

## Flat Electrowetting Optics

Jason Heikenfeld, Andrew Steckl, Neil Smith,  
Don Abeyinghe, and Joseph Haus

### Abstract

A new class of liquid electro-optics based on electrowetting is able to replicate the high performance of solid geometrical optics. Scaled-down electrowetting optics can be arrayed in order to achieve a flat and large area form factor. Techniques for applying electrowetting devices to light valves and arrayed microprisms are reviewed. Electrowetting light valves (ELVs) reconfigure the geometry of an opaque oil film in order to modulate light transmission. Electrowetting microprisms (EMPs) translate liquid contact angle modulation into prism apex angle modulation, and therefore beam deflection. Both approaches provide compelling performance improvements when compared to existing electro-optical devices for displays and beam steering.

### Introduction

For several decades, electro-optic devices based on liquid crystals have enabled flat panel displays [1] and phased-array beam steering applications [2]. For liquid crystal displays, image quality is now fully satisfactory for even HDTV, but typical optical transmission efficiency is low at ~7% (93% of backlight lost). For transmissive beam-steering, fine-angle control can be achieved, but for a single liquid-crystal plate efficient steering is typically limited to only several degrees of deflection. Looking forward, the ultimate flat optical element might be one that could directly mimic the high performance associated with classical geometrical optics. Our working group is developing a new class of liquid-based optics, not using

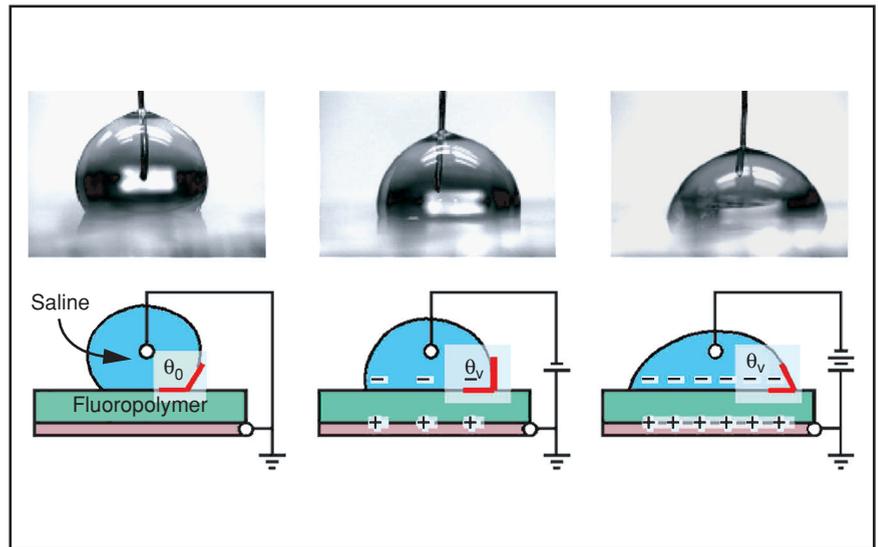


Figure 1: Basic electrowetting device of sessile droplet/fluoropolymer/electrode. For optical applications, the saline is surrounded by density-matched oil in order to eliminate effects of gravity and vibration.

birefringence like liquid crystals, but using high-speed electrowetting modulation of saline/oil liquid geometry. A review is provided on recent work at Cincinnati in electrowetting light valves (ELVs) that achieve >80% transmission efficiency for displays [3,4], and electrowetting microprisms (EMPs) that are capable of >10° of continuous beam deflection [5].

The underlying mechanism for liquid modulation in both ELVs and EMPs is electrowetting [6]. Basic electrowetting on dielectric behavior is shown in Fig. 1. A saline droplet and an electrode are separated by a ~1 μm hydrophobic dielectric such as DuPont Teflon AF (amorphous fluoropolymer). Electrowetting of the hydrophobic dielectric occurs as voltage is applied between the droplet and the electrode beneath the fluoropolymer. Removing the voltage discharges this parallel plate capacitor and the droplet returns to the dewetted state. Although a conclusive theoretical model is still an item of debate, for most operating regimes it is well accepted that electrowetting modulation can be predicted utilizing a combination of Lippmann's electrocapillary equation and Young's relation for a three-phase air/saline/fluoropolymer or oil/saline/fluoropolymer contact line:

$$\cos(\theta_v) = \cos(\theta_0) + \frac{1}{2} \cdot \frac{\epsilon \cdot V^2}{\gamma \cdot d} \quad (1)$$

THE FLAT ELECTROWETTING OPTICS EFFORT IS LED BY DR. JASON HEIKENFELD, ASST. PROF. OF ELECTRICAL AND COMPUTER ENGINEERING, UNIVERSITY OF CINCINNATI  
PHONE: 513 556 4763,  
EMAIL: HEIKENJC@EMAIL.UC.EDU,  
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Here,  $\theta_0$  is the contact angle without externally applied electrical potential,  $\theta_V$  is the contact angle at an electrical potential  $V$ ,  $\epsilon$  is the permittivity of the dielectric layer beneath the droplet,  $\gamma$  is the saline/air or saline/oil interfacial surface tension (mN/m), and  $d$  is the thickness of dielectric layer. For most systems, this so-called electrowetting equation is accurate up to the point of contact angle saturation. For a saline/air system, saturation occurs at  $\theta_V \sim 50-70^\circ$ . The RMS voltage for an AC voltage may be substituted for DC voltage, so long as the bias frequency exceeds the response time for change in meniscus curvature. Switching speed increases rapidly with decreasing liquid volume according to  $\tau \propto (\rho \times v/\gamma)^{1/2}$  where  $\rho \times v$  is the density-volume product [7]. Recently, electrowetting inside a carbon nanotube has been achieved and a  $\sim 1$ ns (GHz) wetting speed was suggested [8].

### ELVs for Flat Panel Displays

Two types of electrowetting displays have been developed at Cincinnati. The first reported approach utilized light wave coupling [9]. This is a waveguide approach for displays where the electrowetting cells operate as a switchable optical cladding. In a state of coupling, wave-guided violet light is coupled to fluorescent electrowetting oils which emit red, green, and blue light at very high intensity ( $>1000$ 's  $\text{cd}/\text{m}^2$ ). The second approach developed at Cincinnati is transmissive electrowetting light valves (ELVs) [3,4]. Here an opaque oil acts as a switchable optical shutter. Only ELVs will be reviewed herein since they function as a spatial light modulator and are of potentially broader use than displays.

A basic ELV structure is shown in Fig. 2. Details on fabrication of the device have been previously reported [3]. ELVs have a few distinguishing features from other

electrowetting devices. First, the devices utilize an opaque oil layer. Black oil coloration is achieved by doping the oil with a combination of  $\sim 3-5$  wt.% of red, yellow, and blue chromophores (dyes). Secondly, a hydrophilic grid is added and is permanently wetted by the polar saline solution ( $\sim 73$  mN/m). This technique for caging the oil within an individual cell (pixel) using a hydrophilic grid was first proposed by Hayes and Feenstra [10] for reflective electrowetting displays [11]. An ELV display with VGA resolution, would utilize  $640 \times 480$  individual pixels, each pixel having its own volume of black oil and defined by the hydrophilic grid.

ELV pixels are operated as follows. With no applied voltage, interfacial surface tension confines the hydrophobic oil as  $\sim 10-100$   $\mu\text{m}$  thick film between the saline and the hydrophobic fluoropolymer. The saline and oil are density matched such that gravity and vibration have no effect upon device operation. This configuration at zero voltage represents an ELV in the OFF state (minimum transmission, Fig. 2 left). Various states of optical transmission can be achieved by applying voltage to the ELV cell (Fig. 2 right). As the voltage is increased, the oil geometrically reconfigures to a fraction of its original coverage area and transmission increases (Fig. 3). This reconfiguration is determined by the saline as it electrowets the fluoropolymer dielectric. The voltage response of the oil/saline contact line is given by the electrowetting equation. As voltage increases, saline contact angle decreases. Therefore the oil, which had an initial contact angle near  $0^\circ$  must experience an increase in contact angle (i.e. the oil must switch from a film to a spherical cap geometry). The oil is electrically insulating, experiences no electrowetting, and is simply manipulated by the advancing contact line for the saline solution. The charge build-up across the fluoropolymer and repulsion of the oil is analo-

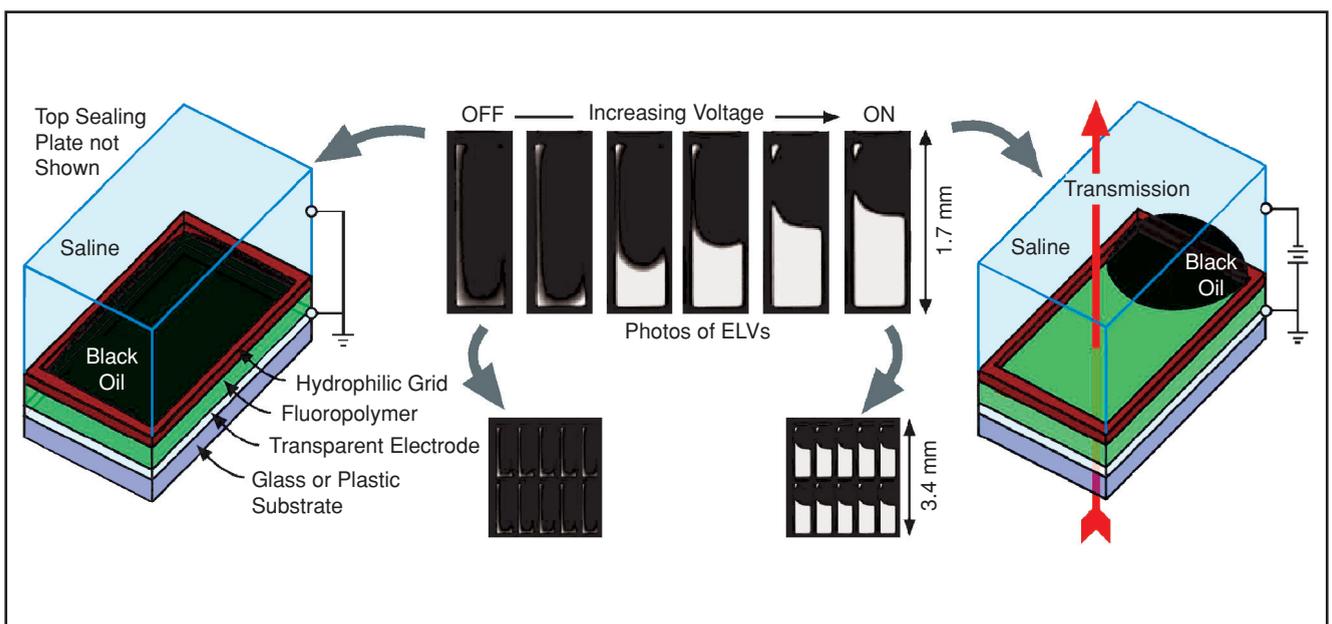


Figure 2: Angled-view diagrams (left/right) and top-view photographs (center) of transmissive electrowetting light valves. Application of voltage causes electrowetting of the saline and repulsion of the black oil to a fraction of the pixel area. Adapted from [4].

gous to a loaded spring. In DC operation no power consumption is required to hold the ELV in any given state of transmission, and upon grounding the device, the oil rapidly (<10 ms) 'recoils' to a film geometry. ELV transmission can be expressed as:

$$\%T = 1 - \frac{A_{oil}}{A_{cell}} (1 - e^{-\alpha z_{eff}}) \quad (2)$$

where the variables are the area of oil coverage ( $A_{oil}$ ) inside the ELV cell area ( $A_{cell}$ ), absorption coefficient of the oil ( $\alpha_{oil}$ ), and an effective oil thickness ( $z_{oil}$ ) derived from spherical cap geometry of the oil layer. The value for  $z_{eff}$  is largely dominated by the reduced oil thickness near the oil/saline contact line. This thin region of oil results in undesired OFF-state light-leakage and reduction of ELV contrast ratio (C.R. =  $\%T_{max}/\%T_{min}$ ). The plot of ELV transmission vs. voltage shown in Fig. 3. reveals that >80% transmission can be achieved [4]. The data shows a contrast ratio of 40:1. Higher contrast ratios will be achieved by improving the chromophore doping and by optically masking areas with light leakage at 0V. ELVs are capable of achieving switching speeds of ~3 ms or faster. For displays, this allows use of field sequential RGB backlights instead of RGB color-filters. The ability to generate color without filters, and to transmit light of all polarizations, results in an ELV panel which is projected to provide ~20 lm/W efficiency compared to the ~2 lm/W for a typical liquid crystal display panel [4]. This allows for higher brightness (sunlight legibility) or reduced power consumption (longer battery life) for portable display applications. ELVs are also unique in that they exhibit Lambertian appearance (transmit all angles, all polarizations).

### EMPs for Flat Panel Optics

The most mature electrowetting technology is that of liquid-based lenses. Electrowetting lens technology is currently being commercialized by Varioptic (France) for applications such as miniature fast-focus lenses for camera-phones [12,13]. Alternate electrowetting lens formats have also been demonstrated [7]. These prior efforts in electrowetting optics operate by switching a spherical saline/oil meniscus from concave to convex. Lens sizes are typically limited to ~3 mm diameter, beyond which gravity begins to become an issue and switching speed slows significantly (>100 ms). To create large area flat electrowetting optics, a more attractive approach may be to array many small, high-speed, electrowetting elements. Cincinatti and the Univ. of Dayton have recently demonstrated electrowetting micropisms (EMPs), a new approach that utilizes a cylindrical saline meniscus inside a long rectangular channel. Diagrams and photos of EMPs in operation are shown in Fig. 4. Details on EMP fabrication can be found elsewhere [5]. A completed EMP channel is formed between two sidewalls consisting of fluoropolymer coated electrodes. These sidewalls therefore can function as electrowetting plates. A channel is filled with a saline-liquid with surface tension close to

that of water ( $\gamma \sim 73$  mN/m). Increased salt doping (KCl, LiCl, etc.) in the saline solution is useful because it increases the refractive power of the solution, and reduces

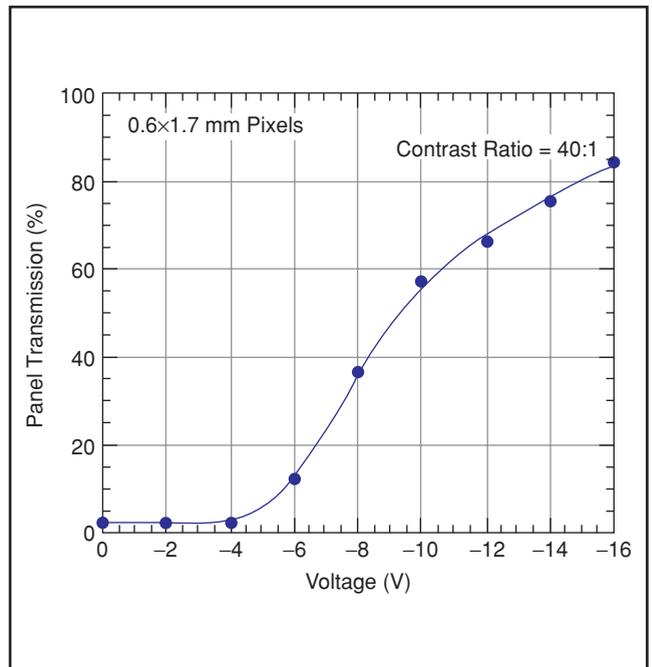
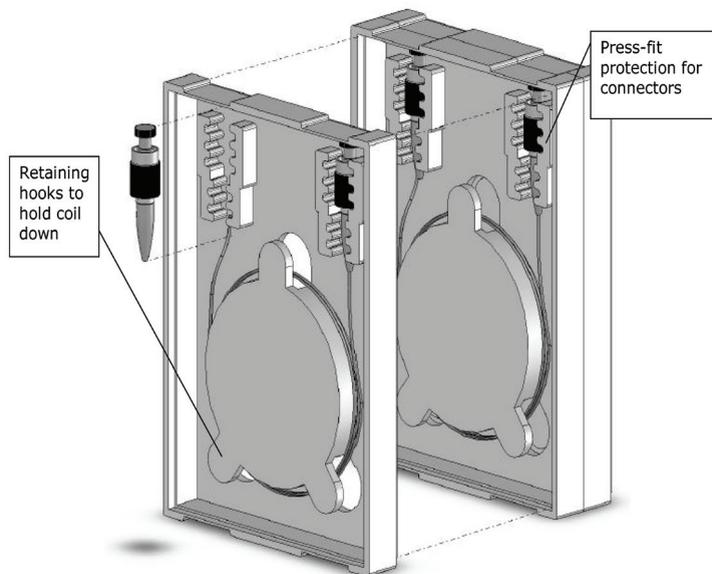


Figure 3: Cell transmission vs. voltage for ELVs. Adapted from [4].

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the freezing point for operation in cold-environments. Initial experiments use saline liquid only (not saline/oil). Therefore the EMP channel spacing is limited to ~1 mm or less in order to alleviate the effect of gravity on the liquid meniscus curvature.

EMP operation requires three electrical connections. For a single EMP, the simplest configuration is two voltage sources attached to the sidewalls and the saline electrically grounded. As shown in Fig. 4b, 4c, when placed between sidewalls at zero-voltage, the saline forms a convex shaped meniscus due to a large saline/fluoropolymer contact angle ( $\theta_0 \sim 115^\circ$ ). When voltage is applied the saline electrowets the surface and the contact angle ( $\theta_V$ ) decreases. This change in contact angle is directly related to change in prism apex angle ( $\phi$ ) according to  $\phi = |90^\circ - \theta_V|$ . In order to obtain a straight-line meniscus from side-wall to side-wall, the contact angles on both the left and right sides should be inverted about  $90^\circ$  contact, or  $\theta_V(\text{right}) = 180^\circ - \theta_V(\text{left})$ . Therefore, some combination of voltage is always applied to both side-walls. Predictive

voltage levels for contact angle inversion, and flat menisci, are easily obtained from Eq. 1. In order to illustrate possible steering angles through modulation of EMP apex angle, the angular deviation ( $\delta$ ) of a light beam passing through a prism with an index of refraction  $n > 1$ , apex angle  $\phi$ , and angle of incidence  $\alpha_i$  ( $0^\circ$  in our case) can be expressed as:

$$\delta = \alpha_i - \phi + \sin^{-1} \left[ (n^2 - \sin^2 \alpha_i)^{1/2} \sin \phi - \cos \phi \sin \alpha_i \right] \quad (3)$$

Eqs. 1 & 3 can be combined to generate theoretically predicted EMP behavior. A theoretical plot of deflection vs. prism apex angle is shown in Fig. 5a. The plot corresponds to a saline refractive index of  $n = 1.36$ . Experimental results have shown up to  $14^\circ$  ( $\sim \pm 7^\circ$ ) of total continuous deflection using a saline solution of  $n = 1.36$ . The experimentally achieved value is marked on the plot. The voltage response for deflection is shown as an inset in Fig. 5a. The deflection range is limited by the non-ideal phenomenon of electrowetting contact-angle saturation. For these first devices, contact angle saturation limits the switchable apex angle to  $\sim \pm 20^\circ$  which translates to  $\sim \pm 7^\circ$  beam deflection. This steering range is still  $\sim 7X$  greater than that typically achieved for liquid crystal beam-steering devices based on a single-plate optical-phased-array. Also included in Fig. 5a is marking of theoretical steering performance expected from a saline/oil system (instead of saline/air). For this system a high index silicone oil is utilized ( $n > 1.55$ ) and low index saline ( $n < 1.35$ ). Although the index contrast for this two-liquid system is reduced ( $\Delta n < 0.3$ ) compared to saline/air ( $\Delta n > 0.35$ ), a larger change in contact angle, and therefore apex angle, can be achieved for oil/saline systems. Oil also is advantageous in reducing contact-angle hysteresis due to pinning of the saline contact line at physical or chemical heterogeneity at the fluoropolymer surface.

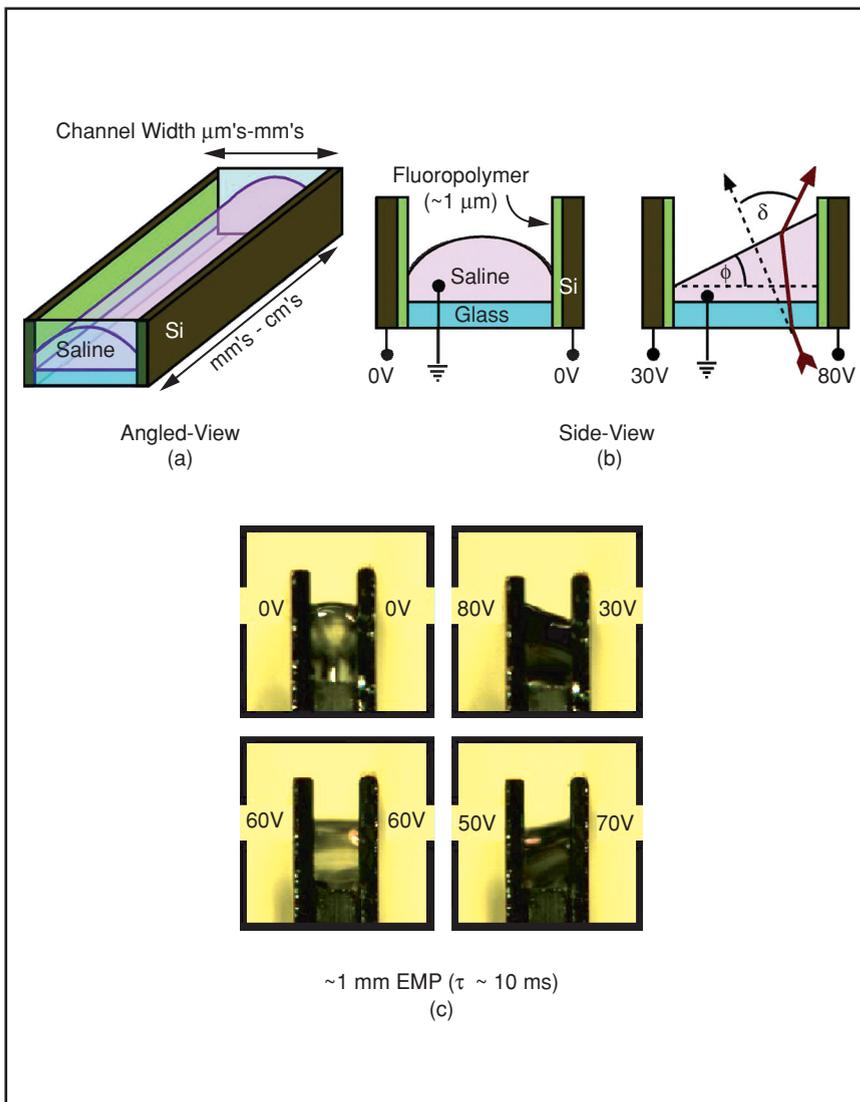


Figure 4: Electrowetting micropisms (EMPs) shown as: (a) angled-view, (b) side view, (c) photos of EMPs in operation. Adapted from [5].

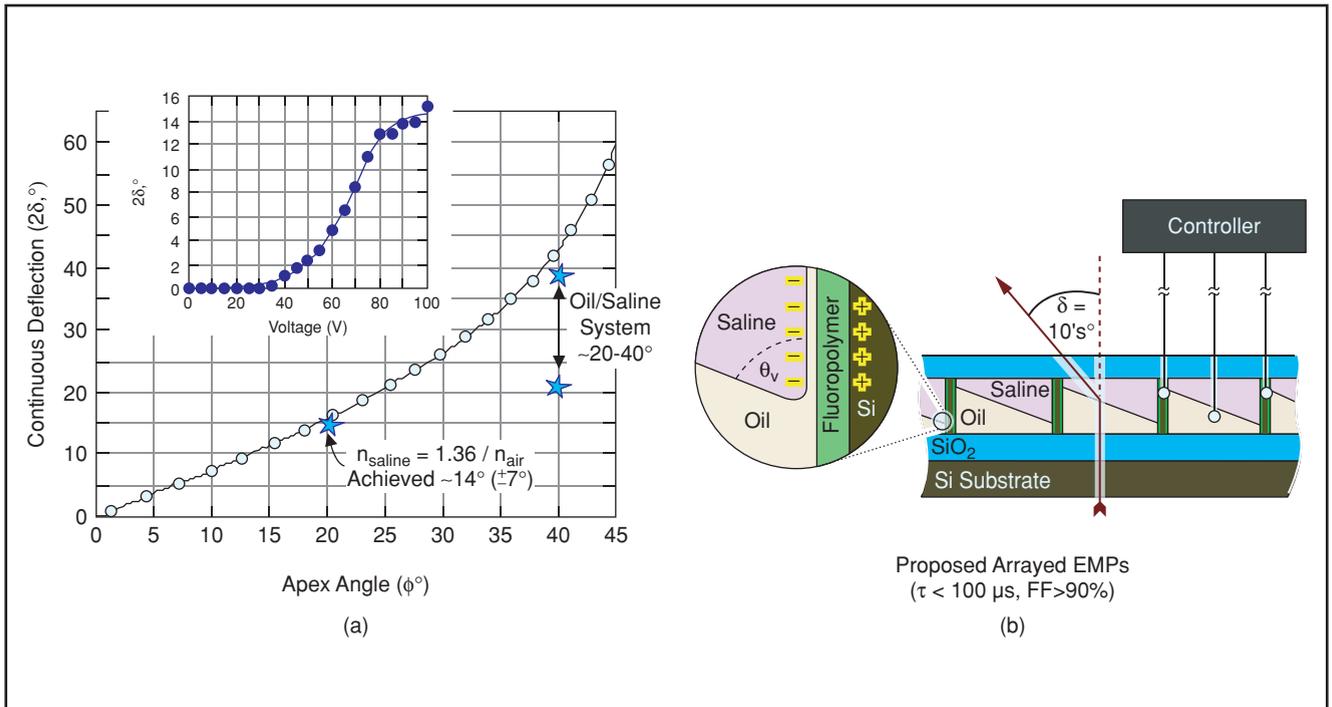


Figure 5: (a) Theoretical plot of continuous deflection vs. apex angle and measured continuous deflection vs. voltage (inset). For large aperture infra-red applications, such as those requiring high laser power, (b) proposed is linear arrays of EMPs integrated in SOI wafers with a fill factor of >90%. Adapted from [5].

cussed in the introduction, small size electrowetting devices are able to operate much faster than large size devices. For long-channels, the cylindrical meniscus geometry needs to be stabilized since a spherical meniscus is energetically favored (minimizes system energy). Techniques have been demonstrated at Cincinnati to stabilize long EMP channels, and will be reported in future publications.

## Conclusion

Two approaches for creating flat transmissive electrowetting optics have been presented. The first, electrowetting light valves (ELVs), provides high transmission efficiency (>80%) and allows transmission of light at any polarization or incidence angle. The second, electrowetting microprisms (EMPs) provides wide-angle steering capability that can be extended to linear or concentric arrays. Electrowetting optics may one-day extend to nano-scale diffractive optics and to possible use in guided-wave optics.

## Acknowledgements

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## President's Column

(continued from page 3)

### Winning as a Goal

*"It takes but one positive thought when given a chance to survive and thrive to overpower an entire army of negative thoughts," Robert H. Schuller*

We've all been in meetings in which people offer several reasons as to why something cannot be done. These people suck the creative life-force out of the room. Given that people are naturally risk averse, a few well-placed negative comments are all that is necessary to kill a proposed activity.

It takes much courage, intelligence, perseverance, and vision to champion an activity. If you believe in your idea, you must be its advocate and overcome the naysayers. On numerous occasions and despite initial resistance, I have seen Paul take the initiative, stick with it, and produce a golden outcome.

### SWOT Analyses: "Opportunities" Always Come Before "Threats"

*"Winning isn't everything...it's the only thing." Vincent van Gogh.*

I am going to tweak the common understanding of this well-known quote, and it is probably the most important of Paul's legacies.

Ubiquitous SWOT (Strengths, Weaknesses, Opportunities, and Threats) analyses deal with potential "opportunities" before identifying "threats." To Paul, new ideas are always opportunities, and he rarely sees a new scenario as a threat. He is the master of naturally finding a win-win scenario so that our members can benefit. "Winning is ... the only thing" to Paul since, I believe, he simply doesn't feel threatened by any small possibility of a downside.

Perhaps the best example of this attitude is the manner in which Paul inter-

acts with our key sister societies (e.g., IEEE ComSoc, OSA, and SPIE). I can attest to the fact that their leaders hold Paul in great esteem for his openness, fairness, insight, and integrity. They trust him since he is always looking for the win-win approach. I can't remember an instance when he felt that something beneficial for a sister society could be detrimental to LEOS. This approach also applies to our individual members, for whom he never felt that dual loyalty to more than one society was harmful, but just the opposite – it strengthens our collective perspective.

### Paul, Lots of Good Luck!

We all wish you and Randi much happiness and health in your retirement. I cannot thank you enough for all that you have done for me and for LEOS. It has been a genuine pleasure and privilege.