Set of two orthogonal adaptive cylindrical lenses in a monolith elastomer device

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Abstract: A microfluidic device that operates as a set of two adaptive cylindrical lenses focusing light along two orthogonal axes is designed, fabricated and characterized. The device is made out of a silicon elastomer, polydimethylsiloxane, using soft lithography, and consists of a few chambers separated by flexible membranes and filled with liquids of different refractive indices. The cylindrical lenses can be both converging and diverging; their focal lengths are varied independently and continuously adjusted between -40 and 23 mm by setting pressure in the chambers. Applications of the device to shaping of a laser beam, imaging and optical signal processing are demonstrated.

OCIS codes: (080.3620) Lens Design; (080.3630) Lenses

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1. Introduction

Adaptive optical elements are of great importance for various imaging and information processing systems, providing a "knob" for dynamic focusing, scanning and correcting aberrations. Traditionally, tuning of refractive optical systems has been made by moving lenses and changing the distance between the lenses, the objects and the image plane. An alternative strategy is varying the focusing power of a lens by either changing the refractive index of its material or changing its shape. The former option has been implemented with birefringent liquid crystals, LC, which can substantially change refractive index along one of the directions of linear polarization if an electric field is applied [1-4]. Unfortunately, the LC layers are usually very thin, and thus the overall modification of the optical path practically attainable with the LC devices is quite small (typically not more than a few wavelengths)[4]. Therefore, considerable numerical aperture can only be achieved with LC microlenses[4].

Variation of the focusing power of a lens by changing its shape requires essential deformability of the material the lens is made of. One of the options is to use a refractive interface between two immiscible liquids (or a liquid and a gas). Due to the surface tension such an interface naturally acquires a spherical shape and acts as a lens. As it has been demonstrated recently, the curvature of the interface and the focusing power of the lens can be tuned by application of an electric field using the electro-wetting effect [5,6]. Another implementation of a lens with a variable shape is a soft plastic shell filled with a liquid [7,8]. This old design has been recently revisited [9-12] due to development of soft lithography [13] and wide use of molded polydimethylsiloxane (PDMS) structures.

PDMS is a chemically inert, optically transparent silicon elastomer, which is an attractive material for adaptive lenses, because it is amorphous, easily moldable and can be made with a wide range of elastic moduli [14]. Moreover, flat-parallel PDMS membranes of optical quality can be readily fabricated with a variety of thicknesses. The adaptive PDMS single aperture lens [9-11] and microlens [12], which has been demonstrated recently, share a common design. A chamber with a shape of a short cylinder is molded in PDMS and is covered by a glass plate on one side, a circular flexible PDMS membrane on the other side, and is filled with a liquid. A gauge pressure applied to the chamber causes the membrane to bend. That creates, depending on the sign of the gauge pressure, a convex or concave interface between the liquid and the atmosphere air and a converging or diverging lens, respectively.

This design is based on a fast and simple fabrication protocol [9-12], and it allows constructing adaptive lenses with diameters from 200 μm to 20 mm and numerical apertures reaching 0.3 at highest pressures [10, 12]. Nevertheless, this design imposes a few limitations on the operation of the adaptive lenses. The lens becomes diverging when the gauge pressure in the chamber is negative. That makes the chamber subject to leakage of air from the atmosphere. Because emergence of air bubbles would seriously compromise operation of the lens, the chamber needs to be made air-tight. This requirement is very difficult to meet for a device with a thin membrane, which is made of PDMS and exposed to the atmosphere, since PDMS is a porous, gas-permeable material. Further, the thin PDMS membrane is permeable for vapors of low-molecular liquids (e.g. water). If the liquid inside the cavity is a solution or a mixture of low-molecular liquids, evaporation from the cavity may change its refractive index and cause a continuous drift in the properties of the lens. Because the density of the liquid is always much higher than that of the air, the shape of the flexible membrane is sensitive to the gravitational force, acceleration and mechanical shocks. Last, the thin membrane exposed towards the outside makes the lens easy to damage.

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Here we propose an alternative design of a liquid filled adaptive lens made of PDMS, which addresses the deficiencies of the existing constructions. In its simplest form the device has two chambers separated by a thin PDMS membrane and filled with liquids of different refractive indices. Modulation of the wave front of light occurs at the interface between the two liquids and is proportional to difference between their refractive indices and to the curvature of the membrane, which is controlled by difference in pressure between the two chambers. The both chambers always remain positively pressurized with respect to the atmosphere that prevents appearance of gas bubbles. The both cavities are separated from the atmosphere by thick layers of material that reduces evaporation of the liquids. Sensitivity of the shape of the membrane to the gravity and mechanical shocks depends on difference in density between the two liquids and can be reduced to a minimum if the densities are matched[6]. Last, placement of the flexible membrane in the interior of the lens makes the device more robust and less vulnerable.

2. Concept of operation

In order to demonstrate an implementation of the proposed design we have constructed and characterized a device with three chambers and two flexible membranes, Fig. 1. It operates as an assembly of two orthogonal independently controlled adaptive cylindrical lenses. Its prospective applications include focusing and shaping of laser beams, and astigmatism corrections.

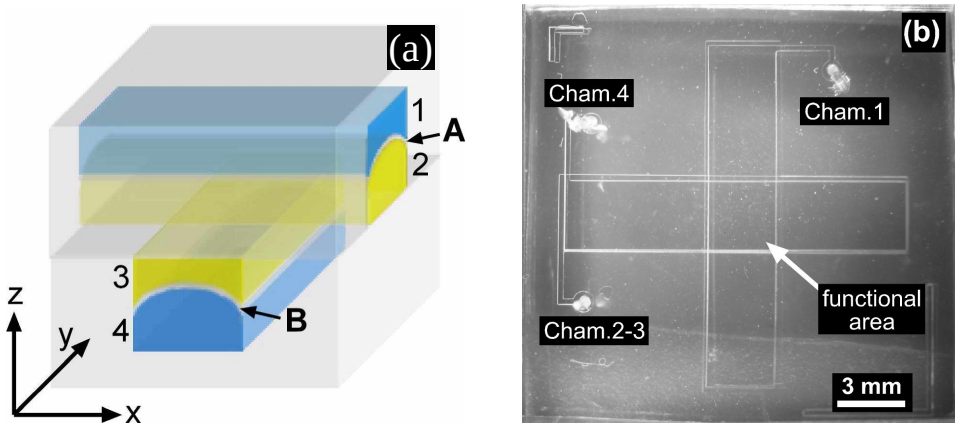

Fig. 1. (a) A schematic drawing of the device, demonstrating its operation as a positive cylindrical lens along the *y*-axis and a negative cylindrical lens along the *x*-axis. Numbers and letters A and B designate chambers (and layers) and membranes, respectively. The low refractive index liquid in chambers 1 and 4 is shown as yellow, and the high refractive index liquid in chambers 2 and 3 is shown as blue. (b) A micrograph of the fabricated device. Three inlets are connected to chambers 1, 2-3 and 4.

The device is made of 4 separate layers of PDMS, and has 4 layers of liquid-filled chambers, which are bonded together (Fig. 1). The main functional element in each layer is a ~250 μm deep rectangular chamber with a length to width ratio of about 5:1. The chambers in layers 2 and 3 (chambers 2 and 3) are connected and create a single cross-shaped chamber in the mid-plane of the device. The chambers in layers 1 and 4 (chambers 1 and 4) are separated from the chambers 2 and 3, respectively, by ~200 μm thick flexible membranes, A and B, which are 15×3 mm is size. Both membranes are parallel to *xy*-plane, with the long sides of membranes A and B directed along axis *x* and *y*, respectively. The membranes are centered with respect to a common axis, the optical axis of the device, which is parallel to the *z*-axis. The cross-shaped chamber in the mid-plane is filled with a liquid having a high refractive

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index, n_2. The chambers 1 and 4 are filled with another liquid, which has a lower refractive index, n_1. The optically functional area of the device is a 3×3 mm square window in the center, where the two membranes overlap.

Differences in pressure of the liquid in chamber 1, P_1, and chambers 2-3, P_2, cause bending of membrane A. The thickness and maximal deflection of the membrane (~250 μm) are much smaller than its width, and the width is 1/5 of the length. Therefore the shape of the bent membrane in the central 3 mm window is nearly cylindrical with the curvature in the *xz*-plane much smaller than the curvature in the *yz*-plane. The membrane creates a cylindrical interface between the liquids in chambers 1 and 2, which acts as a cylindrical lens modifying the wave front of light along *y*-axis. The lens is converging if $P_2 > P_1$ and the membrane bends towards the chamber 1 (as shown in Fig. 1(a)), and diverging if $P_2 < P_1$. If we neglect the phase modification by the curved membrane itself (it acts as a diverging lens independent of the direction of bending), we can estimate the focal length of the lens as $f_y = R_A /(n_2 - n_1)$, where R_A is the radius of curvature in *yz*-plane. Similarly, the interface between chambers 3 and 4 acts as a converging or diverging cylindrical lens (modifying the wave front along the *x*-axis) depending on the sign of $P_2 - P_4$. Its focal distance can be estimated as $f_x = R_B /(n_2 - n_1)$, where R_B is the radius of curvature of the membrane B.

A beam of light propagating through the functional area of the device passes through two cylindrical lenses perpendicular to each other. Their focal distances, f_x and f_y, are set by the pressure differences $\Delta P_x = P_2 - P_1$ and $\Delta P_y = P_2 - P_4$, respectively, and can be varied independently. A situation with $\Delta P_x > 0$ and $\Delta P_y < 0$ resulting in $f_x > 0$ and $f_y < 0$ is shown in Fig. 1(a). For the appropriate operation of the device, P_2 is set sufficiently high above the atmospheric pressure, so that P_1 and P_4 remain above the atmospheric pressure even for the largest negative values of ΔP_x and ΔP_y. This prevents formation of gas bubbles inside the device.

3. Fabrication

The device was fabricated using the technique of soft lithography [13]. It was assembled out of two almost identical parts, each of which consisted of two layers of patterned PDMS, 1-2 and 3-4, respectively. The four PDMS layers were cast individually using two designated master molds. The first mold was used for layers 1 and 4, and the second mold - for layers 2 and 3 (Fig. 2). The both master molds were 6" silicon wafers with 250 μm thick relief of cured SU8 epoxy on them. They were fabricated with contact photolithography by spin-coating the wafers with SU8-2100 photoresist (MicroChem, Newton MA) and exposing them to UV-light through appropriately designed photomasks.

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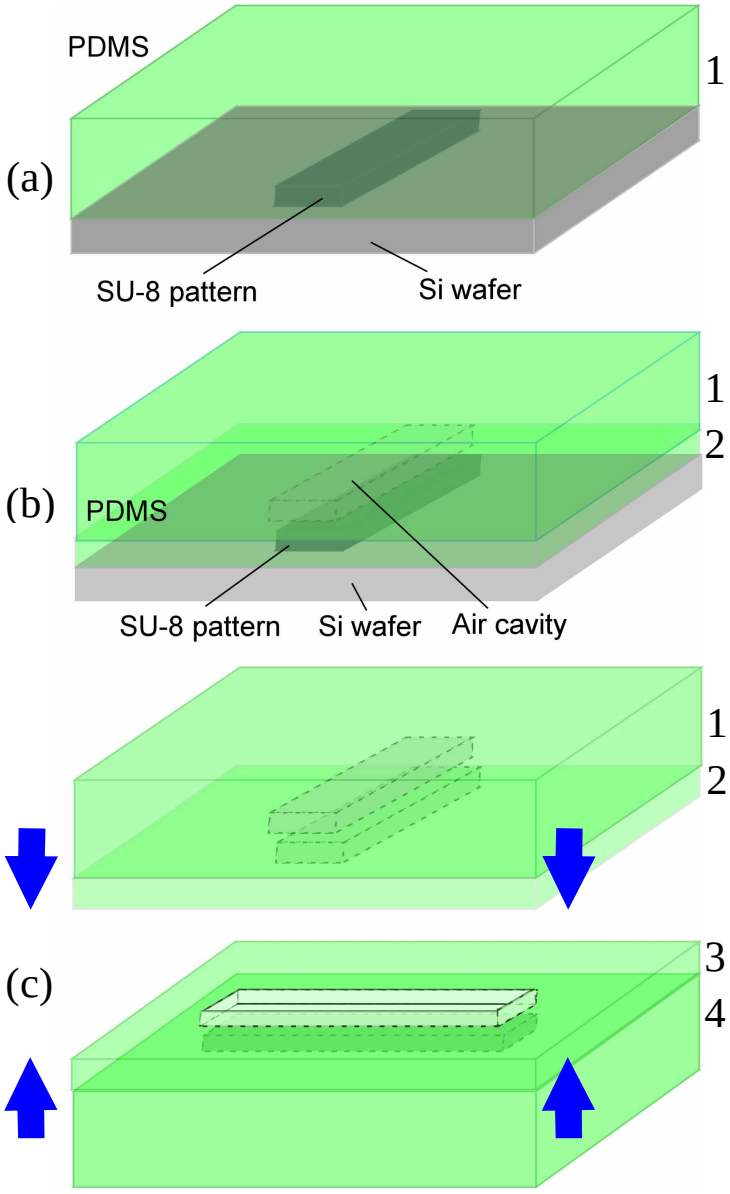

Fig. 2. Schematic drawing showing consecutive steps of the device fabrication. (a) The master mold defining chamber 1 with the PDMS cast on the top. (b) The PDMS chip with chamber 1 is aligned on top of the master mold that defines chamber 2 and is spin-coated with a thin layer of PDMS. (c) Two parts of the device with chambers 1 and 2 (top) and 3 and 4 (bottom) are brought into a contact and bonded.

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To make the layers 1 and 4, a ~4 mm thick layer of PDMS pre-polymer (a 5:1 mixture of resin and curing agent of Sylgard 184 by Dow Corning) was poured on the first mold and partially cured by baking in an 80 °C oven for 30 min. The solidified PDMS was peeled off from the mold and cut into individual chips. In order to make ports for feeding liquids to the chambers 1 and 4, a hole was punched in each chip with a gauge 16 luer stub. The thin PDMS layers 2 and 3 were made by spin-coating the second master mold with a ~450 μm thick layer of the PDMS pre-polymer (Sylgard 184) with the resin and curing agent mixed in a proportion 20:1. The mold was baked in an 80 °C oven for ~30 min to partially cure PDMS.

The mold relief features forming the chambers 1 and 4 were 15×3 mm, and those forming the chambers 2-3 were 15.5×3.4 mm. In order to complete the two two-layer parts of the device, the 4 mm thick chips (1st and 4th layers) were placed on top of the PDMS on the second mold. The rectangular chambers 1 and 4 were manually aligned with the slightly larger chambers 2 and 3, respectively (Fig. 2). The mold was then baked in an 80 °C oven for 2 hours to completely cure PDMS and to produce monolith two-layer chips [15]. That created the ~200 μm thick 15×3 mm membranes A and B separating the rectangular channels. The frames of those membranes were defined by the 4 mm thick layers of PDMS (layers 1 or 4), and had little compliance compared with the membranes.

The two-layer PDMS chips were trimmed to their final sizes and peeled off from the mold. After that holes were punched in the chips with layers 1-2 using a gauge 16 luer stub to make ports for feeding liquid to the chambers in layers 2-3. The chips were treated with oxygen plasma to make their surfaces adhesive, and bonded together by bringing layers 2 and 3 in a contact with an appropriate alignment of the membranes.

4. Filling the device and controlling the pressure

The device was tested with distilled water as the low refractive index liquid ($n_1 = 1.33$) and a microscope immersion liquid (#5095, Cargille Laboratories Inc.) as the high refractive index liquid ($n_2 = 1.58$). The immersion liquid had a density of 0.981 g/cm^3, very close to the density of water, and viscosity of ~10 cPs, about 10 times higher than the water viscosity. The liquids were kept in three separate 1 cc plastic syringes and fed to the device inlets through flexible tygon tubing with inner diameter of 1 mm. The syringe with the immersion liquid was connected to chambers 2-3, while the two syringes with the water were connected to chambers 1 and 4, respectively. The syringes were held upright and open to the atmosphere. They were attached to sliding stages on vertical rails that allowed setting and controlling hydrostatic pressure [16]. The chambers were filled with the liquids by connecting the syringes to a source of compressed air with a pressure ~20 kPa for about two hours. The pressurized liquids displaced the air, which diffused out of the chambers through the pores in PDMS.

After filling the device the gauge pressure in the chambers 2-3 was set to a constant value $P_2 = 4.65$ kPa (a difference of 480 mm between levels of the immersion liquid in the syringe and of the chambers in the device). The differential pressures ΔP_x and ΔP_y were generated hydrostatically and evaluated by measuring the differences in the levels of water in the corresponding syringes and the level of the immersion liquid[16].

5. Results and discussion

We characterized the device experimentally for laser mode shaping, imaging and optical signal processing applications. First, we found the reference values of ΔP_x and ΔP_y, at which the corresponding cylindrical lenses had zero focusing power ($f_x = 0$ and $f_y = 0$, respectively). They were both equal to $\Delta P_0 = 0.6$ kPa. The non-zero value of ΔP_0 is probably due to some non-uniformity in thickness or residual curvature of the microfabricated PDMS

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membranes. The insertion loss of the device was ~13%, and we expect it to be reduced to as little as 7%, if appropriate anti-reflection coatings are applied to the two PDMS-air interfaces.

Next we measured the dependence of the focal lengths f_x and f_y on ΔP_x and ΔP_y, respectively. The measurements of the dependence of f_x on ΔP_x were performed with $\Delta P_y = \Delta P_0$ and vice versa. The results are shown in Fig. 3. A 0.5 mm collimated beam derived from a single mode HeNe laser (λ = 632.8 nm) was incident along the optical axis of the device onto the center of its functional area (the 3×3 mm square, where the two membranes overlap, Fig. 1). The shape of the beam at various distances behind the device, *z*, was recorded by a CCD camera (Pulnix TM-7EX, camera, 768×494 pixels, 8.4×9.8μm pixel size) positioned at the optical axis in the path of the laser beam.

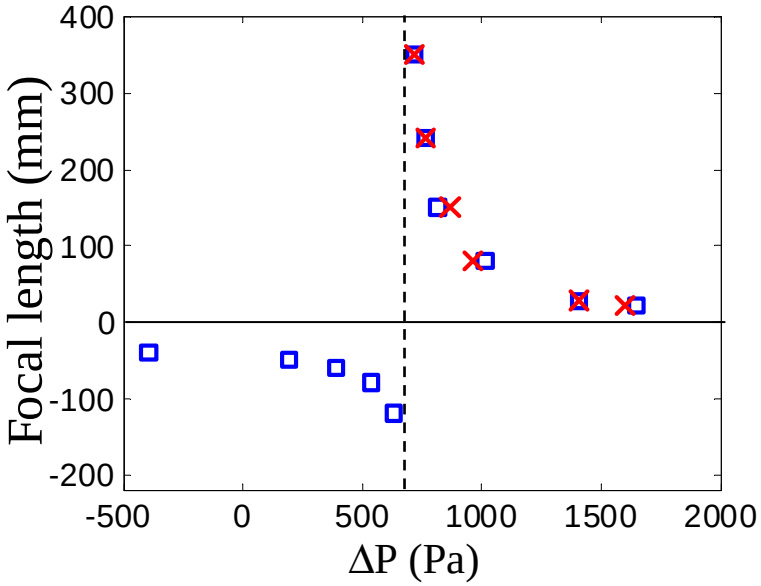

Fig. 3. Focal lengths of the cylindrical lenses focusing light along the *x*-axis (squares) and *y*-axis (crosses) as functions of the pressure differences, ΔP_x and ΔP_y, respectively.

For $\Delta P_x > \Delta P_0$ ($\Delta P_y > \Delta P_0$) the focal length f_x (f_y) was positive and it was found as a distance *z* (measured from the mid-plane of the device), at which the size of the beam in the *x*-direction (*y*-direction) was the minimum. One can see (Fig. 3) that the dependencies of f_x on ΔP_x and f_y on ΔP_x are very similar, indicating that the two cylindrical lenses are nearly identical. The both focal lengths are infinite at $\Delta P = \Delta P_0$ and become as small as ~23 mm at high ΔP. The saturation in the dependence of f on ΔP at $\Delta P > 1.8$ kPa is primarily due to the finite depths of chambers 1 and 4 (Fig. 1, 2).

In order to measure negative focal lengths at $\Delta P_x < \Delta P_0$, we placed a converging spherical lens with a focal length of 100 mm at a distance of 60 mm in front of the device. We then calculated f_x at various ΔP_x (Fig. 3) based on the focal distance for the composite optical system (the distance between the focal point and the mid-plane of the device), which was positive for $f_x > -40$ mm and was measured using the same procedure as before. By varying

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ΔP_x from ΔP_0 to -0.4 kPa, f_x was varied from -∞ to -40 mm (Further reduction of ΔP_x resulted in even smaller negative f_x, but those could not be measured with the set-up we used).

Dispersive properties of water and the immersion liquid in the visible light range are substantially different. As λ increases from 400 nm to 700 nm, n_1 drops from 1.34 to 1.33, while n_2 goes down from 1.62 to 1.57. Therefore, the focal lengths of both cylindrical lenses are expected to vary by as much as 16% across the visible spectrum range. Nevertheless, the chromatic aberration should not affect the laser mode shaping and focusing applications, and can be reduced with an alternative set of liquids.

A representative profile of the beam focused in both *x*- and *y*-directions and recorded by the CCD camera is shown in Fig. 4. The CCD array was positioned in the focal plane at $z = f_x = f_y = 32$ mm (at $\Delta P_x = \Delta P_y = 1.22$ kPa). The extension of the beam (full width at half maximum) in both *x*- and *y*-directions (Fig. 4(a) and (b), respectively) is ~40 μm (see also inset in Fig. 4(a)).

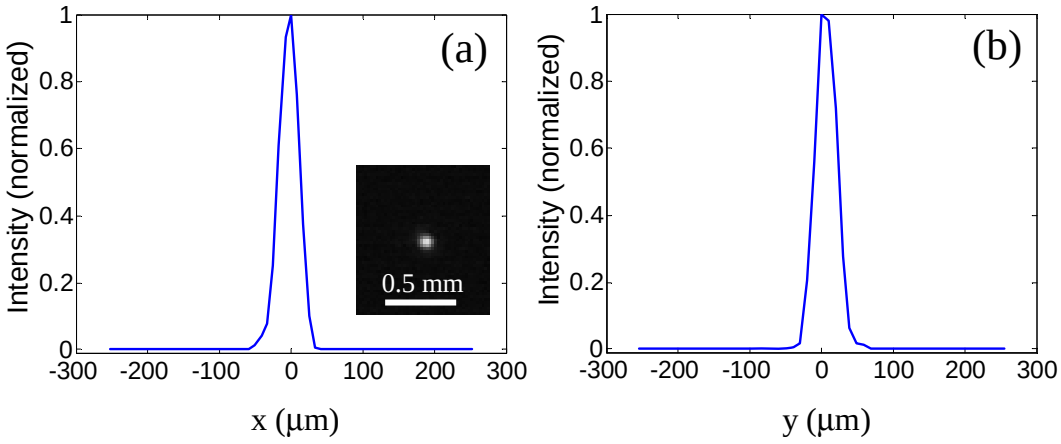

Fig. 4. Intensity profiles of a laser beam focused at 32 mm from the device and captured by a CCD camera in the focal plane: (a) along the *x*-axis and (b) along the *y*-axis. *Inset in (a):* a fragment of read-out of the CCD camera.

Variation of f_x and f_y can be used for independent adjustment of extension of a laser beam along the *x*- and *y*-axis, respectively, and for changing the shape of the beam, as shown in Fig. 5. The incident HeNe laser beam is collimated to the same diameter of ~0.5 mm as before, and the pressures are initially set to the same value as before, $\Delta P_x = \Delta P_y = 1.22$ kPa , corresponding to $f_x = f_y = 32$ mm. Thus at *z* = 200 mm, where the CCD array is placed, the beam is expanded about fivefold and has a roughly circular shape with a diameter of about 2.5 mm (Fig. 5(a-c)). As it is shown in Fig. 5(d-i), if ΔP_y or ΔP_x is set to 0.8 kPa, the beam becomes focused along the *y*-axis (Fig. 5(d-f), $f_y = 200$ mm) or the *x*-axis (Fig. 5(g-i), $f_x = 200$ mm), respectively, and the shape of the beam becomes highly elliptical with an aspect ratio of ~10.

Comparing the beam intensity profiles in Fig. 5(b) and 5(e), and Fig. 5(c) and 5(i) one can see that focusing of the beam in the *y*-direction has no appreciable effect on its profile in the *x*-direction and vice versa. Therefore, variations of ΔP_x and ΔP_y are directly translated into changes in f_x and f_y, respectively, with practically no cross-talk.

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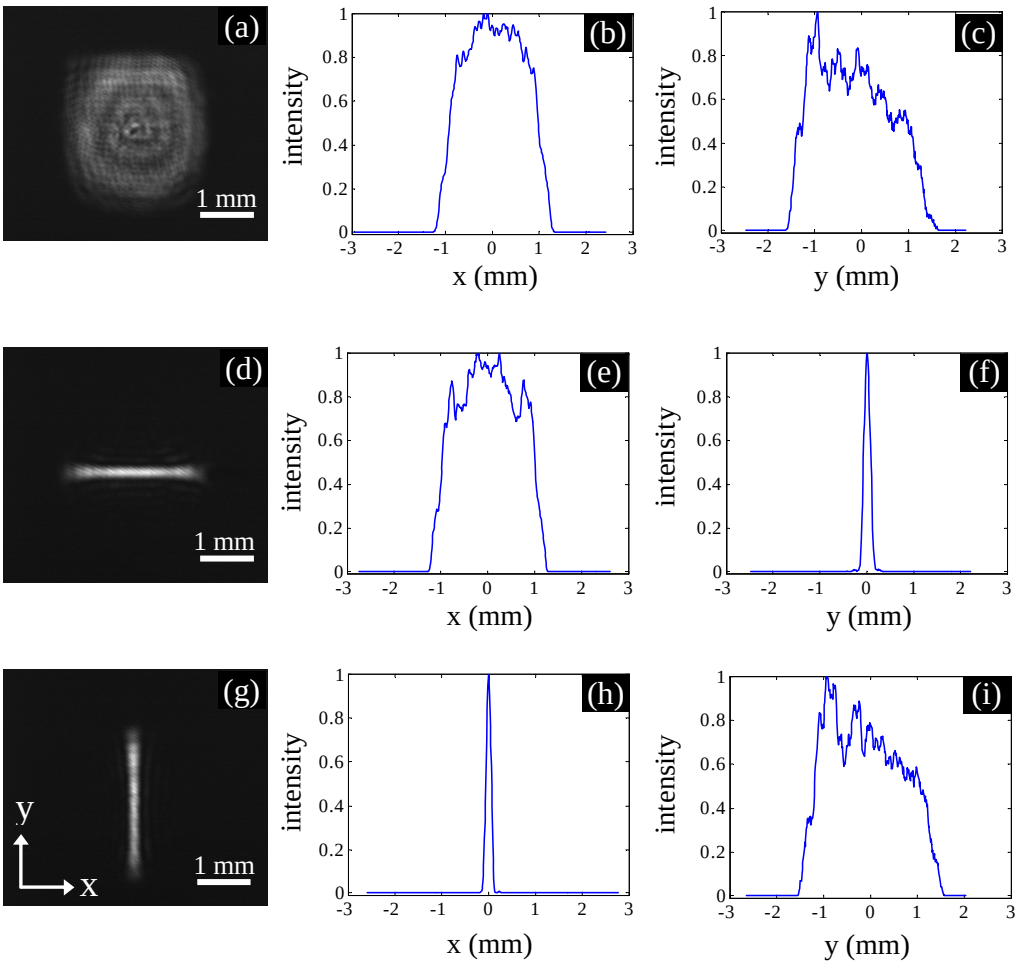

Fig. 5. Demonstration of the laser mode shaping with a CCD camera placed at z = 200 mm behind the device. The driving pressures are: (a-c) $\Delta P_x = \Delta P_y$ = 1.2 kPa; (d-f) ΔP_x = 1.2 kPa, ΔP_y = 0.8 kPa; (g-i) ΔP_x = 0.8 kPa, ΔP_y = 1.2 kPa. The panels (a), (d) and (g) show patterns of light on the CCD. The panels (b), (e) and (h) show intensity profiles in the *x*-direction (along a line going through the center of the laser spot), and the panels (c), (f) and (i) show intensity profiles in the *y*-direction. The intensity profiles in (b) and (e), (c) and (i) are nearly identical that implies practically no cross-talk between the two lenses. Movie (started by a click on (a)) shows the transition between (a) and (g) after ΔP_x is switched from 1.2 kPa to 0.8 kPa.

A real time movie, showing gradual transition from the 2.5 mm wide circular spot to a sharp vertical line (the beam focused in the *x*-direction) can be viewed by clicking on Fig. 5(a). The response of the lenses to variations of ΔP is somewhat analogous to the response of an *RC*-circuit to variations of voltage. For the lenses the counterpart of the resistance is proportional to viscosity of the liquids filling the device, and the counterpart of the capacitance (ratio of change in volume to change in pressure) is proportional to compliance of the PDMS membranes. The characteristic response time of the device in its current configuration is a few seconds. We believe that the response time can be reduced by at least an order of magnitude, if the chambers 2-3 are filled with an immersion liquid with a lower

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viscosity, and if the membranes are made of PDMS with a higher Young's modulus. (Young's moduli of some special formulations of PDMS can reach ~8 MPa [14], while the 20:1 mixture of the resin and curing agent of Sylgard 184 that we used for the membranes has Young's modulus a few times lower than the nominal 3 MPa for a 10:1 mixture).

In addition to the laser mode shaping, the device can be applied to imaging and optical signal processing. To demonstrate those capabilities, we used a resolution target consisting of a set of three 90 μm wide and 450 μm high slits at distances of 180 μm from each other, Fig. 6(a). The target was placed at a distance $l_1 = 46$ mm in front of the device (measured from the mid-plane) and illuminated by a collimated HeNe laser beam directed along the optical axis. The recording CCD array was positioned behind the device at the same distance, $l_2 = 46$ mm. The device was operated in a regime of a spherical lens with $f_x = f_y = f$ by setting $\Delta P_x = \Delta P_y = \Delta P$. Fig. 6(b) shows the light pattern on the CCD obtained at $f = 23$ mm (corresponding to $\Delta P \approx 2$ kPa), which is a sharp 1:1 image of the target. The pattern of light on the CCD at $f = l_2 = 46$ mm ($\Delta P \approx 1.1$ kPa) is shown in Fig. 6(c), and it corresponds to a Fourier transform of the target with the zero and +/-1 orders of diffraction clearly seen. The +/-2 orders are missing because of the 50% duty cycle of the target (Ronchi pattern) that suppresses even orders of diffraction. The +/-3 orders of diffraction appear as faint bright spots on the left and on the right, and the higher odd orders of diffraction have power too low to be seen. The possibility of switching between an image and its Fourier transform without moving any components of the optical system could be useful for dynamic optical information processing.

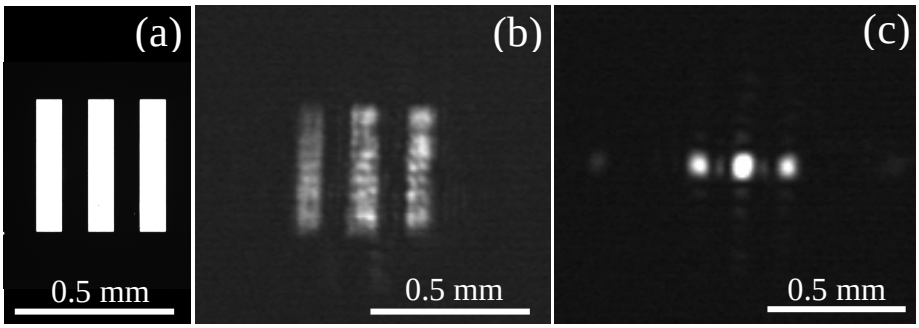

Fig.6. Demonstration of imaging and optical signal processing. (a) Image of a target taken under a microscope; (b) image of the target projected on the CCD by the device at $2f = l_1 = l_2$; (c) Fourier transform of the target (diffraction pattern) projected on the CCD at $f = l_2$.

6. Summary

We designed, fabricated and characterized a microfluidic device that operates as a set of two adaptive cylindrical lenses, which focus light along two orthogonal axes (*x* and *y*). The device has four chambers that are filled with two liquids of different indices of refraction and separated by flexible PDMS membranes. The focal lengths (f_x and f_y) of the both lenses can be continuously varied between -40 and 23 mm and adjusted independently, with practically no cross-talk, by setting pressures in the chambers. The interior of the device is always positively pressurized that prevents formation of air bubbles even when both f_x and f_y are negative. The membranes and the chambers are covered by ~5 mm thick layers of PDMS, which makes the device mechanically robust and protects the liquids from

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evaporation. The densities of the high and low refractive index liquids we used differed by only 2%, and an alternative set of liquids could result in an even better density matching. Therefore, if the membrane curvature is controlled by direct adjustment of volumes of the liquids in the chambers (rather than by setting the pressures), e.g. by a syringe pump or an on-chip peristaltic pump[15], the device is expected to have very little sensitivity to gravity and to mechanical shocks. The response time of the device, which is currently a few seconds, could be significantly reduced by using liquids with lower viscosity and PDMS formulations with higher Young's modulus.

The proposed device can be used for laser beam shaping, adaptive correction of astigmatism, focusing and imaging, and optical information processing.

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