Demonstration of Fluorescent RGB Electrowetting Devices for Light Wave Coupling Displays

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Abstract

We present an emissive light valve approach which possesses ~10-40X higher theoretical luminous efficiency than transmissive LCD light valves. This innovative light valve approach has been applied to a novel fluorescent display technology utilizing light wave coupling. Switchable pixelation has been achieved using an innovative electrowetting modulation method. Maximum luminance values of 950, 5530, and 530 cd/m^2 have been achieved for red, green, and blue emission, respectively. Switching speeds of ~100 ms and ~10 ms for ON/OFF switching have been demonstrated, respectively.

Introduction

A long-standing competition between transmissive and emissive displays continues to present day. Established and novel emissive displays have experienced difficulty in keeping pace with rapid advancements in transmissive LCD displays[1]. LCD researchers have made impressive breakthroughs in order to overcome many of the limitations thought to be inherent to any display based on liquid crystals. LCDs can be classified as a TRANSMISSIVE light valve approach. By utilizing the light valve approach pixel luminance for LCDs is determined by the panel backlight. However, even at maximum transmission, color LCDs typically are only able to transmit 5-10% of light from the back-light module. Furthermore, for LCD pixels in the OFF state, light is absorbed and wasted, instead of recycling the light for use at pixels in the ON state. We present the demonstration of an EMISSIVE light valve technology for displays. This novel approach possesses ~10-40X higher theoretical luminous efficiency than LCD light valves. This new light valve has been applied to a unique display panel and lighting concept we have developed: Light Wave Coupling (LWC) [2]. As shown in Fig.1, the LWC display device we report here innovatively combines three critical components: (1) an UV light storage plate edge pumped by an ultra-efficient violet light source; (2) a light wave coupling region defined by apertures in an optical cladding on the UV light storage plate; (3) red, green, and blue fluorescent oils which are switchably coupled to the UV light storage plate through electrowetting.

Building an LWC Light Valve

The UV light sources chosen for edge-pumping are preferably closer to the violet (~400 nm) portion of the electromagnetic spectrum. Use of violet light instead of shorter wavelength UV (<350 nm) light sources reduces optical absorption losses in the display optics and acts a 'soft' excitation source which does not photo-degrade the organic fluorescent oils. Violet light sources include custom developed cold-cathode-fluorescent lamps or arrays of violet InGaN LEDs. The light storage plate is chosen simply from flexible (polymer) or rigid (glass) substrates which have a refractive index of ~1.5 and are UV

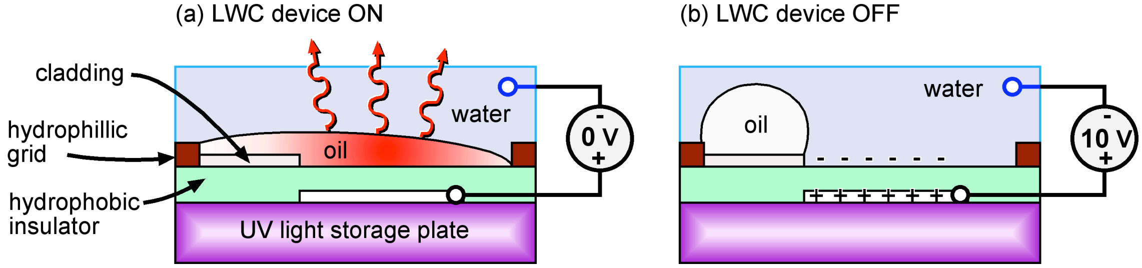

Fig. 1 Device structure and operation for electrowetting-based switching for LWC displays.

transparent/stable. Violet light introduced to the *specular* UV storage plate propagates in the plate via internal reflection according to:

$$n_{air} \sin\theta_{air} = n_{wvg} \sin\theta_{wvg}, \quad n_{air} \sin 90 = n_{wvg} \sin\theta_c, \qquad (1),$$

A specular storage plate (slab waveguide) is chosen instead of a traditional diffuse backlight because (as will be discussed later) it allows for the advantage of recycling of light at pixels in the 'OFF' state. All edge facets of the UV light storage plate are mirrored for further light recycling. Referring back to Fig. 1, a thin (<100 nm) transparent ITO electrode is patterned onto the UV light storage plate. The ITO has a refractive index >1.5, so it optically becomes part of the UV light storage plate. Onto the ITO and UV light storage plate, a hydrophobic (water repelling) insulator is uniformly coated. This hydrophobic insulator has a refractive index >1.5 as well, and similar to the ITO, optically becomes part of the UV light storage plate. Next a hydrophobic optical cladding layer is patterned onto the hydrophobic insulator. This optical cladding layer has a refractive index <1.3 and therefore internally reflects violet light back into the UV light storage plate. Next, a hydrophilic (water attracting) pixel grid is photolithographically fabricated and defines the pixel aperture by laterally confining the fluorescent oil. Fluorescent oils are dosed into these light wave coupling cells or pixels. Optical requirements for the oil is that it be UV transparent and have a refractive index of ~1.5 which allows optical coupling to the UV light storage plate. In order for the specialized oils to

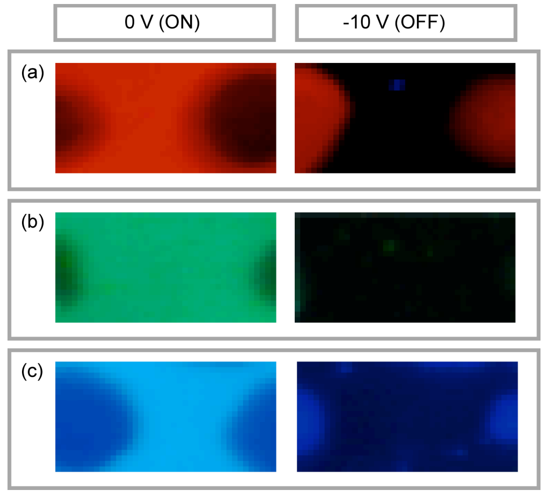

Fig. 2 Photos of red, green, and blue, LWC devices switched ON (0V) and OFF (-10V).

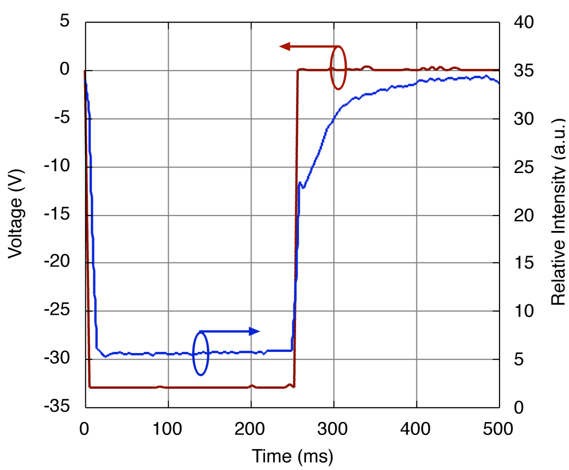

Fig. 3 Applied voltage and relative emission intensity vs. time for an LWC pixel switched off (at 0s) and on (at 250 ms).

fluoresce, they are doped at ~1 wt.% with non-polar lumophores. Lumophores are specialized fluorescent organic compounds that emit intense visible light when excited by violet light. The organic lumophores used for LWC are different from organic lumophores used in OLEDs and PLEDs in that they do not degrade when exposed to moisture or oxygen. Under violet light excitation, an internal quantum efficiency of ~80% to ~90% has been measured for all three lumophores. This particular combination of highly efficient inorganic excitation sources and organic fluorescent lumophores is an extension of our larger research effort in Hybrid Inorganic/Organic light emitting devices (Hybrid I/O^{TM})[3]. A water layer and counter electrode is then added to complete the LWC display device.

LWC Operation

Intensity modulation for LWC pixels requires that the refractive index be effectively modulated at each pixel by $\Delta n \sim 0.2$ or greater. This, therefore, modulates optical coupling of light from the UV light storage plate to the fluorescent pixels (see Eq. 1). Liquid crystal materials can achieve such large variance in refractive index but are polarization dependent which prohibitively complicates their uses for LWC. To control the pixels, we have adapted the basic principle of electrowetting[4] to the optical switching requirements of LWC. The first implementation of electrowetting for displays was recently developed at Philips using color-filtering oils for high-brightness reflective displays[5]. The basic device structure for the electrowetting switching

Fig. 4 Large flexible LWC signage showing proof of concept of LWC for large format applications.

method for LWC displays is shown in both the ON and OFF states of operation in Fig. 1. The device structure includes three layers which are specially designed in terms of surface tension or surface energy. The interfacial surface tension relationship between the layers governs the following configuration for lowest system energy. With no applied voltage to the system, high surface tension polar liquid (water) forms a film above a lower surface tension non-polar liquid (fluorescent oil) which further forms a film above a low surface energy hydrophobic insulator and hydrophobic cladding. With no applied voltage to the system, these materials always remain in this layered film geometry. Since the fluorescent oil has a refractive index of ~1.5, it will receive ~400 nm light from the waveguide through apertures in the hydrophobic cladding. This causes the device to brightly fluoresce (ON state) as 400 nm violet light excites the lumophores in the oil. RGB electrowetting LWC devices in the fully ON state are shown at left in Fig. 2.

The device is switched OFF as an external voltage of ~10-40V is applied to the device electrodes (ITO and water). This causes the polar water to be electrostatically attracted toward the hydrophobic insulator and to repel the non-polar fluorescent oil up onto the solid optical cladding layer. The optical cladding layer prevents violet light from locally reaching the fluorescent oils by internally reflecting light back into the waveguide. Furthermore, in regions of the device without the optical cladding layer, the low refractive water (n~1.3) contacts the hydrophobic insulator causing additional internal reflection of violet light. Since the oil may be displaced as much as 90% in lateral area, the cladding-covered portion of the device need not be large. The cladding layer and water in combination now form a continuous optical cladding layer which internally reflects (and recycles) violet light at all areas of the device. RGB electrowetting devices in the fully OFF state are shown at right in Fig. 2. The magnitude of oil displacement is approximately proportional to the applied voltage, therefore allowing for straightforward grayscale operation.

LWC Performance

Maximum luminance values of 950, 5530, and 530 cd/m^2 have been achieved for red, green, and blue emission, respectively. As shown in Fig. 3, OFF switching speeds of ~10 ms have been demonstrated. ON switching speeds of ~100 ms has also been demonstrated. The ON switching speed is a strong function of total oil volume and total area of the oil in the ON state. We, therefore, expect that as the pixel size is reduced from the current ~1 mm dimensions to ~100's µm dimensions, that the switching speed for both ON and OFF switching will be <10 ms for full video compatibility. Since the switching method for electrowetting is purely capacitive, no power is consumed for LWC pixels while held in the ON or OFF emission states. Furthermore, the capacitance is comparable to that of a standard transmissive liquid crystal cell, allowing for low-driver power consumption.

A white luminous efficiency of ~7 lm/W has already been achieved for the light wave-coupling method [5]. It is projected that prototype development will result in video rate LWC panels which exhibit efficiency values of >10 lm/W. As shown in Fig. 4, fixed image 'signage' LWC panels with printed solid lumophores already lend strong promise for extending these single device results to large rigid or flexible display panels. This lends strong promise to the ultimate commercial viability of innovative LWC displays using electrowetting switching.

Future Development

Significant research and development is still needed for LWC to realize its full performance potential. However, early device results are very promising. Current development is focusing on advanced cell design and miniaturization. Improved fluorescent oils and hydrophobic insulator coatings are continually being evaluated. These two elements are most critical to development of a high-performance display technology. LWC displays using electrowetting switching present a compelling higher-performance alternative to existing display technologies.

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