P-59: A Novel Fluorescent Display Using Light Wave Coupling Technology

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Abstract

A novel fluorescent pixelated display and signage technology is reported using light wave coupling (LWC). Full-color LWC devices have been demonstrated with >2 lm/W, >500:1 contrast, and >1000 cd/m² luminance. With use of existing display components, theoretical performance of ~1 ms pixel response time, lifetime >30,000 hrs, and >10 lm/W efficiency, are fully expected for flexible and rigid panels.

1. Introduction

The competition for flat panel market share continues to intensify. The dominant flat panel display technology, liquid crystal displays (LCDs), has achieved enormous success [1] by developing technologies for overcoming many of the limitations inherent to liquid crystal cells. Alternative display technologies, focusing on emissive structures for which the eye has a natural affinity, are constantly challenging the supremacy of LCDs [2]. Since LCD is likely to continue its historically proven path of success, only a dramatically higher performance/lower cost emissive display technology could be expected realistically threaten a large portion of LCD market share.

LCDs can be classified as a light valve approach. The most elegant aspect of the light valve approach is that pixel luminance is determined by the panel backlight. By simply adding highly-efficient lamps on can reach >1000 cd/m² panel luminance. Furthermore, the near-absence of electrical power dissipation at the pixel, allows the lifetime of the display to be determined by the lamp sources. However, in terms of acting as an efficient light valve, liquid crystal cells perform extremely poorly considering that even at maximum transmission, they absorb >90-95% of transmitted light. A further wasting of light is incurred for liquid crystal cells in the off state, since even when switched off, liquid crystal cells fully absorb incident light which could in theory be recycled. In short, liquid crystal light valve technology is an order of magnitude away from reaching its fullest potential.

We introduce for the first the time light wave coupling (LWC) display. LWC is a novel light valve approach which possesses ~10X the effective transmission of a liquid crystal light valve. LWC also recycles unused light, and is an *emissive display technology*. LWC is a truly hybrid technology, in that it combines light valve and emissive display technology along with inorganic and fluorescent organic light emitters (Hybrid I/O™) [3]. We present here the fundamental operation and performance of early-stage LWC display devices, and calculated LWC performance for display applications large and small.

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2. Light Wave Coupling

The foremost similarity between LWC and LCD is that both technologies utilize optical waveguides plates. However, LWC devices use a specular waveguide plate (storage of violet light), whereas LCDs utilize a diffuse waveguide plate (white backlight). For a typical specular waveguide plate (refractive index n_{wvg}=1.5) in air (n_{air}=1.0), light propagates in the plate via internal reflection according to:

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

for which a critical propagation angle (maximum allowed, θ_c) in the waveguide is ~42°. Ignoring Fresnel reflective losses, the relationship in (1) further shows that violet edge light which is incident on the waveguide edge facet at *any* angle, will couple and propagate within the waveguide plate via internal reflection. If the waveguide edge facets are properly mirrored, violet light therefore travels back-and-forth within the waveguide for very long distances. For example, polymethylmethacrylate (PMMA) waveguides exhibit 0.1 dB/m loss to violet light (λ<420 nm), which allows a propagation distance of ~30 m before 50% light attenuation occurs. This effectively creates a light storage plate which is functional for panels well exceeding even the largest HDTV size requirements. This short wavelength light can then be selectively distributed via optical transmission or refraction to fluorescent color-conversion-media (CCM). The fluorescent compounds in the CCMs simply absorb violet photons (~3 eV) and efficiently down convert (re-emit) them as visible photons (~2.0-2.6 eV). This requires that the CCM are optically coupled to the waveguide surface and have refractive index comparable to, or higher than, the waveguide. This simplest embodiment of LWC operation is depicted in Fig. 1.

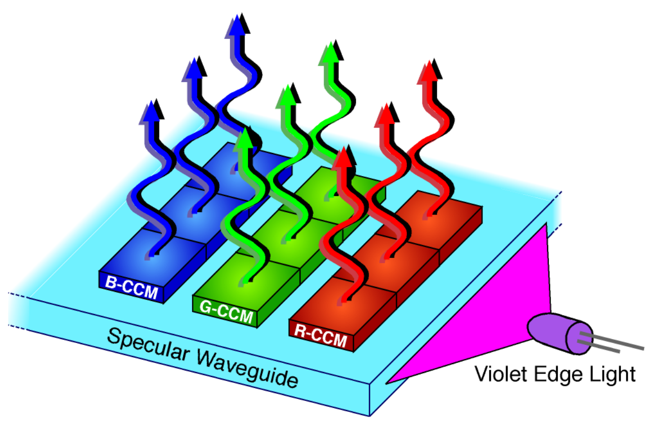

Figure 1. Basic LWC: coupling of high efficiency violet light sources to a *specular* waveguide plate which in turn distributes violet light to optically coupled fluorescent CCMs.

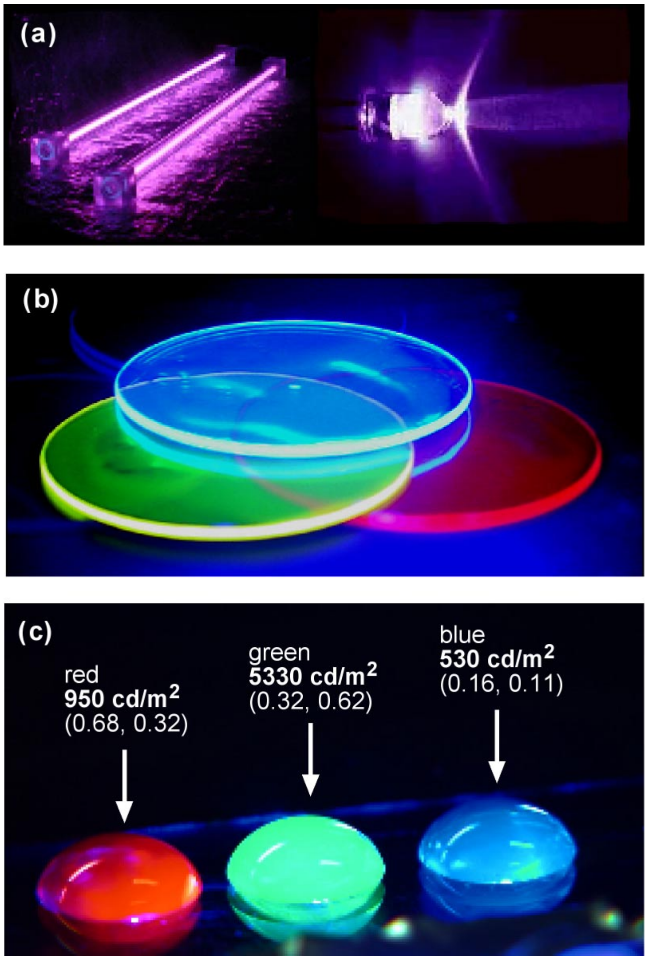

Figure 2. Example LWC display components: (a) violet CCFLs or LEDs (λ<420 nm), (b) spin cast/cured solid CCMs on glass wafers and exposed to violet light, (c) liquid CCMs coupled onto a waveguide propagating violet light.

Table 1. LWC vs. LCD peak theoretical luminous efficiency comparison.

	LCD	LWC
Source	CCFL - 80 lm/W	CCFL - 80 lm/W*
Waveguide	50% efficient	50% efficient
Polarizers	40%x80% (two)	100% (none)
Source Utilization		
10% pixels on	10%	60%
50% pixels on	50%	90%
100% pixels on	100%	100%
Color Filter	30%	100% (none)
Emission Outcoupling	100% (none)	80%
Net Efficiency		
10% pixels on	0.4 lm/W	19 lm/W
50% pixels on	2 lm/W	29 lm/W
100% pixels on	4 lm/W	32 lm/W

*equivalent efficiency after CCM conversion to white

Example components of LWC displays are shown in Fig. 2. Both solid and liquid CCMs have been developed, and their respective functionality described later in Section 3. Internal optical quantum efficiencies in the range of ~80-95%, and internal power conversion efficiencies of ~70%-90% have been achieved for red, green, and blue CCMs. Efficient CCMs and violet light sources allow LWC to provide two major performance advantages. First, as shown in the photos of Fig. 2b, 2c, fluorescent CCMs can be utilized to provide full color emissive image quality. Second, as outlined in Table 1, the combination of efficient violet light sources (Fig. 1a) and loss-less optical coupling to CCMs results in record levels of display efficiency and luminance. The theoretical panel efficiency comparison in Table 1 includes only dominant loss mechanisms and therefore is ~2-4X higher than expected measured panel efficiency results for both LCD and LWC. LWC uses no polarizing media, and provides loss-less optical coupling from the waveguide to the CCM. This is a strong distinction from photoluminescent LCDs[4] which require lossy polarizing media. In the event of a LWC pixel in a non-emissive state, waveguided violet light is recycled by reflecting back into the specular waveguide. This is in contrast to a liquid crystal light valve which accepts all incident light, regardless of whether a pixel is in an emitting or non-emitting state. The fluorescence in LCW is inherently isotropic (~Lambertian), and can be optically reflected such that ~80% of emission is forward coupled out of the display at all view angles. For 50% pixel usage the end result is ~10X panel efficiency advantage over LCD displays. For low pixel usage (10%) the efficiency comparison is even more striking with a ~40X efficiency advantage for LWC. Discussion on the role of driver power on panel efficiency is provided in the next section.

3. Switching Methods and Characteristics

Currently, two distinct switching mechanisms have been developed for LWC. LWC switching mechanisms are compatible with both active and passive matrix addressing schemes. The determination of which switching mechanism is to be most strongly pursued is still under consideration. Currently, the leading switching mechanism is projected to have fewer manufacturing steps, and half the materials cost, of low-cost color STN-LCD panels, while maintaining the performance advantages associated with much higher cost AM-LCD panels. Assuming a comparable high-volume manufacturing base, approximate projected street price for 40" HDTV LWC panels in 2010 is $500, which compares very favorably to projections for comparable LCD pricing ($1300) and PDP pricing ($1200).

The basic structure behind each of the two switching mechanisms is shown in Fig. 3. Detailed discussion on pixel layout and switching are currently proprietary and will be released at a later date. However, some of the basic laws and performance attributes of LWC pixel switching are described below. Both switching mechanisms are based on simple actuation schemes. In each scheme the refractive index above the waveguide surface is effectively modified, which modulates pixel intensity by controlling the amount of violet light optically refracted from the waveguide and into the CCM, or internally reflected back into the waveguide. This is directly related to the evanescent decay of violet light at the waveguide surface:

$$E(z) = E_o e^{-\alpha z}, \qquad \alpha = \frac{2\pi\, n_{wvg}}{\lambda_o}[\sin^2\theta_i - \sin^2\theta_c]^{\frac{1}{2}} \qquad (2),$$

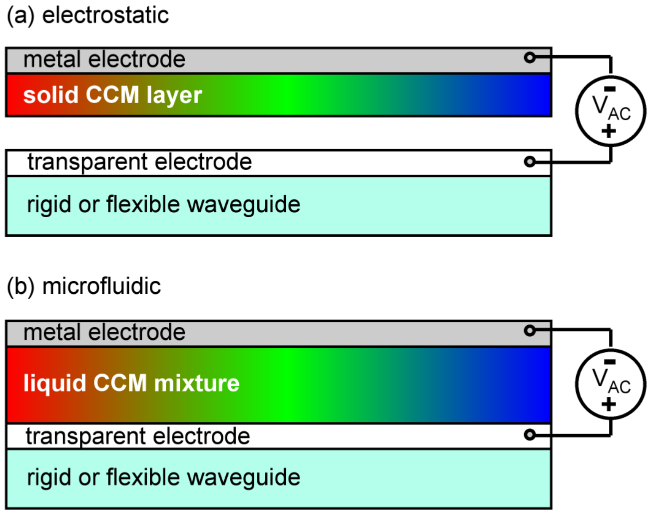

Figure 3. Basic switching mechanisms for LWC pixel modulation. The drawings are simplified but representative.

It is this very strong decay (~1 µm) of evanescent light at the waveguide surface that allows high switching contrast. Shown in Fig. 4 are photographs demonstrating this high contrast switching capability for both LWC switching mechanisms. The electrostatic switching mechanism in (3a) requires only a single solid membrane actuation, whereas the mechanism in (3b) requires only a double liquid membrane displacement. The CCMs in both mechanisms are electrically insulating so no direct current is passed through the CCM. This completely alleviates current related degradation found in display technologies such as OLEDs. Both switching mechanisms can be designed for bi- or multi-state stable, or hysteretic operation, which allows low-cost passive matrix addressing. Grayscale operation for mechanism 3a is achieved using duty cycle modulation and grayscale operation for mechanism 3b is voltage modulated and compatible with STN-LCD drive circuitry.

Since LWC is such an optically efficient light valve technology, it becomes critical to keep the electrical power dissipated in light valve actuation as low as possible. LWC switching power consumption is capacitive (~CV^2) and comparable to STN module power consumption since the pixel capacitance (~1 nF/cm^2) and required drive voltages (~5 to 10 V) are both very low. This power dissipation in light valve actuation is directly proportional to the display refresh rate. Therefore, the LWC display efficiency potential shown in Table 1 is fully realized in low refresh rate, battery-powered, portable displays such as PDAs, cell-phones, and e-books. However, light valve power consumption is more significant in higher refresh rate applications such as HDTV. For example, in LCDs the module power (logic and light valve drivers) is typically ~10% of the backlight power. LWC requires very little violet light power compared to LCD white backlight power. Therefore the module power begins to play a larger role in the panel power consumption. Still, module power is not expected to be the efficiency limiting mechanism for moderate to high luminance LWC displays (100-1000 cd/m^2).

4. Reaching the Full Potential of LWC.

Although in early stage development, a comprehensive study has been made of the projected specifications of LWC panels. These LWC specifications are shown in Table 2. The specifications are largely based on the performance of commercialized electro-optical components in other technologies, which are also key components assembled into an LWC panel. Currently the averaged luminous efficiency of RGB LWC devices is >2 lm/W. This is expected to quickly exceed ~5 lm/W in the coming months and to rapidly advance to the final goal of 10's of lm/W efficiency. LWC displays exhibit much lower reflectivity than powder phosphor based displays such as CRT, PDP, and FED. LWC displays can be ~90% transparent which allows viewing the panel from both sides or contrast enhancing using a simple rear black absorbing film. Another method for contrast enhancement in sunlight legible displays will be that of a circular polarizing (CP) film. Dark contrast is already very high at >500:1. Video response is less than 10 ms for both LWC switching mechanisms, allowing artifact-free video images. LCD compatible drive voltages are utilized. Obtaining an ultra-wide color gamut is easily achieved for LWC due to the wealth of fluorescent compounds which can be utilized to create CCMs. LWC is an emissive display and therefore has unlimited view angle. The min pixel pitches are satisfactory for the vast majority of flat panel display applications. Lifetime is determined by the violet light source which edge lights the waveguide. With the rapid progress in GaN LED technology for solid-state lighting, 100,000 hr LWC panel lifetimes are expected in the future. Panel depth and size cover applications ranging from small ultra-thin panels for cell phones, to large panels for hang-on-the-wall HDTV. LWC is fully compatible with flexible or rigid substrates. For flexible displays and/or displays which are manufactured using roll-to-roll processing, LWC possesses several key advantages over OLED and LCD panels. With comparison to LCD panels, there is no cell-gap dependence on pixel emission for LWC. With comparison to OLED panels, LWC is not susceptible to degradation due to moisture penetration and therefore does not require complex barrier systems deposited onto the flexible

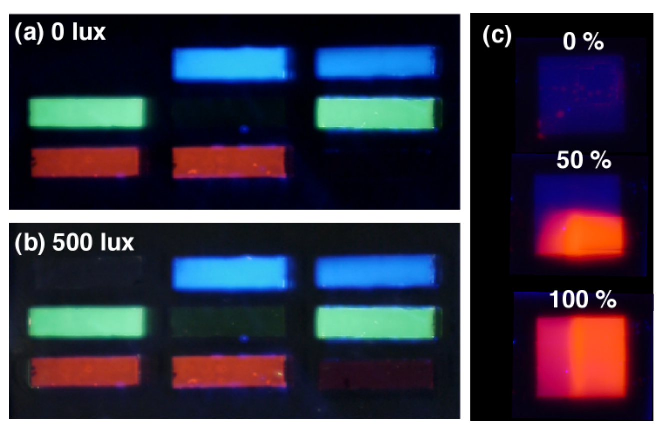

Figure 4. Photos showing pixel contrast achievable for electrostatic actuation in (a) 0 lux; (b) 500 lux (one pixel turned off for each RGB set); (c) microfluidic actuation at 0%, 50%, 100% luminance.

Table 2. Projected performance of electrostatically and microfluidically modulated LWC display panels.

	LWC electrostatic	LWC microfluidic
Peak Luminance	>1000 cd/m^2	>1000 cd/m^2
Peak Efficiency	~30 lm/W	~30 lm/W
Diffuse Reflectivity	<5%	<5%
Specular Reflectivity	~10%	~5%
Reflectivity Reduction	Optional CP filter	Optional CP filter
Total Reflectivity	<2%	<2%
Adjusted Efficiency	~10-30 lm/W	~10-30 lm/W
Dark Contrast	>500:1	>500:1
Video Response	~1-10 µs	~1-10 ms
Drive Voltage	5V	5 to 10V
Color Gamut	Exceeding EBU	Exceeding EBU
View Angle	Unlimited	Unlimited
Min Pixel Pitch	~25 µm	~10 µm
Lifetime	>30,000 hrs	>30,000 hrs
Panel Depth	~0.05" to 1"	0.05" to 1"
Ideal Diagonal Range	1" to 40"	2" to 60"
Flexible	Feasible	Likely

substrate. In comparison to both OLED and high-performance LCD, LWC can be bi-stable and therefore requires no active matrix addressing. This eliminates substrate concerns related to the higher processing temperatures required for a-Si or p-Si thin-film-transistors. LWC device processing can be performed entirely below 200 °C, and likely entirely below 100 °C, which vastly broadens the choices of flexible substrates.

LWC also exhibits promise beyond pixelated displays. The fact that LWC panels can be ~90-95% transparent allows for unique single and multi-image signage applications. Stacking of multiple thin panels and individually edge-lighting each panel allows for the creation of simple motion, multi-images, or 3D images. An example of a single flexible LWC signage panel is shown in the photo in Fig. 5. These signage panels simply use inkjet or silk-screening for image definition and are of primary interest for advertising markets, especially narrow-casting advertising.

5. Summary

LWC display technology is now in full development at Extreme Photonix. Prototyping is focused on first developing a video-capable QVGA LWC panel. The primary challenge in meeting

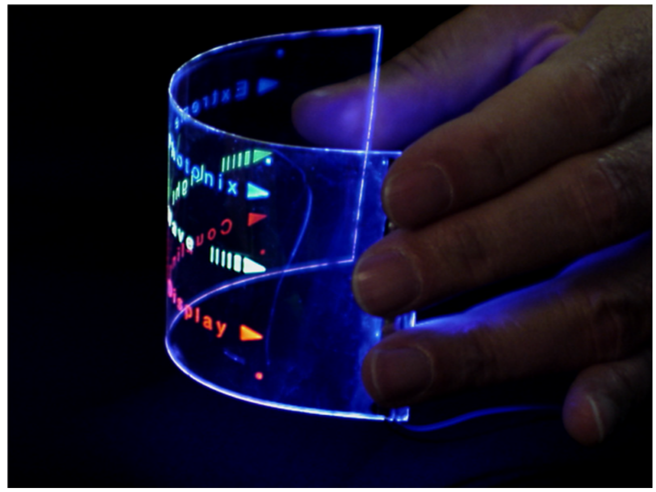

Figure 5. Photos of LED edge-lit flexible LWC signage.

the full potential of LWC is the integration of existing electro-optical components. Early multi-pixel devices already demonstrate integration feasibility in large pixel counts (>1k to >1M). As development continues, LWC should demonstrate a very compelling argument to its superiority over leading flat panel display technologies.

6. Acknowledgements

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7. References

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