field $\mathbf{E}$ in the conducting fluid can be determined by the gradient of the electrical scalar potential ϕ

$$\mathbf{E} = -\nabla\phi \quad (1)$$

In a dielectric medium, the electrical scalar potential ϕ is governed by

$$\nabla \cdot (\epsilon \nabla \phi) = 0 \quad (2)$$

where ϵ is the permittivity of dielectric medium. The permittivity jumps across the interface between different dielectric medium. The charge density in the conducting fluids can be determined based on the Poisson's equation

$$\rho_e = -2z_0 e n_0 \sinh\left(\frac{z_0 e \psi}{k_b T}\right) \quad (3)$$

where z_0 is the valence of the ions, e is elementary charge, n_0 is the reference value of the ion concentration, ψ is zeta potential of PDMS wall, k_b is Boltzmann constant, and T is the absolute temperature.

The multi-phase microfluidic system can be described by Navier-Stokes equation coupled with the electric force.

$$\nabla \cdot (\rho_i \mathbf{v} \mathbf{v}) - \nabla \cdot [\mu_i (\nabla \mathbf{v} + \nabla \mathbf{v}^T)] = -\nabla p + \mathbf{E} \rho_e \quad (4)$$

The gravity is neglected in this model. An incompressible media is assumed

$$\nabla \cdot (\rho_i \mathbf{v}) = 0 \quad (5)$$

The jumps of the properties near the interface were smoothed with Heaviside function over the whole computational domain²⁸

$$\begin{cases} \alpha_{\text{conducting}} = (1 - H_r) \alpha_{\text{non-conducting}} + H_r \alpha_{\text{conducting}} \\ \alpha_{\text{non-conducting}} = H_r \alpha_{\text{non-conducting}} + (1 - H_r) \alpha_{\text{conducting}} \end{cases} \quad (6)$$

where α can be either the density ρ , or the dynamic viscosity μ or the electric permittivity ϵ . The Heaviside function H_r is related to the normal distance from the interface and is calculated using²⁹

$$H_r = \begin{cases} 0 & \text{for } g < -\gamma \\ \frac{g + \gamma}{2\gamma} + \frac{1}{2\pi} \sin\left(\frac{\pi g}{\gamma}\right) & \text{for } |g| \leq \gamma \\ 1 & \text{for } g > \gamma \end{cases} \quad (7)$$

where $\gamma = 1.5\Delta x$ and Δx is the grid size.²⁹

Fig. 2 Numerical model of the lens: (a) Domain calculated in numerical simulation, (b) velocity profile in rectangular chamber for diverging mode. The flow rates of the core and cladding streams are fixed at same value of 0.5 ml/h. The voltage applied to the cladding stream is $V = 5000$ V. (c) Numerical ray-tracing results. The flow rates of the core and cladding streams are fixed at same value of 0.5 ml/h. The voltage applied to the core stream is $V = -3000$ V.

Since the thickness of the microchannel ($120\ \mu\text{m}$) is small comparing to the other dimension (1 mm), the depth average method³⁰ was used in this work to reduce the three-dimensional model to two-dimensional model.

Level set method

The level-set method is used to model the interfaces between different fluids.²⁹ A level set function $\mathcal{G}$ is introduced over the whole computational domain to describe the shortest normal distance from the interface. The interface is represented by $\mathcal{G} = 0$. The signs “+” and “-” are used to distinguish the two liquid phases. The level-set function is defined as

$$\mathcal{G} = \begin{cases} -d & \mathbf{r} \in \Omega_{\text{non-conducting}} \\ 0 & \mathbf{r} \in \Gamma_{\text{interface}} \\ d & \mathbf{r} \in \Omega_{\text{conducting}} \end{cases} \quad (8)$$

where $\mathbf{r}$ is the position vector in the computational domain Ω , Γ is the interface, and d is the shortest normal distance from all interfaces. The evolution of the interface between two immiscible phases is governed by the level-set function

$$\mathbf{v} \cdot \nabla \mathcal{G} = 0 \quad (9)$$

A reinitialization procedure is employed to maintain the level set function as a signed distance function to the interface with some degree of accuracy

$$\frac{\partial \zeta}{\partial \tilde{t}} = \text{sign}(\mathcal{G})(1 - |\nabla \mathcal{G}|) \quad (10)$$

where $\tilde{t}$ is a pseudo time for the variable ζ . The steady state solution of ζ is always a level-set function. The initial condition of Eq. (10) is

$$\zeta(\mathbf{r}, 0) = \mathcal{G}(\mathbf{r}) \quad (11)$$

For numerical purposes, it is useful to smooth the signed function as

$$\text{sign}(\mathcal{G}) = \frac{\mathcal{G}}{\sqrt{\mathcal{G}^2 + |\nabla \mathcal{G}|^2 (\Delta x)^2}} \quad (12)$$

Boundary conditions

For an electric field, the voltages (V_{inlet} and V_{outlet}) are added to inlets and outlets to calculate electrical potential distribution. V_{inlet} and V_{outlet} are the voltages set by a high voltage DC power supply. For the pressure gradient, the average velocity at the inlet is set as $u_i = q_i / wh$, where q_i is the volumetric flow rate provided by a syringe pump in the corresponding experiment and w and h are the channel width and height, respectively. Outflow boundary conditions are used for the outlets. The initial level-set function is set to an assumed shape and evolved under Eq. (9) to its steady state shape.

Numerical method

The governing equations of the Navier-Stokes equation Eq. (4), continuum equation Eq. (5), and the electrical potential Eq. (2) are solved on the Cartesian staggered grid by a finite volume method. The SIMPLER algorithm is used to couple the velocity and pressure.³¹ The Power Law is applied to predict the combined convection-diffusion effect. The level set Eq. (9) and the reinitialization Eq. (10) are solved by constructing high-order weighted essentially non-oscillatory (WENO) schemes with local Lax-Friedrichs flux³² and Godunov flux³³, respectively, and advected by the total variation diminishing (TVD) Runge-Kutta method³⁴. The solution procedure can be summarized as follows:

- (a) Guess the locations of the interfaces,
- (b) Calculate the value of $\mathcal{G}$ for all nodes for the interface,
- (c) Calculate the properties for all nodes using Eqs. (6) and (7),
- (d) Solve the distribution of electric potentials using Eqs. (1) and (2),
- (e) Solve the continuity and momentum equations given by Eqs. (4) and (5) according the electric field and boundary conditions,
- (f) Calculate the value of $\mathcal{G}$ using Eq. (9) according the velocity distribution from step (5),
- (g) Calculate the value of ζ according Eq. (10) and the solution of step (6),
- (h) Set $\mathcal{G}(\mathbf{r}) = \zeta(\mathbf{r})$ and
- (i) Repeat steps (3)-(8) until the solution converges.

Fabrication and experimental setup

Soft lithography technique was used to fabricate the microchannel in polydimethylsiloxane (PDMS).³⁵ The mask was printed on a transparency film with a resolution of 8000 dpi. A $120\text{-}\mu\text{m}$ thick SU-8 layer was first spin-coated on a silicon wafer after soft bake (65°C , 10 min) and hard bake (95°C , 45 min); the SU-8 layer was then exposed and developed. PDMS (Dow

corning corporation, USA) was mixed from the two components (base and curing agent) with a weight ratio of 10:1. The mixed PDMS free of bubbles was poured onto the SU-8 mould. The PDMS part was then kept at room temperature for 36 hours to cure. Subsequently, the cured PDMS was peeled off from the master mould. The fluidic ports with a diameter of 0.5 mm were punched into the PDMS part. Finally, another cured flat PDMS slab and the PDMS with the microchannel were treated the surface using oxygen plasma and bonded together. With this technology, a channel height of 120 μm can be achieved for the microfluidic network.

In the experiments, all liquids were kept in 10-ml glass syringes (10 ml gastight, Hamilton). The syringes were driven by syringe pumps (KDS230, KD Scientific Inc, USA, 0.2 $\mu\text{l/h}$ to 500 l/h, accuracy of 0.5%) to deliver the fixed flowrates. The greyscale images were captured using a sensitive CCD camera (HiSense MKII) attached to the microscope. A digital camera (DCRDVD803E, SONY) was used to record the colour images. Laser light (output of 200 mW, wavelength of 532 nm) was coupled into a multimode optical fibre (AFS105/125Y, THORLABS Inc) with a numerical aperture $\text{NA}=0.22$. The optical fiber was inserted into a pre-fabricated microchannel with a width of 130 mm to act as a point light source. Stainless steel tips (EFD, 5123PC-B, USA) were used to connect the inlet port and hard Teflon tubing. The inner and outer surfaces of the tips were covered with Polytetrafluoroethylene. Platinum wires (Sigma-Aldrich, 0.1 mm diameter) were used as electrodes. The electric fields are provided by a high voltage DC power supplies (Model PS350, Stanford Research System, Inc).

In the focusing mode, the core stream is ethanol ($\text{RI } n = 1.36$; viscosity $\mu = 1.2 \times 10^{-3} \text{ Ns/m}^2$). In order to add the electric field to ethanol, NaCl was diluted in ethanol with a concentration of $7 \times 10^{-4} \text{ M}$. The cladding stream is cinnamaldehyde ($\text{RI } n = 1.62$; viscosity $\mu = 5.7 \times 10^{-3} \text{ Ns/m}^2$). The auxiliary cladding stream is a mixture of 73.5% ethylene glycol and 26.5% ethanol ($\text{RI } n = 1.412$; viscosity $\mu = 9.8 \times 10^{-3} \text{ Ns/m}^2$). This mixture has the same refractive index as PDMS ($n=1.412$). Similar to ethanol, NaCl was diluted in ethanol with a concentration of $7 \times 10^{-4} \text{ M}$. During the experiments, the flowrates of the core stream and cladding stream were fixed at 0.5 ml/h and the flowrate of the auxiliary cladding stream was fixed at 0.05 ml/h. To tune the lens curvature, an electric field was applied to the core stream. In the diverging mode, the core flow was stopped to allow cinnamaldehyde from the cladding inlets to become the new core stream, and therefore changing the role of the auxiliary cladding liquid from light-scattering protection to providing a mismatched refractive index for refracting the light rays. In this mode, the flow rates of two streams were fixed at 0.5 ml/h, the electric field is added to the new cladding stream. A mixture of 73.5% ethylene glycol and 26.5% ethanol ($n = 1.412$) with fluorescence dye Rhodamine B (Sigma-Aldrich, excitation wavelength of 540 nm, emission wavelength of 625 nm, 1 g/L) were pumped into the ray-tracing chamber to visualize the light rays refracted by the concave lens.

Results and discussion

Focusing mode

Figure 3 shows typical images of the lens by adjusting the electric field applied to the core stream under the fixed flow rates of 0.5 ml/h. The zeta potential of PDMS with NaCl solution is about -85 mV.³⁶ The surface charge of the PDMS wall is negative and

Fig. 3 The interfacial shape of the micro optofluidic bi-concave lens in focusing mode at different electric fields and fixed flow rates. The flow rates of the core stream and the cladding stream are all 0.05 ml/h: (a) $V=-5000 \text{ V}$; (b) $V=-4000 \text{ V}$; (c) $V=-3000 \text{ V}$; (d) $V=0 \text{ V}$.

the ion within the electrical double layer (EDL) is positive by attracting of negative wall charge.³⁷ Under a positive electric field, the ion with positive charge moves and drags the core liquid flow along the electric field. As result, the core stream flows faster. Under the fixed pressure-driven flow rate, the core stream with the higher velocity will occupy a smaller part of channel. The cladding fluid will occupy a larger part of the channel and the curvature of the interface increases. At the same time, if a negative electric field is applied to the core stream, the ion with positive charge moves and drags the core liquid flow opposing the pressure-driven flow. The core stream becomes slower and occupies a larger part of channel. The cladding fluid will occupy a smaller part of the channel, and the curvature of the interface decreases. Figure 3 shows that the curvature of the interface at $V=-5000 \text{ V}$ is smaller than that at $V=0 \text{ V}$.

Fig. 4 The experimental ray-tracing results for focusing mode under different electric field in the cladding streams and fixed flowrates of core fluid and cladding fluids: (a) $V=0 \text{ V}$; (b) $V=-2000 \text{ V}$; (c) $V=-5000 \text{ V}$

Fig. 5 Focusing mode: (a) Relationship between the external electric field and the curvature of the interface under fixed flowrates in the focusing mode of the optofluidic bi-concave lens, (b) Relationship between the external electric field and the focal length under fixed flowrates in the focusing mode of the optofluidic bi-concave lens. The flowrates of core stream and cladding streams are fixed at 0.5 ml/h.

The optical performance of the optofluidic concave lens in the focusing mode was carried out experimentally and numerically using the ray-tracing method. Figure 4 shows the experimental ray-tracing results for focusing mode under different electric field in the cladding streams and fixed flow rates of core fluid and cladding fluids. In the experiment, the fluorescence dye in the ray-tracing chamber is excited by the green laser from a fibre of a wavelength of 532 nm and recorded as a grey-scale image. In the numerical simulation, a custom Matlab program based on Snell's law⁸ was implemented to trace the ray. Due to the refractive index of the core liquid (ethanol, $n=1.36$) being lower than that of the cladding liquid (cinnamaldehyde, $n=1.62$), the optofluidic concave lens possesses light focusing effect. In order to measure the focal length of the optofluidic concave lens, the gray-scale images of the light rays in the ray-tracing chamber were captured. The flowrates of the cladding stream and the core stream are fixed at 0.5 ml/h.

Figure 5(a) shows the manipulation of the lens interface by adjusting the electric field added to the core stream under the fixed flow rates for the focusing mode of the optofluidic bi-concave lens. The error bars in Fig. 5 indicate the effect of flow fluctuation inside the lens chamber. In the experiments, the flow

Fig. 6 The interfacial shape of the optofluidic bi-concave lens in diverging mode based on the different applied voltages and fixed flow rates. The flow rates of core stream and cladding stream are all 0.05 ml/h: (a) V=4500 V; (b) V=4000 V; (c) V=3000 V; (d) V=0 V

rates of the core stream and the cladding streams were fixed at 0.5 ml/h, and the auxiliary cladding stream was fixed at 0.05 ml/h. The voltage added to the core stream changed from -5000 V to 1000 V. When the voltage is 0 V, the core stream is purely pressure driven. Under the same flowrates, the cladding stream ($\mu=5.7 \times 10^{-3} \text{ Ns/m}^2$) with high viscosity occupies a large part. The curvature of the interface between the core and the cladding stream is about 1.96 mm^{-1} . If the negative electric field is applied to the core stream, the core stream flows slower and occupies a larger part of the channel. The curvature of the interface decreases. The effect of electroosmosis becomes stronger with the increasing magnitude of the negative electric field. The curvature of the interface decreases with the increasing field magnitude. For the smooth curved interface, the curvature of the interface can be calculated according the radius of the interface using the relationship of $\kappa = 1/R$ where R is the radius of interface. The curvature reduces to 1.62 mm^{-1} when $V=-5000 \text{ V}$. A positive electric field drives the core stream flowing faster. The smaller core stream increases the curvature of the interface. The sensitivity of electroosmosis becomes low at high positive electric field.

Figure 5(b) shows the numerical and experimental focal length at different applied voltage and fixed flow rates of 0.5 ml/h. The intersection position of the rays and the optical axis is regarded here as the focal point. The focal point is calculated according the angular aperture of ray in the image space. The results show that the negative electric field increases the focal length and the positive electric field decreases the focal length. Figure 5 indicates that the numerical results have a good agreement with the experimental results.

Diverging mode

The diverging mode can be simply switched from the focusing mode by stopping the liquid (ethanol) of the core inlet. By this way, the previous cladding liquid (cinnamaldehyde) in focusing mode will converge in the rectangular chamber and becomes a

core stream. The auxiliary cladding liquid (mixture of 73.5% ethylene glycol and 26.5% ethanol) not only prevents light-scattering but also refracts light rays. The flowrates of the new core stream (cinnamaldehyde) and the new cladding stream (mixture of 73.5% ethylene glycol and 26.5% ethanol) are fixed at 0.5 ml/h. The electric field is applied to the new cladding streams.

Figure 6 shows a series of lens interfaces by adjusting the electric field applied to the cladding streams under the fixed flow rates of 0.5 ml/h. Similar to the previous case of focusing, under the positive electric field, the ion with positive charge within the cladding streams moves and drag the cladding stream flow along the electric field. The cladding stream flows faster. Under the fixed flow rate, the cladding stream with higher velocity will occupy a smaller part of channel. The core stream occupies a larger part of the channel and the curvature of the interface decreases. At the same time, if a negative electric field is added to the cladding streams, the positive ions move and drag the cladding liquid to flow opposing to the pressure. The cladding stream flows slower. Under the fixed flow rate, the cladding stream with slower velocity occupies a larger part of channel. The

Fig. 7 The experimental ray-tracing results for diverging mode under different electric field in the cladding streams and fixed flowrates of core fluid and cladding fluids: (a) $V = 0$ V; (b) $V = 5000$ V. The core fluid occupies a smaller part of the channel and the curvature of the interface increases. Figure 6 clearly shows that the curvature of the interface at $V=4500$ V is smaller than the curvature at $V=0$ V.

In the diverging mode, the light beam from the optical fibre will expand because the refractive index of the core liquid is higher than that of cladding stream. The similar experimental and numerical methods of ray-tracing method in the focusing mode are used to investigate the optical performance of diverging lens. The rays with the angular aperture in the image space were extracted from the recorded images. The divergent angle is the angle of the outer rays. Figure 7 shows the experimental results with flow rates fixed at 0.5 ml/h. The results show that the divergent angle can be changed using electric field at fixed flow rates. If the electric field is 0 V, the divergent angle is about 37.5° , Fig. 7(a). The divergent angle reduces into about 28° if the applied voltage increases to $V=5000$ V, Fig. 7(b).

Figure 8(a) shows the relationship between the electric field and the curvature of the interface under fixed flow rates for diverging mode. In the experiments, the flow rates of the core stream and the cladding streams are fixed at 0.5 ml/h. The voltage applied on the cladding stream changed from -1000 V to 5000 V. If the voltage is 0V, the core and cladding streams are purely pressure driven. The curvature of the interface between the core and the cladding stream is about 1.9 mm^{-1} . When the negative

electric field is added to the cladding stream, the cladding stream is slower and occupies a larger part of the channel. The curvature of the interface increases. For instance, the curvature is 1.96 mm^{-1} at $V=-1000$ V. The curvature of the interface increases with the

Fig. 8 Diverging mode: (a) Relationship between the external electric field and the curvature of the interface under fixed flowrates in the diverging mode of the optofluidic bi-concave lens, (b) Relationship between the external electric field and the focal length under fixed flowrates in the diverging mode of the optofluidic bi-concave lens. The flowrates of core stream and cladding streams are fixed at 0.5 ml/h.

increasing negative electric field. The positive electric field drives the cladding stream faster and decreases the curvature of the interface. For instance, the curvature is only about 1.57 mm^{-1} with $V=5000$ V.

Figure 8(b) shows the comparison between experimental results and the numerical simulation of the divergent angle. The results were obtained when the flow rates of the core stream and the cladding streams were fixed at 0.5 ml/h and the voltage along the cladding stream changed from -1000 V to 5000 V. If the positive electric field is very high, the curvature of the interface is small. The impact of the interface on the refraction of the light ray is small. Owing to the aperture, the opening angle of the light beam originating from the fibre is about 6° . The divergent angle was then expanded to 28° when the voltage reaches its highest value of $V=5000$ V. The divergent angle increases monotonously

as the positive electric field decreases, and reaches 38° with $V=1000$ V.

The radiant flux and the size of the illumination area can be controlled using the lens in diverging mode by adjusting the electric field. Moreover, this tuneable diverging lens may be useful for the correction of spherical aberration in an optofluidic lens systems.

Conclusions

This paper reports the design and characterization of an optofluidic bi-concave lens, which can perform both light focusing and diverging. The optofluidic bi-concave lens can simply switch from focusing mode to diverging mode. In focusing mode, the auxiliary cladding stream is introduced to sandwich the biconcave lens for protecting the light rays from scattering at the rough chamber wall. The core stream is conducting fluid and an external voltage is applied to the core stream. In the diverging mode, the core stream in the focusing mode is blocked, and the auxiliary cladding liquid not only avoids light-scattering but also becomes the low refractive-index cladding of the lens, the cladding streams of the focusing mode would join together in the chamber and become the core stream of the diverging mode. A voltage is applied to the cladding stream to control the lens curvature. In the numerical simulation, the electric force acts as a body force. The governing equations are solved using finite volume method on a Cartesian fixed staggered grid. The level set method was used to capture the interface. The results showed that the characterization of optofluidic bi-concave lens can be controlled using an external electric field under fixed flow rates. The optofluidic bi-concave lens can simply switch from the focusing mode to the diverging mode. In the focusing mode, the focal length can be adjusted electrically. A positive electric field in the core stream leads to a shorter the focal length. And a negative electric field results in a longer focal length. In the diverging mode, the light can be extended to a bigger divergence if a negative electric field is added to the cladding streams.

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