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Research Article

Microfluidic Optical Shutter Flexibly x-y Actuated via Electrowetting-on-Dielectrics with <20 ms Response Time

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Tunable microoptics deals with devices of which the optical properties can be changed during operation without mechanically moving solid parts. Often a droplet is actuated instead, and thus tunable microoptics is closely related to microfluidics. One such device/module/cell type is an optical shutter, which is moved in or out of the path of the light. In our case the transmitting part comprises a moving transparent and electrically conductive water droplet, embedded in a nonconductive blackened oil, that is, an opaque emulsion with attenuation of 30 dB at 570 nm wavelength over the 250 μm long light path inside the fluid (15 dB averaged over the visible spectral range). The insertion loss of the cell is 1.5 dB in the "open shutter" state. The actuation is achieved via electrowetting-on-dielectrics (EWOD) with rectangular AC voltage pulses of $2 \cdot 90$ V peak-to-peak at 1 kHz. To flexibly allow for horizontal, vertical, and diagonal droplet movement in the upright x-y plane, the contact structures are prepared such that four possible stationary droplet positions exist. The cell is configured as two capacitors in series (along the z axis), such that EWOD forces act symmetrically in the front and back of the 60 nl droplet with a response time of <20 ms.

1. Introduction

"Tunable optics" or "active optics," as it is called synonymously, deals with optical set-ups, where the optical properties can be changed during operation without the need to mechanically move solid parts. This idea is especially useful for microoptics, where large modules and abrasion should be avoided as much as possible. Tunable microoptics has been a vivid area of research for the last 10 years and many concepts incorporate fluid volumes (droplets), which are moved or manipulated otherwise in order to achieve the desired device function [1, 2]. For instance, such tunable micro optofluidic (TMOF) modules can be dynamic lenses [3–5] and irises, or shutters/switches, respectively [6–11].

The most common and seemingly most practicable actuation principle is based on electrowetting-on-dielectrics (EWOD) [11–26]. Here, the droplet, typically made of electrically conductive water, is used as one electrode of a capacitor. The other electrode is made of a conductive layer, frequently of the transparent indium tin oxide (ITO). A d_{diel} thick dielectric layer forms the insulator in-between "electrodes." Loading the capacitor by applying a voltage V leads to the storage of electrostatic energy, which reduces the surface energy/tension $\gamma_{l,\text{diel}}$ of the liquid (index l) droplet on the dielectric layer (index diel) to an effective value:

$$\gamma_{l,\text{diel}}^{\text{eff}} = \gamma_{l,\text{diel}} - \frac{CV^2}{2A}, \quad (1)$$

where C is the capacitance of the arrangement and A the area of the droplet "above" the electrode. The contact angle θ of the droplet on the dielectric layer (when compared to Young's angle θ_0 for zero voltage) is always reduced according to the Young-Lippmann equation (in case of partial wetting in the off-state):

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_0 \varepsilon_{\text{diel}}}{2d_{\text{diel}} \cdot \gamma_{la}} \cdot V^2, \quad (2)$$

where ε_0 is the dielectric constant, $\varepsilon_{\text{diel}}$ the dielectric number of the dielectric layer, and γ_{la} the surface tension/energy of the interface between liquid/droplet and ambient (often air or, in our case, oil). Since in (2) the contact angle is a function of the voltage squared, the polarity of the voltage has no effect and an AC voltage is typically employed [27]. For AC frequencies of around 100 Hz and more the droplets cannot follow the oscillation and an averaging effect occurs. In that case the quantity V in (1) and (2) has to be regarded as an effective voltage ($V = V_{\text{eff}}$). Here we use a frequency of 1 kHz. The utilization of an AC voltage prevents charging of the device with respect to the surroundings. It also decreases the saturation angle slightly [28].

According to (1) the application of a voltage leads to a reduction in surface energy/tension, $\gamma_{l,\text{diel}} \rightarrow \gamma_{l,\text{diel}}^{\text{eff}}$, and thus to a decrease in the contact angle and an increase in the radius of curvature (i.e., a decrease in surface bending) of the droplet. If the latter, for example, were employed as a tunable planoconvex lens, its focal length could be increased this way.

However, EWOD can also be utilized in a different manner. If the contact layer, that is, the second electrode of the capacitor, is structured and the droplet is only partially "covering" this electrode, upon application of a voltage there will be an inhomogeneous electric field between the electrode and the droplet and across the dielectric layer. As a result, the ionic droplet will experience a net force moving the droplet further onto the biased contact. Thus EWOD is suitable for droplet actuation [29–32].

In this contribution we report on an optical droplet shutter, moved in or out of the optical path with different possible stationary positions. The transparent conductive droplet is surrounded by a nonconductive oil, which is blackened by the addition of a dye. The cell is standing upright and is operated by the actuation of the droplet via EWOD forces. We use an arrangement with two capacitances, thus allowing the EWOD forces to act on the front and rear of the droplet symmetrically.

A similar concept was introduced in 2011, where the response time was about 100 ms for voltages around 2 · 90 V peak-to-peak [7, 8]. For the same voltage the EWOD response time of <20 ms of our device is significantly smaller. We neither used a fluoropolymer film [33, 34] nor a silica-based sol-gel layer [35–38] in order to increase hydrophobicity, which made the device technology considerably simpler. This has been possible since, in our case, the dye makes the oil slightly polar [39].

Our approach is also close to the concept reported in [11], which is centered around a TMOF iris, where the iris diameter can take on continuous values as opposed to our discrete switch, but with a single capacitance in contrast to our double capacitance layout. The response time of about 15 ms is even better than that of our device.

Our concept, especially the layout of the electrical contacts, offers the possibility of addressing one of four discrete droplet positions, to which the droplet can even be moved diagonally. This effect can be used not only in optics, but, for example, also in lab-on-a-chip technologies with digital (i.e., droplet-based) microfluidics (lab-on-a-chip 2.0) [40–45].

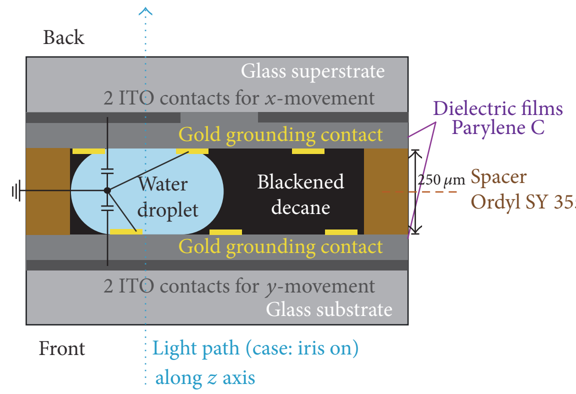

Figure 1: Cross-sectional view (not to scale): layer sequence of the double capacitor device/module/cell. More details (e.g., on layer thicknesses) are given in the text. Since the droplet is squeezed flatly onto the dielectric layers and the lines of the gold structure are thin and narrow, there should be no phase distortion of the transmitted light wave. If either the lower/front or the upper/rear dielectric layer were missing, the set-up would constitute a single capacitor EWOD set-up.

2. Device Layout, Materials, and Technology

The transparent water droplet (with 0.1 weight-% NaCl dissolved) is embedded in an oil, which is (blackened) decane [46]. The blackening is achieved by emulsifying the oil with the dye Sudan Black B (both purchased from Sigma Aldrich, St. Louis, Missouri, USA). Our weight mixing ratio (decane : dye, 18 : 1) gives 30 dB attenuation at 570 nm wavelength over the light's path length of 250 μm inside the fluid and 15 dB averaged over the visible spectral range. The insertion loss of the device in the case of the open shutter is 1.5 dB.

The squeezed droplet has a diameter of 0.5 mm and a thickness of 250 μm, resulting in a droplet volume of approximately 60 nl. For such small volumes the gravitation is much smaller than forces from surface tension and friction [2]. This means the device/module/cell can be positioned vertically without changing the shape of the droplet and the droplet does not move due to gravity.

The layer sequence is given in Figure 1. The arrangement represents two capacitors in series with the water droplet as one electrode of each capacitor. Both capacitors consist of the water droplet, a 3.5 μm thick Parylene C layer each (from SCS coatings, Indianapolis, Indiana, USA) [47–49] as the dielectric layer, and two structured ITO contact layers each, such that there are two front (1a, 1b in Figure 2) and two rear ITO structures (2a, 2b in Figure 2). The sub- and the superstrate were purchased from Sigma Aldrich, St. Louis, Missouri, USA, as 1.1 mm thick glass slides covered with a 20 nm thick ITO film. Sub- and superstrate are separated by a 250 μm thick spacer layer made of Ordyl (from Elga Europe, Milano, Italy).

In order to electrically contact the droplet, another contact structure, that is, a grounding contact, has to be brought in. We have used 200 nm thick gold films for this contact [50]; however, it could be replaced by an ITO contact in the future

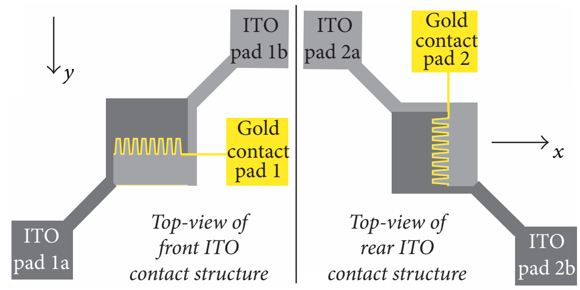

Figure 2: Front view: sketch of the 2 × 2 ITO contact structures and the 2 × 1 gold grounding contacts. The contact structures allow for the addressing of one of four possible droplet positions.

in order to increase the overall optical device transmission. As a matter of fact we employed two gold structures, one in front of and one behind the droplet in order to get a symmetric set-up and EWOD forces symmetrically distributed over the front and rear of the droplet. Thus, altogether, there are six contact structures, four made of ITO and two of gold; see Figure 2.

Since other applications might require a different light path arrangement, the shutter should have some flexibility in the direction of droplet movement. For that reason, one of our own target specifications has been that the design should be flexible enough to allow for horizontal, vertical, and diagonal droplet movement in the upright x-y plane and for four different stationary droplet positions. Therefore, all four ITO contacts are structured and positioned as in the case of address lines, as it is depicted in Figure 2.

The ITO contacts above/in front of the superstrate are responsible for the droplet movement along the x direction, while the ITO contacts above/behind the substrate take care of the y movement. The z axis is the direction of light propagation. Also, one of the meander-shaped gold grounding contact stripes is oriented along the x direction, while the other is aligned along the y direction. All contacts are shaped in such a way to always guarantee contact of the droplet to any neighboring contact pad, towards which the droplet might be moved next. By simultaneous application of voltages between ground and two neighboring contact pads (e.g., applying voltages to ITO pads, 1b and 2a in Figure 2) the droplet can also be moved diagonally.

3. Results

Figure 3 shows the final module in operation, in an upright position and illuminated from the rear, at four points in time and positions of the bright/transparent droplet. The gold grounding contacts can be observed as meander-shaped dark lines.

We get a small EWOD response time of <20 ms for $2 \cdot 90$ V peak-to-peak operation voltage.

Due to the specific shape and orientation of the four ITO contacts, functioning as address lines, the droplet can be moved either horizontally or vertically or even diagonally. The latter occurs, when two neighboring contacts are switched on simultaneously, as is illustrated in Figure 4. This figure was taken with an "exposure time" of 20 ms, so the droplet seems to be smeared over different positions of its diagonal movement. Hence the response time for the start of the droplet motion has to be even below 20 ms and the velocity of the droplet can be estimated to be larger than 35 mm/s.

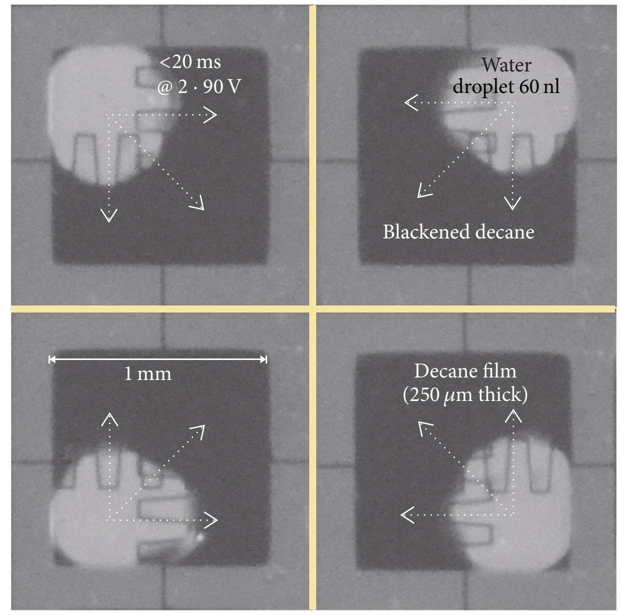

Figure 3: Front view: device/module/cell, standing upright and illuminated from the rear, at four different points in time and for four positions of the water droplet. The gold grounding contacts are observed as meander-shaped dark lines; to increase overall transmission, these might be substituted by other transparent ITO contacts in the future. All contact structures are designed such that the droplet can be moved in any direction, that is, horizontally, vertically, and diagonally, depending on the sequence of application of voltages to the contacts.

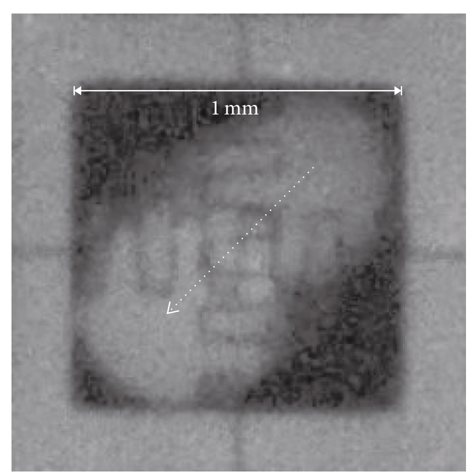

Figure 4: Front view: video frame showing a *diagonal* droplet movement; the droplet seems to be smeared over due to the "exposure time" of 20 ms. The response time for the start of the droplet movement is even lower. Droplet velocity is >35 mm/s.

4. Conclusions

We have presented a double capacitor design for liquid droplet actuation via electrowetting-on-dielectrics (EWOD), within the context of a movable optical shutter (the droplet) with a constant opening diameter of about 0.5 mm. The opening, that is, the transparent 60 nl droplet, can be moved in and out of the light's path by way of EWOD. In order to ensure symmetry we also introduced an electrical double middle grounding contact to the droplet, so far made of gold.

The concept results in a small EWOD response time of less than 20 ms for actuation voltages of $2 \cdot 90$ V. The droplet velocity is >35 mm/s. The insertion loss of the cell is 1.5 dB in the "open shutter" state. The on-off attenuation ratio is 30 dB at 570 nm wavelength and 15 dB averaged over the visible spectral range due to the opaqueness of the blackened oil around the droplet.

Moreover, due to the specific layout of the contact structures as address lines, the droplet can be moved either horizontally or vertically or even diagonally. This should give a further degree of freedom for any application in set-ups of tunable microoptics.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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