High-transmission electrowetting light valves

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High-efficiency spatial light modulation has been demonstrated for transmissive electrowetting (EW) light valves (ELVs). The ELV structure consists of a competitive oil/water-on-dielectric EW cell fabricated on an optically transparent substrate. ELVs are configured as display devices by attaching a diffuse backlight powered by white converted InGaN light emitting diodes. The oil film contains ~1wt. % nonpolar organic chromophores which absorb with near-neutral optical density across the visible light spectrum. Using the EW effect, spatial light modulation is achieved as the water layer locally displaces the oil film. The transmissivity of the cell can be modulated from ~5% (zero bias) to >80% (~30 V). ELV switching speed depends on cell size, typically ~10–100 ms for 1 and 3 mm^2 cells. Additional optical enhancement can decrease the off-state ELV transmissivity to <1%. *© 2005 American Institute of Physics*. [DOI: 10.1063/1.1901816]

Physical movement of liquids on hydrophobic dielectrics can be achieved through application of an electric field, an effect known[1] as electrowetting (EW). EW liquid manipulation is the result of an electrostatically modulated decrease in contact angle consistent with an increase in polar liquid wetting (contact area) of a hydrophobic dielectric surface. In a very simple interpretation, field induced polarization of the liquid/hydrophobic–dielectric interface increases the effective surface energy of the hydrophobic–dielectric, therefore temporarily rendering the dielectric "less-hydrophobic." Complementary movement of two immiscible polar and nonpolar liquids is also achievable[2] in competitive EW systems. The rapidly expanding EW field includes various applications: biomedical lab-on-chip,[3] micromechanical motors,[4] variable focus lenses,[5] convex/concave invertible lenses,[6] fiberoptic communications switches,[7] reflective[8–10] displays, and fluorescent[11] displays. The broad applicability of EW stems from an ability to achieve robust and rapid (<10 ms changes in physical position,[3,4,8] optical surface curvature,[5,6] and effective refractive index[7,10,11] of single or multiple immiscible liquid systems. In this letter, we report on high transmissivity (>80%) spatial light modulation of electrowetting light valves (ELVs). Unlike liquid crystal devices[12] (LCDs), the ELVs provide spatial light modulation that is inherently independent of both transmitted light polarization and incidence angle (optical path length).

ELV devices with the structure shown in Fig. 1 were fabricated on Corning 1737 glass substrates. A lower patterned ground electrode consists of an ~50 nm 90%/10% In_2O_3/SnO_2 (ITO) film which is transparent (>90%) and electrically conducting (<40 Ω/□). DuPont Teflon® AF 2400 amorphous fluoropolymer is then dissolved at ~1wt. % in fluorosolvent (3M Corp. FC-75 Fluorinert®) and dip-coated onto the ITO/glass substrate. After an ~15 min baking and annealing cycle, the fluoropolymer forms a transparent <1 μm thick dielectric film with a surface energy of $\gamma < 20$ dynes/cm (hydrophobic). Next, a hydrophilic grid ($\gamma \sim 40$ dynes/cm) is optically patterned from a photocurable polymer that is resistant to dissolving or swelling in oils and cleaning solvents. The hydrophilic grid lines are ~150 μm wide, ~40 μm thick, and define an ELV cell which is ~1×3 mm^2 in area. After the hydrophilic grid is photopatterned, a special treatment renders it optically opaque in order to prevent light leakage in the separation space between adjacent ELV cells. A few hundreds of μL of deionized water (>16 MΩ cm) are then dosed over arrays of ELV cells. Next, ~100 to ~300 nL of black oil is inserted into each ELV cell, forming an oil layer thickness of 10's of μm. The specialized oil has a surface tension of ~25 dynes/cm, causing it to form a continuous film positioned between the water (~73 dynes/cm) and the hydrophobic dielectric (<20 dynes/cm). This water/oil/hydrophobic-dielectric layered geometry is due to interfacial surface tension relationships.[2] The oil is further confined laterally by the hydrophilic grid[8] that strongly attracts, and is wetted by, the overlying water layer. Interfacial surface tension forces dominate over gravitational forces since the oil has near-

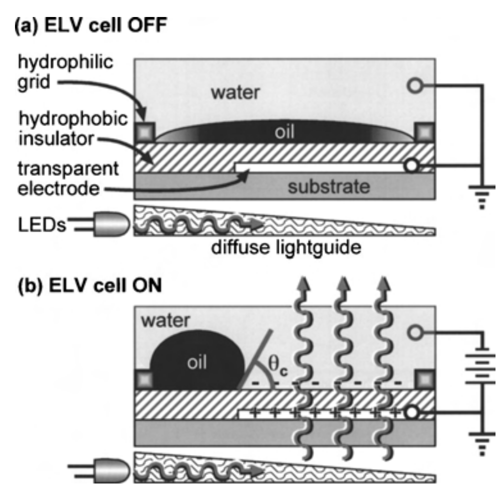

FIG. 1. (Color online) Schematic diagrams of the ELV device structure in the OFF (a) and ON (b) states of transmission.

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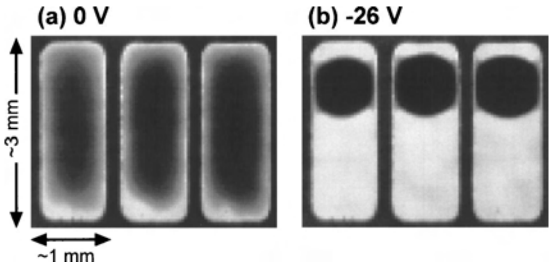

FIG. 2. Images of optical transmission through ELV cells biased at: (a) 0 V; (b) −26 V.

unity specific gravity. The oil is rendered opaque through ~1 wt. % doping with selected chromophores. The chromophores are nonpolar organic compounds that strongly absorb visible light without radiative decay. A combination of color-complementary chromophores are utilized to obtain neutral density absorption across the visible spectrum. Since nonpolar chromophores are selected, they are soluble in the oil only and cannot diffuse into the polar water layer. An electrode wire is then inserted into the water layer. For optical switching characterization, a diffuse light-guide (backlight) is placed underneath the ELV array. The light-guide is edge lit with a white-phosphor-converted InGaN light emitting diode (LED) array. This configuration is similar to that used for small-size LCD panels.[12]

The completed ELV device structure shown in Fig. 1 is operated as follows. Under conditions of zero applied bias [Fig. 1(a)] to the water layer, interfacial surface tensions cause the black oil to form a continuous film between the water and hydrophobic-dielectric layer. The black oil layer therefore absorbs light across each ELV cell as shown in the image of Fig. 2(a). The application of voltage and resultant increased wetting of the water layer causes the oil layer to be displaced to a fraction of ELV cell area, as shown in Fig. 1(b) and the image of Fig. 2(b). In this situation, unhindered light transmission from the lightguide occurs in all areas where water contacts the hydrophobic-dielectric. This displacement of the oil layer is governed by an electrostatically modulated decrease in the water contact angle θ_c [Fig. 1(b)]. This competitive electrowetting[2] behavior follows a combination of the Lippman and Young equations for electrowetting in a three-phase water/oil/dielectric system:

$$\cos\theta_c = \cos\theta_0 + \frac{\varepsilon_o \varepsilon_r}{2z\gamma_i} V^2, \qquad (1)$$

where θ_0 is the contact angle without applied bias V, ε_r, and z are the relative dielectric constant and thickness of the hydrophobic-dielectric, and γ_i is the interfacial surface tension between the water and oil.

ELV cell transmission versus applied voltage was measured after repeated ON/OFF actuations of the ELV devices. The transmission measurements plotted in Fig. 3(a) reveal a threshold voltage of ~8 V and >80% transmission for ~24 V modulation above threshold. This transmission level is several times higher than that typically achieved[12] for LCD light valves, and is independent of incident angle *and* polarization. Switching response for the ELVs plotted in Fig. 3(b) is on the order of ~100 ms. The switching ON [−24 V or −32 V, Fig. 3(b)] time is governed by electrowetting forces and is faster than the switching OFF (0 V) time which is governed by purely capillary forces. At the cost of increased threshold and operating voltage, the switching OFF time can be decreased by increasing the dosed oil volume beyond the minimum for filling of the ELV cell (max θ_c). The slight oil overfill utilized in the ELVs reported here is partly responsible for the nonzero [Eq. (1)] threshold voltage shown in Fig. 3(a). Preliminary results with smaller area ~1×1 mm^2 ELVs are exhibiting <10 V operation (threshold + modulation) and ~10 ms switching times. This is consistent with other recently reported results[13] for reflective electrowetting devices.

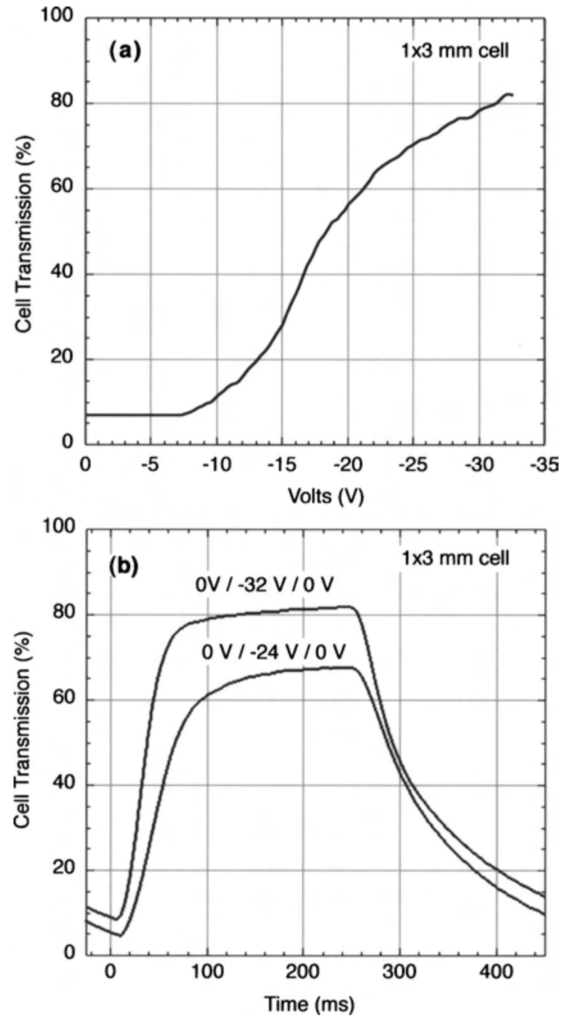

FIG. 3. ELV cell optical transmission as a function of: (a) voltage; (b) switching time for −24 V and −32 V square wave bias.

The ability of ELVs to achieve low voltage and fast switching leaves black/white contrast ratio as the major area of future ELV research and performance improvement. As shown visually in Fig. 2(b) and measured in Figs. 3(a) and 3(b), light leakage causes the ELV device to exhibit ~5%–10% transmission in the fully OFF state. This light leakage presently limits black/white switching contrast to ~10:1. A general relationship for ELV cell transmission that is independent of cell-geometry can be given as:

$$\%T = 1 - \frac{A_{\mathrm{oil}}}{A_{\mathrm{cell}}}(1 - e^{-\alpha z_{\mathrm{eff}}}), \quad z_{\mathrm{eff}} = F_1(\theta_c) \propto \frac{V_{\mathrm{oil}}}{A_{\mathrm{oil}}}, \qquad (2)$$

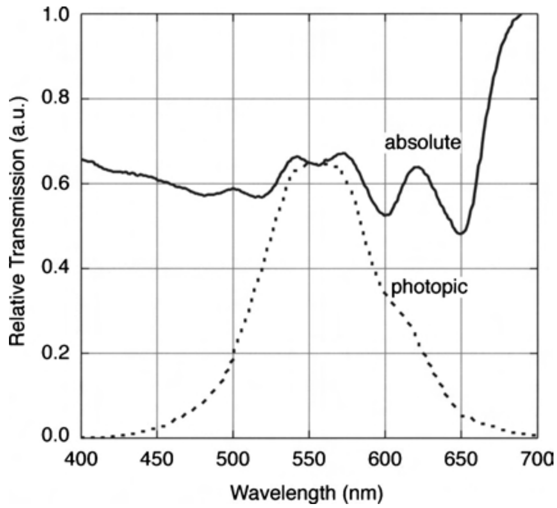

FIG. 4. Optical and photopic transmission spectra of oil:chromophores utilized in ELV cells.

$$A_{\mathrm{oil}} = F_2(\theta_c), \quad \alpha \propto \eta_{\mathrm{chr}},$$

where the variables are cell transmission ($\%T$) which can be related to the percent area for oil coverage (A_{oil}) in the ELV cell (A_{cell}), absorption coefficient of the oil (α), and an effective oil thickness (z_{eff}) derived from the spherical cap geometry of the oil beneath the water. Both the oil effective thickness, $z_{\mathrm{eff}}=F_1(\theta_c)$, and the oil coverage area, $A_{\mathrm{oil}}=F_2(\theta_c)$, are dependent on the water contact angle (θ_c) which governs the geometrical change in the oil versus applied voltage [Eq. (1)]. The crude approximation $z_{\mathrm{eff}} \propto V_{\mathrm{oil}}/A_{\mathrm{oil}}$ is given only to highlight the decrease in oil transmission with decreasing oil area. $F_2(\theta_c)$ can be obtained by deriving the geometrical complement of area for a water-only spherical cap model.[14] The oil absorption coefficient α (cm^{-1}) is proportional to chromophore concentration (η_{chr}) in the oil. For perfectly black oil ($\alpha \to \infty$), Eq. (2) reduces to a function of oil coverage only. However, for the practical case (even when $A_{\mathrm{oil}}=A_{\mathrm{cell}}$) the transmission is dominated (and the contrast is reduced) by light leakage near the cell edges. Switching contrast may be partially improved through increasing the wt. % of chromophores doped into the oil. Presently, chromophore solubility and/or polar impurities (oil resistivity) effectively limit the maximum usable chromophore concentration. Surface energy modification or optical masking near the cell edges may also improve ELV contrast.

The ELV devices discussed here use a near-neutral density filtering approach, as shown in oil transmission plot of Fig. 4. The oil measured in Fig. 4 was placed in a 4 mm cuvette and intentionally lightly doped ($\leqslant 1$ wt. %) so that a strong transmission signal could be recorded. Transmission weighted against the photopic response of the human eye (lm/W converted) is also shown to reveal that light leakage below ~450 nm or above ~650 nm has a negligible effect on ELV applications where the human eye is the optical detector (displays). The ELVs reported here are monochromatic. However, multiple colors or wavelengths can be obtained through color filtering or through the use of primary color LEDs. Multiple wavelength generation is also possible through the use of two or three ELVs in the optical path, employing complementary cyan, magenta, or yellow chromophore doping of the oil.[8]

In summary, high efficiency spatial light modulation has been demonstrated for transmissive electrowetting light valves (ELVs). Greater than 80% transmission and ~10–100 ms switching speeds are exhibited by the ELVs. The ELVs provide spatial light modulation that is inherently independent of both transmitted light polarization and incidence angle (optical path length).

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