Directly Patterned 2645 PPI Full Color OLED Microdisplay for Head Mounted Wearables

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Abstract

The world's first directly patterned full-color OLED microdisplay with > 2600 ppi will be presented. This display is built on a 1920x1200-pixel CMOS backplane and uses RGB emitters, eliminating the need for color filters. This technology results in very-high-luminance microdisplays, ideally suited for wearable AR and VR applications.

Author Keywords

OLED; AMOLED; microdisplay; augmented reality; virtual reality; high resolution; head-mounted display

1. Introduction

As consumer, industrial and military markets move towards augmented reality (AR) and virtual reality (VR) applications, there is a pressing need for a full color, high brightness, high contrast and low power microdisplay suitable for wearable head mounted display (HMD) applications. In augmented reality, where the image is projected against the real world environment, high brightness (>2,000 cd/m^2) is necessary to render data or images that can be viewed even in ambient lighting or when used with inefficient lenses or waveguides. It is also important to have a high contrast ratio so that the projected display area does not glow and become washed out relative to the surroundings. Finally, low power and a compact form factor are necessary for head mounted displays where weight, appearance, user comfort and battery lifetime are critical factors for real world applications and user adoption.

Active matrix organic light emitting diode (AMOLED) microdisplays have many of the key characteristics necessary for these HMD applications. They are usually small (< 1" diagonal) and lightweight (< 3 grams) with low power consumption and contrast ratios of more than 10,000:1 [1,2]. Monochrome AMOLED microdisplays can achieve extremely high brightness (up to about 23,000 cd/m^2 for monochrome green[3,4]); however, high brightness full color displays have presented a challenge. Conventional AMOLED microdisplays are fabricated using a monowhite OLED deposited across the display area with a color filter array either photolithographically patterned on top of the thin film seal layer or on a separate glass substrate which is aligned to the OLED substrate. The monowhite OLED emits through the color filter array to achieve red, green and blue (RGB) colors (Figure 1a). Such an approach can generate high quality displays at luminances that are well suited for direct view VR applications but the color filter array absorbs up to 80% of the generated light, reducing the power efficiency and limiting the maximum brightness of the display to several hundred candelas per meter square - too low for AR applications (though recent innovations have begun to drive this limit upwards [5,6]).

The use of color filters in AMOLED microdisplays is necessitated by the high pixel density required for near eye applications. While TVs and cell phones can afford pixel densities of <500 ppi, AMOLED microdisplays frequently have pixel densities of >2500 ppi. Large displays with low pixel densities can have individual side-by-side RGB subpixels directly patterned using fine metal masks to define the pixel area; however, the small size of the subpixel in AMOLED microdisplays (often ~3 µm) precludes the use of fine metal masks, leaving manufacturers with few alternatives to a white OLED with color filters. There have been previous efforts to directly pattern full color subpixels to the scale compatible with AMOLED microdisplay resolution; however, to date these have all been limited to 10-20 micron size subpixels in passive drive OLED [7-9] or very long single color 5 micron (or larger) thick stripes [10-14].

Here we report on recent work at eMagin to overcome this challenge and, without the use of fine metal masks, directly pattern RGB subpixels as small as 3.2 micron x 9.6 microns with a 9.6 micron pixel pitch for an overall display resolution of 2645 ppi (Figure 1b). To the best of our knowledge, this report is the first demonstration of a full color (RGB) directly patterned AMOLED microdisplay. By eliminating the need for a color filter array and enabling the use of efficient phosphorescent materials, this work makes critical progress towards high brightness AMOLED displays ideal for HMD applications.

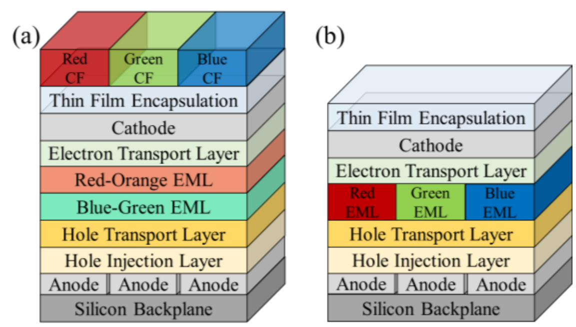

Figure 1. Structure of (a) conventional white OLED with color filter (CF) array in comparison with (b) directly patterned OLED with red, green and blue emitter layers (EML) eliminating the need for color filters.

2. Method

Top emitting organic light emitting diode (OLED) devices were fabricated on a WUXGA resolution (1920 x 1200) CMOS backplane (0.18 micron) featuring a 9.6 micron pixel pitch (2645 ppi) discussed previously [15-16]. Each 9.6 micron pixel is comprised of three 3.2 micron x 9.6 micron subpixels and is patterned with a highly reflective anode of 2.45 micron x 8.85 micron subpixels with 0.75 micron gap between subpixels (70.5% fill factor). In the direct patterned (DP) approach introduced here, common hole injection layers and hole transport layers are deposited through an open metal shadow mask across the entire array (though in principle these material could be directly patterned as well). On top of these layers, red, green or blue emitter layers are directly patterned individually for each color.

For this work, a fluorescent blue emitter is used along with phosphorescent red and green from Universal Display Corporation.

Following these emitter layers, the electron transport layers and cathode layers are again deposited across the entire array through an open metal shadow mask and eMagin's thin film encapsulation is applied. As the AMOLED now directly emits red, green and blue, the color filter array is no longer required, simplifying the manufacturing process; however, all other post-OLED processes are comparable to conventional AMOLED microdisplays. Packaged AMOLED microdisplays were tested both in an active drive mode as well as in a passive two point mode in which the silicon backplane is bypassed. Emission characteristics (luminance, color coordinates and spectra) were measured by a Minolta CS-100A and by a Photo Research PR680 spectroradiometer/spectrophotometer. Microscope images of the display were taken using a Carl Zeiss microscope as well as with a Tucsen camera.

This approach was tested in several phases to be discussed in this paper. First, monochrome green displays were made for a direct comparison of a conventional AMOLED in which the emitter layer is deposited across the entire array versus a directly patterned AMOLED in which the green emitter is patterned on each of the three subpixels separately. Secondly, dual color red-green displays were fabricated with one pixel receiving a phosphorescent green emitter and the remaining two pixels receiving phosphorescent red emitter. Finally, full color RGB AMOLED microdisplays were fabricated and the performance compared to conventional eMagin WUXGA AMOLEDs with a monowhite emissive layer and color filters.

3. Results

Monochrome Green

Phosphorescent monochrome green displays were fabricated using both a conventional open metal mask as well as by using eMagin's DP technique to pattern the monochrome green emitter on all pixels. As can be seen in Figure 2, the alignment and coverage of the monochrome green emitter is very good. This allowed for a direct comparison between the performance of a standard production WUXGA monogreen display and the DP WUXGA monogreen display. In both the actively driven and the passive two-point modes, the DP device and the conventional device perform comparably. Figure 3 shows emission spectra and J-L characteristics for both devices. There is little deviation in performance; at 20 mA/cm^2 both devices achieve a luminance of 5,000 cd/m^2, matching the performance of eMagin's monogreen XLT OLED microdisplay. This result indicates that there appears to be no performance degradation due to eMagin's technique of directly patterning organic materials.

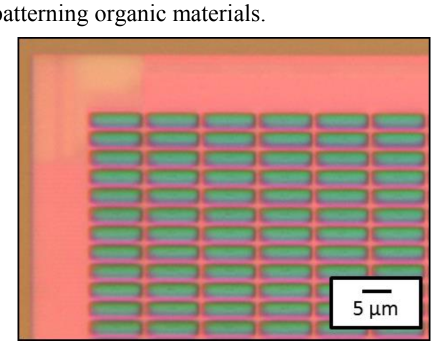

Figure 2. DP green emitter on WUXGA pixel array.

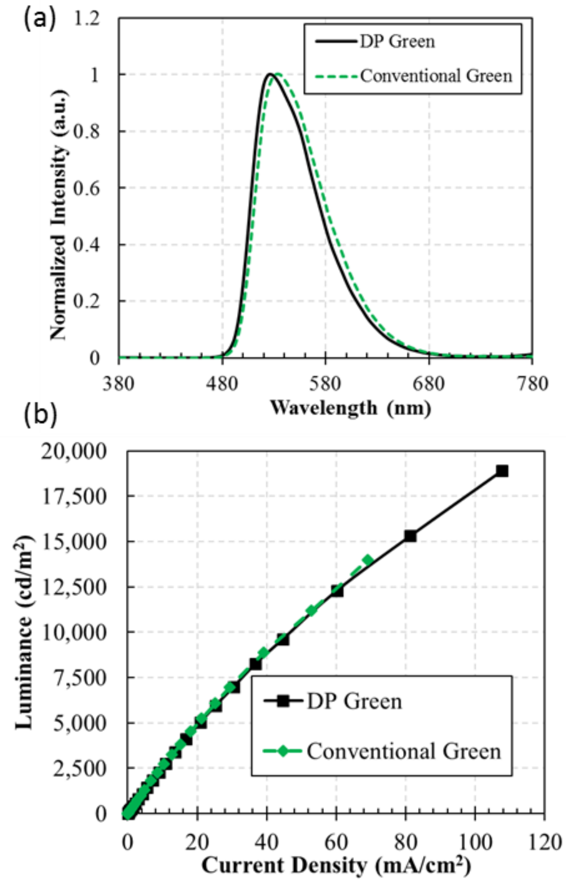

Figure 3. (a) Emission spectrum and (b) J-L characteristics of DP and conventional monogreen AMOLED

Dual Color (Red-Green)

Red-green dual color displays were fabricated using separate phosphorescent red and green emitters on a WUXGA CMOS backplane. As the green emitter is stronger than the red emitter, two red pixels were deposited for every green pixel. For this initial demonstration, the subpixel anode area was reduced slightly to 1.95 µm x 7.8 µm though future efforts will return to full area pixels. As with the monochrome green device, only the emissive layers were directly patterned on the subpixels, all other layers used an open metal mask to deposit the material across the device's active area. The spectrum for the two red channels, the green channel as well as the all pixels on spectrum is shown in Figure 4a. Both red and green channels give distinct peaks and when an actively driven display is inspected under high magnification, emission from each individual channel can be directly observed (Figure 4b). With all pixels on, this device can generate up to 4500 cd/m^2 with a CIEx of 0.457 and CIEy of 0.507. The individual green channel has coordinates of (0.306, 0.643) and the two red channels have coordinates of (0.611, 0.373).

Full Color (RGB)

Finally, full color (RGB) directly patterned OLED microdisplays were fabricated. In an initial demonstration, VGA resolution microdisplays with a 28.8 micron pixel pitch (882 ppi) were fabricated as shown in Figure 5a. Following this demonstration, full color (RGB) directly patterned OLED microdisplays were fabricated on a standard WUXGA CMOS backplanes (2645 ppi)

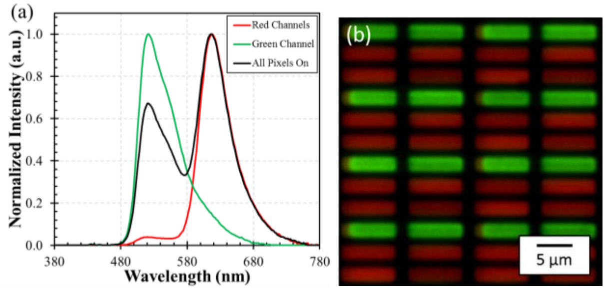

Figure 4.(a) Emission spectra for dual color display. (b) Optical microscope (63X) image of emission with all pixels on from directly patterned dual color display.

and, as before, the only modification to the standard device structure was to directly pattern individual channels of red, green and blue organic emitters. As in the dual color displays, the anode size was slightly reduced for these initial demonstrations; however, the fill factor remains 50%, remarkably high given the small feature size of 3.2 micron x 9.6 micron for each subpixel.

Figure 6 shows an optical microscope image of a directly patterned RGB microdisplay while being actively driven and all three colors can be observed distinctly. Figure 7 shows the individual red, green and blue channels spectra (Figure 7a) as well as the all pixels on spectrum (Figure 7b) . As can be seen, all three colors are present in a single OLED microdisplay free of color filters. With 100% pixels on in passive two-point mode (Figure 7c,d), the device reaches >2000 cd/m^2 with white coordinates of (0.32, 0.43). Work is on-going to further increase the luminance and optimize the color balance of the display which is currently green-rich as green is the most efficient of the three emitters. As is typical of AMOLED displays [17], luminance increases as the field size is shrunk and fewer pixels are on (as would frequently be the case). In Figure 8, the luminance with 10% of pixels on is enhanced by ~40% relative to all pixels on.

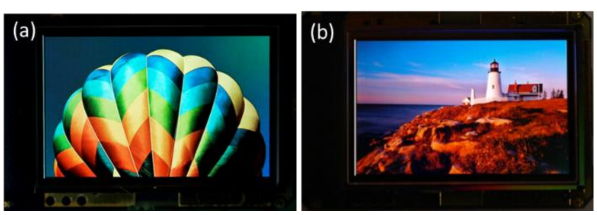

Figure 5. Optical image of actively driven (a) VGA and (b) WUXGA resolution DP full color AMOLED microdisplay.

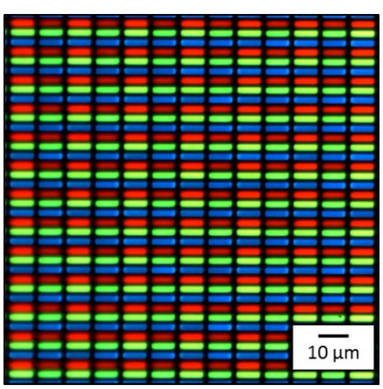

Figure 6. Optical microscope (40X) images of an actively driven, full color direct patterned AMOLED microdisplay.

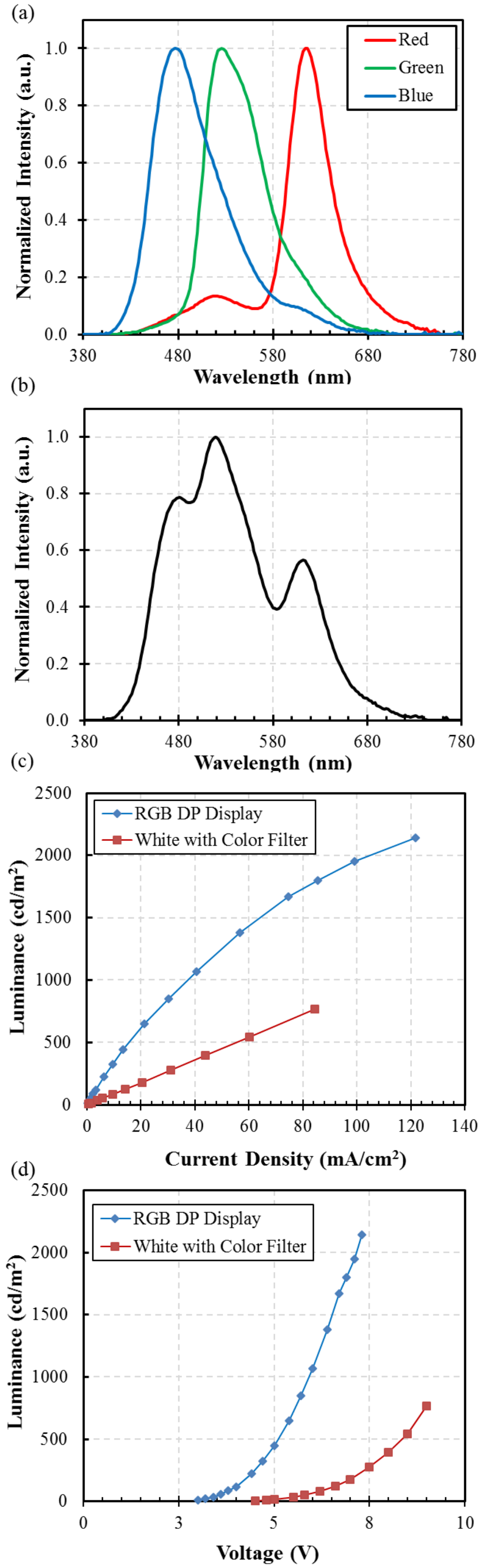

Figure 7. (a) Red, green, blue and (b) all pixels on spectra of an actively driven DP RGB AMOLED microdisplay. (c) J-L and (d) V-L comparison of DP RGB and conventional white with color filter AMOLED.

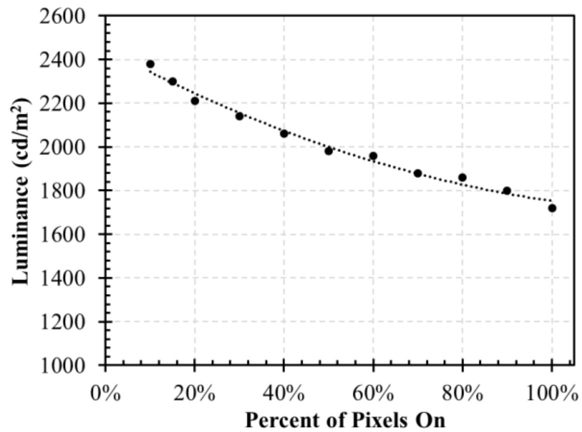

Figure 8. Luminance as a function of percentage of pixels on in an actively driven full color DP microdisplay.

Figure 7c and 7d also compares the directly patterned display to eMagin's standard WUXGA OLED microdisplay using the white with color filter approach. As can be seen, the directly patterned display already is achieving 2-3 times the luminance at a given current of a conventional OLED microdisplay and up to 10X more luminance at a given voltage. With continuing improvements and optimization, it is expected that directly patterned displays will achieve luminances in excess of 5,000 cd/m^2 at reduced current densities.

4. Conclusions

To the best of our knowledge, this is the first ever demonstration of directly patterned RGB emitters in an AMOLED microdisplay with >2600 ppi and WUXGA resolution (subpixel dimensions of 3.2 micron x 9.6 micron). Monochrome and dual color displays were also fabricated using this technique. By eliminating the need for color filters and enabling the use of more efficient phosphorescent emitters, peak luminances of 4,500 cd/m^2 have been achieved in dual color (red-green) displays and luminances of >2,000 cd/m^2 in full color with ongoing work to further improve these luminances and the device power efficiency. This technology represents an important step towards the high brightness displays required for augmented and virtual reality applications.

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