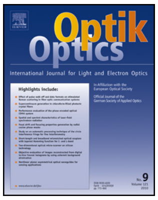
Optik 125 (2014) 6661–6664

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



# Optical switch based on hydraulic actuation

Chao Liu, Qiong-Hua Wang*, Ming-Huan Wang

*School of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China*

A R T I C L E  I N F O

*Article history:*
Received 26 November 2013
Accepted 6 June 2014

*Keywords:*
optical switch
liquid
hydraulic actuation

A B S T R A C T

In this paper we demonstrate an optical switch based on hydraulic actuation. Two chambers are filled with dyed oil and water, respectively. The oil–water interface changes as the external pressure is applied to the chamber. A transparent pillar shaped platform with a round dome is fixed on the top substrate and submerged in the oil. When pressure is increased, the shape of the oil–water interface can be changed from concave to convex and the oil is pushed aside. As a result, the water touches the transparent pillar thus forming a light channel which allows the incident light to pass through. Our experiments show that the device can obtain a wide optical attenuation from ~1 dB to ~29 dB. The diameter of the aperture can be tuned between 0~5.1 mm by changing the external pressure. The switchable aperture ratio of the device is ~39%. By using two immiscible liquids with matched densities, the gravity effect can be overcome. The proposed optical switch has potential applications in variable optical attenuators and adaptive irises.

## 1. Introduction

Optical devices using liquids often referred to as optofluidic devices, have found widespread applications in tunable focus lenses [1,2], displays [3], and beam tracking [4–6] because of their optical isotropy and high transmittance. Among them, polarization-independent optical switches have attracted many designers' interests in recent years. Optical switches have wide applications such as adaptive irises, which can control field of view, prevent scattering light and improve imaging quality. In addition, optical switches can be used as optical attenuators which have potential applications in fiber-optical communication, photonic signal processing and for controlling luminous flux. If the optical switches are arranged in an array, they can be applied to displays [7–18]. Many mechanisms have been proposed to design an optical switch by changing a liquid–liquid interface. Dielectrophoretic and electrowetting actuation are two promising approaches because they both allow controlling of a liquid–liquid interface directly through application of a voltage. Optical switches based on these two methods have their unique advantages, but some problems still persist. For example, the size of the devices based on dielectrophoretic effect, whose order of magnitude is micron, is not large enough. So the tuning range of aperture is limited, which will constrain its real applications. Electrowetting based devices usually need a rather high applied voltage which can destroy the dielectric layer. Furthermore, the fabrication is complicated since sophisticated and costly technologies have to be applied to obtain defect free dielectric thin films. Compared with the approaches mentioned above, the method based on liquid pressure to control the liquid–liquid interface is a simple and convenient way to achieve the function of optical switch with a high optical attenuation and a large switchable aperture ratio.

In this paper, we propose an optical switch based on hydraulic actuation. Compared with our previous work [11], we actuate the device based on different mechanism: electrowetting actuation and hydraulic actuation. In our previous work, we control the liquid–liquid interface by changing the external voltage. While in this paper, the change of the liquid–liquid interface depends on the liquid surface tension and the liquid pressure known as mechanical-wetting [2].

## 2. Device mechanism and fabrication

Fig. 1 shows a schematic side view of the proposed optical switch. The device is filled with two immiscible liquids, and we injected liquid into the chamber to obtain a pressure rise. The liquid–liquid interface is changed by applying pressure. In our experiment, we can measure the volume of the injected liquid instead of measuring the liquid pressure. The liquid–liquid interface depends on the surface tension between the liquid and the middle-substrate as is described in Laplace Equation:

$$P = \frac{2\gamma}{R}, \tag{1}$$

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* Corresponding author. Tel.: +86 02885470027.
*E-mail address:* qhwang@scu.edu.cn (Q.-H. Wang).

http://dx.doi.org/10.1016/j.ijleo.2014.06.171
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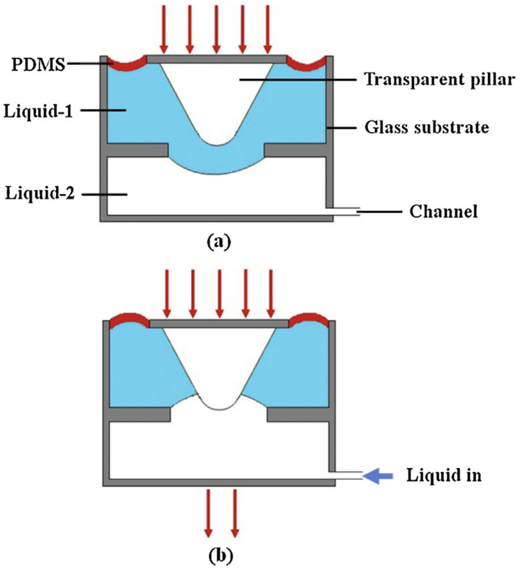

**Fig. 1.** Schematic side view of the device. (a) Switch-off state. (b) Switch-on state.

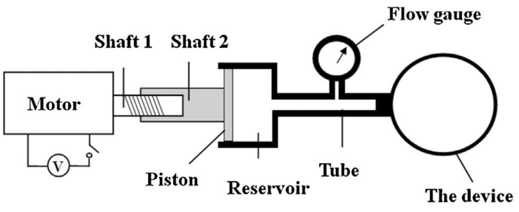

**Fig. 2.** Actuating system of the proposed device.

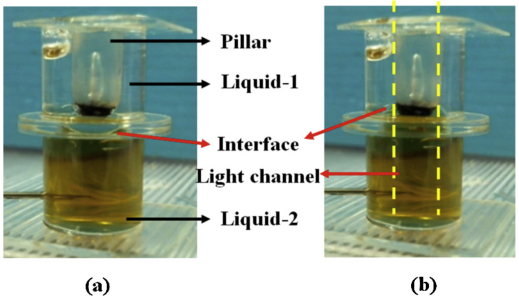

**Fig. 3.** Optical switch in the transition process. (a) Side view of switch-off state. (b) Side view of switch-on state.

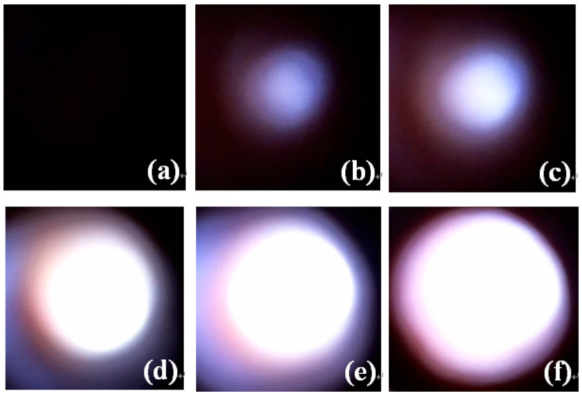

**Fig. 4.** Variable apertures under different liquid pressure. (a) State 1. (d) State 2. (c) State 3. (d) State 4. (e) State 5. (f) State 6.

where $P$ is the liquid pressure, $\gamma$ is the liquid surface tension, and $R$ is the curvature of the liquid interface. In the initial state, the transparent pillar with a round dome is immerged in the oil such that the device is in the switch-off state as shown in Fig. 1(a). Then water is injected through a channel to change the curvature of the liquid interface. When the volume of the water increases, it can push the oil aside and touch the transparent pillar, thereby forming a transparent channel which allows the incident light to pass through, as shown in Fig. 1(b). In this case, the device is in the switch-on state.

The fabrication of the proposed optical switch is described in the following. Two PMMA (polymethyl methacrylate) made cylindrical chambers with a middle-substrate are stacked together by glue UV-331. The diameter and height of the chamber are 8 mm and 7 mm, respectively. A channel is also fabricated in the bottom chamber which is used to inject the liquid. A transparent pillar with a round dome is fixed on the top substrate, which has two holes. The diameter of each hole is 1 mm. The height and diameter of the pillar are 7 mm and 4 mm, respectively. The top substrate is covered by a PDMS (polydimethylsiloxane) membrane (thickness is ~50 μm, Young's modulus is ~3 MPa), which seals the top oil chamber. The top chamber is filled with silicone oil dyed with Sudan Black-B as Liquid-1 (the density is 0.98 g/cm$^3$). The bottom chamber is filled with water as liquid-2 (a density of 1.00 g/cm$^3$).

In all experiments, we used a motor-controlled pump to drive the proposed device. The actuating system is shown in Fig. 2. A tube was used to connect the actuating system and the device. The pumped liquid volume was measured using a flow gauge.

## 3. Experiment and discussion

In the first experiment, we chose water as liquid-1 and carbohydrate as liquid-2, respectively. In order to observe the shape change of the water-oil interface clearly, the transparent pillar was fabricated with a bubble inside and its round dome was printed black as shown in Fig. 3(a). In the initial state, the pillar was immerged in liquid-1 and the liquid–liquid interface's curvature was convex. Then we injected liquid-2 through the channel, the interface's curvature changed from convex to concave. So liquid-2 touched the pillar which formed a light channel, as shown in Fig. 3 (b). Such an experiment shows that the proposed device can function as an optical switch.

In a second experiment, we chose dyed oil as liquid-1 and water as liquid-2 to achieve efficient light attenuation in the off-state. We placed a LED (light-emitting diode) back light to illuminate the device at normal incidence. A CCD camera was placed on the opposite side to record the variable aperture under different liquid pressure. The results are shown in Fig. 4.

Fig. 4 shows that the actuated aperture changes under different liquid pressure. Fig. 4(a) is the initial state. The size of the aperture changes as water is injected into the device, as shown in Figs. 4(b)–4(e). When the volume of the water is ~5.5 mL, the maximum aperture is reached, which does not change as the pressure increases as shown in Fig. 4(f). In this off-state, the measured aperture is ~5.1 mm. We can see that the range of tunable diameter is 0–5.1 mm and the aperture ratio is ~39%. The actuated aperture versus liquid capacity was also measured and the results are shown in Fig. 5. Theoretically, if we enlarge the diameter of the pillar and hole of the middle-substrate, we can reach a higher aperture ratio and a larger range of tunable aperture. However, in practice, the maximum of the interface's curvature will decrease when the hole and the pillar are enlarged, because surface tension can no longer balance gravity.

Optical attenuation is one of the key factors to judge the function of an optical switch. In a third experiment, we used a laser beam (λ=632.8 nm) to illuminate the device in order to check the function