Electrowetting manipulation of any optical film

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Electrowetting manipulation of any optical film is reported. A square channel was constructed with four sidewall electrodes, coated with a hydrophobic dielectric, and filled with saline and oil. In a first experiment a dielectric mirror film was suspended between the oil/saline meniscus. Electrowetting at each sidewall produced a saline contact angle change of $35° < \theta < 170°$. This change in contact angle tilted the mirror and ±105° of laser beam deflection was achieved. A second experiment utilized a Mylar film imprinted with a diffraction grating (625 lines/mm). Electrowetting tilting of the grating was shown to alter the diffraction of the laser beam. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2750544]

A recent explosion of growth in electrowetting research[1–3] can be partially attributed to the discovery of numerous applications in photonics. Innovations include, but are not limited to, liquid lenses,[4–6] high-brightness displays,[7,8] and area tunable reflectors.[9,10] Nearly all practical optical electrowetting devices utilize density-matched and immiscible liquids such as oil/saline in order to reduce the influence of gravity or vibration. Such systems manipulate light through refraction[11] at an oil/saline interface or through optical shuttering[7,12] with an opaque oil layer. However, there does not yet exist a means by which electrowetting can manipulate sophisticated optical elements such as multilayer dielectric reflector films or surface gratings. Reported here is the unification of electrowetting manipulation and any optical film (Fig. 1). The optical film is surface energy treated such that it can be suspended between an oil/saline meniscus [Fig. 2(a)]. The liquids and the optical film are then voltage-manipulated inside a square channel consisting of four electrowetting sidewalls. Experiments include ±105° of laser beam steering with dielectric mirror and ±50° tilting of a linear surface grating. These preliminary results provide very wide-angle beam steering as compared to digital micromirror devices[13] (~10°–20°) or liquid crystal optics[14] (~5°–10°). Presented herein are fabrication, electrowetting and optical theory of operation, and optical beam steering/diffraction results.

Fabrication of the electrowetting devices was performed as follows. A 5×5 mm^2 square channel was assembled from four rectangular polyethylene terephthalate sheets coated with ~100 nm of In_2O_3:SnO_2 (ITO). The ITO sheet resistance was ~100 Ω/sq. The assembled channel was next placed in a vacuum chamber and conformally coated with ~2 μm of Parylene C dielectric. The Parylene C film was then dip coated with DuPont Teflon AF solution. After the Teflon AF was oven cured the final film thickness was ~200 nm and the surface energy was $\gamma \sim 16$ mN/m. In this work, the term "hydrophobic dielectric" refers to the combined film stack of Parylene and Teflon. The rectangular channel was then epoxied to an ITO coated glass substrate. A ground electrode was attached to the ITO/glass substrate. An individual voltage supply was attached to each of the channel's four sidewalls. Two optical films were tested: a broadband dielectric reflector (3M Vikuity ESR); a 625 lines/mm surface grating formed in Mylar (Digital Optics Corp.). One side of each optical film was made hydrophobic by spin coating ~10 nm of Teflon AF. The other side of optical film was naturally hydrophilic, but could be made increasingly hydrophilic by chemical or plasma treatment. The completed channels were dosed with an electrically conductive saline solution (0.1*M* KCl). In some cases, light blue dye was added to the saline for visualization. The hydrophilic side of the optical film was then placed and wetted onto the saline meniscus. Oil was then dosed into the channel and the oil wetted the hydrophobic side of the optical film. As a result, the optical film was suspended between the saline/oil meniscus. The oil used herein was GE/Bayer SF1555 with specific gravity of 0.968 and refractive index of $n \sim 1.47$. In order to reduce the required operating voltage, 3*M* Novec FC4430 nonionic

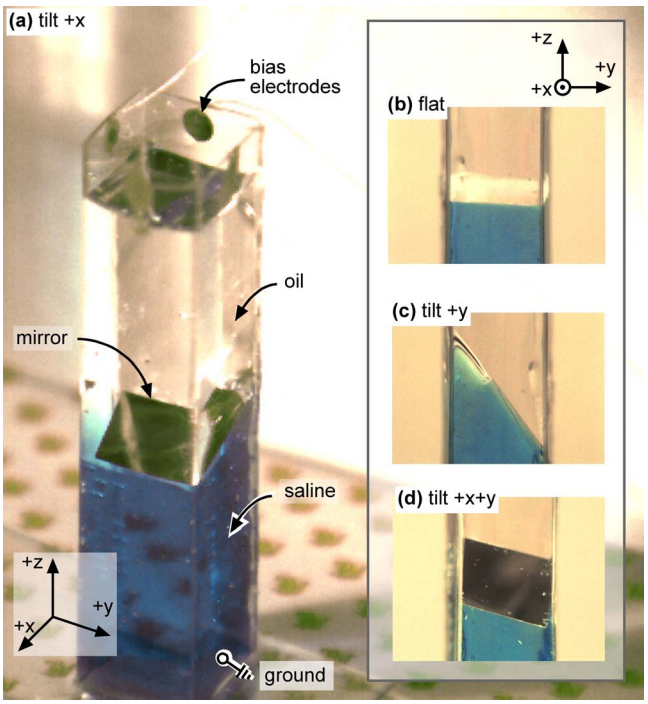


FIG. 1. (Color online) Photographs of electrowetting tilting of a mirror film suspended between a saline (blue) and oil (clear) meniscus. Four electrowetting sidewalls control the saline/oil contact angle inside the 5×5 mm^2 channel.

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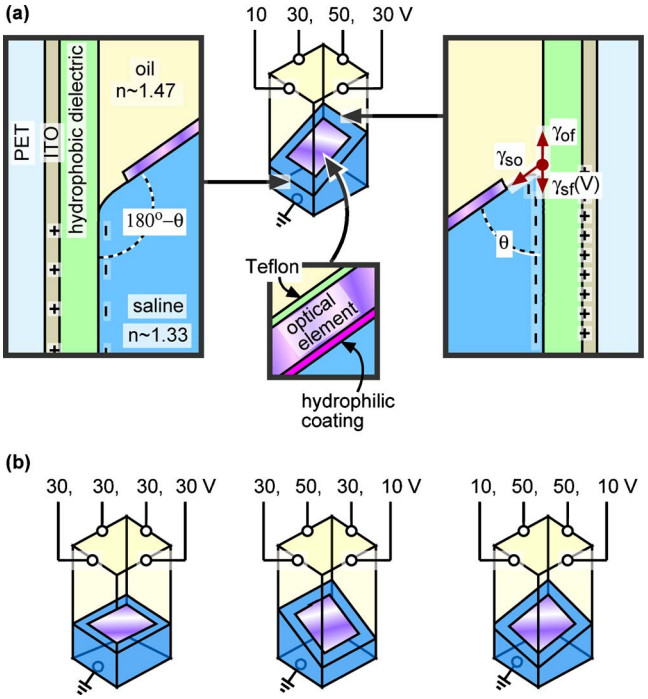


FIG. 2. (Color online) Device diagrams of (a) the role of electrowetting at the channel sidewalls and (b) example voltage configurations for various tilt directions.

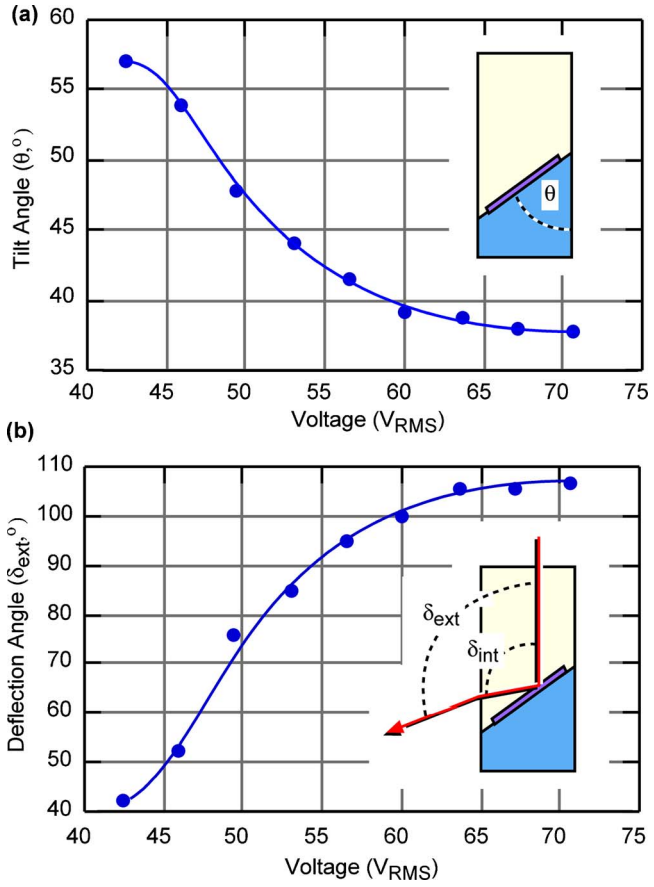


FIG. 3. (Color online) Tilt angle θ and externally measured deflection angle δ_{ext} vs applied voltage. Both data sets range between the lowest value for δ_{ext} (due to total-internal reflection) and the highest value for δ_{ext} (due to electrowetting saturation).

fluorosurfactant was added to the saline at a concentration of 125 ppm.

Since the tilt angle of the optical film is controlled by electrowetting, a brief review of electrowetting is provided. Electrowetting alters the balance of the interfacial surface tensions (γ) near the three-phase saline (S), oil (O), fluoropolymer (F) contact line. At zero voltage these balanced forces are related to the saline contact angle (θ_Y) by Young's equation, whereas the alteration of this balance by application of voltage is predicted by Lippmann's equation, respectively given as

$$\gamma_{SF} = \gamma_{FO} - \gamma_{SO} \cos \theta_Y, \tag{1a}$$

$$\gamma_{SF}(V) = \gamma_{SF}(0) - \frac{1}{2} CV^2, \tag{1b}$$

where C is the capacitance (F/m^2) of the hydrophobic dielectric and V is the dc voltage or ac rms voltage. Equations (1a) and (1b) may be combined to predict contact angle versus voltage.[1] For the materials used herein θ_Y is close to 180° such that the electrowetting contact angle θ can be predicted as

$$\cos \theta \approx \frac{CV^2}{2\gamma_{SO}} - 1, \tag{2a}$$

or

$$V \approx \sqrt{2\gamma_{SO}(\cos \theta + 1)/C}, \tag{2b}$$

where θ is the contact angle of the saline as a function of voltage [Fig. 2(a) right]. In this work, the 0–70 V_{rms} 1 kHz sinusoidal voltage and materials used allow contact angle reduction down to the point of electrowetting saturation[1] at $\theta \sim 35°$. For the four-sided channel, electrowetting at each sidewall is independently controlled. The contact angles at each sidewall alter the geometry of the saline/oil meniscus, and therefore alter the tilt angle of the optical film suspended in the meniscus [Fig. 2(a)]. In order to tilt the flexible optical film without any bending of the film, the contact angles at opposing sidewalls are constrained to θ and $180° - \theta$ (i.e., a straight-line saline/oil meniscus). The required sidewall voltages for tilting the optical film can therefore be predicted by substituting the desired values for θ and $180° - \theta$ into Eq. (2b).

As shown in the inset diagram for Fig. 3(b), experimental beam deflection results were recorded by directing a 633 nm laser downward through the top of the device. Midway down the channel the laser beam was reflected by a suspended 3M Vikuiti™ ESR mirror. The ~65 μm thick ESR film is a multilayer polymer dielectric reflector with >98% reflectivity over wide angles and across the entire visible spectrum. As the sidewalls were electrowetted, the mirror film tilted, and therefore the laser beam was deflected away from its angle of incidence. This laser beam deflection *internal* to the channel is labeled as δ_{int} in the inset diagram of Fig. 3(b). As the beam exits the channel it refracts at the channel/air interface and results in an *external* beam deflection of δ_{ext}. Two cameras simultaneously recorded the tilt angle of the mirror film (θ) and the external beam deflection (δ_{ext}). As shown in Fig. 3, reducing the tilt angle of the mirror to $\theta < 40°$ resulted in $\delta_{ext} > 105°$. The beam deflection in Fig. 3(b) is not plotted down to 0° since at smaller values for δ_{int} the beam experiences total-internal reflection at the channel/air interface. This limit observed for the experiment performed here is not a fundamental limit. Theoretically all

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steering angles within ±105° could be achieved if we were to reduce the height-to-width ratio of the channel. Even optical "blind" spots at the channel corners could be avoided as a beam exiting the channel near a corner is partially refracted toward the corner. Therefore the possible deflection angles that could be accessed by this type of device encompass more than an entire hemisphere. Due to the large size of the 5×5 mm^2 channel, the device switching time is ~100's of ms. With scaling down of the channel size to 100's μm the switching time is expected to decrease to <10 ms as predicted by $\tau\propto(\rho\times\nu/\gamma)^{1/2}$, where $\rho\times\nu$ is the liquid density-volume product.[15]

A theoretical equation for the beam deflection is provided as follows. The electrowetting response of Eq. (2a) can be modified to predict δ_{int} according to

$$\delta_{\text{int}} \approx 180^\circ - 2\cos^{-1}\left(\frac{CV^2}{2\gamma_{SO}} - 1\right). \tag{3}$$

Using Snell's law this equation can then be further developed into δ_{ext} according to

$$\delta_{\text{ext}} = 90^\circ + k\sin^{-1}\left\{\frac{kn_{\text{oil}}}{n_{\text{ext}}}\left[2\left(\frac{CV^2}{2\gamma_{SO}} - 1\right)^2 - 1\right]\right\},$$

$$k = \begin{cases} -1, & \theta \geqslant 45^\circ \\ 1, & \theta < 45^\circ, \end{cases} \tag{4}$$

where n_{oil} is the refractive index of the oil, n_{ext} is the refractive index outside the channel, and the equation is limited to the case of the deflected beam exiting through the sidewalls of the channel. The camera recorded measurements for θ and δ_{ext} in Fig. 3 are in good theoretical agreement. It was found that the voltage response deviated from the theoretical behavior predicted by Eq. (4). The devices presented here are on the larger end of allowable sizes for single electrowetting devices, have low γ_{SO}, and are therefore subject to deviation from Eq. (4). Device miniaturization or improved saline/oil density matching would largely alleviate nonideal effects such as gravity. Device miniaturization is also important as one may speculate that numerous channels can be combined into a two-dimensional array of optical devices. For arrayed devices, the deflected beam must avoid adjacent devices and therefore must exit the top surface of the array. In order to calculate deflection performance for this hypothetical array, one might assume an oil refractive index of $n=1.6$ and mirror tilting of $71^\circ<\theta<109^\circ$. Since the reflected beam will refract as it exists the top of the array, the maximum deflection angle would be δ_{ext} ±80°. This calculation shows that if properly designed, such arrays could achieve wide-angle deflection with only moderate tilting of the mirror films.

An additional experiment was performed with a 127 μm thick Mylar diffraction grating ($n\sim1.65$, 625 lines/mm, Digital Optics Corp.). This experiment was performed to further demonstrate that the device is indeed capable of manipulating any flat optical film. As shown in Fig. 4, a linear grating was spin coated with Teflon AF, suspended in the saline/oil meniscus, and tilted using techniques previously described for the mirror film. For the experiment pictured in Fig. 4, the grating lines were oriented perpendicular to the tilt axis. An experiment was also performed with the grating lines parallel to the tilt axis. For the parallel case, as the grating was tilted the nondiffracted portion of the transmitted beam remained stationary while the higher order diffracted modes shifted in angle.

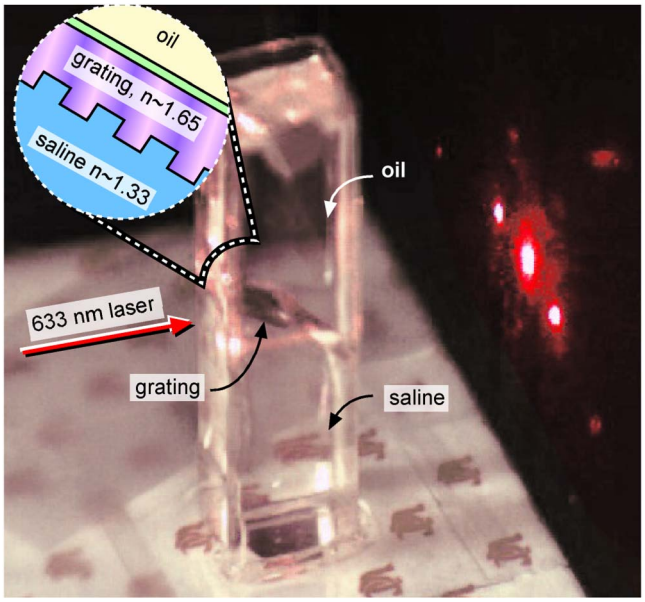


FIG. 4. (Color online) Demonstration of tilting a linear diffraction grating (625 lines/mm). Unlike Fig. 1, no blue dye was added to the saline since for this experiment the 633 nm laser must propagate through both the oil and saline liquids.

In summary, large angle electrowetting control of optical films has been demonstrated. Optical films compatible with this approach include but are not limited to mirrors, gratings, possibly even photonic crystals, scintillators, or optically pumped thin film lasers. Future work will focus on reducing the device size, implementing devices in arrayed format, and relating deflection precision to contact angle hysteresis. Achieving lower operating voltage will involve increased sidewall capacitance, lowering of interfacial surface tensions, and an increase of the refractive index of the oil liquid.

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