Crystal LED Display System for Immersive Viewing Experience

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ABSTRACT

We developed a novel active matrix driving technology that integrates RGB micro LEDs and a micro IC in each pixel for our Crystal LED display system. With precise tiling technology, a large-scale image with immersive viewing experience can be delivered.

1 INTRODUCTION

Light emitting diodes (LEDs) have been widely used in general lighting, traffic lights, backlights for liquid crystal displays, and outdoor billboards. LEDs are currently attracting attention as emission devices for display applications that require high energy efficiency, long lifetime, high brightness, high color purity, and short response time. Microscale LEDs (micro LEDs) for emissive display pixels have recently been reported [1, 2].

We have been developing micro LEDs for high-image-quality display applications. The requirements for such applications are not only the micro-sizing of LEDs but also uniformity in electrical/optical characteristics, precise assembly technology for arraying them, driving method, high contrast ratio in a dark/bright environment, and system integration.

In 2012, we demonstrated the 1st prototype of our Crystal LED display at the Consumer Electronics Show (CES) 2012 [3], as shown in Fig. 1. The diagonal size of the display was 55 inches, and about 6 million micro LEDs (1920×1080×RGB) were regularly arrayed on the display panel.

Figure 1. Prototype of Crystal LED display in 2012

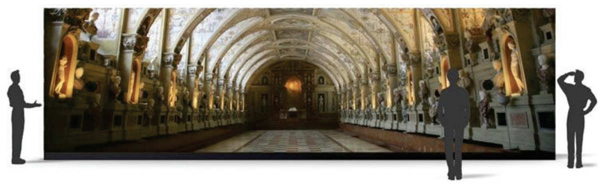


Figure 2. Crystal LED display system commercialized as scalable display system

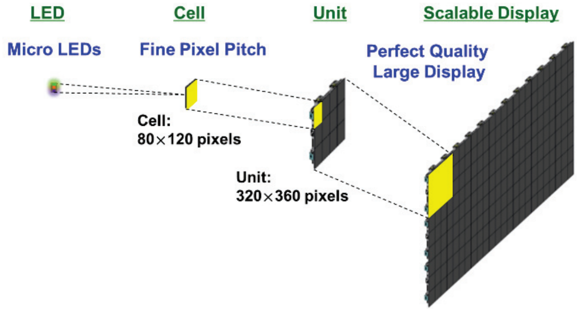


Figure 3. Structure of Crystal LED display system

We then developed this prototype technology further to realize a scalable display system and launched it as the Crystal LED display system. It was the first commercialization of a large-scale display system using micro LEDs. Figures 2 and 3 are an image and schematic of our Crystal LED display system, respectively. Huge images without seams can be produced by highly precise mechanical alignment and accurate uniformity adjustment [4, 5].

We present this technology of integrating micro LEDs, active driving using microscale integrated circuit (micro ICs), and pixel design for high contrast ratio even in a bright environment.

2 Micro LEDs

We developed micro LEDs, the die size of which is around 20 microns. Those LEDs are closely placed, as shown in Fig. 4.

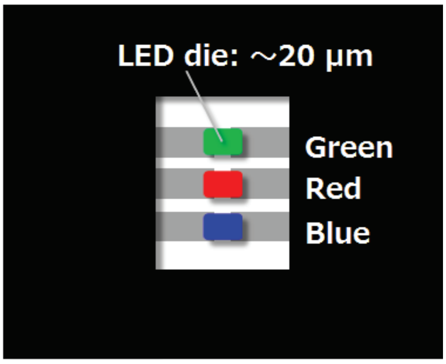


Figure 4. Micro LEDs and their pixel layout

Figure 5. Wide viewing angle by using micro LEDs with Lambertian emission pattern

When the pixel pitch is around 1 mm, the RGB micro LEDs are extremely small compared with the pixel size, and over 99% of the surface can be filled with black. These LEDs have another advantage in that they can be placed close together to avoid color separation.

A wide viewing angle is indispensable for a large-scale display system. Conventional displays with a narrow viewing angle may cause brightness change and/or color shift toward the edge of the display from the viewing position and degrade image quality.

To overcome this issue, we also developed RGB LEDs, the emission patterns of which are very close to Lambertian (cosine shaped curve) patterns. A Lambertian emission pattern is ideal for a large-scale display system because it leads to constant brightness at any angle. Moreover, aligned emission patterns of RGB micro LEDs cause no color shift at an angle, as shown in Fig. 5.

3 Micro IC

Driving a large number of micro LEDs to reproduce high-quality video images is another significant challenge. LEDs generally have a wavelength shift with currents and variations in the current-luminance characteristics. It is therefore difficult to achieve good linearity of luminance and stable chromaticity with conventional current amplitude modulation with conventional thin-film transistors (TFTs) that result in variation in threshold voltage and mobility.

Conventional LED displays use a passive matrix with external ICs. Passive matrix driving of micro LEDs in a large-scale display system causes issues such as excessively high current densities, impedance deviations of different wiring length on a matrix, and cross talk between lines. These issues give rise to limitations such as resolution, luminance, reliability, and motion-picture quality.

To address these issues, we developed a novel active matrix technology with pulse width modulation (PWM) driving. RGB micro LEDs and a micro IC are placed in each pixel and integrated into the active matrix system.

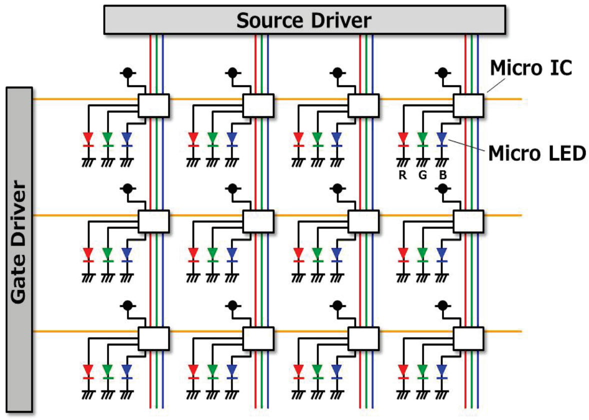


Figure 6. Schematic of active matrix driving using RGB micro LEDs and micro IC in each pixel

A schematic of this active matrix is shown in Fig. 6. The distinctive point of this active matrix is that each micro IC drives the RGB micro LEDs with constant current PWM, as shown in Fig. 7. A micro IC also has a memory function that enables frame sequential driving in this system.

There are many technical advantages for this system. An accurate pulse can be generated for micro LEDs owing to the short wiring length between the IC and micro LEDs in each pixel, which enables us to avoid the issues of impedance deviation and cross talk in a passive matrix. With an active matrix and frame sequential driving, the duty ratio of emission time can also be maximized. Thus, we can maximize the luminance of the panel by maintaining the drive currents of micro LEDs at an appropriate level in terms of efficiency and reliability. With constant current PWM, the emission wavelength of micro LEDs does not shift against the image signals or luminance. This enables precise color management and grayscale control.

Integrating this novel active matrix driving and video processing controls, such as dithering, results in superior linearity from 0.01 to 1,000 cd/m^2 [5].

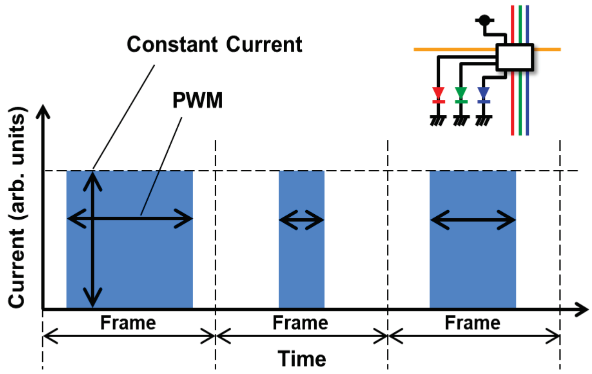


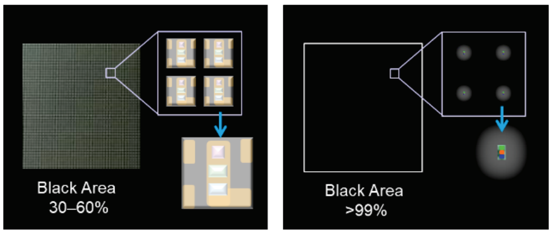
Figure 7. Waveform of constant current PWM of micro LED by micro IC

4 High Ambient Contrast Ratio

LED displays have been used in bright environments by taking advantage of their high luminance characteristics. Applications of LED displays have greatly expanded by narrowing the pitch, and the demands for high-image quality in a bright environment as well as high luminance have been increasing in design simulation, visual entertainment, and installation in corporate lobbies and luxury homes. For example, many companies have installed narrow-pitch LED displays at their headquarter lobbies, which are around 1,000 lx environment. In this section, we discuss the high-contrast ratio in a bright environment, which is difficult to achieve with conventional LED displays.

Images on the LED display surface using typical conventional surface mount devices (SMDs) and micro LEDs are shown in Fig.8. When the pixel pitch is around 1 mm, the black area of a typical SMD panel is 30–60% for the reference, while that of a micro LED panel is over 99%, as mentioned above.

Figure 9 shows photographs of typical conventional SMD and micro LED panels with the same pixel pitch of almost 1.2 mm and luminance of 1,000 cd/m^2 under different environmental light conditions. The micro LED panel displayed higher-dynamic-range images with smooth gradation from low to high luminance, which was maintained irrespective of the environmental light conditions. This feature reproduces the reality of an object and depth perception, which are important factors for delivering an immersive viewing experience in a bright environment.



(a) SMD panel (b) micro LED panel

Figure 8. Images of display surface of (a) typical conventional SMD panel and (b) micro LED panel

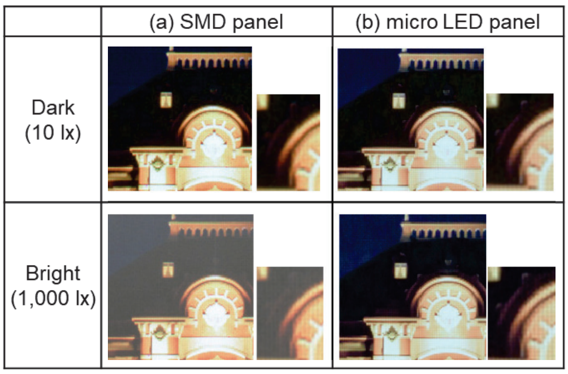


Figure 9. Photographs of (a) typical SMD panel and (b) micro LED panel in a dark/bright environments

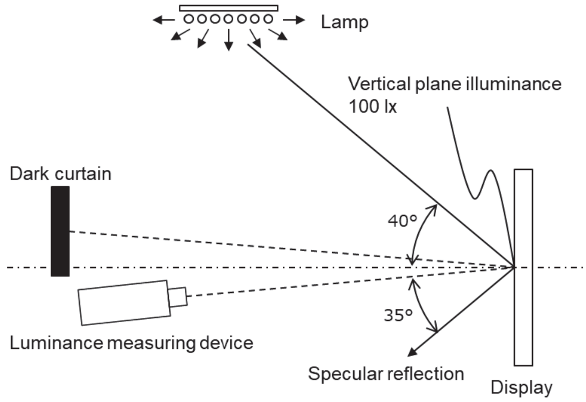


Figure 10. *ACR* evaluation system for a large-scale display

To quantify these differences, we referred to the definitions for ambient contrast ratio (*ACR*) [6, 7] and set up an evaluation system to measure a large-scale display, as shown in Fig. 10.

An illumination lamp was placed in front of the display panel 40° to the normal of the display surface, and the vertical plane illuminance was adjusted to 100 lx. The luminance of the display panel was measured at 35° from the specular reflection of the lamp. The reason for not measuring the luminance from the normal of the panel was to avoid the reflection of the luminance measuring device. For the same purpose, a dark curtain was placed in the specular reflection direction of the luminance measuring device. The *ACR* is defined as

$$ACR = \frac{L_{\mathrm{on}}}{L_{\mathrm{off}}} ,$$

$$L_{\mathrm{on}} = L_{100\%} + R_{100\,\mathrm{lx}} ,$$

$$L_{\mathrm{off}} = R_{100\,\mathrm{lx}} ,$$

where L_{on} and L_{off} are measured luminance with 100% white signal and 0% black signal, respectively. $L_{100\%}$ is the emission luminance of the display with 100% white signal and $R_{100\,\mathrm{lx}}$ is the luminance of the scattering reflection from the display.

When $L_{100\%}$ was 1,000 cd/m^2, the *ACR* was 440:1 for the typical conventional SMD panel and 14,000:1 for the micro LED panel. The *ACR* of the micro LED panel was significantly higher.

We simulated the *ACR* considering the ratio of the black and non-black areas. The scattering reflectivity of the non-black area including RGB LEDs was significantly higher than that of the black area. These scattering reflections were calculated based on actual measurements, and the dependence of the *ACR* on the non-black area was simulated using these values, as shown in Fig. 11.

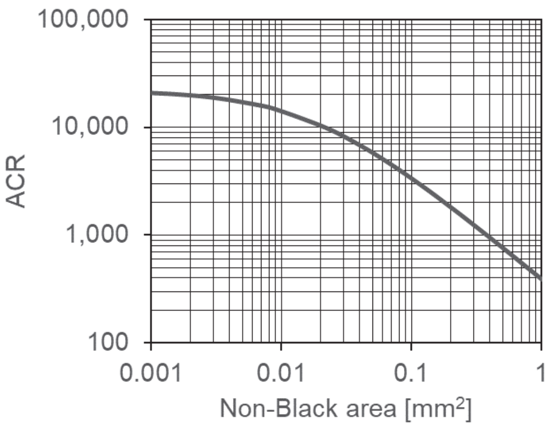


Figure 11. Simulated *ACR* relative to non-black area including RGB LEDs

In this simulation, a pixel pitch of almost 1.2 mm, luminance of 1,000 cd/m^2, and illuminance of 100 lx were assumed. When the non-black area corresponded to the size of the SMD, the simulated *ACR* was consistent with that experimentally measured for the SMD panel. The *ACR* improved dramatically as the non-black area became smaller. For a non-black area < 0.01 mm^2, the *ACR* improvement gradually saturated because the scattering of the black area was relatively dominant. From this simulation, we will be able to design a display panel with a wide ranging *ACR*.

We also set the target display performance to $L_{100\%} \geq$ 1,000 cd/m^2 and $ACR \geq$ 10,000:1 (equivalent to $R_{100\,lx} \leq 0.1$ cd/m^2 under 100 lx) through sensory tests to achieve high image quality even in a bright environment. With the simulation described above, we designed the non-black area to ~0.01 mm^2 and the size of a micro LED to ~20 microns to meet the target.

With these designs and our novel active matrix driving technology using micro ICs, our Crystal LED display system could deliver immersive viewing experience in a bright/dark environment as shown in Fig.12.

5 CONCLUSIONS

We developed 20-micron micro LEDs with a Lambertian emission pattern, which lead to a perfect wide viewing angle. With these micro LEDs, we could decrease the non-black area and increase the *ACR*. After evaluations and simulations on the *ACR*, we designed a pixel layout of RGB LEDs and a non-black area to achieve both high luminance of 1,000 cd/m^2 and high *ACR* of > 10,000:1 in a 100-lx environment.

We also developed micro ICs to produce a high dynamic range of superior luminance linearity and stable color chromaticity. By integrating this technology with precise mechanical alignment, our Crystal LED display system can deliver a more immersive viewing experience than ever before.

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Figure 12. Photograph of 200-inch Crystal LED display system for immersive viewing experience