HTML ABSTRACT + LINKS

A microfluidic 2×2 optical switch

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A 2×2 microfluidic-based optical switch is proposed and demonstrated. The switch is made of an optically clear silicon elastomer, Polydimethylsiloxane (PDMS), using soft lithography. It has insertion loss smaller than 1 dB and extinction ratio on the order of 20 dB. The device is switching between transmission (bypass) and reflection (exchange) modes within less than 20 ms. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1839281]

Optical switching devices play an important role in modern telecommunication networks providing unique functionalities such as optical add/drop, optical cross connect, and ring protection. A variety of switching devices based on electro-optic, thermo-optic, mechanical, acousto-optic, and magneto-optic modulation techniques have been developed during past years.[1–5] A few designs used the effect of total internal reflection (TIR) and had crossing regions between coupled waveguides filled with index matching liquids.[6,7] A gas bubble with the liquid–air interface acting as a mirror was either driven into the crossing region by a thermo-capillary force[6] or created in it using the inkjet technology.[7]

In this letter we demonstrate a 2×2 all optical switch based on control of TIR by flowing two different mixable liquids through microscopic channels made of a transparent silicon elastomer. With the advent of soft lithography and rapid prototyping,[8] the silicon elastomer Polydimethylsiloxane (PDMS) has become a material of choice for many microfluidic R&D and lab-on-a-chip applications. The devices made of PDMS are inexpensive and their fabrication does not require high-level facilities. PDMS has quite low Young's modulus that allows construction of adaptive lenses with thin flexible membranes.[9,10] The flexible elastomer membranes are also a key element in pressure-actuated micro-valves that can be integrated in the microfluidic devices.[11,12] A specific advantage of PDMS for a fluidic optical switch is its low index of refraction, $n_e = 1.41$, which can be easily matched by low viscosity, nontoxic aqueous salt solutions.

The device, shown schematically in Figs. 1 and 2, has two distinct layers of microchannels separated by thin flexible membranes in the regions where they overlap. The first, flow layer contains the main functional element of the device—a 10-mm-long, 2-mm-wide, and 75-μm-thick flat-parallel mirror channel. It can be filled with either pure water from inlet 1 or an index matching salt solution from inlet 2 (see Fig. 1). The channels connecting the inlets and the outlet with the mirror are 100 μm thick and 800 μm wide and have rounded shapes. They are completely sealed by the flexible membranes when a pressure of 15 psi is applied to the membranes through channels (control lines) in the second, control layer of the chip.[11] The membranes serve as pressure-actuated integrated "push-up" valves.[12] Three of the control lines are connected to the valves on the two inlet channels and the outlet channel (valves 1, 2, and 5). The fourth control line (simultaneously switching two membrane valves, 3 and 4) and the vent in the flow layer serve the purpose of purging the dead volumes between the two inlet valves (1 and 2) and the T-junction connecting the inlets with the mirror channel (Fig. 1).

The liquids were held in 60 cc plastic syringes, mounted vertically and connected to the elastomer chip by flexible tygon tubing with an inner diameter of 1 mm. The outlet and vent syringes were open to the atmosphere, while the syringes feeding the inlets were sealed and pressurized to 6 psi by compressed air. The pressure in tubing connected to the control lines was switched between zero and 15 psi using a manifold of solenoid valves with a response time of about

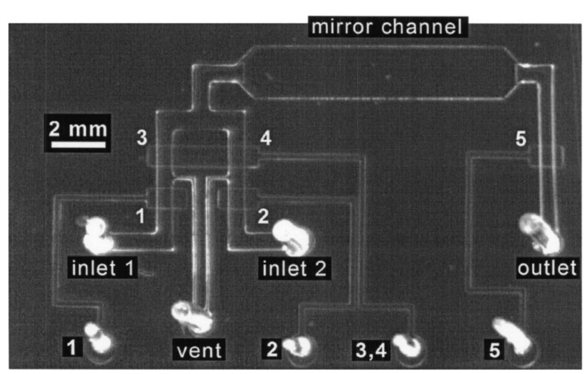

FIG. 1. A microphotograph of the switch device. Control layer inlets are labeled by numbers of the membrane valves they actuate. Rounded channels can be clearly distinguished from rectangular ones (the mirror channel and channels in the control layer).

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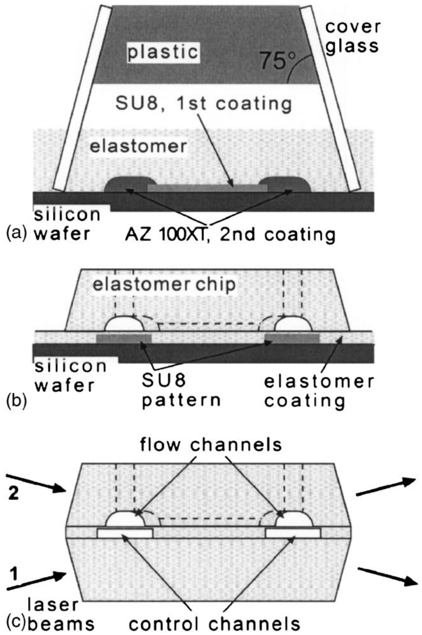

FIG. 2. Schematic drawings showing construction and consecutive stages of fabrication of the switch. (a) The flow layer master mold with the PDMS cast and facet forming structure on top of it. (b) PDMS chip with engraved flow layer channels aligned on top of the control layer mold coated with a thin layer of the elastomer. (c) The complete three-layer elastomer chip with four optical quality facets. The arrows on the left show directions of incident laser beams 1 and 2, and the arrows on the right show transmitted and reflected beams.

4 ms. The valves were driven by a homemade controller interfaced with a PC through a National Instruments DAQ card.

All the membrane valves were normally pressurized and closed, and there was no flow in the channels. The optical switching was performed by filling the mirror channel with a liquid having a different index of refraction. If, for example, the water had to be exchanged by the salt solution, valves 2–5 were opened simultaneously (by switching pressure in the corresponding control lines to zero) to start flow from inlet 2 toward the outlet and the vent. The valves 2, 3, and 4 were closed after 100 ms, a time interval corresponding to a liquid discharge of about 4 mirror channel volumes $(7\ \mu\text{l})$ in the flow from inlet 2 to the outlet. Closing valve 5 was delayed by 20 ms to allow pressure relief in the mirror channel.

The condition of TIR at the interface between the PDMS elastomer with a refraction index $n_e \approx 1.41$ and de-ionized water with $n_w \approx 1.33$ is met at angles of incidence larger than 70.6°. Therefore the microfluidic chips were made with optically flat, clear facets at angles of 75° to the plane of the channels on both sides (see Fig. 2), and the incident beams were directed normally to the facets, Fig. 2(c). The index matching liquid was a solution of about 35% KI and 15% NaBr (by weight) in water. Its viscosity was nearly as low as the viscosity of water $(10^{-3}\ \text{Pa s})$ allowing high flow rate and fast switching at moderate driving pressures.

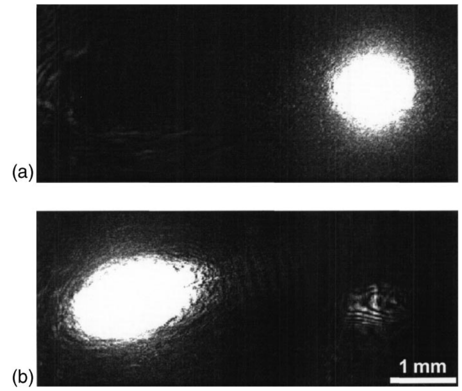

FIG. 3. Images of reflected (left) and transmitted (right) beams (after passing the switch) formed on a CCD array in the bypass mode (a) and exchange mode (b).

The device was made using the technique of soft lithography and was assembled from three layers of PDMS (see Fig. 2). Two of the layers had microchannel relief engraved on their surfaces (flow and control channels), and they were cast using two different master molds. The molds were fabricated by the regular near-UV contact photolithography using 8000 dpi resolution masks designed to implement the desired geometry of the molds. To make the master mold for the flow layer, a 4 in. silicon wafer was first spin coated with 75-μm-thick layer of a negative photoresist (SU8-2050 by MicroChem) and patterned through a photomask. That produced flat parallel relief to cast the mirror channels. Next, the wafer was coated with about 100 μm layer of a positive resist, AZ100 XT by Clariant. It was patterned through another photomask (aligned with respect to the 75 μm SU8 layer), and baked on a 140° hot plate for 30 min after development to round the AZ 100XT relief[11,12] [see Fig. 2(a)]. The mold for the control channels was made by spin coating another 4 in. wafer with a 100-μm-thick layer of SU8-2050 resist and patterning it through a third photomask.

The resin and catalyst parts of the silicon elastomer (Sylgard 184 by Dow Corning) were mixed in a proportion of 5:1 and poured onto the first mold to a depth of 5 mm. In order to make the flat 75° facets and assure optical quality of the surfaces we used trapezoidal plastic bars with silanized cover glasses glued to their sides [see Fig. 2(a)]. The cover glasses were immersed into the liquid elastomer and the construct was baked for 25 min in an 80 °C oven to partially cure the elastomer. The elastomer was then separated from the glasses and the wafer, cut into individual chips, and holes were punched in the chips with a gauge 16 luer stub to make ports for the flow layer.

In parallel the second mold was spin coated with a $\sim$160-μm-thick layer of elastomer (20:1 mixture of the resin and catalyst). The elastomer was partially cured in the oven, and the chips were placed on top of it aligned with the photoresist relief on the mold[11,12] [see Fig. 2(b)]. After 2 h of baking in the oven a monolith of completely cured elastomer

TABLE I. Insertion loss and extinction ratio (in dB) for transmitted and reflected beams in the two states of the switch and for two inputs at TE and TM.

	Bypass TE (dB)		Exchange TE (dB)		Bypass TM (dB)		Exchange TM (dB)	
Laser beam	1	2	1	2	1	2	1	2
Insertion loss	0.78	0.84	1.1	1.1	0.71	0.67	0.83	0.78
Extinction ratio	22.7	24.4	18.2	17.7	17.8	22.5	21.7	16.7

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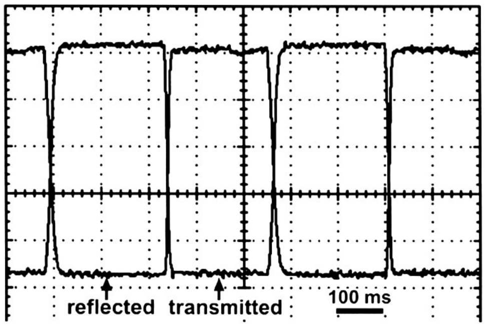

FIG. 4. Power of transmitted and reflected beams as a function of time measured by fast photodetectors and visualized with an oscilloscope during a series of periodic switching events.

with integrated valves was formed. The elastomer was cut into individual chips and holes were punched in the chips with a gauge 20 luer stub to make ports for the control layer. The control channels on the surface of the chips were sealed by ~5-mm-thick pieces of the elastomer with flat surfaces and the same trapezoidal profile with 75° facets [see Fig. 2(c)], which were made using a procedure similar to that described earlier. (Both surfaces were treated with oxygen plasma for improved bonding.) The complete three-layer device had a hexagonal profile with the microchannels near the midplane. It was optically clear and the interfaces between different layers were not detectable by eye.

Characterization of the device was performed using a 2 mm collimated beam derived from a single mode HeNe laser source ($\lambda=632.8$ nm). The laser beam was directed to the mirror channel (see Fig. 1) either from above [beam 1, Fig. 2(c)] or below [beam 2, Fig. 2(c)] normally to one of the facets. Thus, the angle of incidence on the surface of the mirror channel was 75° for both beams. The channel acted as a mirror (exchange mode) and a transparent window (bypass mode) when it was filled with water and with the index matching solution, respectively.

Images of the transmitted (bypass) and the reflected (exchange) beams (captured with a Cohu CCD camera) are shown in Fig. 3. The mode of the beam in the bypass state of the switch is characterized by a high quality Gaussian shape [see Fig. 3(a)]. In the exchange state the mode is somewhat elliptical, which is probably due to a slight curvature of the PDMS-microchannel boundaries. The beam quality could be improved by using a more elaborate fabrication procedure and PDMS with a higher Young's modulus.[13]

Power of transmitted and reflected beams was measured with a Newport 818-SL power meter. A linear polarizer was placed in front of the device to explore its performance for two orthogonal states of polarization. Results of the measurements for beams 1 and 2 coming from below and above [see Fig. 2(c)], the two orthogonal linear polarization states and the two switching states are summarized in Table I as values of insertion loss and extinction ratio in dB. The latter was defined as the ratio between the powers of the reflected (transmitted) and the incident beam in the bypass (exchange) mode. The TE polarization corresponds to the electric field orthogonal to the plane of incidence.

The cross talk of the device in the bypass state strongly depends on exact matching of refractive indices of PDMS and the salt solution. At the incidence angle of 75° the measured extinction ratio of 20 dB (see Table I) in the bypass state for TE polarization corresponds to an index mismatch of about 0.001. An extinction ratio of ~45 dB, which is a standard requirement for modern telecommunication switches, should be reached by reducing the index mismatch down to 0.0001. The extinction ratio in the exchange state is mainly limited by the small width of the mirror channel (2 mm) and can be further improved by better collimation of the beam.

Part of the insertion loss, about 0.3 dB, is due to reflections from the two PDMS–air interfaces and can be eliminated by AR coating the facets. The insertion loss inside the device is ~0.4–0.8 dB, which is comparable with state of the art optical switching components. The polarization-dependent loss is on the order of 0.1–0.3 dB. Those numbers could be reduced by improving the index matching, quality of the mirror channel surface, and by increasing the width of the mirror.

We tested dynamic performance of the device by switching it periodically and measuring power of the beams with fast silicon photodetectors (Thorlabs 201/579-7227) connected to a digitizing Tektronix oscilloscope. A representative time series is shown in Fig. 4. The transition from bypass to exchange state occurred within about 20 ms (based on 10%–90% criterion), while the transition from exchange to bypass took less than 10 ms. This speed meets current standards for most switching applications (e.g., protection and routing). The switching speed is mainly limited by the rate of flow in the microchannels and can be further increased by applying higher pressures and increasing channel depths.

The demonstrated optical switch is a free space device with the width of the mirror (2 mm) sufficient for even noncollimated laser beams. Since it is based on one-phase flow of two mixable liquids, its size can be varied without subtle effects on its performance. Those are two main advantages of this device compared with the bubble photonic switches implemented in waveguides.[7] In addition, the device fabrication is based on the soft lithography replication process, which is expected to reduce cost per unit, making this switching technology appealing for low-end applications. The switch can also be integrated with other microfluidic devices for lab-on-a-chip applications.

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