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Review on Luminous Properties of Double-Side-Emitting LED Displays Employing All-in-One Devices

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ABSTRACT

Although single-side-emitting LED displays are widely used in many different applications, they are inherently limited in situations where content needs to be displayed on both sides simultaneously. This work demonstrates a double-side-emitting LED display with all-in-one packed electronics as pixels. Time-division multiplexing (TDM) driving configurations can enhance the red-light output of double-side-emitting LED displays while reducing temperature and increasing color gamut by reducing the temperature. Double-side-emitting LED displays achieved a temperature reduction of 6.2 K and increased brightness by 173.5 cd/m^2.

KEYWORDS: *LED Display, Chromaticity, grayscale, all-in-one LED.*

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I. INTRODUCTION

LED screens have completely altered the way in which we perceive the world around us. The applications of LED Displays include signage sports installations, transportation, events, corporate and conference applications malls, healthcare and education and learning centres. This is owing to excellent efficiency, brightness, and a long lifespan [2],[3],[4],[5],[6] of LED displays. Traditional LED displays have a single-sided emissive construction, making them unsuitable for new applications that require content to be displayed on both sides at the same time. Synchronizing real-time timetables, announcements, or commercials on both sides of a transit hub, or providing various content to audiences on opposite sides of conference stages, etc are examples. Double-side emitting displays provide space-efficient solutions with good brightness uniformity, making them ideal for applications that prioritize compactness and multi-user engagement.

Nevertheless, compared to single-side displays, double-side-emitting displays have not been thoroughly studied despite their potential, and thermal management is still a major obstacle. As a result, double-side-emitting LED display technology merits further investigation. Fortunately, double-side-emitting LED displays are now easier to accomplish thanks to the advent of all-in-one packaged LED devices [7], [8], packaging red, green, and blue (RGB) trichromatic LEDs and Micro-ICs within a single elementary unit.

This work demonstrates double-side-emitting LED displays and proposes time-division multiplexing (TDM) driving configurations to optimize chromatic properties and reduce self-heating effects. Grayscale and temperature affect chromaticity coordinates and color gamut. Full-color LED displays typically use field-programmable gate array (FPGA) technology, which has various advantages [9], [10], [11], and [12]. Its robust hardware parallel processing allows for efficient graphic rendering on large-area tiled LED screens. FPGA's hardware programmability allows for extensive options for customization. All-in-one packed LED devices make it easier to drive FPGAs by transmitting data to Micro-ICs via the FPGA's serial port [8]. Changing the chromaticity coordinates of a single color in a full-color LED display can drastically impact the whole color gamut [6], [13], [14]. LED displays' emitting wavelengths shift with grayscale and ambient temperature [8]. Additionally, increased duty cycle of pulse-width modulation (PWM) can cause redshift and broadening of the electroluminescence spectra due to self-heating [15],resulting in color gamut changes. Double-sided emitting displays exhibit a stronger thermal effect due to the increased heat produced by the second set of emitters. To improve the design of double-side-emitting LED displays, it is important to study their chromatic characteristics under various working conditions. The double-side-emitting LED displays and proposed time-division multiplexing (TDM) driving setups are used to optimize chromatic properties and reduce self-heating. The effects of grayscale and temperature on chromaticity coordinates and color gamut have been determined[1].

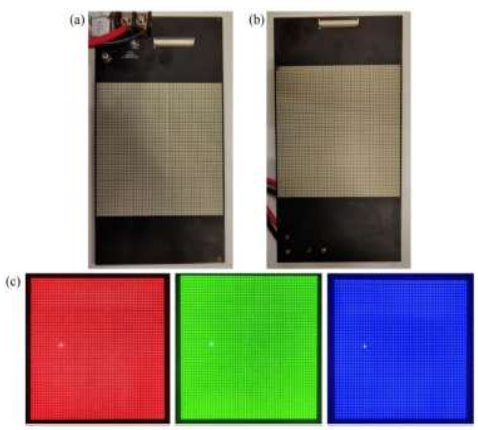

Fig 1. Optical photographs of (a) front and (b) back of the double-side emitting LED displays. (c) Optical photographs of displaying three primary colors[1].

II. EXPERIMENT

The all-in-one LED devices function as display pixels. The utilized all-in-one packaged LED devices have the same structure and driving mechanism as disclosed in prior research [7]. The LED devices were soldered to the front and back sides of a printed circuit board, resulting in double-sided LED displays. The single-side and double-side emission modes were evaluated on the same sample using the identical TDM. Reconfiguring the FPGA-generated pulse sequences allows for selective activation of single or double-side modes. This software-defined technique allows for mode change without requiring physical device modifications. All optical measurements are conducted on the same integrated pixel structure under consistent operating conditions. The devices consist of vertically-structured red LEDs (Aluminium gallium indium phosphide), laterally-structured green LEDs, blue LEDs (Indium gallium nitride), and a Micro-IC. The dimensions are 1.5 mm by 1.5 mm. Spectra were acquired using a spectrometer (QE65 Pro, Ocean Optics). The DT1310 single probe thermometer was used to measure the temperature. A multi-field luminance meter (LM-3, Everfine) was used to measure the luminance.

A. DISPLAY MODULE FABRICATION

The FPGA generated serial logic sequence signals using a return-to-zero code, identical to earlier literature [8]. The LED devices in each row of pixels were connected sequentially via data input pin (DIN) and output pin (DO). Figures 1(a) and (b) show a black printed circuit board (PCB) used to solder the all-in-one LED devices on the front and back surfaces. Signal transmission lines are arranged on both top and bottom Cu layers, with intermediate layers including VCC and GND. To simplify power circuits vias are used to establish connections to the power layer. The front and rear locations of all-in-one LED devices are mirrored. The spacing between adjacent all-in-one packed LED devices is 0.3 mm, resulting in two square display arrays of 60 × 60 pixels on the front and back sides, respectively. To make connecting and installing connectors easier, signal terminals from the FPGA to the PCB are placed along the edges of the LED arrays[1].

B. FPGA DRIVING

Driving data was sequentially transmitted to pixels in the same row in double-side-emitting LED displays. TDM can drive double-side-emitting LED displays by separating frames into several slots. The rows in the display can be separated into subgroups[1]. In each slot, only one subgroup would be powered. This work covers four types of TDM configurations: There are four modes: (i) Mode A, which powers all rows in each slot; (ii) Mode B, which powers 30 rows in each slot; (iii) Mode C, which powers 15 rows in each slot; and (iv) Mode D, which powers two rows of pixels in each slot[1].

III. RESULT AND DISCUSSION

In Fig. 2, the surface temperatures of displays generating red color increase as the grayscale increases due to self-heating [15]. Fig. 2 shows that under the identical TDM settings, the double-side operation produces higher temperatures than the single-side operation [1]. Using Mode A with a grayscale of 48, the temperature of the double-side operation is 335 K, while the single-side operation is 330 K. Using TDM to reduce temperature is necessary for double-side-emitting LED displays, as they consume more power during operation [1].

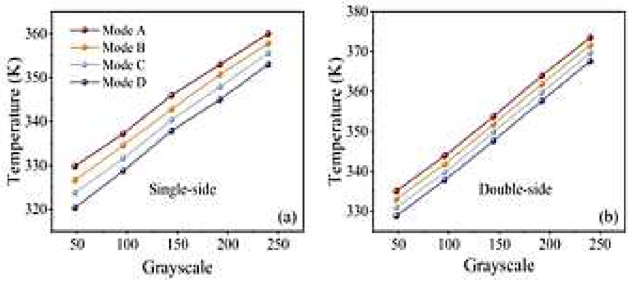

Fig. 2. The temperature measured during emitting red color for different TDM configurations, (a) single-side operation, (b) double-side operation[1]

As the number of rows of pixels powered simultaneously grows, so does the display temperature. Display surface temperatures are highest with Mode A and lowest with Mode D in an equivalent grayscale operation, indicating that TDM reduces display temperature. When grayscale is set to 48, the temperature difference between Modes A and D is 9.5 K for single-side operation and 6.2 K for double-side operation[1]

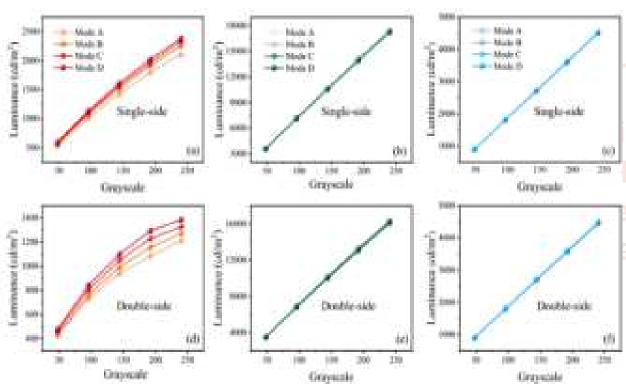

Fig 3.The luminance under different TDM,(a)–(c) single-side operation, (d)–(f) double-side operation.[1]

Figure 3 ,displays the brightness of red, green, and blue emissions measured under different TDM setups. The TDM mode has no effect on the brightness of the displays' green and blue emissions. The luminance of red emission in displays varies with TDM mode due to thermal droop. AlGaInP-based red LEDs have a lower external quantum efficiency than RGB LEDs at higher temperatures [6], [16], [17]. Further research is needed to determine why double-side operation results in lower red emission brightness compared to single-side operation. The luminance of red emission under mode D emits more red light than mode A on the same grayscale.

At grayscale 240, the luminance difference between modes D and A is 276 cd/m^2.for single-side operation and 173.5 cd/m2 for double-side operation. TDM effectively enhances the red emission light output of double-side-emitting LED displays. This improvement is primarily due to lower thermal load in Mode D. Mode D reduces display illumination and operating temperatures by dividing it into 30 subgroups and powering only 2 rows every time slot. Mode A powers all rows simultaneously, leading to greater localized temperatures and increased thermal droop, particularly in temperature-sensitive AlGaInP red LEDs[1].In TDM modes B to D, pixels receive driving data in time slots, resulting in lower power demand and thermal load. Mode D's limited activation per slot minimizes power consumption and temperature rise, preventing thermal droop and maintaining LED efficiency. Simultaneous Mode A activation leads to increased power consumption, higher temperatures, and reduced light output, especially for red LEDs that lose brilliance at higher temperatures[1]

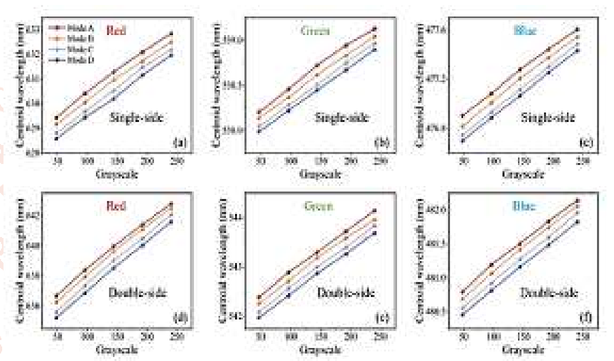

Fig. 4. Centroid wavelength of (a)–(c) single-side operation and (d)–(f) double-side operation[1]

The centroid wavelength and full width at half maximum (FWHM) are commonly used to analyze variations in emission spectra with different grayscales and temperatures. The wavelength at which the emission spectrum peaks is known as the centroid wavelength, and it offers information on the emission's centre frequency. The width of the spectral line at half of its greatest intensity is measured by the FWHM, which shows the resolution and spread of the emission spectrum. Figures 4 and 5 show the trends in centroid wavelength and FWHM of emission spectra under different grayscale and TDM settings.

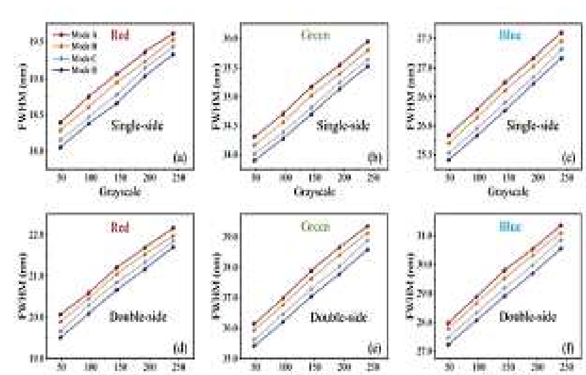

Fig 5. FWHM of (a)–(c) single-side operation and (d)–(f) double-side [1] operation.

Figures 4 and 5 indicate that increasing grayscale causes the centroid wavelengths of spectra to redshift and the FWHM to rise. As the grayscale grows, self-heating causes bandgap shortening and thermal widening, resulting in this phenomena [15].Under the same grayscale, Mode D has a shorter centroid wavelength and FWHM than Mode A due to the lower temperature (see Fig. 2). For red emission in Mode A, the centroid wavelength varies between 629.4-632.8 nm for single-side operation and 636.6-642.7 nm for double-side operation, yielding an overall redshift of 7.2-9.9nm.

Red emission FWHM varies from 18.4 nm to 19.6 nm for single-side operation and 20 to 22.2 nm for double-side operation, with an overall increase of 1.6-2.6 nm. Under the same TDM, the higher temperature in the double-side operation leads to a poorer redshift in centroid wavelength and spectrum broadening.

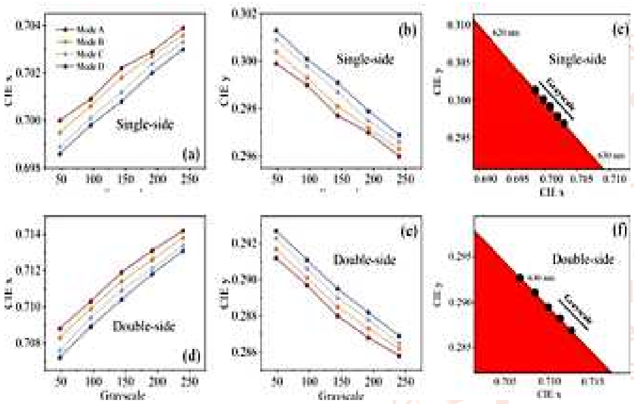

Fig. 6. Chromaticity coordinates (*x*, *y*) of red. (a) CIE *x*, (b) CIE *y*, and(c) chromaticity coordinates of Model D for single-side operation. (d) CIE *x*,(e) CIE *y*, (f) chromaticity coordinates of Model D for double-side operation[1]

Figure 6 shows the chromaticity coordinates (x, y) of the red emission of several grayscale screens based on the spectra. As grayscale increases, CIE x gradually increases and CIE y declines. As a result, the chromaticity coordinates (x, y) move towards the lower right corner of the CIE-1931 chromaticity diagram.

When double-side operation exceeds single-side operation, the chromaticity coordinates (x, y) shift to the lower right corner of the CIE-1931 color space, allowing for a wider color gamut. However, higher temperatures may reduce the efficiency of the double-sided process. Optimizing operating parameters for red emission in displays is crucial for balancing color gamut and efficiency.

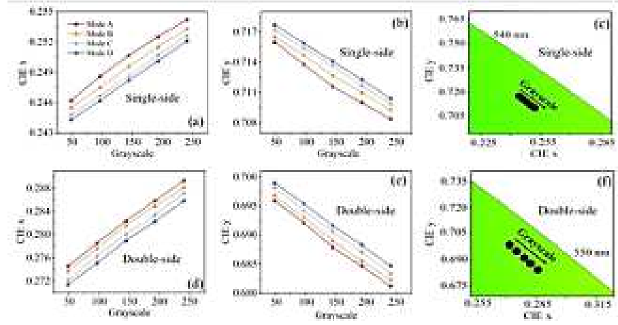

Fig 7. Chromaticity coordinates (*x*, *y*) of green. (a) CIE *x*, (b) CIE *y*, and c) chromaticity coordinates of Model D for single-side operation. (d) CIE *x*,(e) CIE *y*, (f) chromaticity coordinates of Model D for double-side operation.

Fig.7 shows that the green emission's chromaticity coordinates (x, y) follow the same grayscale pattern as the red emission. As grayscale rises, CIE x gradually increases while CIE y drops, shifting the chromaticity coordinates of green light emission spectra to the lower right in the CIE-1931 chromaticity diagram. However, this shift reduces the triangular area created by the chromaticity coordinates of the RGB primary colors, resulting in a smaller color gamut. Mode D reduced the lower-right-direction shift caused by temperature lowering, resulting in a wider color gamut compared to Mode A's chromaticity coordinate in the same grayscale.

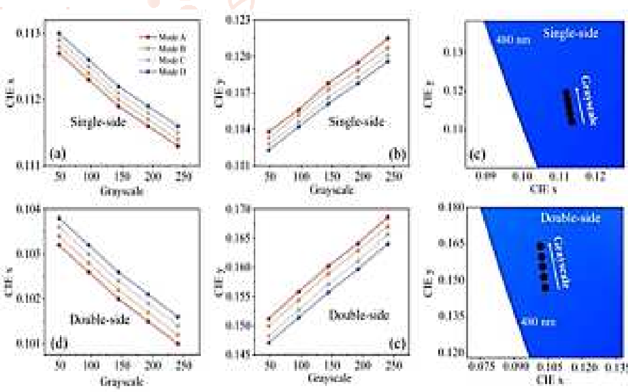

Fig. 8. Chromaticity coordinates (*x*, *y*) of blue. (a) CIE *x*, (b) CIE *y*, and (c) chromaticity coordinates of Model D for single-side operation. (d) CIE *x*,(e) CIE *y*, (f) chromaticity coordinates of Model D for double-side operation

In Fig. 8, as grayscale increases under an identical TDM, the chromaticity coordinates (x, y) of blue emission shift to the upper left in the CIE-1931 chromaticity diagram. This reduces the triangle area formed by the RGB primary colors. When switching from Mode A to Mode D, CIE x increases and CIE y falls, expanding the color spectrum. When the temperature of a double-side operation exceeds that of a single-side operation, the chromaticity coordinates (x, y) of the blue emission shift towards the upper left direction of the CIE-1931 chromaticity diagram, resulting in a reduced color gamut. Reducing temperature using grayscale or Mode D can improve color gamut. Changing the grayscale causes consistent changes in both single- and double-side operations. Double-side operation differs from single-side operation in that it has a higher temperature. This causes the chromaticity coordinates (x, y) of blue and green emissions to move towards the center of the CIE-1931 chromaticity diagram, while red emission moves to the corner. Adopting appropriate TDM configurations can reduce temperatures. To optimize color gamut, further research is necessary. To study the color gamut, three standards were typically used: SMPTE RP431-2:2011 (DCI-P3), ITU-R RecommendationBT.2020 (Rec. 2020), and National Television Systems Committee (NTSC). The color gamut values for various grayscale combinations were computed under the identical TDM configuration. The maximum coverage ratio for the Rec. 2020, DCI-P3, and NTSC standards[6], [21] was calibrated [1]. Rec. 2020's coverage ratios peak at red grayscale 240, green grayscale 48, and blue grayscale 48. When grayscale decreases, the chromaticity coordinates of green and blue emissions move toward the corner of the CIE-1931 chromaticity diagram; when grayscale increases, the chromaticity coordinates of red emissions move toward the same corner[1].

CONCLUSION

Double-sided LED displays have been demonstrated using all-in-one devices as pixels. The temperature and chromatic parameters have also been optimized using the TDM driving approach. TDM configurations can lower temperature and boost light output for double-side-emitting LED displays in the same grayscale. The difference in red emissions between modes D and A is 276 cd/m^2.for single-side operation and 173.5 cd/m^2. for double-side operation at grayscale of 240. Mode D reduces temperature, resulting in higher coverage ratios for Rec. 2020, DCI-P3, and NTSC standards.

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