Display Technology Letters

Ultra-High Transmission Electrowetting Displays Enabled by Integrated Reflectors

Y. Lao, *Student Member, IEEE*, B. Sun, *Student Member, IEEE*, K. Zhou, *Student Member, IEEE*, and J. Heikenfeld, *Senior Member, IEEE*

***Abstract*—A reflector technique for increasing the transmission performance of a back-lit electrowetting display is presented. The electrowetting display pixel structure consists of an opaque oil film that blocks light transmission. Electrowetting with $\sim$ 5–10 V breaks up the oil film and creates a transmissive area for the pixel. With real-world electrowetting materials and device constraints, the transmissive area typically reaches 60% to 80% of the pixel area. By integrating a simple thin-film reflector between the backlight and the remaining oil film area, the effective transmission can be boosted to $>$ 90%. This high efficiency is promising for battery-powered applications and for high-brightness sunlight-legible displays.**

***Index Terms*—Display, electrowetting, light valve, microfluidics.**

I. Introduction

TRANSMISSIVE displays dominate portable communication and computing applications despite the fact that reflective displays offer much lower power consumption. Presently, most consumers prefer the higher image quality and affordability provided by transmissive liquid crystal displays [1]. With present power consumption levels at an acceptable level, it could be argued that if higher efficiency transmissive displays are developed such displays will continue to dominate in portable applications. With the average transmission efficiency of commercial liquid crystal displays at $<$ 10% there is significant room for improvement. Electrowetting [2] is an emerging alternative for reflective [3] and transmissive [4] displays. Electrowetting displays (EWDs) utilize a colored oil film that can change in area via application of electromechanical force [5]. Reported here is an integrated reflector technique and model that boosts the effective EWD transmission to $>$ 90%. This technique can also decrease the pixel switching time and therefore better enable field-sequential color generation [6].

II. Device Structure and Operation

A proposed device structure for a transmissive EWD is shown in Fig. 1(a). The device will utilize a backlight unit comprising an edge lit waveguide or direct-lit source such as an electroluminescent film. For simplicity, the backlight supporting glass substrate, and thin film transistors are labeled as 'substrate/backlight'. Materials and fabrication for the EWD pixel have been previously reported [7] and are briefly reviewed herein. A thin film reflector such as Al ($R > 90\%$) or a multilayer dielectric film ($R > 98\%$) [8] is first patterned onto the substrate. Next, thin-film transistors (not shown) and a lower electrode of In_2O_3 : SnO_2 are deposited. The substrate is then uniformly coated with a hydrophobic dielectric. The hydrophobic dielectric comprises a $\sim$ 150-nm SiN dielectric and a $\sim$ 50-nm fluoropolymer for the purposes of electrical insulation and hydrophobicity, respectively. Next, SU-8 negative resist is patterned and forms a $\sim$ 12-μm thick hydrophilic grid. This hydrophilic grid defines the pixel border (typically between 50$\times$150 μm and 300$\times$900 μm). At this point, the EWD is dipped through an opaque oil film that is floating upon water. This self-assembly process [7] doses an oil layer into each pixel

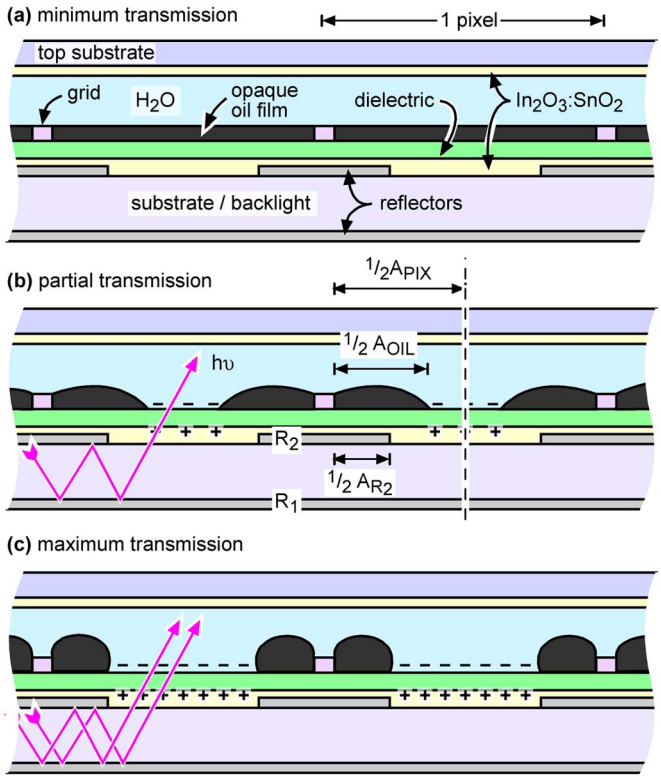


Fig. 1. Diagrams of EWD pixels in the: (a) OFF state; (b) partially transmissive state; and (c) state of maximum transmission. The diagram in (b) also contains key terms of the optical model described herein.

Manuscript received November 1, 2007. This work was supported in part by Sun Chemical (U.S.A), Motorola University Partnerships in Research (U.S.A), and the Industrial Tech. Research Institute (Taiwan).

The authors are with the Novel Devices Laboratory, University of Cincinnati, Cincinnati, OH 45221 USA (e-mail: heikenjc@email.uc.edu).

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Digital Object Identifier 10.1109/JDT.2008.920172

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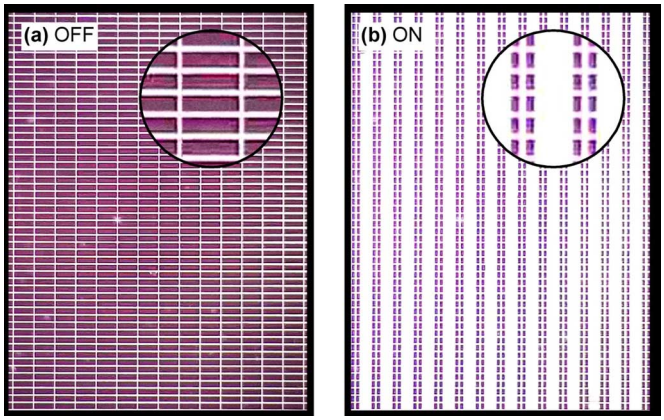


Fig. 2. Photographs of electrowetting display pixel arrays in the (a) OFF state, (b) ON state. The pixel dimensions are 300×900 μm.

that is the same thickness as the hydrophilic grid height. The EWD is edge sealed with a top-electrode/substrate and is then ready for operation. As shown in Fig. 1(b) and (c), application of voltage between water and the lower $In_2O_3 : SnO_2$ electrode creates a downward electromechanical force that causes the oil to dewet from the fluoropolymer via process similar to spinodal dewetting [9]. Once the oil dewets, fringing fields at the oil–water–fluoropolymer contact line result in a horizontal electromechanical force [5] that drives the oil to a fraction of its original coverage area. Larger voltages result in smaller oil area and higher optical transmission. When voltage is removed, interfacial surface tension forces rapidly ($\sim$ 10 ms) drive the oil back to a film state and the transmission is turned off. Photographs of arrays of 300×900 μm pixels in operation are shown in Fig. 2.

III. Optical Model for Reflector Enhancement

Turning attention back to Fig. 1(b), a model for the role of the reflectors can be explained as follows. Terms "A" represent a percentage area of the pixel, and terms "R" represent the percentage of light reflected off a surface. First considered is the sequential propagation path of light within the EWD: 1) light reflects off R_1 before it reaches the pixel surface; 2) a percentage of the light $[R_1(1 - A_{\mathrm{OIL}})]$ is able to exit the EWD through the pixel open area; and 3) a percentage of the light $(R_1 \cdot R_2 \cdot A_R)$ is reflected back into the waveguide and the process repeats itself. This sequential process results in a net percent transmission $(\%T)$ that can be expressed as

$$\begin{aligned}\%T = {} & R_1(1 - A_{\mathrm{OIL}}) + R_1R_2A_R[R_1(1 - A_{\mathrm{OIL}})] \\ & + (R_1R_2A_R)^2[R_1(1 - A_{\mathrm{OIL}})] \\ & + (R_1R_2A_R)^3[R_1(1 - A_{\mathrm{OIL}})] \ldots . \end{aligned} \tag{1}$$

This optical series can then be expressed in simpler form as

$$\%T = \frac{R_1(1 - A_{\mathrm{OIL}})}{1 - R_1R_2A_R}. \tag{2}$$

This equation provides a means to calculate the net percent transmission of the EWD with an integrated reflector. As will be seen in the following discussion, very high optical transmissions are theoretically possible.

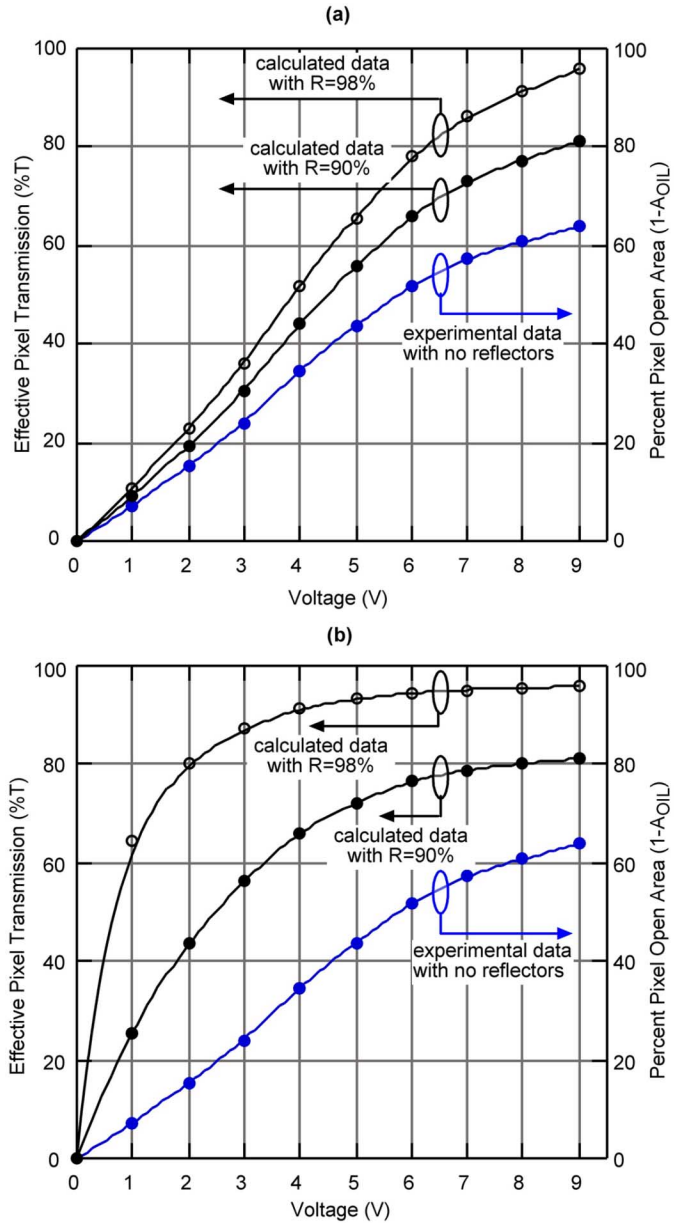


Fig. 3. Plots of effective pixel transmission area versus voltage for (a) a reflector area (A_R) that occupies 36% of the pixel area and (b) a reflector area that is equal to the oil area at a given voltage. The plot in (b) is not physically realizable since the reflector area cannot change with voltage. Rather, the data found in (b) is provided to show the maximum effective transmission area that can be achieved for various voltage levels and oil areas.

IV. Experimental and Theoretical Results

Traditional EWD pixels were characterized in order to understand the potential benefit provided by an integrated reflector. The open area of the EWD pixel $(1 - A_{\mathrm{OIL}})$ as a function of 30-Hz AC square wave voltage is shown in Fig. 3(a) (blue data points). This is experimental data shows that $\sim 64\%$ open area can be achieved with only $\sim$ 9 V operation for 300×900 μm pixels. These experimental data points were then entered into (2) for two reflectance values $R = 90\%$ (an Al reflector) and

$R = 98\%$ (a broadband multilayer dielectric reflector [8]). For simplicity, these R values are substituted for both R_1 and R_2 in (2). A fixed value for A_R of $\sim 36\%$ was chosen because it matches the minimum experimentally achieved value for A_{OIL}. After the $\%T$ values were calculated by (2), they were plotted in Fig. 3(a) (black data points). As can be seen in the plots, integrated reflectors with $R = 90\%$ and $R = 98\%$ boost the maximum value for $\%T$ to $\sim 80\%$ and $\sim 95\%$, respectively. These effective transmission values for an EWD with an integrated reflector are approximately an order of magnitude greater than that typically found for a liquid crystal display.

The calculated data in Fig. 3(a) explores only the scenario of a single value for A_R of 36%. For an EWD pixel that is operated to 9V this is the best design because it matches the minimum value for A_{OIL} (i.e., provides the maximum achievable value according to (2). However, the transmission enhancement with the integrated reflector technique is so substantial that it is not necessary to drive the pixel all the way to 9 V to obtain high transmission efficiency. For example, consider the extreme case of driving the pixel with only 2 V to $A_{\mathrm{OIL}} = 85\%$. If one implemented $A_R = 85\%$ and a dielectric reflector with $R = 98\%$, according to (2) b one would still achieve $\%T = 80\%$. Therefore, additional calculations were made in order to explore the maximum possible values for $\%T$ for pixels driven with lower voltages. Such calculations are simply achieved by substituting $(1 - A_R)$ for $(1 - A_{\mathrm{OIL}})$ in (1) and (2), and are plotted in Fig. 3(b).

V. Other Issues and Speculation

Further discussion is provided so that the full extent of challenges and opportunities can be understood for EWDs with an integrated reflector. The first issue is the maximum optical contrast between pixel ON and pixel OFF states. As the electrowetting pixels are scaled down the oil film thickness must also decrease [7]. As oil films with 10 wt. % of dye become thinner $(< 5\ \mu\mathrm{m})$, the oil can become partially transmissive and, therefore, limit the contrast of the EWD. Further work is needed to increase present contrast ratios of 10's:1 to 100's:1. Contrast reduction due to bright ambient light is less of a concern since the reflective portion of the pixel (R_2) is concealed by the opaque oil at all times. Other important factors for an EWD with an integrated reflector should be addressed. If thin-film transistors are fabricated on the substrate, an Al pixel reflector (R_2) may require deposition after the high temperature transistor processing is complete. A multilayer SiN–SiO_2 reflector, therefore, may be most attractive due to high temperature resistance and higher reflective efficiency. The reflector at the backside of the backlight (R_1) can be simply laminated and clearly could be a polymer dielectric reflector like that of a 3M Vikuiti® Enhanced Specular Reflector film with $> 98\%$ reflectivity [8]. A possible area of practical concern is pixilation (i.e., detection by the human eye of the dark area of each pixel). For most applications and viewing environments this is not a major concern so long as the pixels are small $(< 100\ \mu\mathrm{m})$. For larger pixels, the pixel may still be controlled by a single electrode but the pixel may be subdivided with multiple hydrophilic grids into several smaller pixel regions that each have a reflector (R_2) and oil droplet.

With proper design, the integrated reflector approach might also provide an additional benefit in pixel switching speed. When the voltage is removed in an EWD pixel, surface tension forces drive the oil back to a film geometry. The slowest motion of the oil is when the oil nears complete coverage of the pixel cell. This is because as the oil approaches a film geometry the imbalanced surface tension forces driving the oil motion are approaching equilibrium (i.e., reduced driving force). An integrated reflector could be strategically placed in the cell to optically mask the slowest portion of the oil movement, and as noted in the analysis of this paper, do so with little cost to the optical efficiency of the EWD pixel. This would decrease the switching time of the pixel which is already < 10 ms for a traditional EWD pixel. As a further result, field-sequential color generation could be utilized. This brings the discussion to the key benefit of the transmissive EWD platform with an integrated reflector. Consider a field-sequential backlight that receives light from red, green, blue LEDs with ~ 80 lm/W net luminous efficiency. Given a backlight efficiency of $\sim 50\%$, field sequential color (i.e., no color filters), $R_1 = 98\%$ and $R_2 = 95\%$, it is predicted that the net efficiency for an EWD could exceed 30 lm/W. Once again, it should be noted that this is approximately an order of magnitude greater than that of commercial liquid crystal displays. This would further reduce the cost and complexity of the backlight unit for high brightness or large area backlit displays. Transflective operation could be equally attractive. Given the high efficiency of light recycling in the backlight, a pattern of black text on a white background (i.e., most pixels fully open) could allow sunlight legibility even with the backlight turned off.

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