Electrowetting driven optical switch and tunable aperture

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Abstract: We demonstrate an electrowetting based optical switch with tunable aperture. Under the influence of an electric field a non-transparent oil film can be replaced locally by a transparent water drop creating an aperture through which light can pass. Its diameter can be tuned between 0.2 and 1.2 mm by varying the driving voltage or frequency. The on and off response time of the switch is in the order of 2 and 120 ms respectively. Finally we demonstrate an array of switchable apertures that can be tuned independently or simultaneously.

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1 Introduction

Optical switches and tunable optical apertures (or diaphragms) have great potential in various areas of application, such as communication, microscopy, display and lab-on-a-chip. Traditionally, such switches and apertures are controlled mechanically. However the operation of small-scale mechanical parts gives rise to complications such as increased friction and long term wear. Due to their well defined and stable interfaces along with their optical isotropy and high transmittance, liquids have been used extensively to achieve various optical phenomena (optofluidics) [1]. Various techniques have been used to manipulate liquids such as elastic membranes [2], stimulus responsive hydrogels [3], electromagnetism [4] and dielectric effects [5–7]. Also electrowetting [8–14] is an attractive method to manipulate water drops. Various optical devices have been fabricated based on electrowetting including tunable lenses [15], beam steering devices [9], displays [13] and switchable apertures [5–7, 16].

Here we present an electrowetting driven optical switch with tunable aperture. Our optical switch can attain 100% intensity attenuation and has a response time of ~2 and ~120 ms for switching on and off, respectively. The diameter of the resulting aperture can be tuned between 0.2 and 1.2 mm. Our device makes use of the same operating principle as the one described by Ren et al. [5–7], yet it offers a much more robust design and reliability, as well as higher switching speeds and a broader tunability. First, we describe the design and the physical mechanism of the device based on our recent theoretical understanding of the underlining process [17]. Next we describe the controllability of the resulting aperture in relation to the applied voltage and frequency. Finally we consider an array of switchable optical apertures. The device presented can be used for various promising applications as optical shutters, lab-on-a-chip devices.

2. Optical switch/aperture configuration

A schematic of the optical switch has been presented in Fig. 1 (side view). The device consists of two substrates with a non transparent oil in between. The lower substrate consists of a glass plate coated with a conducting and transparent Indium–Tin–Oxide (ITO) layer on which an SU8 film is spin coated (4-5 µm thick). On top of this SU8 film a thin layer of Teflon AF (~20 nm thick) is deposited to make the surface more hydrophobic. The upper glass plate, 140 µm thick with a 1.2 mm diameter hole, is also coated with Teflon AF. Top
and bottom substrates are separated by a 60 µm thick glass spacer and all elements are glued
to each other using UV curable NVA 81 [18]. A water reservoir is created on top of the upper
glass plate by placing a rubber ring around the hole. As shown in Fig. 1 the water-oil
meniscus is pinned to the upper edge of the hole in the top cover slip. This design keeps the
pressure in the water phase approximately constant during the operation of the device. The oil
between the top and bottom substrate is decane to which a mixture of Sudan black and red
(Sigma Aldrich) is added. The device is placed on an inverted microscope to view it from
below. Light traversing the water reservoir cannot pass through the oil layer since it is
absorbed by the dye (Fig. 1(a)).

When a voltage is applied between the water phase and the ITO layer of the lower
substrate (electrode), an electric field is generated within the oil phase. Due to the resulting
electric stresses the water-oil meniscus is deflected downwards. Its shape is determined by the
balance between the electric stress and the surface tension stress (or equivalently the Maxwell
stress and Laplace pressure, respectively) [17, 19]. As the voltage increases, the deflection
increases until it reaches a critical threshold. This threshold value depends on the aspect ratio
between the radius of the hole and the height between the glass plates as well as the physical
properties of the fluids [17]. Once the threshold is reached, the meniscus becomes unstable
and abruptly snaps down to the lower substrate (centre of the meniscus touching first as
presented in Fig. 1(b)), where it creates a transparent spot (Fig. 1(b)). The dynamics of this
process are governed by the balance of Maxwell stress, surface tension and viscous stresses.

The resulting optical switch can be tuned/operated by applying a DC voltage, an AC
voltage or by applying amplitude modulation. In case of amplitude modulation we apply a
fixed base frequency (1 kHz) and modulate the amplitude of the applied voltage at various
frequencies. The amplitude modulation frequency will be addressed in this article as the
applied frequency.

3. Optical switch

Figure 2 presents the side view of the optical switch (Media 1) in operation. To get clear
images of the water-oil meniscus, in this case no Sudan black or red was added to the oil
phase. The optical switch was operated by applying a base frequency of 1 kHz and
modulating the amplitude at 0.5 Hz. The images shown have been selected from a movie recorded while operating the switch. Figure 2(a–c) presents the
swtiching-on, as the amplitude of the driving voltage increases and the water meniscus bends
towards the lower substrate until it snaps to it. Figure 2(d–f) presents the switching-off, as the
amplitude decreases and the water meniscus retracts from the lower substrate.

To determine the optical attenuation, which is one of the key aspects of the switch, the
interface was driven using a modulation frequency of 1 Hz at 50 V_{rms}, and images were
acquired in transmission using a CCD camera with a frame rate of 250 fr/s in combination
with the inverted microscope. The device was illuminated with the standard halogen lamp of
the microscope using green filter (490-550 nm). Figure 3 presents selected images from the
recorded movie (Media 2). Figure 3(a:i) and 3(a:viii) show the “off state” whereas 3(a:ii)
shows the “on state”; the other images show intermediate states. To determine the variation of the light intensity during a cycle a small area, corresponding to the smallest bright spot (Fig. 3(a:vii)), was selected. The mean intensity of this area is plotted versus time, remarkably close to 100% reduction in intensity is observed (limited by the dark noise of the camera), corresponding to a transition from the “on” to the “off” state, intensity attenuation can be improved by using Keystone liquid oil dyes as reported in [20].

Along with the intensity attenuation, the response time is another key parameter defining the performance of the optical switch. To measure the response time we recorded the transmitted intensity as a function of time with a high speed camera operating at 10 kfps. Figure 4(a) presents the “switching-on” time, which is defined as the time it takes to increase the light intensity from 10% to 90% of the total intensity [21]. The obtained response time going in a single step from 0 to 50 V is very short i.e. ~2 ms. In this situation the meniscus freely bends down and snaps to the lower substrate. The “switching-off” response time now going in a single step from 50 to 0 V is substantially longer i.e. ~120 ms as presented in Fig. 4(b). This difference in response times is caused by a combination of several effects. The “on-time” is particularly short because the Maxwell stress pulling on the liquid-liquid interface increases as the interface moves downward during the transition. The aspect ratio (surface spacing/hole diameter) of the current device corresponds to the regime of the electrohydrodynamic “touch-down” instability described in ref [17]. The only dissipative process hindering the process is viscous dissipation primarily in the thin oil layer that is being squeezed out [22-23]. In contrast, the reverse off-switching process involves the motion of a three phase contact line, which is known to involve substantial dissipation [24]. Other aspects such as Young’s angle (160° in this case), contact angle hysteresis due to surface roughness as well as charge trapping [20] may also play a role. Moreover, the gain in energy upon switching back is merely given by the oil-water interfacial energy times the reduction in surface area, which is much smaller than the gain in electrostatic energy upon switching on. Both response times are expected to depend also on the viscosity of the fluids used (1 mPas for water and 5 mPas for oil phase) and the interfacial tensions (water-oil 41 mN/m, water-oil + dye 5 mN/m) as reported in [6, 20]. A detailed analysis of the response time, however, is beyond the scope of the present paper.
4. Optical aperture

The device can also be used as an optical aperture. Its diameter is controlled by the modulation frequency and maximum amplitude of the applied voltage. Figure 5(a) presents a complete cycle. As the amplitude increases (modulation at 1 Hz) the meniscus deflects towards the lower substrate. Around 42 V there is a sudden snapping of the meniscus to the lower substrate (snap-on) and the aperture diameter jumps from 0 to its maximum diameter i.e. 1.2 mm, upon further increase of the driving amplitude the diameter remains almost constant. Note that the diameter of the aperture cannot increase beyond the diameter of the hole in the top plate even if the liquid spreads further. On subsequent lowering of the amplitude the aperture diameter starts to decrease from 1.2 mm at about 42 V to ~0.2 mm at about 20 V, when the water meniscus snaps back closing the aperture (snap-off). Once the aperture has formed, by applying a voltage above 42 V, the diameter of the aperture can be tuned from minimum (~0.2 mm) to maximum (~1.2 mm) (dotted lines in the Fig. 5(a)) reversibly and without noticeable hysteresis by varying the voltage between 20 and 40 V.

According to a theoretical analysis by Oh et al. [17], the threshold voltage for snapping of the meniscus to the lower substrate is for our configuration about 47 V (Fig. 5(b)). This agrees well with the observed transition at 42 V. The voltage dependence of the radius of the aperture is also obtained from an energy minimization, taking into account the Laplace and Maxwell pressure as well as the surface energy of the water-substrate contact area. The Maxwell pressure at the contact area can be approximated as [17]

$$\pi_s = \frac{e_0 e_s E_n^2}{2} \approx \frac{e_0 e_s}{2} \left( \frac{V}{d} \right)^2$$

(1)

where $d$ is the thickness of the dielectric SU8/Teflon layer on the lower substrate. Comparing the variation of the surface energy due to this Maxwell pressure with that of the interfacial energy of both the oil-water and water-substrate interface, with varying radius of the aperture, one can estimate this radius for a given voltage as well as the minimum voltage for maintaining an aperture, which is around 16 V. We observe a minimum voltage of 20 V; see both red lines in Fig. 5. This deviation is primarily due to the approximation of the water-oil interface by a parabolic shape. Comparing both red lines in Fig. 5 one can observe that also the voltage dependence of the aperture size is qualitatively described by the model calculation. A more detailed analysis is possible using the method of energy minimization as done in [25].

The variation of the diameter by applying amplitude modulation as depicted in Fig. 5 can be investigated as a function of the modulation frequency. Figure 6(ai-ii) presents the minimum and the maximum aperture diameter at 1 Hz. At frequencies below 2 Hz the meniscus completely detaches from the lower substrate giving rise to the maximum variation

![Figure 5](image-url)
of the aperture diameter. At higher frequencies the meniscus cannot detach from the lower substrate, resulting in some finite minimal diameter. Figure 6(a:iii-iv) presents the minimum and maximum apertures at 20 Hz (Media 3). Figure 6(b) shows the change in aperture diameter and the minimum diameter as a function of applied frequency; the minimum diameter increases with increasing frequency. The results presented here and in the previous paragraph suggest that we found a novel and reliable optical switch with controllable aperture size by tuning the applied voltage and/or applied frequency.

Finally, it is worthwhile to note another unique aspect of the present design: Traditionally small optical apertures suffer from diffraction along to their sharp edges. For the present aperture the transmitted intensity decreases continuously from its maximum value in the center to zero over a range that is determined by the absorption of the dye and the geometrically determined shape of the oil-water interface (see Fig. 1). Figure 7 shows examples for a few different aperture diameters without any indication of diffraction. It is also interesting to note that the present design can produce beam with a Gaussian intensity profile from a flat initial profile. We plan to explore these aspects in miniaturized versions of these apertures in future research.

5. An array of optical switches and apertures

The optical switch with tunable aperture as presented here has great potential in optical communication, display and in lab-on-chip devices, because they can be arranged in an array of individually addressable apertures. Here we demonstrate this potential by presenting a device consisting of two optical switches/apertures, positioned close to each other, that can be addressed independently without any cross talk, see Fig. 8. In Fig. 8(a-c) the right switch is addressed (50 V, 1 Hz). The left switch is addressed in the same way in Fig. 8(d-e). Finally,
voltage is applied to both switches/apertures Fig. 8(f) presents the on state of two switches simultaneously.

![Fig. 8](image)

**Fig. 8.** a) Two optical switches, positioned close together, can be addressed independently.

### 6. Conclusions

We presented an electrowetting based optical switch with tunable aperture. By switching we can achieve close to 100% intensity attenuation. The response time for switching on and off is ~2 and ~120 ms respectively. The response time can be improved by lowering the viscosity of the fluids used and by optimizing the device geometry (hole diameter and aspect ratio). The aperture of the device can be tuned by varying the applied voltage and/or frequency. Moreover the aperture presented here can be used to create a diffraction free spot due to its smooth edges. Eventually, this switching mechanism can be used to create arrays of optical switches with tunable aperture which might be useful in microscopy, optical communications, displays and Lab-on-chip.

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