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(Some figures in this article are in colour only in the electronic version)

Abstract

The interest in dynamically tuning light has attracted great attention to the fabrication of tunable microlens arrays. Here we discuss the fabrication and characterization of a simple, robust, yet tunable microfluidic optical device with integrated microlens array. The microfluidic device with desired channel structure was micromachined on a polycarbonate plate with a resolution up to 100 μm, followed by thermal bonding two plates above their glass transition temperature. The microlens arrays were replica molded on a glass slide, which was then attached to the polycarbonate plates. By simply actuating the liquids with variable refractive index into the fluidic channel to immerse the lens arrays without moving or deformation of microlenses, a large change of focal length of more than 10 times (f = 0.74 to 8.53) was achieved. When a dye-containing liquid was pumped into the microfluidic channel to cover the lenses, the light transmission through the lenses was reduced from about 95% to 55% when the dye concentration was increased to 10 w/v %. The knowledge we gain from these studies will provide important insights to construct new, adaptive, micro-scale optical devices with multiple functionalities.

1. Introduction

Recently the fabrication of dynamically adjustable optical structures have attracted great attention due to the importance of the tunability of optical properties for various device applications , including tunable photonic waveguides[1], miniature optical sensing[2], electronic display[3], and wide-zoom cell phone and PDA cameras[4]. Of many optical components, microlens arrays have played an import role in focusing, detection, imaging and coupling of light. However, most synthetic microlenses only have simple functions, and their optical properties are fixed. In comparison, millions of years of evolution have perfected many of the optical features of biologically formed lenses with a wide range of tunability, including variable focus, double vision, wide field-of-view, tunable transmission and wavelength selectivity.[5, 6] It will be highly desirable to have compact, multifunctional, and tunable microlens arrays that mimic the biological design and functions.

Several tunable microlenses have been demonstrated. For example, in gradient index (GRIN) lenses, the refractive index of a lens can be controlled using an electrostatic potential.[7, 8] A microlens made of flexible polymeric materials, which are either filled with liquid[9, 10] or placed on a microfluidic chip[11, 12], deforms upon mechanical actuation of liquids, thus, tuning the lens focal length.[11] Similar approach has been applied to a microdoublet lens, consisting of a tunable liquid-filled lens and a solid negative lens.[13, 14] The liquid-filled lens can either change the shape into bi-convex or meniscus under pressure of pumping liquid or be filled with liquids with different refractive indices, which minimizes optical aberrations and maximize the tunability of focal length or field-of-view. In a quite different approach, we have recently demonstrated a conducting liquid as a tunable microlens.[15, 16] The liquid lens can reversibly change its position and curvature in response to

applying voltage between the droplet and a planar electrode embedded in a dielectric substrate at a certain distance from the liquid - solid interface. Another approach to change lens focus is to use responsive hydrogels as lens materials that will change lens shape in response to external stimuli.[17] Nevertheless, most of the reported examples of tunable lenses have rather limited tunable range and complexity.

An interesting feature of the lens design has been described in a light-sensitive brittlestar. This organism forms a pore network surrounding the lenses,[6] which is used for the diurnal transport of pigment-filled chromatophore cells. This design feature is a key component of an adaptive optical device that provides transmission tunability, diaphragm action, wavelength selectivity, minimization of the "cross-talk" between the lenses, and improved angular selectivity.[18] The variable transmission and wavelength selectivity are of particular interest in applications, including electronic display[3], a high contrast spatial light modulator[7], and gray scale photolithography[19]. Inspired by the unique lens design and the consequent outstanding optical properties in brittlestars, we search for novel approaches to create a structure that combines microlens arrays with microfluidics.[20] Here we present a simple and effective fluidic channel that can be easily fabricated and integrated with microlens arrays, allowing dynamic tuning of the refractive index and light absorption of the surrounding medium to achieve a wide zooming range (up to 10 times) and variable transmission.

2. Materials, Design and Fabrication

2.1. *Fabrication of microlens arrays*. The microlens arrays were fabricated using the replica molding technique (see Fig. 1). First, the microlens array master were fabricated through photoresist reflow on the silicon wafer.[21] A Silicon wafer was

cleaned by sonication in isopropyl alcohol and acetone for 20 minutes, respectively, followed by the exposure to oxygen plasma (Harrick Plasma Cleaner, NY, USA) for 5 minutes to generate hydroxyl groups on the surface. Photoresist Shipley 1818 (Rohm & Haas Electronic Materials, MA, USA) was spun on the pre-cleaned silicon wafer at 1000 rpm for 30 sec, pre-exposure baked at 115 ^{o}C for 60 seconds and cooled to room temperature. The film was then exposed to an ultraviolet light at 365 nm (BLAK-RAY lamp, Model B) for 30 seconds through a photomask (dots, 100 μm in diameter and 150 μm pitch). The film was post-exposure baked at 115 ^{o}C for 60 seconds, and developed in CD-30 Developer (Rohm & Haas Electronic Materials, MA, USA). A poly(dimethylsiloxane) (PDMS) precursor (RTV 615, GE Silicones, NY, USA) was mixed with its curing agent in a ratio of 10:1 by weight, and cured at 65 ^{o}C for two hours to replicate the master. Glass cover slips (VWR Micro Slides, precleaned, plain, 25 x 75 mm) served as the substrates for the microlens arrays throughout the experiment. They were rinsed with acetone, alcohol, followed by immersing in a 0.1M aqueous potassium hydroxide (KOH) solution for 15 minuets to remove any contaminants and generate hydroxyl groups on glass. The substrates were then rinsed with DI water and air-dried. For rigid lenses, Norland 68 (Norland Products. Inc., NJ, USA) was molded on a pre-treated glass substrate using the PDMS stamp by exposing to UV light for 10 minutes.

2.2. *Design and fabrication of microfluidic channel.* The channel design and dimension is shown in Fig.2. The microfluidic devices were fabricated from two polycarbonate plates (Ensinger Ltd., Pontyclun, UK). One of which was machined with Computer Numerical Control (CNC) machining system (Fadal VMC15XT milling machine, CA) (see Fig. 3A). Specifically, the microconduits and chamber

were machined in a 250 μm thick polycarbonate plate. The conduits had a square cross-section with width and depth of 250 μm, respectively. In order to reduce the surface roughness, the conduit and chamber inner surfaces were polished subsequently. After machining and cleaning with isopropyl alcohol, the plate was bonded with second polycarbonate plate (250 μm thick), which would serve as the transparent window, in a hot press machine (Twelve Ton Press No. 3850, CARVER Inc., IN) at 140 °C and the press force was 1340 Newton (Fig. 3B). After 50 minutes of pressing, the hot plates were cooled to ambient temperature under pressure. The PC plates with the microfluidic channel were flipped facing down and bond together with the glass slide with microlens arrays through a double-sided tape at four corners (Fig. 3C). Finally, two plastic tubings were glued to the end of the channel as inlet and outlet, respectively (Fig. 3D), for actuation of fluids.

Fluids with different indices, including phenylmethylsiloxane homopolymer (PMM-0011, n=1.470, viscosity at 25^{o}C, 10-20 cSt.), dimethylsiloxane-ethylene oxide block copolymer (DBE-712, n = 1.4416, viscosity at 25^{o}C, 20 cSt.), and trimethylsiloxy terminated polydimethysiloxane (DMS-T11, n = 1.399, viscosity at 25^{o}C, 10 cSt.), were used as received from Gelest Inc. (PA, USA).

2.3. *Optical characterization*: The microlens arrays were observed using Olympus BX51 optical microscopy in transmission mode with a 40 x objective. Images were taken using a Color CCD camera (HANDYCAM, DCR-PC 330, Sony Corporation). The geometry and sizes of the fabricated lenses were studied using Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) on a JEOL 6300F FEG HRSEM and Digital Instruments Dimension 3000, respectively, at the Penn Regional Nanotechnology Facility (PRN). Focal length of microlens arrays in different

reflective index liquids was measured using Olympus IX81 inverted microscope with an oil-immersion objective (Olympus 60 x, numerical aperture = 1.45) and an appropriate set of filters (540LP and 630SP, Omega Optical).[22] 514.5 nm circularly polarized light from an Ar^+ ion laser (National Laser Company, Salt Lake City, Utah, USA) was used as a source of excitation. QuickTime 5 Professional, MATLAB (Mathworks Inc.), and custom Labview software were used to analyze the optical properties of the microlenses.

3. Results and Discussion

3.1. Calculation of the Focal Length of the Microlenses. For image formed by refraction at a spherical surface, the image focal length (*f*) is defined as[23]

$$f = n_2 R/(n_2 - n_1) \qquad (1)$$

where R is the lens radius, and n_1 is the refractive index of the surrounding medium, and n_2 is the refractive index of the lens. For a thin, hemispherical lens, R can be defined as[21]

$$R = \frac{(D/2)^2 + h^2}{2h} \qquad (2)$$

where D is the base diameter of lens and h is the thickness, respectively. The focal length of the lens, therefore, is a function of lens shape (lens diameter and thickness), and index contrast between the lens material and the surrounding medium. In our experiment, microlens arrays from optical adhesive Norland 68 (n = 1.54) were replicated from a PDMS mold under UV exposure. A lens master for replication was fabricated by resist reflow.[21] Lenses with a diameter of 100 μm and a pitch of 150 μm were used throughout the experiment. Limited by the resolution of the photomask printed on the transparency, edge roughness and inhomogeneity of the lens diameter

was observed, resulting in some variation of the lens thickness. Since the lenses were relatively large and thin, the lens thickness was estimated as ~3 μm according to the scanning electron microscopy (SEM) and atomic force microscopy (AFM) measurement (see Fig. 4) to provide the guidance for the calculation of the lens focal length by eq 1 and 2. For example, for n_1 = 1.0 (air), n_2=1.54 (Norland 68), D = 100 μm, and h = 3 μm, the focal length is 1.15 mm. More uniform lens arrays can be obtained from a higher resolution photomask.

3.2. *Design of the fluidic channel with integrated microlens arrays.* The integration of microlens arrays with a fluidic channel offers an attractive possibility to achieve a wide range of tunability of the lens optical properties, including varied focal length, transmission, numerical aperture and wavelength selectivity. Recently we have developed an electrowetting pump in recirculating fluidic channels that can digitally tune the optical fiber properties.[1, 24, 25] The electrically controlled and fully reversible motion of the fluid plugs in these channels alters the refractive index profile experienced by the optical waveguide modes of the fiber. When combined with in-fiber gratings and etched fibers, this fluidic system yields dynamically adjustable narrow and broadband fiber filters, respectively. The non-mechanical operation, low power consumption, fast switching speeds (on the order of milliseconds), and excellent optical characteristics indicates a promising potential for electrowetting-actuated fluidic tuning in many photonic components.

Using the similar concept of dynamically tuning the optical properties using microfluidics without mechanically moving the optical components, here we attempt to fabricate a simple, robust, yet effective fluidic channel that can be integrated with microlens arrays. Registration marks to align the channel with the microlens arrays

are not necessary. Control of fluid movement can be separated from the lens/channel. In our experiment, two polycarbonate (PC) plates, one of which was milled the desired channel structure by computer controlled micromaching with a resolution up to 100 μm, were bonded together through hot pressing at 140^{o}C, close to the glass transition temperature of PC, 148^{o}C (see Fig. 3). PC is highly transparent, which is essential for accurate measurement of variable focal lengths and transmission. A glass slide with molded microlens array were then attached to the bottom PC plate using double-sided tape to ensure flat contact, which minimizes measurement errors caused by possible non-flatness in polycarbonate plates. Glass can be easily cleaned using acetone or alcohol for recirculation of different liquids. Liquids with different refractive indices, dye concentrations, and pH values were actuated in and out of the channel using a syringe pump. In most cases, after we introduced the liquids, we either kept the liquid still in the channel or use a slow pump rate of 50 μl/min to minimize any disturbance to the microlenses and optical measurement. However, we did not observe any damage to the microfluidic channel or detachment of the microlenses with a pump rate up to 200 μl/min. The pump rate can be increased to a few mL/min when the microlens array/glass is permanently bonded to the PC plate. It can be achieved by casting a thin, uniform layer of epoxy (e.g. SU8) at the corners of the glass slide. After placing the PC microfluidic channel on top of the glass slide, the whole device is heated above the glass transition temperature of epoxy, followed by UV or thermal curing of the epoxy to glue glass and PC plates together.

*3.3. Variable focal length of rigid lenses tuned by the refractive index of surrounding liquid***.** Microlens with variable focal length over a wide range is of great interest to increase the efficiency of the light detection, recording, imaging, and coupling.

Although many approaches have been proposed, including change of the refractive index and shape of the lenses, here we demonstrate that it is more straightforward and efficient to vary the refractive index of the surrounding medium to achieve high focal length adjustment.

First, we fabricate a rigid lens array from optical adhesive, Norland 68. The lens shape and position are fixed, and liquids with different indices are actuated into the fluidic channel to cover the lens array. The focus length of the lens array increases along with the increase of the liquid's refractive index. The zooming range will depend on the geometry of the lens and the index contrast. The focal length was measured using the setup shown in Figure 5. The collimated laser beam is 2 mm in diameter with a peak wavelength of 448 nm. It was aligned to be normal to the lens arrays. The focal point was defined as the smallest and most intense focal spot observed through a CCD camera. The position of the focal plane of the lens arrays were adjusted using a micromanipulator in the z-direction with a resolution of 1 μm. The relative distance from the focal plane to a zero reference point was recorded as the focal length. The accuracy of the measurements is limited by our ability to visually identify the focal plane.

To facilitate the smooth actuation, liquids with low viscosity (≤ 20 cSt.) were chosen in our experiment. By simply actuating the liquids with variable refractive index, ranging from n = 1.00 (air) to n = 1.47 (phenylmethylsiloxane homopolymer, PMM-0011), into the fluidic channel to immerse the lens arrays, a large change of focal length, more than 10 times (f = 0.74 to 8.53), was achieved (see Figure 6). The tunable range of focal length can be further increased using fluids with index closely match to that of Norland 68, n =1.54. For example, by varying the concentration of aqueous solution of sodium dichromate ($Na_2Cr_2O_7 \bullet 2\ H_2O$) while keeping the low

viscosity, we can fine-tune the refractive index from 1.33 to 1.5.[1] The dynamical tuning of focal length presented here is large, yet achieved by a simple and straightforward method without moving or deformation of microlenses.

In comparison, in the liquid crystal immersed GRIN lenses, change of refractive index upon application of a voltage is small, $\Delta n \approx 0.1\text{-}0.2$, resulting in a relatively small optical path modulation.[7] In the electrowetting tunable liquid lens, the contact angle change becomes saturated at high voltages due to the electrostatic charge accumulated on the surface or the boundary limitation of the electrodes. Thus, the change of focal length is limited to 30 %.[15, 16] In the liquid filled lens or membrane lens assembled in the microfluidic devices, lens shape is mechanically deformed by the application of liquids, and a maximum of focal length change up to 6 times has been demonstrated.[10] When using a more sophisticated microfluidic chip, which consists of a double PDMS membrane lens, focal length change can be increased to more than 20 times.[12] Nevertheless, the tunable range is dependent on the applicable force (or the volume of the fluid pumped in and out of the lens chamber), which will be limited by the mechanical strength of the lens materials.

Since the lens thickness was estimated ~3 μm, we calculated the focal lengths as reference and compared to the experimental results. As seen from Figure 6, within the measurement error the measured image focal length (0.74 to 8.53mm) agrees reasonably well with the expected values (1.19-9.2 mm). The errors could be due to the variation of lens thickness, the inhomogenity of lens diameter originated from the photomask, and the uncertainty in identifying the exact location of the focal planes, especially when the focal length is small.

3.4. Variable transmission using dye-containing solutions. To mimic the transmission tunability in the brittlestar optical system achieved by the migration of pigment-filled chromatophore cells in the channeled network surrounding the lenses, we previously assembled a simple microfluidic device to actuate photoactive liquids within the synthetic porous microlens array.[20] When a dye-containing liquid was pumped through the pores surrounding the lens, we illustrated the reduction in light transmission through the lenses, whose intensity can be adjusted by the dye concentration and/or thickness of the dye layer covering the lens.

Recently a PDMS microfluidic channel filled with light-absorbing dye at desired concentrations has been demonstrated as a tunable photomask.[19] The opacity of the photomask features can be tailored to an arbitrary gray-scale level to produce three-dimensional (3D) microstructures. Clearly such strategy can be applied to microlens arrays filled with desired dye solutions to control the degree of illumination through the lens. It offers a simple and low-cost approach for 3D imaging and lithography with spatial resolution. For a given dye solution, detailed study is needed to predict the transmission through the lens as a function of the dye concentrations.

Congo red, a red-brownish azo dye, was dissolved in water at different concentrations to demonstrate the transmission tunability (see Figure 7). A standard optical microscope equipped with a CCD camera was used to capture optical images in transmission mode through the microlens arrays. The initial focal plane of the lens arrays in water and the light intensity passing through the lenses were observed and recorded as a reference. The microfluidic device containing aqueous solution of a dye was then fixed at the measured focal plane, and the light intensity passing through the lenses was recorded again as the final state. Transmission was defined as the ratio of

the final state light intensity to the initial state light intensity. As seen in Figure 7, the transmission varied from about 95% to 55% when the dye concentration was increased to 10 w/v %. Further decrease of transmission was not investigated because of the solubility of congo red in the aqueous solution. Dyes with higher solubility could be used in the future, allowing broader range of tunability. Since most dyes are wavelength selective, it is possible to mix a variety of dye molecules to enable a wide range of spectral response though the microlens arrays. The sensitivity to specific colors is quite common in biological eyes to view objects under murky conditions, and detect fine shades of colors.

We have shown the wide range tunability of focal length and transmission from rigid lenses, whose shape and position are fixed once fabricated, by changing the refractive index and light absorption ability of the liquids surrounding the lens arrays. However, such tuning of optical properties is rather discreet. To fine-tune the optical properties, we are investigating a multiple channel design (see Fig. 8) to separately or simultaneously pump multiple liquids with different optical characteristics (variable refractive index, light absorbing, light responsive, wavelength selective, etc.). Similar strategy has been tested by us previously to independently pump multiple microfluidic plugs into or out of overlap with an optical fiber, allowing for a variety of different configurations to modulate the fiber transmission.[25] In a separate effort, we have fabricated soft lenses from hydrogels, which could change the shape, volume and refractive index continuously in response to external stimuli (pH, temperature, etc.). The results will be reported elsewhere.[26]

4. Conclusions

We present a simple, robust and cost-effective method that combines micromachining and soft lithography to fabricate microfluidic devices integrated with microlens arrays. The microfluidic device with desired channel structure was fabricated using computer controlled micromachining of a polycarbonate plate with a resolution up to 100 μm, followed by thermal bonding two plates above their glass transition temperature. The microlens arrays (100 μm in diameter, 3 μm thick) were patterned on glass through replica molding, which was then attached to the polycarbonate plates. By simply actuating the liquids with variable refractive index into the fluidic channel to immerse the lens arrays without moving or deformation of microlenses, a large change of focal length of more than 10 times (f = 0.74 to 8.53) was achieved. When a dye-containing liquid was pumped into the microfluidic channel to cover the lenses, the light transmission through the lenses was reduced from about 95% to 55% when the dye concentration was increased to 10 w/v %. The knowledge we gain from these studies will provide important insights to construct new, adaptive, micro-scale optical devices with multiple functionalities.

Acknowledgments.

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Captions of Figures:

Figure 1. Replica molding process to fabricate the microlens array.

Figure 2. Design and dimensions of the fluidic channel integrated with microlens arrays. Illustrative images: (**a**) Top view, (**b**) side view, and (**c**) 3-D view. (**d**) Actual image of the fluidic channel device used in the experiment.

Figure 3. Fabrication process of the microfluidic optical device: **A**. Micromachine the polycarbonate (PC) conduits and chamber, **B**. Thermal press two PC plates at 140^{o}C, **C**. 1) Flip microfluidic channel upside down, and 2) bind glass slide with microlens arrays with microfluidic channels through double-stick tape at four corners, **D**. Attach plastic tubings.

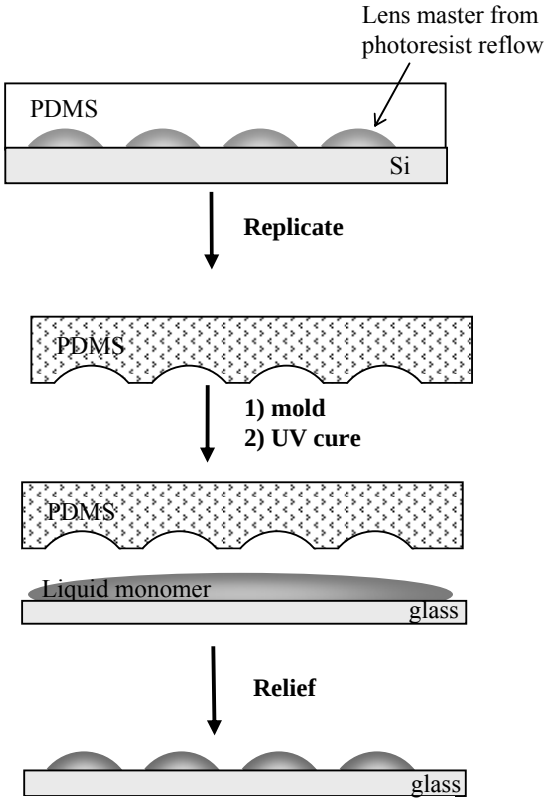
Figure 4. SEM and AFM images of the molded microlenses.

Figure 5. Illustration of the instrumentation setup to measure the focal length.

Figure 6. Measured and calculated focal lengths of microlens arrays versus the refractive index of the surrounding medium. The lines are used to guide the eyes.

Figure 7: Transmission versus the concentration of congo red aqueous solution.

Figure 8. A multiple microfludic channel design to actuate different types of optical fluids.



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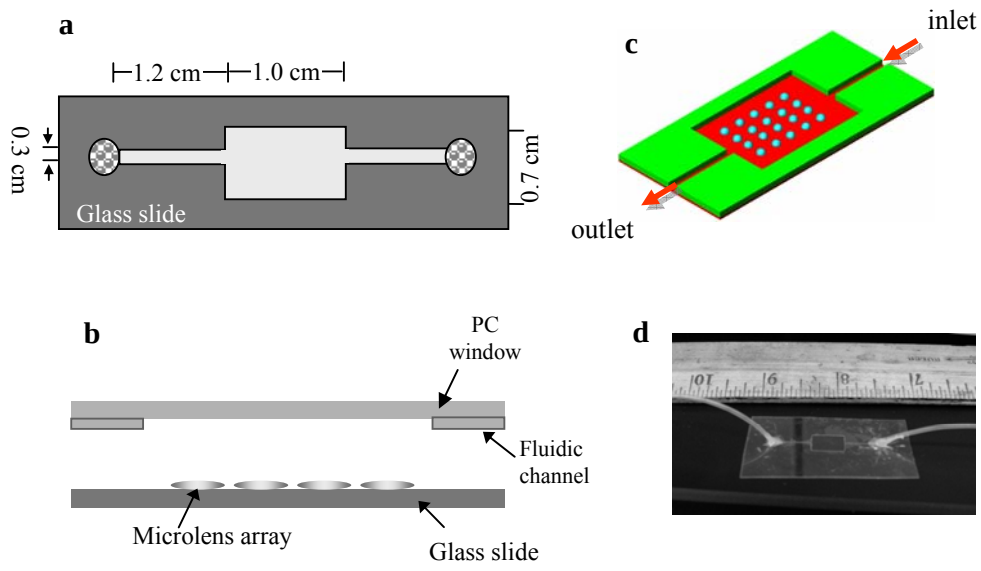

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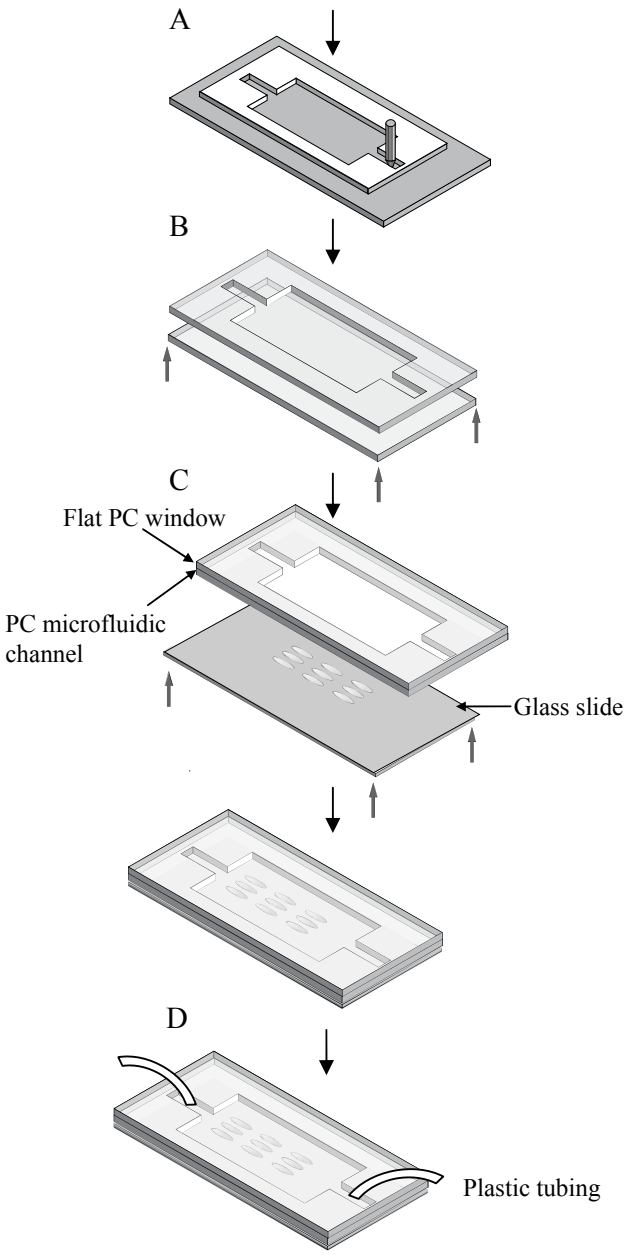

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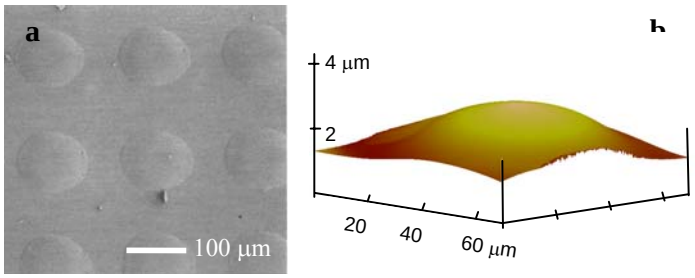

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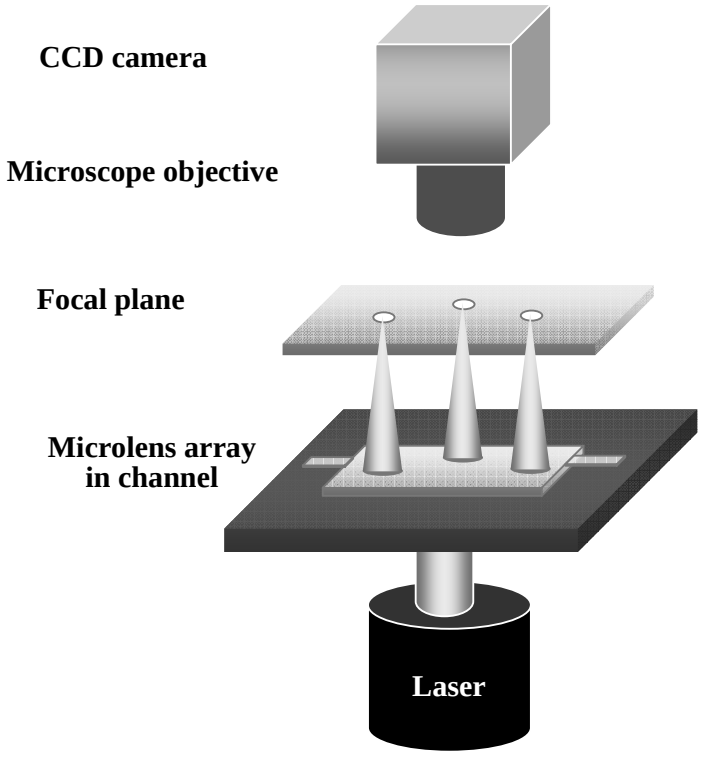

Figure 5. Illustration of the instrumentation setup to measure the focal length.

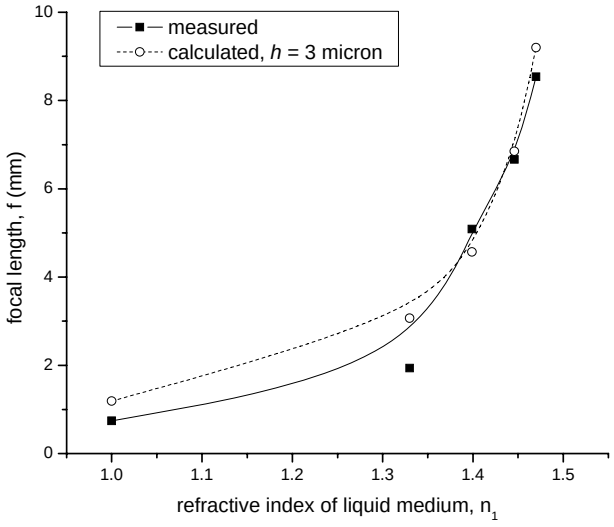

Figure 6. Measured and calculated focal lengths of microlens arrays versus the refractive index of the surrounding medium. The lines are used to guide the eyes.

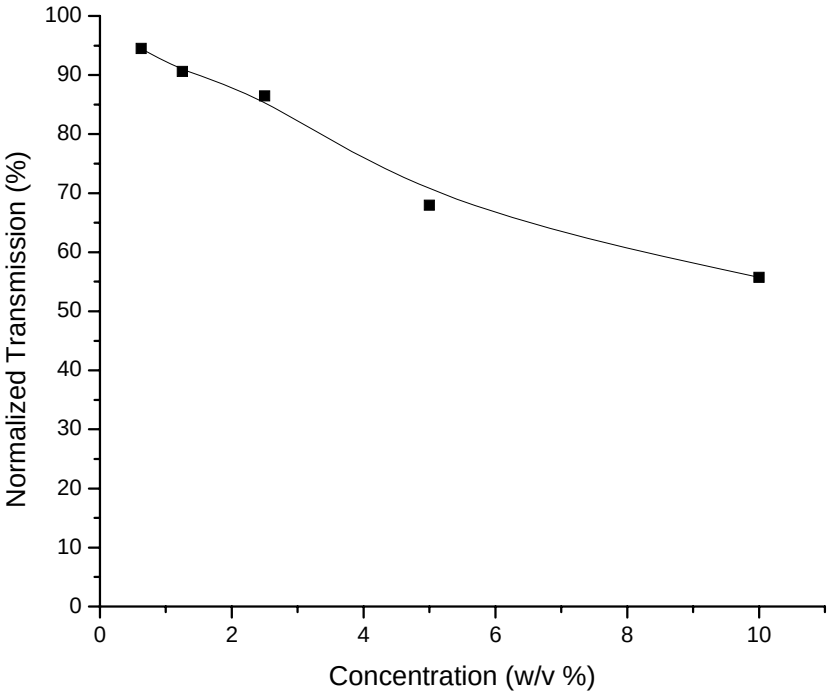

Figure 7. Transmission versus the concentration of congo red aqueous solution.

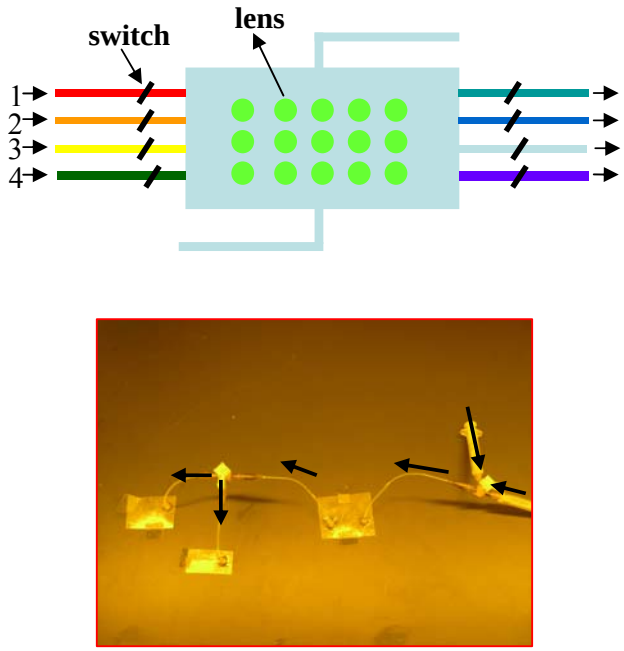

Figure 8. A multiple microfludic channel design to actuate different types of optical fluids.