Photonic Crystal Display Materials

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Abstract

Photonic Ink (P-Ink) technology comprises an active photonic crystal that reflects a band of color that can be tuned by controlling the applied current or voltage. All the individual spectral colors in the visible range can be reflected by a single P-Ink material. This technology provides an opportunity to create a wider range of primary colors than the conventional RGB system, given the same numbers of pixels for color mixing.

Introduction

Photonic crystals (PCs)[1] are materials with a periodic modulation in their refractive index. They are exemplified by opal gemstones and countless other natural materials, and can be used to reflect bright and pure visible colors through coherent Bragg diffraction. While studies on natural and synthetic opals have been ongoing for over half a century, the development of a theoretical framework for PCs in the late 1980s heralded a resurgence of interest and potential applications for these materials. Once the physics were outlined, it took some time for the associated materials chemistry to catch up, specifically around self-assembly routes to PC structures using monodisperse spheres. Over time, by harnessing the incredible diversity of synthetic chemistry, an encyclopedic array of structures could be produced. As an additional matter of great interest, it was found that incorporating active materials into such structures can allow the reflected colors to be tuned over a wide range of spectra, from UV to visible to near-IR.

Opalux Incorporated is developing a platform of technologies based on photonic color. These technologies consist of active polymer-based PC materials that can respond to an array of stimuli such as pressure, stretching, heat, humidity, and electrical current/voltage. Each of these technologies is created through the incorporation of specially formulated polymer materials. One of the technologies is photonic ink (P-Ink), a tunable electroactive material. By applying different voltages to this material, the PC structure can be modulated to reflect any desired spectral color in the visible spectrum. Not only is the color tunable, but switching is carried out at low voltages (1.5 V or lower) and amperages (µAmps), and the resulting color states are bistable.

The e-paper market is growing at a staggering rate, with a diversity of product offerings slated for release in the coming months. However, there are few color e-paper products available on the market; current examples such as E-Ink's Triton technology represent a strong first step, but the available color gamut is quite limited, which suggests that a large and unmet consumer demand still exists. Given its unique opto-electronic properties, P-Ink could form the basis of a next-generation e-paper material. Opalux has been testing and developing the P-Ink technology for display applications, and many of its metrics compare favorably with alternative technologies. This technology maintains the strong advantages of full-spectrum tunability, low-power, and bistability, while providing high reflectivity, saturated colors, and fast switching speeds.

P-Ink Materials

P-Ink materials are nanocomposites, fabricated through a combination of colloidal, inorganic, and polymer chemistry.[2,3] The structural scaffold of P-Ink materials is made up of an ordered array of silica microspheres. The voids between these microspheres are filled with a crosslinked network of a ferrocene-based metallopolymer, which is known to display reversible redox properties.[4] Ferrocene is an organometallic species consisting of an iron atom sandwiched between two aromatic organic ligands. It displays remarkable chemical stability. P-Ink display devices are fabricated by incorporating P-Ink composite films coated on a conductive substrate into a sealed electrochemical cell. A spacer material is used to separate a counter-electrode from the P-Ink film, with the resulting gap filled with an electrolyte. More complex devices incorporating pixels are fabricated using standard lithographic techniques.

P-Ink Display Devices

The color switching of P-Ink film in response to external electrical stimuli is caused by the expansion and contraction of the crosslinked electroactive polymer network. Shown in Figure 1 is the schematic structure of a P-Ink device and how the P-Ink materials respond to external electrical stimuli.

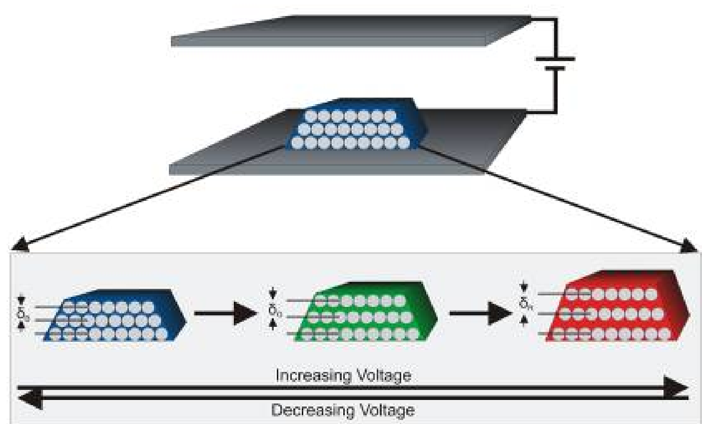

Fig. 1: *This schematic represents the structure of a P-Ink electrochemical cell and the effect of film thickness on reflected colors.*

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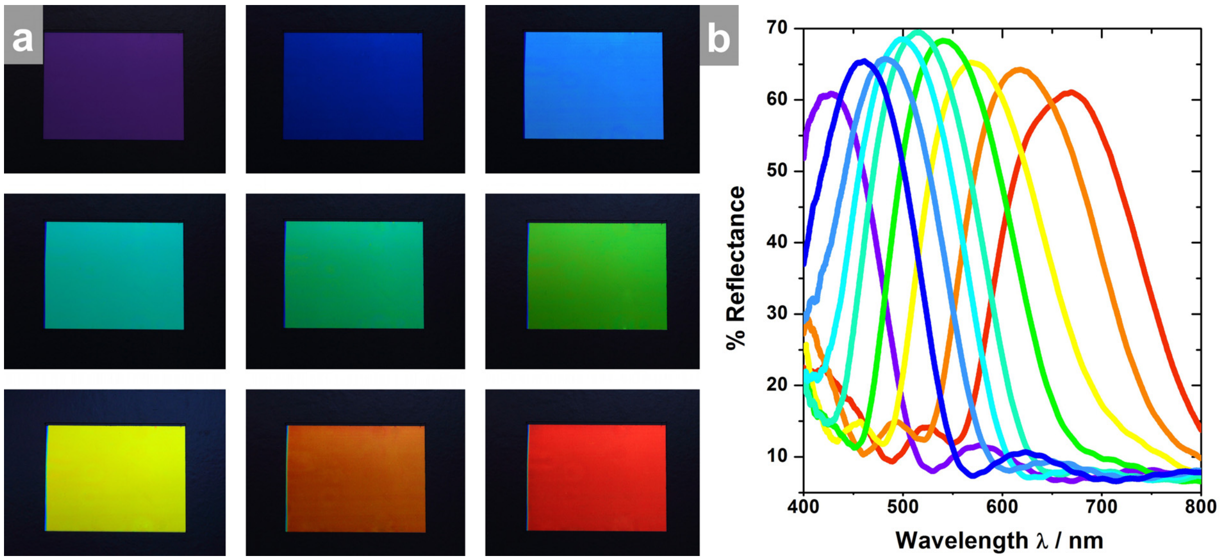

Fig. 2: *Pictures of the display window of a P-Ink device show (a) an array of progressively red-shifted color states from violet to red and (b) their corresponding reflectivity curves.*

The structural scaffold of P-Ink materials is made of an ordered array of silica microspheres. The voids between these microspheres are filled with a crosslinked network of an iron-based polymer, which enables it to store charge. P-Ink display devices are fabricated by integrating P-Ink composite films into a sandwich-type device, not dissimilar to the way LCD screens are structured. When a positive voltage is applied to a P-Ink device, the iron atoms in the polymer can lose electrons to become positively charged. This results in an influx of negatively charged counter-anions from the electrolyte to maintain electrical neutrality in the P-Ink film. Consequently, this electrical charging is accompanied by an increase in volume, which pushes apart the silica spheres. Since the inter-sphere spacing (δ) is what dictates the reflected color of the materials, these devices can span the whole visible spectrum ($\delta_B \rightarrow \delta_G \rightarrow \delta_R$) simply by changing the applied voltage. This process also works in reverse by applying a negative voltage, where the thickness of the film decreases and the reflected light shifts to "bluer" wavelengths.

One key characteristic of Opalux's P-Ink materials is their bright and highly saturated color. A series of pictures showing different color states of a P-Ink device during color switching is presented in Figure 2, together with their corresponding reflectance spectra.

One can see the color progressively shifting toward red, starting from violet when a positive bias is applied. Representative intermediate color states shown in the figure include deep blue, blue, cyan, turquoise, green, yellow, and orange. The average peak reflectivity of these spectra is ca. 60%, with peak widths at half maximum between 75 to 150 nm, which compares favorably to other reflective color technologies.[5] The spectral features of the P-Ink material present a good compromise for reflective color, providing peaks narrow enough to generate good color saturation while being wide enough to generate significant reflectivity. The result is a material reflecting bright and vibrant color states.

To estimate how the colors produced by a P-Ink device compare with standard display technologies, standard CIE coordinates were extracted based on the reflectance curves shown in Figure 2b. The chromaticity diagram used in Figure 3 is obtained from the CIE 1931 standard with a D65 illuminant.

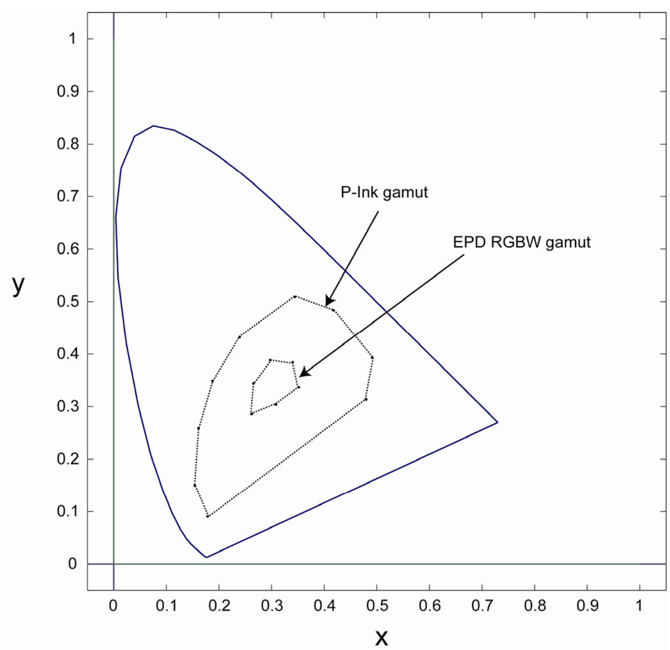

Fig 3: *The CIE diagram shows color gamut produced by a P-Ink reflective display. The gamut of a published electrophoretic display (EPD) color space is defined by the dashed polygon for reference.[6] Note: The EPD RGBW gamut was generated based on prototype devices with color filters, while the P-Ink gamut was produced using a device without the use of a color filter.*

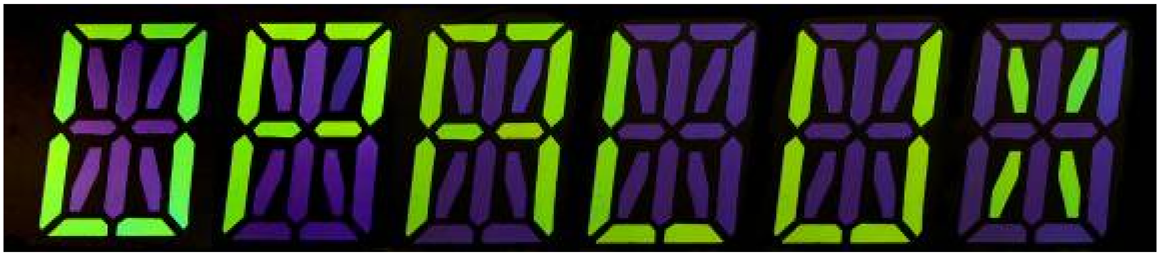

Fig. 4: A pixilated alphanumeric P-Ink display device spells "OPALUX" under ambient office lighting

One can see that the color gamut of P-Ink reflective display devices covers a significant portion of the CIE color space. When compared to other reflective technologies such as electrophoretics, the palette of a P-Ink device is significantly broader.

Fast switching speed is another important attribute of the P-Ink materials. Through continued development, current switching speeds for P-Ink devices are comparable to those of other eBook display technologies -- high enough that switching between any spectral colors in the visible spectrum takes less than 0.2 seconds. The driving scheme for P-Ink displays can either operate via analog voltage control, or by fixed-voltage pulse-width modulation, providing simple options for the development of an electrical driving scheme.

Electrical bistability and low power consumption also render P-Ink materials a viable option for next-generation full-color reflective displays. Preliminary studies indicated that P-Ink devices can retain their color for hours without any external electrical input. In addition, by optimizing the formulation of the composite materials, the authors were able to achieve color switching of P-Ink displays at as low as 0.1 V, while most alternative “e-paper” display technologies require 5 – 30 V input.[5] Both of these properties are crucial for potential applications in areas such as portable electronics and full-color e-paper devices.

A simple demonstration of a pixilated alphanumeric P-Ink display device is shown in Figure 4. It is sequentially switched to spell out "OPALUX", shown under ambient office lighting.

The pixels are fabricated by photolithography, and addressed via separate leads. The precisely defined green color of the switched areas is achieved by applying a controlled voltage to given pixels. As can be seen, the reflective colors are bright and uniform.

Scalability of P-Ink Materials

In addition, P-Ink materials can be produced using established high-throughput roll-to-roll coating processes. This allows not only for an effective cost reduction but also for the fabrication of large, thin, and flexible P-ink devices. A roll of P-Ink materials on a flexible ITO-PET substrate is shown in Figure 5a.

When assembled in a device using all-flexible conductors and substrates, fully flexible P-Ink devices can result. Figure 5b shows three extracted video frames displaying blue, green, and red color states of a flexible P-Ink device. The video was taken when the device was being simultaneously switched and flexed. The performance characteristics of P-Ink flexible devices are comparable with those made on rigid substrates.

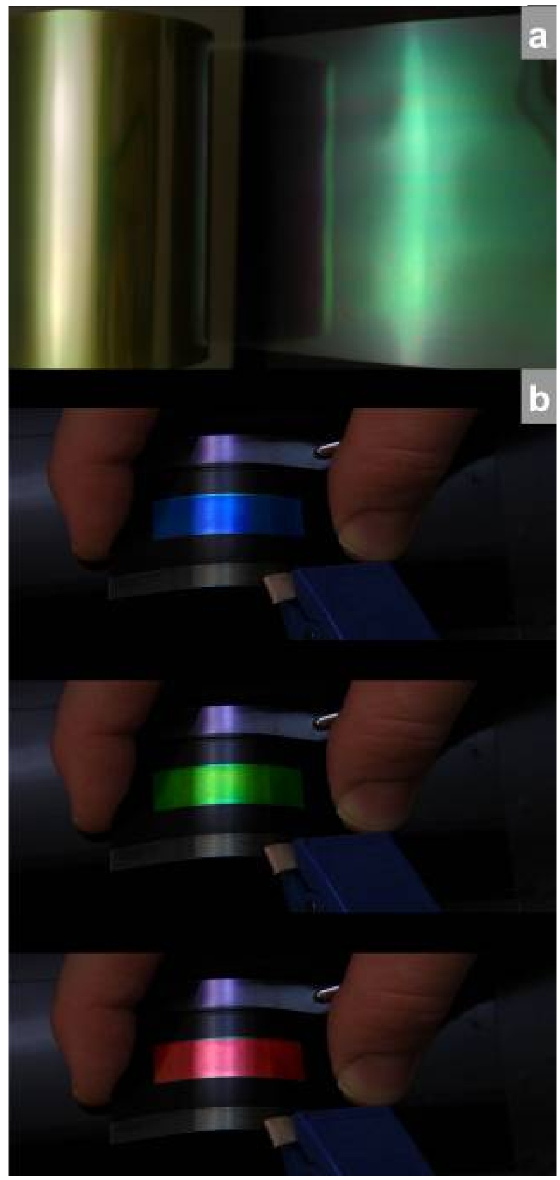

Fig. 5: (a) Above is a roll of P-Ink coating materials on a flexible substrate produced by a roll-to-roll coating process, prior to assembly into a finished display device, and (b) extracted frames from a video taken when a flexible P-Ink device was being simultaneously switched and flexed.

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The Road Map

Recent advances in P-ink's performance include brightness, switching speed, and lowered power consumption. Pixilated displays with individually controlled colors have been demonstrated and roll-coated materials on flexible substrates are available in pilot quantities. Taken together, these achievements bring P-Ink to the threshold of commercialization.

Full characterization of P-Ink is now underway. This includes extensive cycling stability, bi-stability, and UV and environmental stability tests to reflect specific requirements of various markets. In addition, attaining well-defined black, white, and grayscale states will require the integration of additional technologies such as high-resolution active-matrix backplanes for effective color-mixing. However, given the inherent simplicity of the P-Ink display itself, such approaches are readily achievable.

Roll-outs will focus first on simpler and less demanding devices, in color, construction and working environment, to be followed by increasingly sophisticated and higher volume applications. For example, given the intrinsically bright and eye-catching colors produced by P-Ink coatings, a large number of potential applications relate to simple color-changing surfaces, from mobile electronics to office interiors. In addition, due to mechanical flexibility and competitive price points, a variety of simple displays integrated into products such as plastic cards of all types and size, as well as product packaging, are being envisioned. Following the launch and adoption of such simple display products, more complex devices incorporating active-matrix driving schemes will follow. Opalux is now seeking parties interested in developing specific, innovative display concepts.

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Author Biography

Andre Arsenault received his BSc in Biological Chemistry (2001), and his PhD in Polymer and Materials Chemistry (2006) from the University of Toronto. He co-founded Opalux Incorporated in 2006 to commercialize the groundbreaking discoveries made during his graduate work. He is the recipient of the NSERC Innovation Prize, as well as an author in numerous peer-reviewed journals and several patents and patent applications.