Liquid Light

Amidst the LCD's increasing dominance, the new technology of electrowetting is attempting to make a place for itself based on superior light utilization and manufacturing simplicity.

by Jason C. Heikenfeld and Andrew J. Steckl

WHY DEVELOP a new flat-panel-display (FPD) technology? Why try to change a technological landscape already deeply embedded with liquid-crystal displays (LCDs)? These are weighty questions as the LCD strengthens its reputation for dominance by fending off the best advances of many alternative display technologies. However, it is important to note that the present dominance of any display technology is not due to perfected performance or true simplicity in manufacturing. Rather, the currently leading display technologies are simply the "best available" options.

One need only consider that most reflective displays reflect only about one-third of incident light or that backlit LCDs have a power efficiency of only about 1%. Is there room for new technologies? Certainly. And electrowetting light valves (ELVs) for displays are a candidate that has captured the attention of "old display hands." A nascent technology, ELVs promise to deliver record performance in light utilization for *both* reflective and emissive displays. Furthermore, early results are revealing that ELV devices are so inherently simple in fabrication and operation that impressive cost advantages might be gained over existing display technologies.

***Jason C. Heikenfeld** and **Andrew J. Steckl** are with Extreme Photonix, LLC, 3130 Highland Ave., 3rd Floor, Suite 3225, Cincinnati, OH 45219-2374; telephone 513/475-6615, fax 513/221-1891, e-mail: jheikenf.extreme photonix@biostart.org.* *The authors thank Rob Hayes and Johan Feenstra of Philips Research Laboratories, John Imbalzano of DuPont, Paul Cahill of Exciton, Inc., and Doug Koerner of Keystone Analine Corp. for useful discussions and encouragement.*

An Ultra-Simple Light Valve

The fundamental mechanism behind all electrowetting devices is shown pictorially in Fig. 1. The liquid-repelling nature of an electrically insulating hydrophobic film can be counteracted by applying an electric field across the film. As shown in Fig. 1 (top), a highly polar (high surface tension) liquid such as water beads up on a clear, hydrophobic (low surface energy) insulator of amorphous Teflon® that is less than 1 μm thick. By applying a voltage between the droplet and a transparent electrode beneath the hydrophobic insulator, the droplet rapidly (in about 1 msec) wets the surface (Fig. 1, bottom). The process is fully reversible and capacitive, so no power is consumed while the droplet is held in either the wetted or de-wetted state of actuation.

This droplet form of electrowetting is not applicable to displays, but is presented to provide an initial understanding of the basic electrowetting mechanism. Interestingly, in the field of imaging, Varioptic [B. Berge and J. Peseux, *Eur. Phys. J. E.* **3**, 159–163 (2000)] and Philips [S. Kuiper and B. H. W. Hendriks, *Appl. Phys. Lett.* **85**, No. 7, 1128–1130, (2004)] are nearing commercialization of variable-focus electrowetting liquid lenses that do use this basic mechanism.

Other exciting applications of electrowetting include laterally moving droplets (at hundreds of Hz!) on patterned electrodes for lab-on-chip applications [M. G. Pollack *et al.*, *Appl. Phys. Lett.* **77**, No. 11, 1725–1726 (2000)] and optical switches for high-speed fiber-optic communications systems [P. Mach *et al.*, *Appl. Phys. Lett.* **81**, No. 2, 202–204 (2002)]. It is only very recently that the viability of electrowetting for displays was demonstrated [R. A. Hayes and B. J. Feenstra, *Nature* **425**, 383–385 (2003)].

An ELV for displays includes an oil film and a hydrophilic grid that defines the pixels

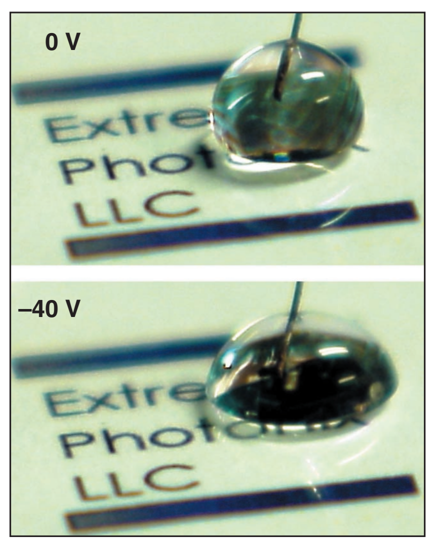

***Fig. 1:** In the basic electrowetting principle, the application of voltage to a glass/ITO/fluoropolymer/water-drop structure effectively changes a hydrophobic surface (top) into a less hydrophobic surface (bottom).*

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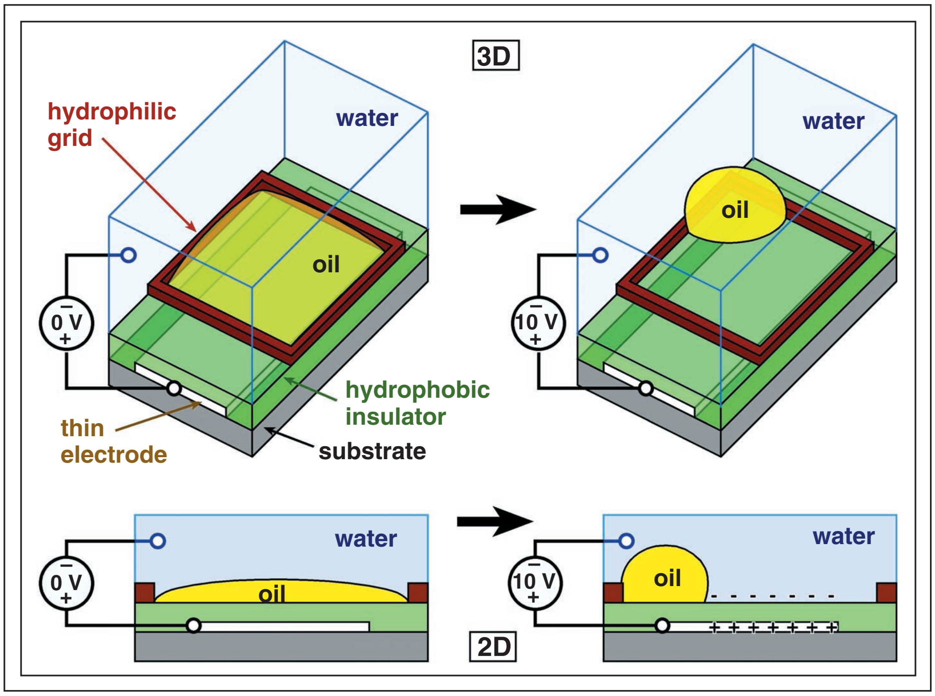


Fig. 2: A generic ELV device structure and its basic operation for displays is shown in 3-D (top) and 2-D (bottom) views. Typical oil volume for a 100 × 100-μm cell is only a few tenths of a nanoliter.

(Fig. 2). Interfacial surface-tension relationships between the polar water (high surface tension), non-polar oil (low surface tension), and hydrophobic insulator (low surface energy) cause the oil to naturally locate as a film between the water and the hydrophobic insulator. The oil is also confined laterally by a water-attracting hydrophilic grid.

Without an applied voltage (Fig. 2, left), the oil forms a continuous film between the water and hydrophobic insulator that is about 10 μm thick. With the application of as little as 5–10 V to the system (Fig. 2, right), the water is *attracted* to the hydrophobic insulator, causing the oil to be displaced and to decrease in lateral area. The removal of the applied voltage returns the oil back to a continuous film inside the hydrophilic grid.

A high-performance light valve can be achieved by making the oil light-absorbing by dyeing it with a colorant; no voltage produces a continuous oil film, which causes light absorption, and the application of more than 5 V produces a displaced oil film and light transmission. Thus, ELV light transmission is approximately equal to the area occupied by the oil film. A large change of more than 70% in area of the oil film can be achieved for high contrast and gray-scale ELV switching (Fig. 3). This simple ELV concept is applicable to reflective displays (with a reflective substrate, as in Fig. 2), transmissive displays (with a backlit glass substrate), and emissive displays (with a UV-light-storage plate as the substrate).

Reflective ELV Displays

The reflective-ELV-display concept was introduced by Hayes and Feenstra at Philips Research Laboratories (Eindhoven, The Netherlands). Philips has a strong initiative in reflective-display development for the emerging electronic-paper market. The Philips reflective-ELV-display approach uses cyan, magenta, or yellow (CMY) dyed-oil film on a reflective substrate (Fig. 4). Without applied voltage, the ELV array reflects only magenta filtered light from the continuous dyed-oil film [Fig. 4(a)]. With the application of –15 V, the dyed-oil film is displaced, and the ELV array begins to reflect white light [Fig. 4(b)]. Since pixel dimensions can be 100 μm or smaller, the human eye averages the appearance of the array as a transition from magenta to white. By increasing the applied voltage to the cell, up to 90% white reflectance can be achieved.

A high-brightness full-color reflective display can be achieved by sandwiching a common water layer between the YMC- and MCY-subpixel ELV arrays and attaching a CYM front color-filter array (Fig. 5). For example, one of the three colored subpixels can consist of cyan and magenta oil layers and a solid-yellow filter (Fig. 5, center). This subpixel can then generate black, green, red, and yellow color based on which of the two oil films is displaced.

This reflective-CMY-ELV-display approach developed by Philips has more than *double* the reflectivity of conventional reflective-display technologies based on liquid-crystal or electrophoretic switching (Table 1). The doubling of reflectivity results from the fact that each of the three colored subpixels comprising a CMY ELV pixel can fully reflect two-thirds of the visible spectrum (for example, yellow is red plus green). Furthermore, two of the three subpixels can both generate saturated red, green, or blue (RGB) reflection. Other reflective-display technologies that use RGB filtering can, at most, reflect only one-third of the visible spectrum at each subpixel and can, at most, provide saturated RGB color at only one out of three subpixels.

Philips has already achieved a 40% reflectivity for full-color cells, with room for improvement to the theoretical limit of just above 60%. It is important to note that the benefit of CMY filtering is *only* applicable to display technologies in which the light transmissivity of the filter medium can be externally switched. Therefore, at this time, only

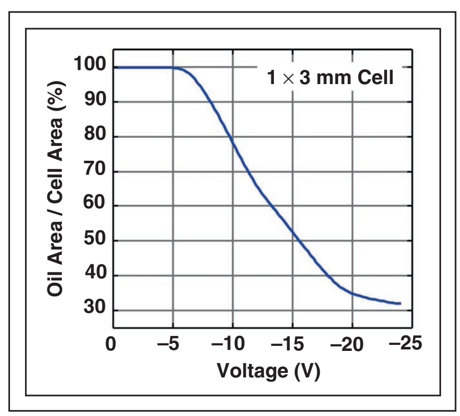
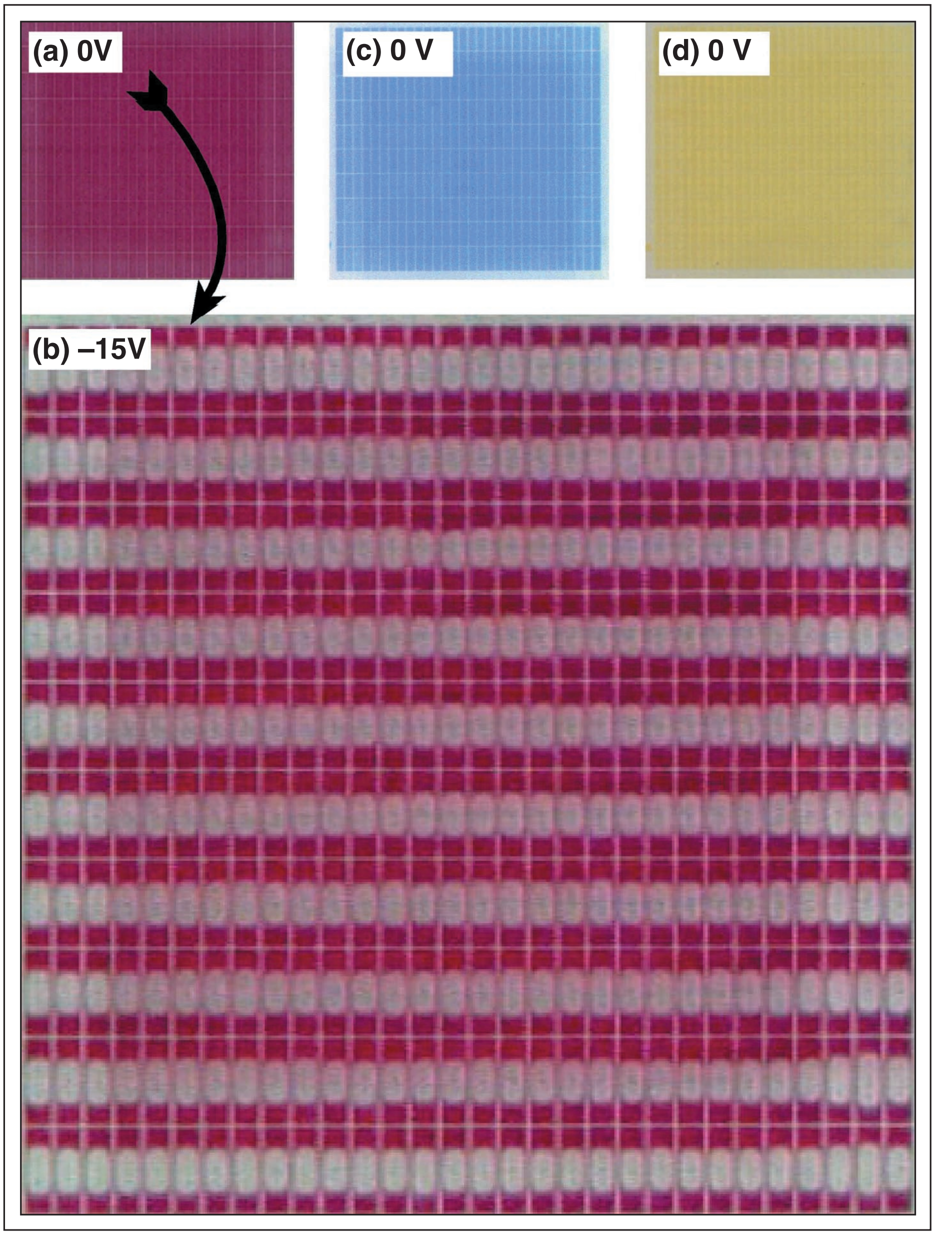


Fig. 3: A typical ELV voltage response is shown. Smaller-sized ELVs can modulate the oil area to as little as 10%. Less than 10-V ELV operation has also been demonstrated.



Philips Research Laboratories

Fig. 4: *A reflective ELV 10 × 30 magenta array of 240 × 80-μm pixels biased at 0 V (a) and –15 V (b), and cyan (c) and yellow (d) arrays at 0 V.*

ELVs can benefit from the high brightness of the CMY-filtering approach.

Because of their high brightness and simple device structure, reflective ELV displays are a strong candidate for electronic-paper applications. Furthermore, the absence of a cell-gap dependence on reflectance permits a straightforward extension of reflective ELV displays to flexible/rollable-display formats. ELVs are not yet suitable for "zero-power" displays because reflective ELV displays are currently not bistable. However, ELVs have a switching capacitance similar to that of LCD cells, which permits a very low power consumption well-suited to video-rate reflective displays in cellular telephones, PDAs, and other portable-display applications.

In terms of display cost, the simplicity of the ELV-device structure should permit reflective ELV displays to be manufactured at a cost comparable to or lower than that of other reflective displays.

Emissive ELV Displays

Following the pioneering reflective-ELV-display work at Philips, Extreme Photonix is developing ELVs for *emissive* displays. The company is now pursuing both color-filtered transmissive and fluorescent emissive ELV displays. The nearly perfect light utilization of reflective ELV displays is also characteristic of emissive ELV devices. The simplest extension of the generic ELV device shown in Fig. 2 to transmissive displays requires that a black oil be used in conjunction with a diffused-white-light backlight located behind a glass substrate. As the black oil is displaced with increasing voltage, light transmittance through the ELV cell is increased to more than 70% (Fig. 6). A standard RGB color-filter plate added to the front of a black-oil ELV array creates the basis for a full-color-display panel.

Extreme Photonix has implemented several other proprietary optical-enhancement techniques that cumulatively lead to a projected panel luminous efficiency of about 10 lm/W, assuming an 80-lm/W backlight with 50% of the pixels on. Use of the previously mentioned CMY-filtering approach with two stacked ELV arrays doubles the average luminous efficiency to about 20 lm/W. This luminous efficiency is an *order of magnitude* greater than the efficiencies achievable for transmissive LCDs. An additional benefit is that, unlike an LCD, a transmissive-ELV-display panel is *inherently* viewable at all angles without variation in image quality.

A transmissive-ELV-display panel should have considerable cost advantages over LCDs because it (1) has no cell-gap dependence, permitting the use of low-cost color-filter arrays; (2) requires no additional films or materials for enhancing viewing angle; and (3) is so efficient that it can use lower-cost and higher-efficiency edge-lit backlights. These potential cost advantages for transmissive ELV displays could be extremely pronounced in high-definition-television (HDTV) applications in which backlight and color-filter-array costs account for approximately one-half of the panel's components and materials cost.

ELVs have also been implemented as a switching mechanism in a novel emissive display developed at Extreme Photonix

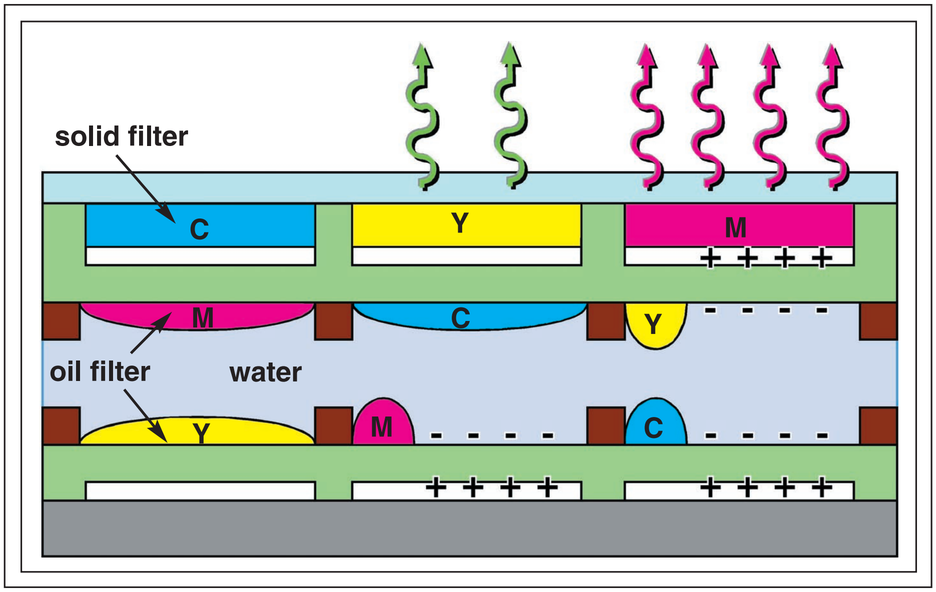


Fig. 5: Shown is a possible subpixel layout for reflective or transmissive CMY ELVs. One subpixel consisting of two differently colored oil layers can produce several colors. The center subpixel, for example, which has cyan and magenta oil layers and a solid-yellow filter, can produce black, green, red, and yellow, depending upon which of the two oil films is displaced.

called light-wave-coupling (LWC) displays [J. Heikenfeld and A. J. Steckl, *SID Intl. Symp. Digest Tech. Papers*, 470–473, (2004)]. LWC displays use a short-wavelength light source [a violet fluorescent lamp or light-emitting-diode (LED) array], which edge-pumps a light-storage plate (a planar waveguide). Violet light from the light-storage plate is selectively coupled to RGB organic fluorescent oils within electrowetting cells. These fluorescent oils emit bright light with saturated colors when excited by violet light. Because no electrical current need be passed through the organic fluorescent oils, their operational lifetime is far superior to the colored organic materials used in organic light-emitting diodes (OLEDs) and polymer LEDs (PLEDs). The result is a theoretical luminous efficiency of about 30 lm/W when 50% of the pixels are turned on in the display panel (Table 2).

This high luminous efficiency is partly due to the lossless optical coupling of ultraviolet/violet light from the light-storage plate to the fluorescent oils. Also, the fluorescent oils possess a quantum efficiency of greater than 90% in the conversion of violet light to saturated RGB light, thus eliminating the need for color filters.

Careful selection of the optical materials and cell geometry allows an LWC display to *recycle* unused light at a pixel even when it is turned off. Therefore, for low pixel usage, as in TV applications, the projected luminous-efficiency advantage of LWC displays can only increase (Table 2).

A demonstration of an LWC display in a signage application was given at SID 2004 (Fig. 7). As can be seen in the photo, LWC technology is also suitable for state-of-the-art transparent signage panels. Fluorescent LWC ELV panels possess the same structural simplicity as transmissive ELV panels, again offering the potential for very-low-cost manufacturing.

No Rewards without Challenges

ELV technology is presently in a very early stage of development for both reflective and emissive displays. Current efforts are heavily focused on creating convincing prototypes that populate high-efficiency ELVs over large array counts, and one goal of early prototypes is to further confirm record-breaking performance attributes.

However, much work still lies ahead in basic ELV-device development. For example,

Table 1: Comparison of Full-Color Reflective FPD Technologies

	LCD	Electrophoretic	ELV
Reflectivity	~10%	~15%	~40%
CR	50:1	10:1	15:1
Speed (msec)	10's	~300	~10
Color	RGB	RGB	CMY
Bistable	Some Are	Yes	No

Note. Data Sources: R. A. Hayes, *Philips Research Laboratories,* personal communication, and R. A. Hayes and B. J. Feenstra, *Nature* **425**, 383–385 (2003).

Table 2: Comparison of Transmissive/Emissive FPD Technologies

	LCD Transmissive	ELV Transmissive	ELV Fluorescent
Maximum efficiency* (lm/W)	~2 (RGB)	~10 (RGB) ~20 (CMY)	~30 (RGB)
Speed	video	video	video
CR	>500:1	100's:1	100's:1
Viewing angle	Polarizer	Transmissive	Emissive
Backlight	White diffuse	White diffuse	Violet waveguide

*Theoretical for 50% pixels "on," based on optical losses for a static image.
Note. Data Source. J. Heikenfeld and A. J. Steckl, *SID Intl. Symp. Digest Tech. Papers,* 470–473 (2004).

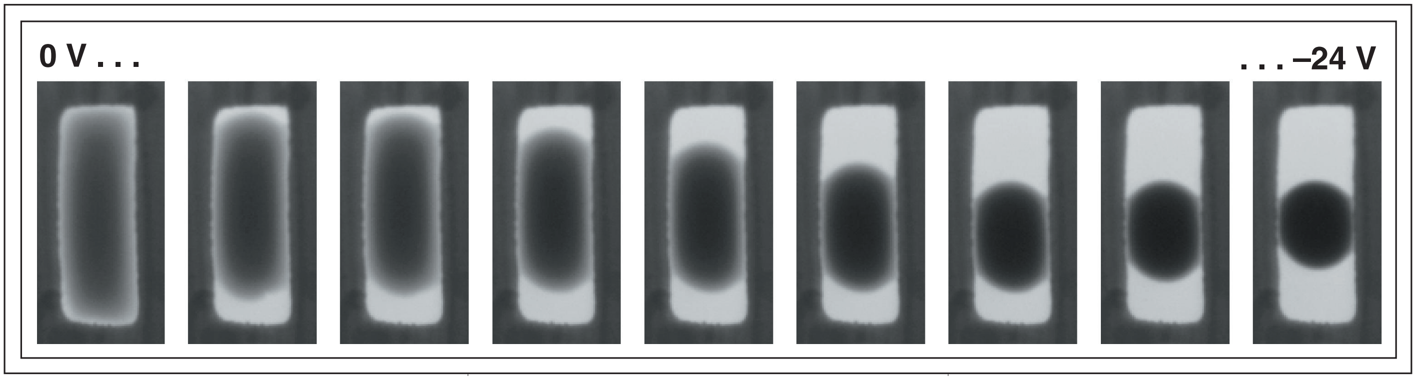


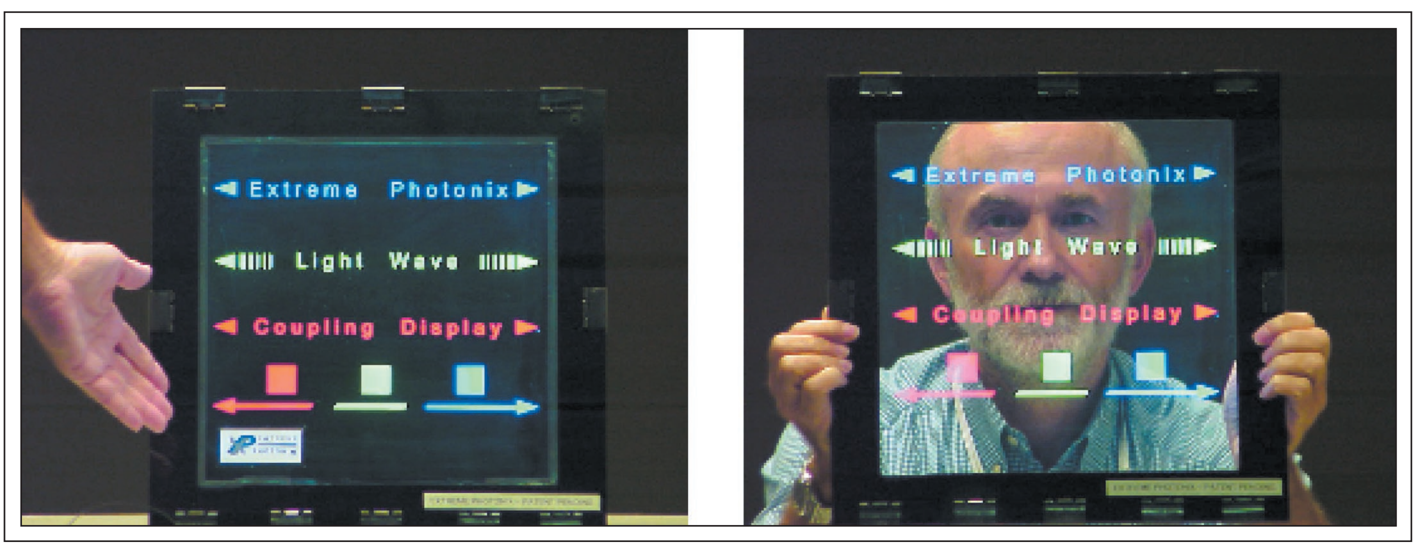
***Fig. 6:** ELV displays can also be transmissive. This backlit 1 × 3-mm ELV pixel is shown as it was progressively modulated from 0 to –24 V.*

organic chemists will have to play a significant role in developing highly saturated black, CMY, and fluorescent dyes for doping into the low-viscosity oils used in ELV cells. Most dyes currently used, such as azo and anthraquinone dyes, have marginally satisfactory optical performance and limited solubility in hydrocarbon oils. In reflective and transmissive ELV displays, poor optical performance of the dyes results in reduced switching contrast. As new dyes are developed, the occasional problems of switching hysteresis and the inability to maintain a dc-switched response must be avoided.

Video-rate switching has already been demonstrated, which makes the development of field-sequential switching promising. Furthermore, with recent ELV R&D results demonstrating less than 10-V operation, ELV displays are now becoming increasingly compatible with passive- or active-matrix LCD on-board or on-glass driver circuits. However, it should be noted that first-generation open-cell ELV-pixel designs are not passive-matrix compatible and that the mating of ELVs to an active-matrix driver array awaits a first demonstration. Since ELV displays rely on liquids with physical momentum, boost-phase voltage-driving techniques might be necessary to allow ELVs to rapidly switch between numerous gray-level states. Repeatable gray-scale switching is currently a problem in first-generation ELV displays, but developers expect that second- and third-generation ELV displays employing specialized electrode patterns, improved cell geometries, and smaller cell or sub-cell dimensions will overcome this difficulty.

Temperature stability is also an issue, but if the same polar and non-polar liquid hosts are used in all ELV cells in a panel, the temperature-induced variance of switching characteristics should be no worse than the temperature variance experienced by LCDs. ELV-cell miniaturization and the use of liquids with nearly equal density should completely alleviate any remaining adverse effects from vibration or gravity. With respect to aging, the primary concern is degradation of the hydrophobic surfaces due to oxidation or contamination.

In manufacturing, one of the challenges is to develop methods for dosing oils in precise volumes measured in nanoliters. Picoliter



Extreme Photonix, LLC

***Fig. 7:** ELVs can also be used in emissive displays. This fluorescent LWC signage display demonstrator, consisting of printed fluorescent patterns, is capable of high-contrast or transparent operation.*

ink-jet technology might be suitable, but it must be specialized for compatibility with oils that have much lower surface tension than that of the solvent or aqueous solutions presently employed in most ink-jet systems.

Because ELV structural and operational simplicity is currently unrivaled, the performance potential of ELVs is impossible to ignore. Once the remaining device issues are resolved and fully functional prototypes are developed – even if only a fraction of the full performance potential of ELVs is realized – commercialization should be able to proceed rapidly. The high efficiency and brightness of ELV displays point to possible market entrance in portable displays such as cellular telephones and PDAs. Because these products incorporate small displays, they represent an easy entry point from the perspective of manufacturing ramp-up. Increased market share is possible should high-volume manufacturing reduce ELV-manufacturing costs to the point at which ELV panels can attract consumers not only on the basis of better performance, but also lower price.

Now is the time for a broad effort to explore the potential of ELVs for displays. ■

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