Color-Tunable Single Pixels Using Stacked Transparent Organic Light Emitting Diodes and Color-Tunable Lighting Domes

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Abstract

Different from liquid crystal devices (LCDs), organic light emitting diodes (OLEDs) are self-emitters. This allows to fabricate light-weight, large-area, mechanically flexible thin film OLEDs using plastic substrates. These devices are widely used in various display applications, such as mobile phones, television devices, and wearable devices. Furthermore, OLED-based light sources can be made mechanically flexible and transparent, offering new opportunities for architecture, visual arts, and decoration.

(i) <u>Color pixels using stacked TOLEDs</u>

In general, full-color pixels are configured from R, G, and B components and stripe, delta, Beyer-type, and PenTile, to name a few. However, employing stacked RGB transparent OLEDs would allow to fabricate color-tunable single pixels without Moiré patterns. Here, we propose a method for generating color-tunable single pixels using stacked transparent OLEDs. This opens new possibilities for color applications in displays and lighting fixtures.

(ii) <u>Spectral shape color lighting dome using LEDs and OLEDs</u>

Lighting domes (A and B) were constructed using inorganic LEDs and organic LEDs. The shape of the constructed lighting domes was "pentakis dodecahedron". The structures looked like spherical frames (bones).

We fabricated a 43-cm-diameter lighting dome (A) that consisted of red, green, and blue light-emitting diodes (RGB LEDs). We also constructed a large-size (2.8-m -diameter) lighting dome (B) that consisted of white inorganic LEDs and an organic LEDs.

Using such a "pentakis dodecahedron", it is possible to determine and simulate incidence and reflection of different chromatic components. Furthermore, it is also possible to measure the angle dependence of chromatic light by attaching a camera to the dome.

Keywords-color tuning; stacked; smart window; TOLED; transparent OLED

I. Introduction

A. *Color Pixels Using Stacked TOLEDs*

OLEDs are made of extremely thin films and are characterized by self-emission of light and very weak dependence on the angle of viewing [1]. Owing to these technically advantageous characteristics, large TV sets (screen size, 55" and 65") have become commercially available. Further, replacement of LCD smartphone screens by OLED screens is underway.

Some additional advantages of OLEDs include their short response time, conductance (~µS), and high contrast ratio (~1,000,000:1). These advantages are instrumental in designing state-of-the-art virtual reality headsets.

Further development of OLEDs is expected with the construction of thin, light, foldable wearable information terminals based on the contemporary concepts of ubiquity and/or ambience.

Transparent electrodes enable to fabricate attractive and unique devices that are transparent when no light is emitted and emit light from both sides on demand [2].

By utilizing these features, vertical-stack-type full color displays can be fabricated, in which red, green, and blue (RGB) devices will be stacked in the vertical direction [Fig. 1(b)]. In this design, a pixel will not be composed of horizontally deployed sub-pixels such as stripe, delta, and Beyer-type subpixels; rather, OLEDs will be controlled individually.

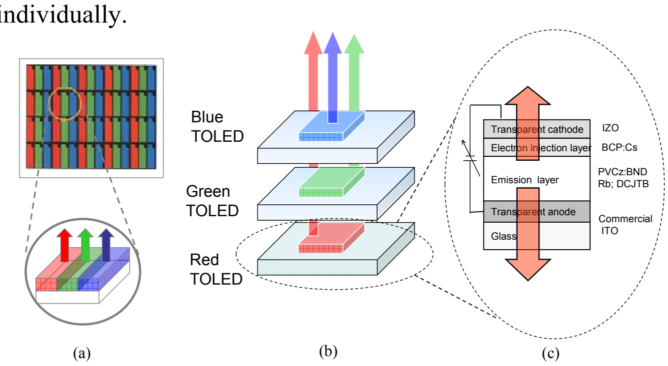

Fig. 1 Arrangement of RGB subpixels in a color display: (a) Conventional color display, (b) vertical stack type color display, (c) cross-sectional diagram of a red TOLED.

Therefore, this approach may allow to fabricate novel displays with high resolution and different color-reproduction characteristics that are not supported by existing conventional displays. Several stack types of OLEDs have already been proposed, such as a color display with a stack of RGB elements [3, 4], high-efficiency multi-photon emission devices [5] with a stack of several light-emission layers, and a tandem-type device [6]. However, it is difficult to implement such devices using polymers, because wet-processing may act to dissolve polymer layers in a multi-layer system. Here, we report color-tunable single pixels using stacked TOLEDs [7].

B. Spectral Shape Color Lighting Domes Using LEDs and OLEDs

Recent advances in nanotechnology made it possible to study chromatic effects of illumination and the effects of the angle of illumination.

Further, because the color and the direction of illuminating light usually vary with time for moving objects (including humans), recording and utilizing these parameters may allow the reproduction of images/persons using lighting domes and chroma keying techniques.

In this study, we constructed a small lighting dome (A) with (inorganic) RGB LEDs, and a large lighting dome (B) with (inorganic) white LEDs and organic LEDs. The lighting domes had the shape of "pentakis dodecahedron". These structures were assembled in the form of a frame (bone), and looked like spheres, as shown in Fig. 2.

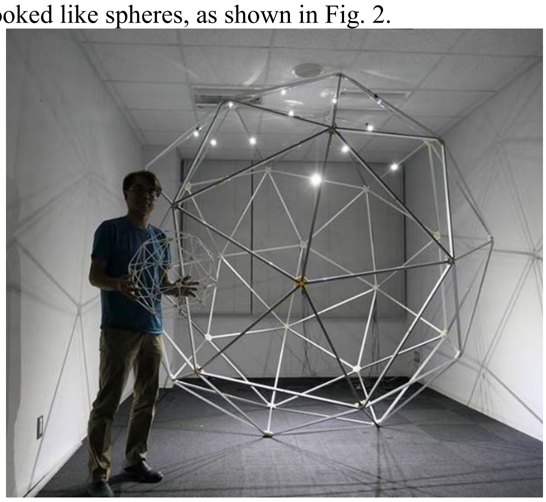

Fig. 2 The assembled lighting domes (A) and (B) (pentakis dodecahedrons).

Using these domes, we evaluated spectral differences associated with using various light sources.

II. Fabrication and Evaluation of Devices

A. Color Pixels Using Stacked TOLEDs

TOLEDs were fabricated using dye-dispersed poly(N-vinylcarbazole) (PVCz), following which the fabricated TOLEDs were stacked. Then, we characterized the fabricated TOLEDs in terms of their color display, including white illumination. Cross-sectional diagrammatic views of different TOLEDs (RGB) are shown in Fig. 1(b). The layer structure is described in Table I. All TOLEDs were fabricated using the same materials (for electrodes and electron injection layers (EILs)) except the material for the light emissive layer (EML). Devices were fabricated on indium tin oxide (ITO)-coated substrates of 100 /sq. Two-millimeter-wide stripes of the anode and cathode were formed perpendicular to each other to create a 4 mm^2 emission area, but in the images shown in Figs. 6 and 7, the light-emissive area, and the anodes and cathodes (diameter, 5 mm) were formed in particular for measuring color coordinates. The materials and the fabrication method of TOLEDs were described in detail previously [7].

TABLE I.
DEVICE STRUCTURES OF RGB TOLEDS

Color	***EML*** (Emission layer)
Red	PVCz:BND:Rb:DCJTB
Green	PVCz:BND:C6
Blue	PVCz:BND:perylene

Structure: Glass/ITO/***EML***/BCP:Cs/IZO

Emission spectrum was analyzed using a photonic multichannel spectral analyzer (Hamamatsu Photonics, PMA-11). The luminance–voltage (L–V) characteristic and the Commission Internationale de l'Eclairage (CIE) color coordinates and emission spectrum were measured using an organic EL luminous efficiency measuring instrument (Precise Gauges, EL-1003 with a Keithley 2400 voltage source).

B. Spectral Shape Color Lighting Domes Using LEDs and OLEDs

The small (A) and large (B) lighting domes consisted of 90 pieces (60 short rods and 30 long rods) and joint parts. The joint parts were of two types: pentagons (12 units) and hexagons (20 units), and were fabricated using a 3D printer (ZORTRAX, M200) with a Z-ULTRAT filament. Inorganic RGB LEDs were attached to the small dome (A). The RGB LED (World semi, WS2812B) is an intelligent control LED light source that features a control circuit and an RGB chip in a small package (8 mm × 11 mm). Each pixel of the three primary colors (RGB) had 256 brightness levels, the full color emission had $(256)^3$ levels.

Inorganic white LEDs were attached to the large dome (B). The white LED (OptoSupply, OSW4XNE3C1S) is a high-power (3 W) light source with a heat sink. Each white LED was controlled by an MR16 LED driver (OptoSupply, OSMR16-W1213), (3 W driver). These LEDs can be controlled by a small micro-computer (Arduino Uno) via the Adafruit 16-channel PWM/Servo Shield.

The large dome (B) also featured two types of OLED lighting panels. One was an OLED1 lighting panel (Lumiotec, P03B0909N-A12A), while the other one was an OLED2 lighting panel sample kit (Konica Minolta, Symfos OLED-010K). These OLED lighting panels were controlled by a dedicated external driver.

III. Results

A. Color Pixels Using Stacked TOLEDs

The optical transmittance curves of the different devices are shown in Fig. 3. The transmission coefficients of the red, green and blue TOLEDs were 78.6%, 77.3%, and 78.0%, respectively, and the transmitted light was within the visible range (380 – 780 nm). When these three devices were stacked to make a full color pixel, the overall transmission coefficient dropped to 49.1%, which was approximately equivalent to the product of the transmission coefficients of the three devices (47.7%).

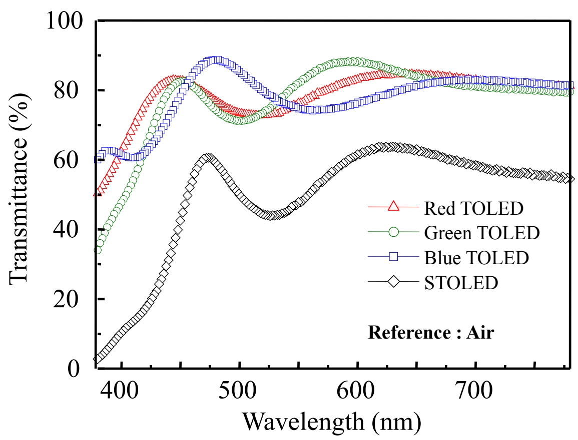

Fig. 3 Transmittance curves of R, G, and B devices, and of a full-stacked TOLED.

The spectra of the RGB TOLED devices (components and full-stacked) are shown in Fig. 4. The wavelengths at the peaks of light emission were 612, 496, and 456 nm, respectively. The spectrum that was obtained when all of the component RGB OLEDs were turned on is shown by closed black diamonds. The spectrum covered the entire visible range. The CIE chromaticities of the individual RGB TOLEDs are shown in Fig. 5. The coordinates were (0:60; 0:39) for R, (0:25; 0:53) for G, and (0:15; 0:17) for B. The white light coordinate was (0:31; 0:33). An average color rendering index (Ra) of 87.8 was achieved.

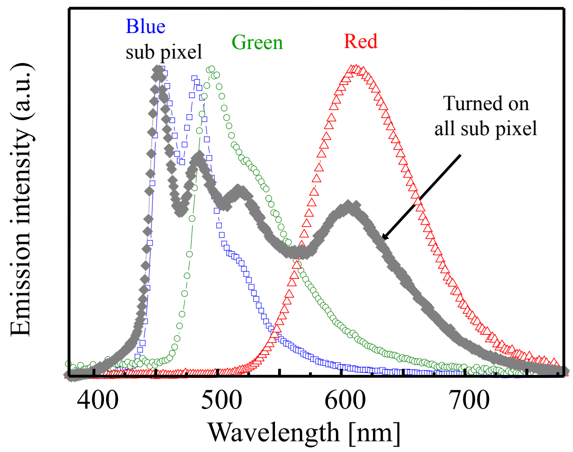

Fig. 4 Light spectra for RGB TOLED devices (components and full-stacked).

In Fig. 6, the photographs of a stack-type transparent OLED (STOLED) show that R, G, B, cyan, magenta, yellow and white colors can be obtained by setting different components ON and OFF. This demonstrates that full color displays based on stack-type OLEDs can be successfully realized by stacking TOLEDs. In such a color display, letters can be observed in the background owing to the device's transparency.

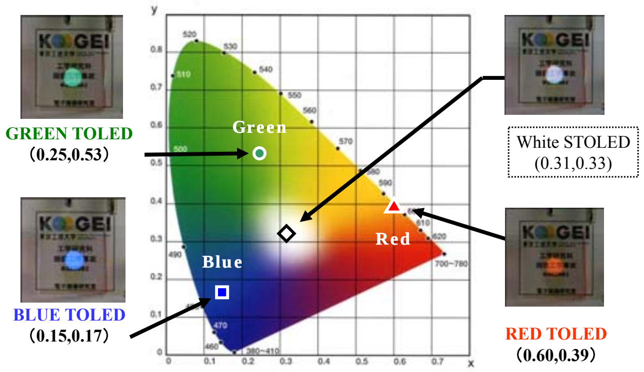

Fig. 5. The light coordinates of red, green, blue, and white basic colors.

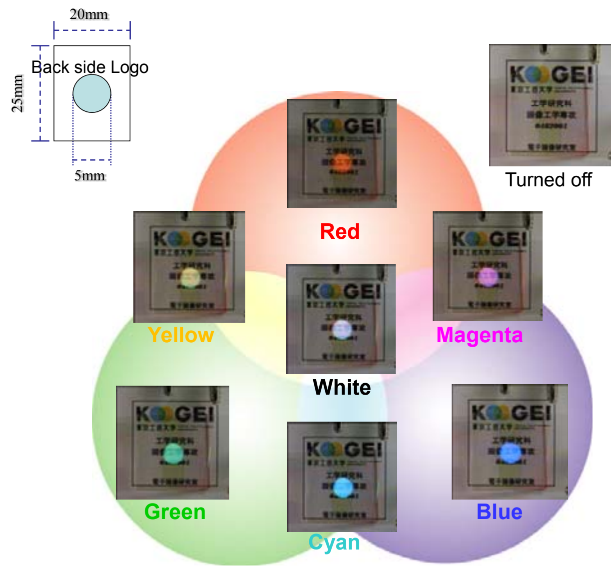

Fig. 6 The photographs of a stack-type transparent OLED (STOLED) show red, green, blue, cyan, magenta, yellow, and white colors.

We fabricated a full-color pixel using a vertical stack of RGB transparent OLEDs; there OLEDs were fabricated separately on individual glass substrates. The proposed approach and the resulting devices are quite unique, which should be advantageous for advanced lighting technologies and imaging displays.

B. *Spectral Shape Color Lighting Domes using LEDs and OLEDs*

Color indication displays have shown great progress with advances in inorganic LEDs and OLEDs. In lighting reproduction systems [8, 9], subjects are surrounded with red, green, and blue light-emitting diodes (RGB LEDs).

A photograph and light spectra for the small dome (A) are shown in Figs. 7(a) and 7(b), respectively.

Fig. 7 (a) The small dome (A) with RGB inorganic LEDs.

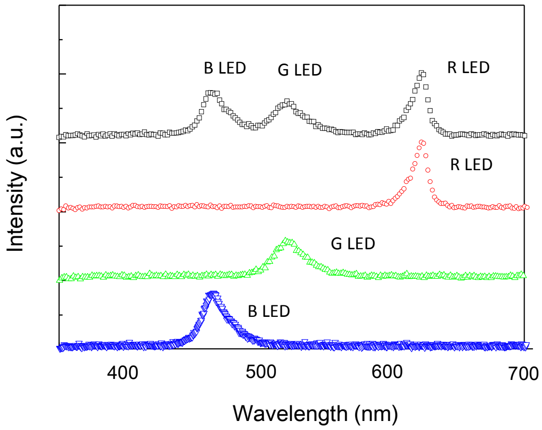

Fig. 7 (b) Light spectra for the small dome (A) with RGB inorganic LEDs.

In the case of RGB LEDs, the spectral peaks are very sharp. The half widths of the peaks were 20 nm (for R), 40 nm (for G), and 30 nm (for B). Therefore, white light yielded two large spectral valleys in the visible region.

The backside figure in Fig. 2 shows the large-size lighting dome (B). This large-size dome featured inorganic white LEDs and two types of OLED lighting panels (OLED1 and OLED2).

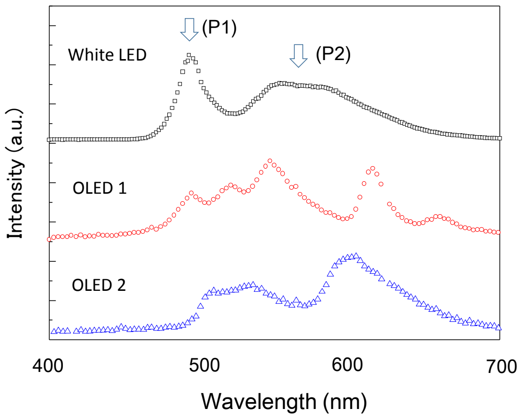

Fig. 8 Light spectra for the small dome (B) with white LEDs and two types of OLED lighting panels (OLED1 and OLED2).

The light spectra for this dome consisted of the sharp component (P1) and the more broadband emitted (P2), as shown in Fig. 8. The white LEDs exhibited blue light directly emitted by the GaN-based or spectrum of a white-light LED, where GaN or InGaN blue source pumps Ce:YAG phosphor. These techniques are widely used because white LEDs can be reasonably manufactured at low cost.

However, the spectrum of the white LED features only two peaks. There is a big spectral valley around the green light region. This valley corresponds to the cool color temperature (CCT) of 6500 K.

The spectrum of OLED1 is shown in Fig. 8. It features a broad peak compared with the LED spectrum, with the average rendering index Ra=81 and CCT of 4900 K. The spectrum of OLED2 is also shown in Fig. 8. It features a broader peak, with Ra=85 and CCT of 4900 K.

Thus, based on this illumination from multiple angles using a high-Ra light source, it is concluded that highly reproducible illumination environments can be constructed.

IV. Conclusions

We obtained a full-color pixel using a vertical stack of RGB transparent OLEDs, each of which was fabricated separately on an individual substrate. This RGB vertically stacked structure requires high stacking technology and wiring technology, but it can be expected to be applied not only to displays but also to lighting devices with high Ra. In addition to the ability to vary the angle of incidence, the approach is effective for designing devices that provide comfortable lighting and ensure good reproducibility of colors.

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