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REVIEW

Tunable optofluidic devices

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Abstract The emerging field of optofluidics provides exciting opportunities for the realization of tunable optofluidic devices (TODs) using a large variety of physical mechanisms. This is because microfluidics is a promising technology for achieving a high degree of tunability—a capability that is not available in many of the current optical devices. In addition, microfluidics holds a great potential for rapid prototyping, miniaturization and integration. TODs already find commercial applications in various fields such as display and imaging, and are expected to become a key player in future optical systems for biology, medicine, communication and information processing. We review the recent progress in the field and discuss potential future directions.

1 Introduction

During the last few years we are witnessing the emergence of a new, multidisciplinary research field of optofluidics, which is essentially the integration of microfluidic science and technology with optical components and methods. The flourish of optofluidics is evident by the exponential growth in number of publications, as detailed by several recent review papers (Psaltis et al. 2006; Monat et al. 2007; Whitesides 2006).

An important result of the optofluidic activity is the realization of TODs. One of the major advantages of integrating microfluidic technology with optical devices is the capability of the optofluidic devices for adaptation and tunability. There are major benefits of using fluids (liquids and/or gases) for achieving tunability: liquids with large variety of refractive indices can be brought to interact with the optical beam. Liquids can also be mixed on a chip to form a specific refractive index of interest. Moreover, liquids form smooth boundaries, which are vital for low-loss optical devices, primarily in guided wave configuration, where the interaction length between the optical mode and the boundary is relatively long. Liquids can also be mixed with gain or absorbing medium, thus allowing to control the amount of gain/loss in the device. Another important feature of liquids is their relatively high thermo-optic coefficient, in the order of 10^{-4}–10^{-3} l/K, making them ideal candidates for thermal tuning.

Many of the optofluidic devices are made of a soft elastomer, polydimethylsiloxane (PDMS). Besides the well-known advantage of rapid prototyping, PDMS, being an elastic medium (typical Young modulus < MPa) allows very large tunability by modifying the geometry of the optical device under the application of internal (usually in the form of gas pressure) or external forces. Flexible elastomer membranes are also key elements in pressure-actuated micro-valves that can be integrated in the optofluidic devices.

One of the fundamental terms in optics is the "optical path length". According to Fermat, the path taken between two points by a ray of light is the path that can be traversed in the least time (the more accurate version of Fermat's principle states that the optical path length must be extremal, i.e. it can be either minimal, maximal or a saddle point). The optical path length is the product of the physical path length and the refractive index of the medium. Thus, changing either the refractive index of the medium or

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the physical path length (or both) leads to optical modulation.

The common approach for tuning optofluidic devices is through refractive index modulation, leading to a change in the phase, the amplitude and/or the polarization of the electromagnetic field propagating through the optical device. Phase modulation is typically achieved via changing the real part of the refractive index, while polarization modulation is achieved by changing the amount or the orientation of the birefringence of the optical medium. Amplitude modulation can be achieved either directly (via changing the imaginary part of the refractive index) or indirectly through interferometric approaches combined with phase modulation or through polarization modulation in conjunction with polarizers. The last concept is used by the most common tunable optofluidic device, namely the liquid crystal display which is very common in everyday life.

In addition to refractive index modulation, an optofluidic device can be tuned through the variation of its geometry, essentially leading to a change in the refractive index distribution of the medium, $\vec{n}(x, y, z)$. Many of the optofluidic device functionalities are determined by the geometry of boundaries between solid and liquid, solid and gas, liquid and gas or liquid and liquid. As many of the optofluidic devices are made of soft elastomer, the device shape can be easily tuned by the application of a driving force. Changing the shape of the elastomer shifts or alters the geometry of the boundary, thus modifying the optical path length.

Various mechanisms can be used to control optofluidic devices, utilizing a variety of physical effects modifying either the geometry of a boundary between the materials having different refractive indices, or the refractive index of the medium itself (Fig. 1). Examples for mechanisms that can be used for geometrical modulation include electrowetting (changing the wetting angle by the application of an electric field), optical trapping and optoelectrowetting (by applying optical control beam). The geometry of a boundary can also be modified by exploiting the high elasticity of PDMS using external force or internal gas pressure actuation. Examples for mechanisms that can be used to change the refractive index include electro optic effect (by applying an electric field), thermo optic effect (through heating of the liquid), magneto optic effect (using a magnetic field), and mixing of liquids (either off chip or on chip using an on-chip microfluidic mixer). In this review, we describe the recent progress in the field of TODs, with focus on the various mechanisms that were used to tune the optofluidic devices, the type of modulation (geometry vs. refractive index), and the functionalities of the optofluidic devices.

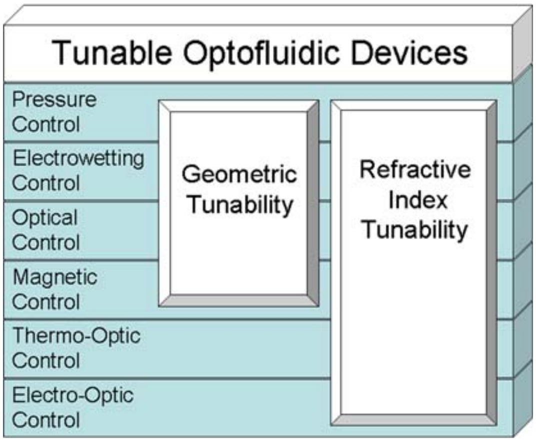

Fig. 1 Tunability of optofluidic devices can be realized by geometric modulation or refractive index modulation. These effects are driven by various control mechanisms (specified on the *left side*)

2 Geometric tunability

We start by describing the important application of optofluidic lens. Nowadays, optical devices and components are being utilized in large variety of applications, ranging from communication and signal processing to biotechnology and medicine. Still, the “bread and butter” optical application is imaging. At the heart of an optical imaging system one can always find the lens. A standard lens, being made of solid, is very difficult for tuning and adaptation. Therefore, tuning of refractive optical systems is typically realized by moving and changing the distance between the lenses, the objects and the image plane. Alternatively, one can use a liquid lens to vary the focusing power of the optical imaging system by either changing the refractive index of the liquid or by changing its shape. The former option will be mentioned briefly in the second part of this review. In this section we focus on lenses that can be tuned via a change in their shape.

Tunable lenses can be realized by controlling the interface between two immiscible liquids (or a liquid and a gas) having different refractive indices. Due to surface tension such an interface naturally acquires a spherical shape and acts as a lens. The idea of using liquid droplets as lenses was first introduced by the British scientist Stephen Gray in the seventeenth century (Gray 1697). As demonstrated recently, the curvature of the interface between a droplet and air (or between two immiscible liquids) can be tuned by the application of an electric voltage using the electro-wetting effect (i.e. the control of surface energy and wetting angle of electrically conducting droplets by the application of an electric field), resulting a large tunability in the focal length of a droplet based lens (Berge 2000; Krupenkin et al. 2003; Kuiper and Hendriks

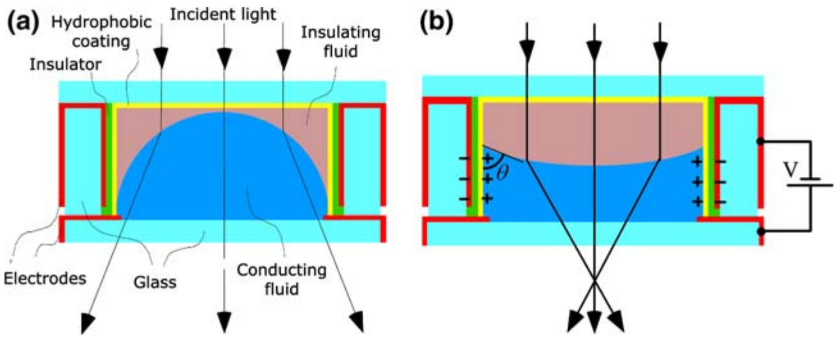

Fig. 2 Philips fluidfocus: electrowetting-driven tunable lens. **a** With no voltage applied, the conducting droplet is spherical, maximizing the contact angle with the hydrophobic walls. **b** With voltage applied, the contact angle between the conducting droplet and the insulated-electrode walls is reduced, the meniscus direction is flipped and the focal length of the lens becomes positive. Focal length can be controlled continuously from negative to positive

2004). Kuiper and Hendriks used a transparent cylindrical chamber containing two immiscible liquids, a conducting salt solution with a refractive index of ~1.38 and an insulating oil with a refractive index of ~1.55 (Fig. 2). The meniscus between the two liquids is the basis for the lensing functionality. The bottom of the chamber is made of hydrophilic glass substrate with conducting electrodes on its edges. The walls of the chamber are coated with electrodes that are covered with an insulating layer and another hydrophobic layer. The transparent top section of the device is also covered with a hydrophobic layer. With no voltage applied, the meniscus between the liquids is perfectly spherical (by engineering the liquids to be density matched), with the salt solution having large contact angle with the hydrophobic coating, making the salt solution side of the meniscus convex. Under the application of an electric voltage between the isolated electrodes and the conducting electrode at the bottom, free charges in the salt solution move according to the new electric potential, decreasing the contact angle between the salt solution and the side walls, and changing the shape of the meniscus. In this way, the focusing power of the lens is controlled with a timescale of few milliseconds, similar to other electrowetting driven applications. A smaller version of a liquid lens, in which droplet size is below the capillary length making the effect of gravity negligible, was recently demonstrated (Krogmann et al. 2006). This tunable lens was defined in Silicon, offering the advantage of relying on a mature and cost effective fabrication process. Commercialized electrowetting variable liquid lenses are used in cellular phone cameras and new generation DVD machines.[1]

Another implementation of a lens with a variable shape is a soft plastic shell filled with a liquid (Wright 1968; Knollman et al. 1971). This old design has been recently revisited (Zhang et al. 2003, 2004a, b; Chronis et al. 2003; Werber and Zappe 2005; Ren et al. 2006) due to the development of soft lithography (Xia and Whitesides 1998) and wide use of molded PDMS structures. The adaptive PDMS single aperture lens and micro lens 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, creating a convex or concave interface between the liquid and the atmosphere air and a converging or diverging lens, respectively. A recent work (Pang et al. 2005) took this concept a step forward by fabricating a device having two chambers separated by a thin PDMS membrane and filled with liquids of different refractive indices (Fig. 3). Modulation of the wave front of light occurs at the interface between the two liquids and is proportional to the difference between their refractive indices and to the curvature of the membrane, which was controlled by difference in pressure between the two chambers. Both the chambers always remain positively pressurized with respect to the atmosphere and the appearance of gas bubbles is thus prevented. Both the cavities are separated from the atmosphere by thick layers of material that reduces evaporation of the liquids. Sensitivity to gravity and mechanical shocks was reduced by matching the density of the liquids. Also, the two chambers had a cylindrical shape and were aligned perpendicular to each other. Therefore, the focus power could be controlled independently for each axis allowing unique applications e.g. beam shaping and aberrations correction.

The examples discussed so far were based on changing the profile of a boundary to control the focal length of a lens. Another interesting work based on similar mechansim is the electrowetting-driven micro prism (EMP) used

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[1] More information can be found at Varioptic web site: http://www.varioptic.com.

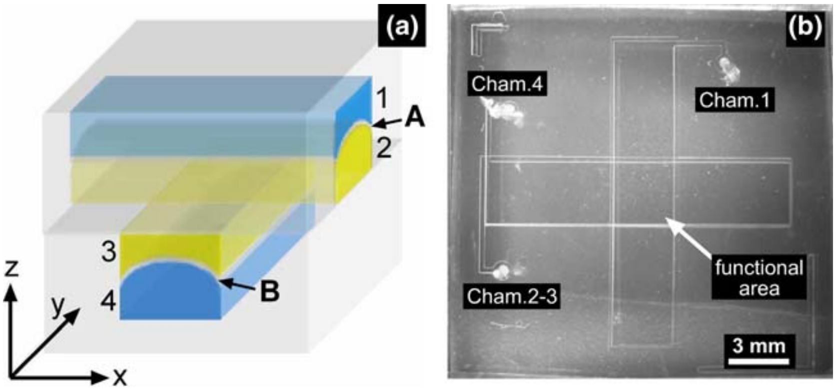

Fig. 3 A pressure-driven optofluidic tunable lens. **a** A schematic drawing of two orthogonal adaptive cylindrical lenses demonstrating operation as a positive cylindrical lens along the *y*-axis and as a negative cylindrical lens along the *x*-axis. Numbers and letters *A* and *B* designate chambers (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. Reprinted from Pang et al. (2005)

for wide-angle beam steering (Smith et al. 2006). This device is made of a rectangular cell with a transparent glass window at its bottom. Two of the cell walls (on the opposite sides) are made of conductive silicon electrodes, covered with an oxide layer for electrical isolation and fluoropolymer to create a hydrophobic surface. The cell is partially filled with electrically grounded salt solution. The shape of the liquid–gas boundary (i.e. the surface separating the salt solution and the air from above) depends on the contact angles with each of the two opposite walls (Fig. 4). With no voltage applied, the boundary has a round profile, minimizing the surface energy. By applying a specific voltage to each of the walls, the boundary becomes flat, and creates a micro-prism, with a deflection angle controlled by the careful choice of the two voltages.

Another work related to the control of a boundary profile is the electrowetting-driven area tunable micro mirror (Wan et al. 2006), demonstrating optofluidic tunability via modifying the shape of a liquid–gas boundary (a plano-convex mercury droplet and air, Fig. 5). The droplet becomes flat under the application of electrical field, and thus can be used as a mirror. Here, the large surface energy of mercury allows the use of relatively large droplets. In contrast to the previous examples, where the boundary was formed between materials having a difference in the real part of the refractive index the mercury tunable mirror device in contrast is based on the imaginary part of the refractive index (zero for air, large value for mercury). Therefore, it is operating in reflection mode. Such a device can also be used as a reflecting negative lens because of the spherical shape of the droplet.

Another type of TOD is the liquid–liquid (L^2) waveguides demonstrated by the Whitesides group and others (Wolfe et al. 2004; Brown et al. 2006), where the

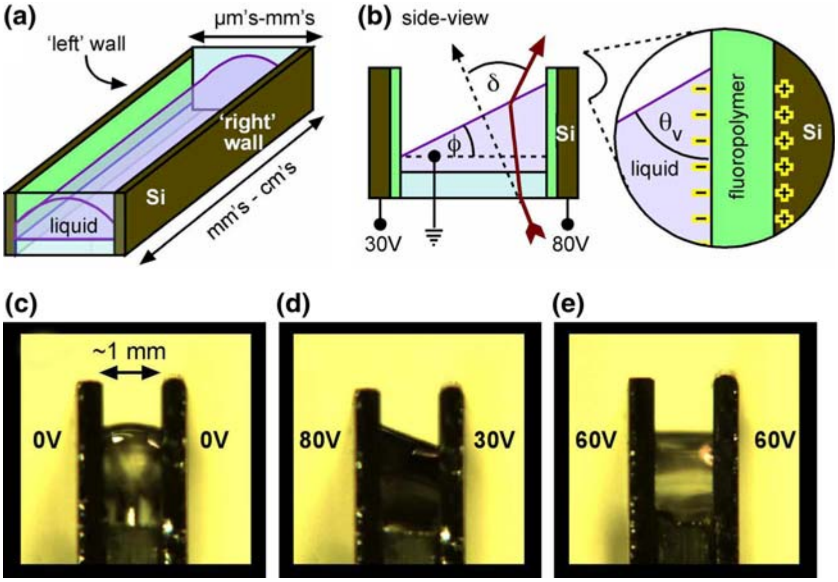

Fig. 4 Slanted view diagram (**a**) of representative channel geometry for EMPs, with no voltage applied. **b** Side view diagram of an EMP voltage connection, angle for prism apex (ϕ), deflection (δ) and liquid-fluoropolymer contact angle (θ).Side-view photographs of EMPs with (**c**) zero voltage and (**d**, **e**) various voltage/prism configurations. The liquid is electrically grounded and voltages are applied to the side-walls. Reprinted from Smith et al. (2006)

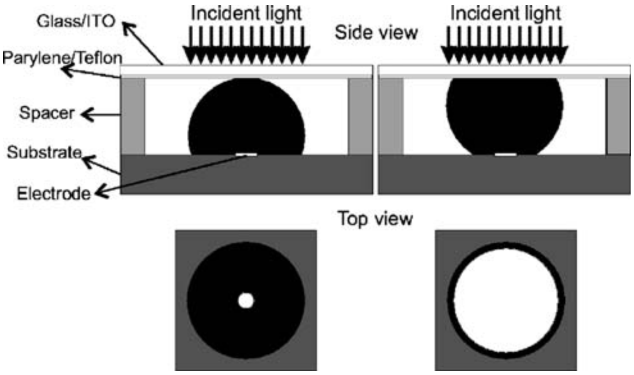

Fig. 5 Schematics of the concept and the experimental setup of an area tunable micro mirror. *Left* no voltage applied, the incident light is diverged by the spherical surface; *right* an applied voltage between the droplet and the transparent top electrode deforms the droplet and forms a high reflective flat surface. The *top* views show the corresponding reflective area (*white*). Reprinted from Wan et al. (2006)

manipulation of light in waveguides that comprise a liquid core and a liquid cladding was demonstrated. The liquids are introduced into the channels of a microfluidic network designed to sandwich the flowing core liquid between the flowing slabs of the cladding liquid. The core/clad boundary can be controlled by manipulating the rate of flow of the liquids, allowing the tunability of the optofluidic waveguides.

Tunability of optofluidic devices can also be achieved simply by stretching of a PDMS substrate. Two recent examples are the tunable optofluidic laser and the complex membrane approach. Tunable optofluidic laser devices were recently demonstrated by several groups and in several configurations, e.g. Fabri-Perot (Bilenberg et al. 2006), ring laser (Gersborg-Hansen et al. 2005) and distributed feedback (DFB) (Li et al. 2006) The optofluidic tunable distributed feedback (DFB) dye laser demonstrated by the group of Psaltis (Li et al. 2006) was fabricated on a monolithic PDMS chip, with a microfluidic channel filled with a liquid of slightly higher refractive index than that of PDMS forming a single mode buried channel waveguide. The optofluidic laser design is based on an earlier work from the same group (Erickson et al. 2006). A DFB structure is realized by creating PDMS posts within the channel, forming a 15th-order Bragg grating at a wavelength of approximately 570 nm. The gain medium is a solution of Rhodamine 6G or Rhodamine 101 in a methanol and ethylene glycol mixture. The device is pumped optically using a pulsed, frequency doubled Nd:YAG laser. Tunability was obtained by stretching the entire PDMS structure, such that the effective period of the DFB structure could be controlled (see Fig. 6). Tunability range of about 30 nm was achieved for Rhodamine 6G and for Rhodamine 101. Combining the mechanical tuning mechanism with the capability to exchange the gain medium could provide tunability range larger than 60 nm.

In many cases, it is desired to control optofluidic devices by applying an internal gas pressure, similar to the approach used for the tunability of the optofluidic lenses. Nevertheless, an internal pressure is expected to deform the membrane in the out-of-plane direction. While this is beneficial for some applications (e.g. the tunable lens), it might pose a stringent limitation of the amount of tunability that can be used, in cases where a planar device is of interest. A possible remedy is to use the recently demonstrated complex membrane approach (Campbell et al. 2006). The approach is based on the fabrication of composite membranes having pieces of rigid UV-cured epoxy grafted inside PDMS. The dimensions and positions of the epoxy parts are defined with high precision by UV-lithography. The use of the composite membranes was

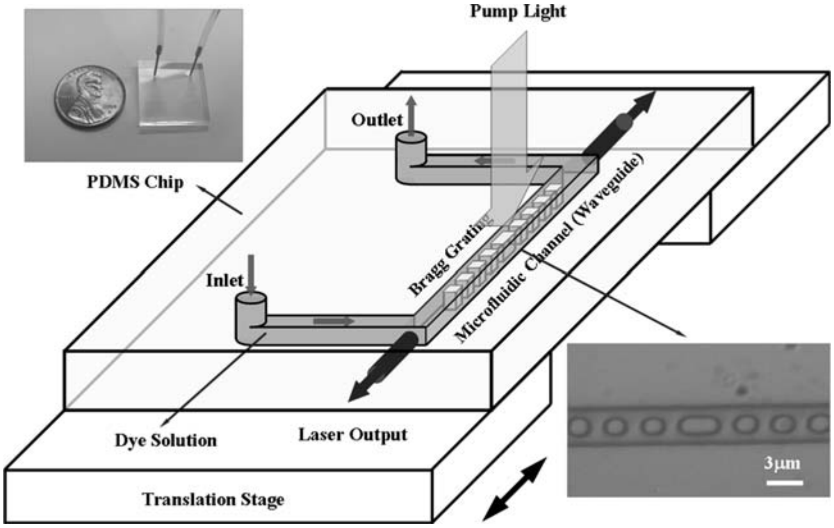

Fig. 6 Schematic diagram of a mechanically tunable optofluidic DFB dye laser chip. The *upper* inset shows an actual monolithic PDMS laser chip. The *lower* inset is an optical micrograph of the central phase-shifted region of the laser cavity. A Bragg grating with 3,080 nm period is embedded in a 3 μm wide microfluidic channel. The movement of the translation stage deforms the chip, which causes the grating period to change. Reprinted from Li et al. (2006)

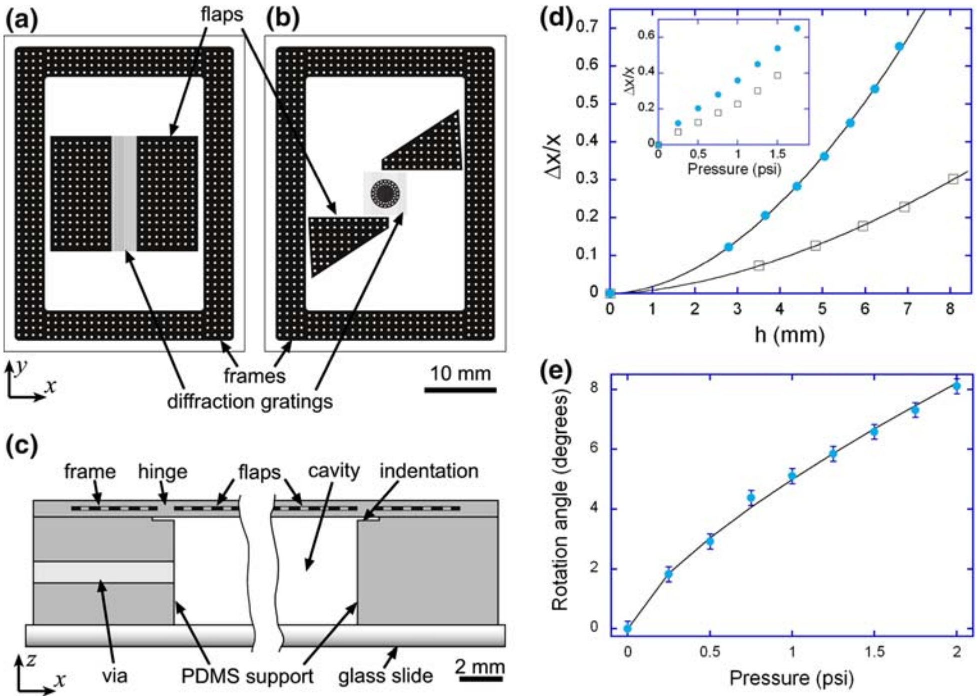

Fig. 7 Composite membrane devices, stretcher and rotator. **a**, **b** Schematic drawings of the composite membranes in the stretcher and rotator, respectively. *Dark areas* correspond to epoxy parts inside the membranes. **c** Schematic drawing showing a cross section of a device. **d** The relative extension of the central PDMS strip as a function of the out-of-plane deformation. For comparison purposes, the results for a standard membrane are shown as well (*squares*). **e** The rotation angle of the rotator device as a function of the applied pressure. Rotation angle of about 7° was demonstrated. Reprinted from Campbell et al. (2006)

demonstrated by realizing two devices that were named as “stretcher” and “rotator” (Fig. 7a–c).

The stretcher has two rectangular epoxy flaps separated from the frame by strips of PDMS, acting as flexible hinges. When the interior of the device is pressurized and the membrane is inflated, the flaps are lifted by turning about the edges of the frame. The composite membrane in the rotator has a circular piece of epoxy in the middle and two trapezoidal flaps located on both sides of the membrane. When the membrane is inflated, the flaps are lifted and a torque to the circle, that rotates in the plane of the membrane is applied. The amount of stretching and rotation was studied by measuring the diffraction of light in the gratings stamped onto the surface of PDMS in these two areas. Results are shown in Fig. 7d, e.

3 Refractive index tunability

Next we focus on optofluidic devices that gain their tunability through the variation of the refractive index of the medium. In principle, one can achieve refractive index tunability either by replacing the content of the optical medium or by directly modifying the refractive index of the existing medium through variety of effects, as mentioned in Fig. 1. We first describe several examples that are based on exchanging the fluidic medium. One can think of replacing liquid with gas or replacing two liquids having a substantially different refractive index. Liquavista used this concept to demonstrate an electrowetting-driven optofluidic reflective display. Each pixel in the array is filled with an absorbing dye (having a large imaginary part of refractive index) and salt solution (with negligible imaginary part of refractive index). If no voltage is applied to the cell, the absorbing dye covers the bottom of the cell with the salt solution on top. When voltage is applied the salt solution pushes the dye towards the edges of the cell, allowing light to pass through and to be reflected from the bottom surface (Fig. 8). This reflective design has the advantage of a very low-power consumption, as it does not use back light illumination (Hayes and Feenstra 2003). The relatively short switching time of electrowetting-driven displays (~few milliseconds) make them suitable for video rate applications. A transmission-mode version of the electrowetting-driven display was demonstrated by Heikenfeld (2005a, b). The two devices share common design, with a major difference of using back light illumination rather than reflective layer. Color displays can be created by grouping of three pixels side by side to each other with RGB (red, green, blue) response. A reflective color display, based on absorption, can also be made of CMY (cyan, magenta, yellow) pixels, one on top of the other. This approach has been demonstrated and commercialized for display in cellular phones by Liquavista.[2]

The exchange between two different liquids was also demonstrated for optical switching applications (Campbell et al. 2004), where water was replaced by an index matched salt solution (and vice versa) within ~10 ms using a set of microvalves and pressurized control channels. The

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[2] For more information see Liquavista web site: http://www.liquavista.com.

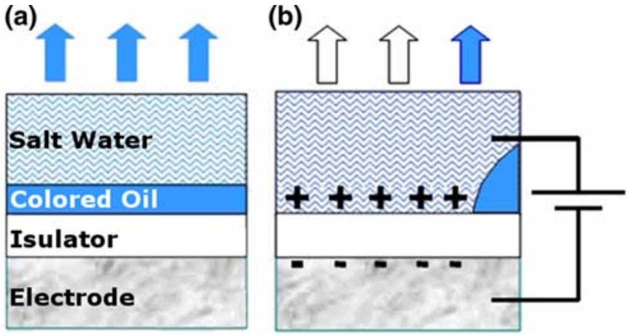

Fig. 8 Schematics of a monochromatic pixel in Liquavista's electrowetting display. **a** With no voltage applied, the colored oil covers the hydrophobic surface. **b** With an applied voltage, the colored oil is pushed aside by the conducting salt solution l and light is reflected from the bottom

exchange of liquids can be also achieved using the electrowetting effect. Mach et al. (2002a) demonstrated a tunable in-fiber optofluidic filter operating by introducing and removing an index matched droplet from a region of stripped waveguide, essentially switching between guided modes and leaky modes which in turn controlls the amount of light transmission through the optical fiber waveguide. A similar structure was used to create narrow-band optical filter, by fabricating a long period grating (LPG) on the stripped fiber (Hsieh et al. 2003). This enabled a tunable attenuation of the light at the resonant wavelength. Erickson et al. (2006) demonstrated the tunability of a 2-D photonic crystal waveguide by infiltrating the photonic crystal with a salt solution. By using different salt concentrations (having different refractive index), the transmission spectrum of the photonic crystal device could be tuned.

Optical trapping is another control mechanism to create tunability (Domachuk et al. 2005). This approach is of great interest, as it allows controlling light with light. A spherical silicone oxide colloid has been trapped and dragged into water-based suspension inside a microfluidic channel. Crossing the channel is an optical beam emerging from an optical fiber and coupled to another optical fiber at the opposite side of the micofluidic channel. By leading the colloid into the optical path of the beam, the colloid refracts the beam and attenuates the light traveling to the output fiber. This manipulation can be used for switching, variable optical attenuation and beam steering applications, towards the realization of all optical networks.

Next we describe TODs that are tuned via modulation of the refractive index of the medium. The common approach for refractive index tunability in the context of optofluidics, is probably by exploiting the electrooptic effect in liquid crystals (LC). The liquid crystal display became a commodity many years ago. LC can also be used for realizing tunable lenses (Berreman 1980; Sato 1979; Naumov et al. 1998). These LC based lenses are easy for operation (as its operation is controlled electrically) and provide decent tuning range. On the other hand, 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. Therefore, the numerical aperture is limited, unless LC microlenses are realized (Commander et al. 2000; Ren et al. 2005). Another approach is to exploit the thermo optic effect. This effect is ideal for achieving optical tunability in optofluidic devices, because the heat can be easily supplied to the region of interest by injecting hot liquid and can be easily dissipated into the flow channel. A thermo optic tunable optofluidic waveguide was recently demonstrated by the Whitesides group (Tang et al. 2006), where the properties of the waveguide were controlled by heating a liquid. The refractive index of most liquids increases with decreasing the temperature. Therefore, an optofluidic waveguide can be realized by cooling the waveguide core, heating the waveguide cladding, or both.

Refractive index can be also controlled by the mixing of two source liquids having different indices of refraction. Microfluidic technology offers various mixing approaches based on, e.g. electro-wetting (Mugele et al. 2006) or complex mixing networks (Garstecki 2005; Jeon et al. 2000). The complex mixing network approach was recently

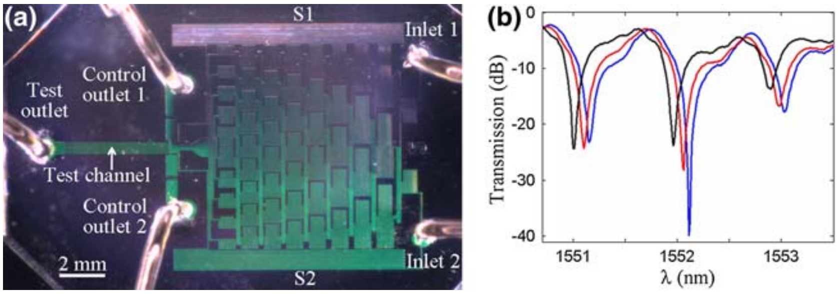

Fig. 9 A micrograph of the integrated optofluidic device with water and green dye injected into inlets *1* and *2*, respectively. The MRR is located at the bottom of the test channel and is tuned by selecting a specific salt concentration to flow around it and vary its effective refractive index. Transmission versus wavelength for three different values of salt concentration. Reprinted from Levy et al. (2006)

utilized for achieving the on-chip tunable microring resonator (MRR) (Levy et al. 2006, Fig. 9). The MRR is positioned at the bottom of a flow-through microchannel, which is a part of a microfluidic chip. The liquids injected into the microchannel constitute the upper cladding of the MRR waveguides. Variation of the refractive index of the liquid is achieved by on-chip mixing of two source liquids with different indices of refraction in desired proportions. This example demonstrates how amplitude modulation can be accomplished by changing the phase of a wave propagating through the device, based on an interferometric approach. Using on chip mixing of liquids was also demonstrated recently for the realization of a tunable optofluidic dye laser (Galas et al. 2005) where a ring resonator, a waveguide for laser emission output, and a microfluidic mixer were all integrated on the same chip. In another work, a tunable optofluidic microstructured fiber was demonstrated (Mach 2002b). This device combines LPG and inner microchannels in the fiber. The tuning liquids consisted of adjacent segments of low (n = 1.28) and high (n = 1.73) index immiscible microfluidic plugs. The liquids are pulled into the fiber one after another and positioned such that the interface between the liquids lies at the edge of the LPG. By using independent microheaters control, it is possible to tune the transmission and the resonant wavelength independently. Tuning range of about 12 nm and attenuation of about 12–15 dB were demonstrated.

4 Future directions

TODs are still in their early stage of research. A major challenge for further development of TODs is the improvement of control approaches. Currently, tunability of many TODs relies on an external pressure source, which is undesired for applications requiring miniaturization and integration. Integration of TODs with on-chip microvalves networks (Unger et al. 2000) and on-chip micropumps (Laser and Santiago 2004) would be an important step forward. As for electrowetting-driven TODs, they are currently limited in both voltage and speed. Further efforts for reducing the operating voltage and enhancing the speed of tunability are required. Voltage can be reduced by decreasing the thickness of the dielectric isolation and hydrophobic layers. Berry (2006) demonstrated a significant change in wetting angle by applying a low voltage, ~3 V, using a dielectric isolation of 11 nm and a hydrophobic layer of 6 nm. Speed of tunability can be further enhanced by reducing the droplet size and optimizing the dielectric constant of the materials (Mugele and Baret 2005). In guided wave applications, where droplets in the order of tens of microns can be used, speed of tunability is expected to be in the microsecond regime.

Controlling TODs with light holds a great promise towards the realization of all optical systems. In this context, an interesting direction is the optoelectrowetting approach. Basically, a light beam passes through a photoconductive layer and changes its conductivity, thus enabling electrowetting. Continuous optoelectrowetting was already demonstrated for trapping and transport of pico litre droplets on a surface (Chiou et al. 2003). Another optional path for controlling TODs with light is by exploiting nonlinear effects. Liquids having large optical nonlinearities could be used for this purpose. Liquids can be also mixed with nanocrystals for enhancing nonlinearities. TODs could, in principle, be controlled by the application of magnetic field. Manipulating droplets with magnetic field was demonstrated by Egatz-Gómez et al. (2006) using paramagnetic particles that were trapped inside the droplets due to capillary forces.

Finally, the improvement in controlling TODs, combined with the capability to manipulate smaller amounts of fluids could be a major step towards the implementation of TODs in subwavelength photonic applications.

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