Abstract
An improved full color active matrix electronic paper display (EPD) prototype using a custom design color filter array with E Ink’s electrophoretic technology is reported. Improvements over previous efforts are achieved by using a) improved ink formulations with higher dynamic range, b) 4 bit gray scale for each color and c) a color filter design with RGBW pixel layout to improve brightness and dynamic range. As a result, the whiteness of the background page is preserved while enabling color. In addition, due to the “paper-like” optics, the brightness and saturation of the optical states are largely independent of viewing angle or illumination conditions.

1. Introduction
During the past few years, electrophoretic paper displays (EPD) have steadily advanced in capabilities and performance in the monochrome domain [1-6]. However, there is a significant market potential for a color EPD that is commercially viable with enhanced color performance.

One application for this color electronic paper display module is for seeing digital information outdoors. Digital cameras, ATMs, kiosks, GPS devices and electronic signs can be seen clearly at any angle, even under sunlight using the new display module. The display will also be useful for any portable electronic device that requires a battery. The new display module will enable cell phones, PDAs, and wireless tablets to run substantially longer on a single charge, allowing designers to make more compact devices by reducing battery size and weight [7].

2. Previous Design
In our earlier publication [8-9], we described the first efforts to integrate a color filter array (CFA), EPD optical material, and a commercially available TFT array. The QVGA panel was 320 (x3) x 234 and had an active area with 5.0” diagonal. The QVGA research prototype display was driven to produce 3-bit color (2 optical states per subpixel).

3. Improvements
The major improvements from the original design are threefold: ink performance, CFA design, and the driving circuitry. Several experimental ink formulations were evaluated in conjunction with a CFA designed and supplied by Toppan Printing Co. Ltd. The resulting 12-bit color EPD is shown in Figure 1.

3.1 Electro-Optical Properties of the Ink
Since the introduction of a CFA reduces the maximum attainable brightness when compared to monochrome devices, one of the

![Image 1](https://example.com/image1)

**Figure 1 – Functional 6.1” diagonal electronic paper color display.**
primary goals of this development activity was to improve the white state reflectivity (WS). The new formulation improved the WS from 47 to 54 L\*\textsuperscript{1}, which corresponds to an increase of 37\% in reflectivity. The display can be fully driven from black to white by applying a 15V bias for 240ms.

### 3.2 Color Filter Array Design

The color filter array (CFA) was improved by moving from a striped RGB to a staggered RGB+White (RGBW) square subpixel layout (see Figure 2). The addition of a white subpixel enhanced the brightness and dynamic range while having minimal impact on color saturation as the relative area for each color subpixel is reduced by only 25\%.

![Figure 2 – Micrograph of the pixel layout (The electrophoretic ink microcapsules are visible under the CFA).](image)

### 3.3 Driving Electronics

The electronic system used to run the panel consisted of an Xscale based single board computer running Linux coupled to a custom display controller daughterboard. A handful of simple C programs and shell scripts on the host system format and store the pixel data into the frame buffer and manage image flow.

Since EPDs are multi-stable and a relatively close balancing of impulse is needed for high performance, the formulation of a suitable voltage versus time drive signal to update each pixel requires knowledge of both the current state and the next desired state of the pixel. The system used in this prototype supplies both current and next pixel states to the display controller board along with driver control timing signals.

The display controller daughterboard accepts the image output generated by the host system and performs the real time pixel-by-pixel transform from pixel image data to voltage sequence data specified to achieve the image update on the EPD. The logic for this transform is implemented in about five thousand gates in an inexpensive complex programmable logic device. The display controller board also incorporates bias supplies and common plane driving circuitry.

The images were globally updated with a waveform achieving four bits per subpixel, or 16 bit per RGBW quad. The effective color depth is approximately 12 bits per color quad. The improved color depth enabled the elimination of dithering and excellent rendering of flesh tones and vignettes, necessary for the reproduction of photographic images.

### 3.4 Backplane

The backplane used in the construction of the color EPD is identical to those used for standard EPD. The resolution was approximately 166 pixels/inch. The entire image area is 600 by 800 pixels and the display size is 6.1” diagonal. By using a 2x2 grouping of the RGBW pixels, the effective resolution for color information is 83 pixels/inch. However, as discussed in section 3.6, it is possible to improve the apparent resolution by subpixel addressing and spatial filtering.

### 3.5 Color Conversion

The conversion from the RGB to RGBW space is a challenging problem and much thought has been put into creating a good balance between the need for color accuracy and processing power required to run the mapping algorithm.

One of the fastest standard methods of mapping the white pixel is by using \( R_o = R_i, \quad G_o = G_i, \quad B_o = B_i \) and \( W_o = \min(RGB) \) (where \( i \) represents the input image and \( o \) the output image). This is satisfactory for fully saturated graphics but has the tendency to wash out moderately saturated colors like those found in natural scenes.

The method we implemented was to set \( W_o = \min(RGB) \), as above while adjusting the values of the remaining primaries to compensate for the addition of white light.

![Figure 3 – Single-pass transmission spectra of the CFA with ITO, as measured by micro-spectrophotometry.](image)

### 3.6 Color Mapping

Once the color information is translated from RGB to RGBW space, it is then mapped to each individual subpixel on the panel. Subpixel addressing is necessary to maintain the sharpness in images containing fine details and text. The current CFA design allows reproduction of single black lines with only one row of subpixels in the RGBW direction, and two columns in the other direction.

A low-pass windowing filter is used after the color mapping to adjust the contribution of each neighboring subpixel, minimizing

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\( ^1 \) All CIELAB values quoted are using D65/2 viewing conditions.
color imbalance and fringing at sharp edges. To prevent excessive blurring of the images, the level of filtering was adjusted in quantity and direction to obtain the most visually pleasing balance.

Figure 4a – Comparison of Measured and Predicted Chroma projected in the CIE-a*b* plane.

Figure 4b – Comparison of Measured and Predicted Chroma projected in the CIEL*C* plane.

4. Theoretical Analysis
In order to better understand the contribution of the individual components to the final performance of the display, a model of the color EPD was created.

The reflectance spectrum of every gray state of the underlying ink was combined with the transmission spectra of each of the subpixels to predict the color gamut of the system (see Figure 3). The predicted gamut was more saturated and brighter than the measured display (see Figure 4a and 4b). The sources of the losses are under investigation, particularly the interactions between the ITO, the CFA and the ink layer.

5. Prototype construction
Color displays were assembled using pilot coating, lamination and alignment processes. The electrophoretic ink was coated directly on the CFA. This structure was carefully laminated to the active matrix backplane. The edges of the panels were then sealed. The final EPD module was connected to the driving electronics and mounted in a case identical to their black and white counterpart. The final prototype runs on rechargeable lithium polymer batteries incorporated in the casing.

5.1 Alignment
The integration of the display involved precise alignment of the CFA and the TFT in both the horizontal and vertical axis. Measurements from 30 samples showed that a +/-4.0 microns precision in the alignment provides acceptable color channel separation (see Figure 5).

Figure 5 – Alignment data of the CFA to the backplane in horizontal axis (Vertical = o, Horizontal = x)

5.2 Color Performance
With further development and optimization of the components of the color EPD, we expect to reach white state lightness in the range of 60 L*.

A bright white state is important to preserve the paper-like characteristics of the display, and the dark state is crucial for allowing the best color gamut. The saturation of a primary color depends on the ability to prevent other primaries from mixing with it. Therefore, future improvements of the white state should be conducted in parallel with improvements of the dark state.

5.3 NTSC Standard
The NTSC standard is often quoted in literature as a measure of color reproduction capability of emissive displays. This is not suitable for reflective paper-like displays. For example, the color reproduction capability of high-quality newsprint like that of the New York Times represents about 16% of the NTSC standard.

We are currently reproducing a quarter of a high quality newsprint gamut and believe we can reach half through component optimization.

5.4 Conclusion
Based on quantitative and qualitative evaluation, significant improvement has been achieved over the previous prototype by increasing the sub-pixel bit depth from one to four, changing the CFA design, improving color mapping techniques, and improving underlying electronic ink characteristics. The result is a capable color EPD that maintains the advantages of standard EPD like low power and paper-like appearance.
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7. References
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