Multipigment Full-color Electrophoretic Display with Improved Update Time

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ABSTRACT

A new four-pigment electrophoretic display has been developed, delivering a color gamut volume of >10,000 dE³ without a front light and >40,000 dE³ when front-lit in an update time of 500ms. This order-of-magnitude speed improvement over prior multipigment displays enables full-color e-reader devices to be made without color filters.

1 Introduction

Reflective electrophoretic displays have many features that make them ideally suited for e-reader and signage applications. Such displays closely reproduce the visual appearance of printed paper, being highly reflective in ambient light and capable of a high contrast ratio and wide viewing angle. Unlike emissive displays, reflective displays can be viewed for long periods of time without inducing eyestrain or eye damage. Further, because reflective electrophoretic displays can be multi-stable, they require very little power except during an image refresh. This results in extended battery life for applications in which images are switched only infrequently.

Significant progress has been made in recent years towards the goal of providing a reflective display capable of full color.[1] Figure 1 summarizes the state of affairs in E Ink's color electrophoretic displays at the present time. The term "color quality" in this Figure refers to the saturation of colors the display is intended to produce. Not all displays are intended to render every color, and in general there will be a tradeoff between quality of particular colors and the number of colors that can be shown.

The most straightforward color approach is to provide a color filter array (CFA) in close juxtaposition to a black and white modulator. This has been demonstrated with electrophoretic, electrowetting,[2] and frustrated TIR displays.[3]

E Ink has greatly improved the appearance of CFA displays in the new E Ink Kaleido™ line of products. Such displays have the advantage that the speed of the underlying black and white ink is maintained. The chief disadvantage is that the color filters absorb light and therefore give rise to a somewhat dark appearance unless front lighting is provided. The color filter pattern permits only side-by-side combinations of the primary colors, leading to compromises in resolution and color saturation, although these have been partly mitigated by improvements in image rendering. E Ink Kaleido is aimed at e-reader and signage applications.

Multipigment electrophoretic displays have also improved greatly in quality and have enjoyed commercial success, particularly in applications where specific colors, rather than full color, are needed. E Ink Spectra™ 3000 is a three-particle electrophoretic architecture that can render black, white and one additional highly-saturated color. The new E Ink Spectra 3100 utilizes a four-particle architecture to generate a choice of saturated colors in highlights.[4]

E Ink has also commercialized full-color electrophoretic displays capable of producing any color at any pixel location under the brand name E Ink Gallery™. The E Ink Gallery technology produces colors by manipulating the relative positions of four colored pigments in an electrophoretic fluid. The existing E Ink Spectra and E Ink Gallery technologies have been targeted at products such as indoor signs, electronic shelf labels and ID badges. In these applications the refresh time of the display (~10 seconds or more) is not as important as the reflectivity, color quality and power consumption.

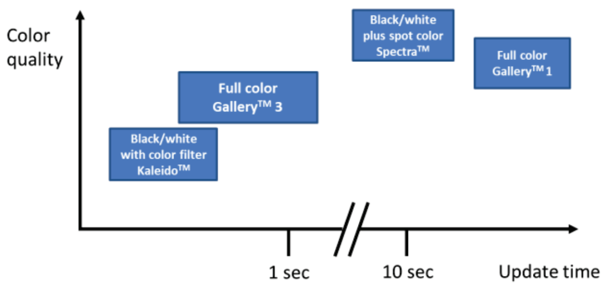

Figure 1. Summary of E Ink's color electrophoretic display technologies

A full-color multipigment electrophoretic display with an order-of-magnitude speed improvement over E Ink Spectra and E Ink Gallery 1 would enable a much greater range of possible applications. In particular, a fast enough update could bring an improved vibrancy of color to e-readers, which are currently mostly black and white.

We now report that the recently-introduced E Ink

Gallery 3 can achieve a color page refresh in as little as 0.5 seconds without compromising image quality, bistability, or power consumption.

2 E Ink Gallery 3 Display Architecture

E Ink Gallery 3 is an extension of the previously-described Advanced Color e-Paper (ACeP) platform.[5] It uses a single electrophoretic layer that contains three transparent, colored pigments having the subtractive primary colors (cyan, magenta, and yellow) and a light-scattering white pigment in a fluid contained in a Microcup® structure. In an e-reader embodiment it is necessary to maintain the fast black and white switching speed of existing bichrome displays, and therefore the three colored pigments are each designed with a charge polarity that is opposite to that of the white pigment. In combination, the three colored pigments adsorb light of all visible wavelengths and move in the opposite direction to the white pigment in an electric field. Therefore the color display behaves similarly to a black and white display when driven with a constant applied voltage. With more complex drive schemes the pigments move more selectively. The color seen by a viewer is controlled by which colored pigments are located on the viewing side of the white pigment, this being the only pigment of the four that significantly scatters light.

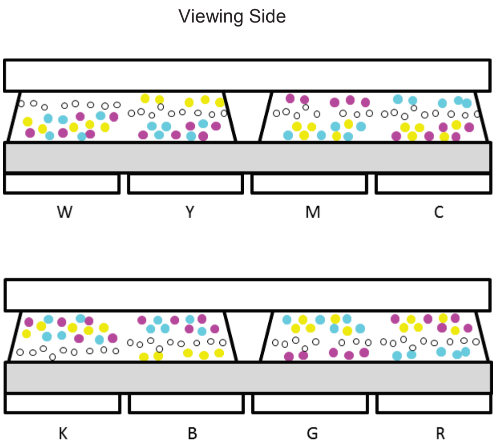

Figure 2. Cross-sectional representation of pigment arrangements in the electrophoretic layer of an E Ink Gallery^{TM} 3 display module for each of the eight basic palette colors

Colors are obtained by the pigment arrangements shown in Figure 2, in which the viewing surface of the display is at the top. At each pixel location it is necessary to produce a minimum of eight colors in order to produce a full color image (i.e., white, black, red, green, blue, cyan, magenta, and yellow). These colors are referred to as the "device palette colors". As shown in Figure 1, the four bottom-row colors are complementary to the four top-row colors and can be rendered simply by inverting the pigment stack, which is achieved by addressing with voltages of opposite polarity. Thus there are only four pigment arrangements necessary to produce a full-color image. In practice, however, the quality of an image is improved if a larger number of device palette colors than this minimum are provided.

Figure 3 shows how a full color image is produced by a dithered pattern of the device primary colors. The image rendering scheme required for an E Ink Gallery image is thus quite different from one used in a more conventional color display in which independent addressing of three color channels is possible.

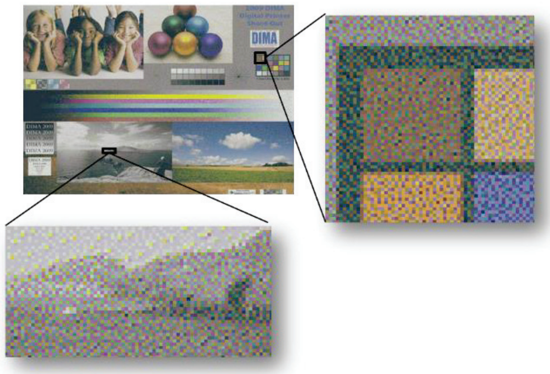

Figure 3. Dithering of device palette colors to form a full-color image in E Ink Gallery^{TM} technology

Addressing the electrophoretic fluid to shuffle the relative positions of the four pigment particles into the required four arrangements uses five different voltage levels, exploiting thresholds that control relative electrophoretic motion of the particles. As shown in Figure 4, these voltages are high positive and negative, low positive and negative, and zero. Two pulses of opposite polarity (so-called "dipoles") can be used to produce any of the device palette colors. Dipoles used for particular colors vary in (a) polarity of the first pulse and (b) magnitudes of the first and second pulses. There are 8 possible combinations that correspond to the 8 ideal arrangements of the pigments. Fine control of pigment positions can be achieved by adjustment of the lengths of each pulse in a dipole and the magnitudes of the voltages applied.

Figure 4 shows only the most basic waveforms required to address an E Ink Gallery 3 module. Practical waveforms are far more complex than those illustrated and are designed to co-optimize color quality, image stability, erasing of previous states, and transition appearance.

Typically the lower applied voltages are in the range of 8 – 15V, the higher voltages in the range of 16 – 30V, the ratio between the two being at least about 2. While five voltage levels is the minimum required, greater color control is achieved when more are provided, and current

E Ink Gallery 3 modules use seven voltage levels.

Figure 4. Representation of the voltage levels in dipole pulses required to form the 8 primary colors in an E Ink Gallery™ 3 display

The higher voltages ideally exceed +/-15V, which is the typical limit for amorphous silicon thin-film transistor arrays. One solution to the problem of addressing with these higher voltages is to use top-plane switching, in which the waveform is divided into temporal segments in which the top plane is set to different voltages. The electrophoretic fluid experiences a field that is proportional to the difference in potential between the top plane and backplane electrodes. The disadvantage of this method is that high voltages of opposite polarity cannot be applied simultaneously, even though this is required if all colors are to be updated in the shortest possible time.

A second solution is to use a backplane capable of higher voltages in combination with a data-line driver that can supply at least 5 voltage levels. Such high-voltage backplanes can be made using modified amorphous silicon architectures, alternative TFT semiconductor materials, or segmented backplanes with higher-voltage driver chips.

When a high-voltage backplane is used images can be refreshed quickly. For example, with a frame rate of 85 Hz (i.e., approximately 12 ms per frame) and 7 voltage levels, a full color image transition can be made using 42 frames (0.5 seconds).

3 Display Results

The electrophoretic display composition as described above has been incorporated into a 300ppi display module equipped with an oxide TFT array backplane and front light, addressed at a maximum voltage of +/-24V. The display has an operating temperature window of 0 – 50 ˚C.

Table 1 and Figure 5 show the color gamut volume (in CIELab color space) available from the E Ink Gallery 3 platform using color waveforms of lengths in the range 500ms – 1.5 seconds. The text mode is 350ms in length and provides black, white and two intermediate grey levels, although more are in principle possible. With longer updates the color quality improves but the transition appearance becomes less desirable. Color transitions that are still faster are possible, allowing pen input in color. With these extremely fast updates there may be incomplete prior state erasing, but this is typically less important for writing applications than for area updates.

Table 1

	Update time (ms)	350 (text)	500	750	1000	1500
Front light off	8 palette color gamut volume (dE^3)		11584	13181	15641	20582
	Contrast Ratio	10	11.7	11	11.3	11.3
Front light on	8 palette color gamut volume (dE^3)		48120	58152	68030	92709
	Contrast Ratio	12.6	18.6	15.1	14.3	15.7

It can be seen from Table 1 that both the color gamut volume and contrast ratio of E Ink Gallery 3 are enhanced when the display is front-lit. This is because the emission spectra of the LEDs comprising the front light can be matched to the absorption spectra of the colored pigments, avoiding illumination of the display at wavelengths where optical modulation is less efficient. The use of colored pigments to make a black state differs in this respect from a normal black and white display, in which the absorption spectrum of the black pigment is approximately constant across the visible range.

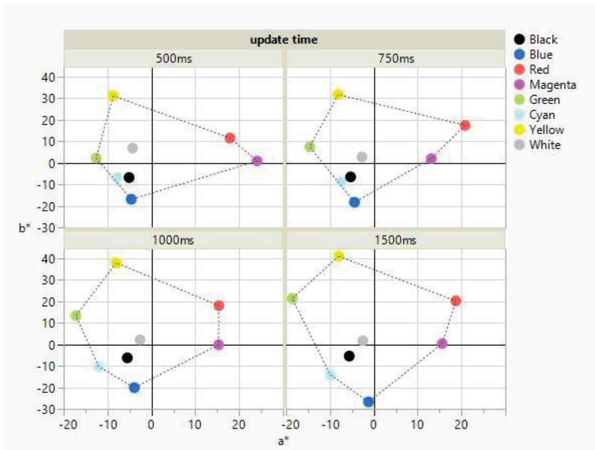

Figure 5. Color gamut available from E Ink Gallery™ 3, showing a* versus b* in CIEL*a*b* color space

Further development of the E Ink Gallery platform is ongoing. We expect to be able to decrease the update time still further while also improving the color capability. The E Ink Gallery™ electrophoretic composition can be incorporated into flexible structures, allowing bendable and rollable embodiments, as shown in Figure 6.

4 Conclusions

An order-of-magnitude update speed improvement has been achieved with a full-color multipigment display. Color update times in the range of 0.5 – 1.5 seconds are now possible, combined with black and white update times of about 0.35 seconds. The display has a resolution of 300ppi and can achieve a color gamut volume of 10,000 – 20,000 dE^3 without a front light and more than 48,000 – 93,000 dE^3 when front-lit. The technology has been launched under the brand name E Ink Gallery 3, and for the first time enables color e-reader products without any reduction of reflectivity by color filters.

Figure 6. E Ink Gallery™ 3 embodiments

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