Bringing True Colors to MicroLED Displays

Although microLED displays are a promising technology, they pose new challenges for metrology. Here, two authors from Instrument Systems show how an imaging light measurement device made of a 150-megapixel RGB sensor and a high-end spectroradiometer can provide faster and more accurate microLED measurements.

by **Tobias Steinel and Martin Wolf**

BECAUSE OF THEIR SUPERIOR PERFORMANCE, MICROLEDS are often considered a disruptive technology that will revolutionize the display world once we've realized an economical way to mass-produce them. One important piece of the puzzle is mastering cost-effective and high-end quality control in production lines. Although it's crucial for creating perfect displays and an impressive user experience, microLED displays' improved optical properties pose challenges to standard measurement equipment. Here, we explore an innovative solution that addresses that concern.

NEARING A BRIGHT AND TRULY COLORFUL FUTURE

MicroLEDs are bright, small, and power-efficient. They promise fully immersive display resolutions and real-world color, and they help increase wearable displays' battery lifetime. In particular, microLED technologies are expected to drive head-mounted devices for augmented and virtual reality (AR/VR) applications.[1]

Each microLED in the millions of pixels on a display is an individual light source with individual variations in color and luminance. To produce high-quality uniform displays, these variations must be tested, corrected, and kept below visual noticeability. To assure the highest quality under the constraints of economical production takt times, fast and accurate optical testing has to be provided for every pixel on the entire display.

Additionally, in typical mass production, microLEDs and displays are produced by different manufacturers at different locations under different conditions. So, it is of the utmost importance to measure absolute color as the human eye would see it and in a manner that is traceable to international standards and accompanied by an efficient auditing strategy. Only absolute measurements guarantee the same high-quality display experience, no matter where the displays are produced and shipped. If all these challenges are met, customers may enjoy a truly natural and immersive visual experience at a reasonable cost.

SOLVING TESTING CHALLENGES

Solving the challenges of quality assurance requires testing and correction on the subpixel level. We must measure all individual light sources such as microLEDs and derive highly accurate luminance and color values for each pixel of the display. This enables defect detection and correction and calibration of individual pixel deviations, which are sometimes referred to as luminance and color demura.

Once we know all the pixels, we may start evaluating the complete display, assessing display uniformity, pixel defects, white balance, color gamut, contrast, or the measurement of intensity modulations. That means all classical display tests

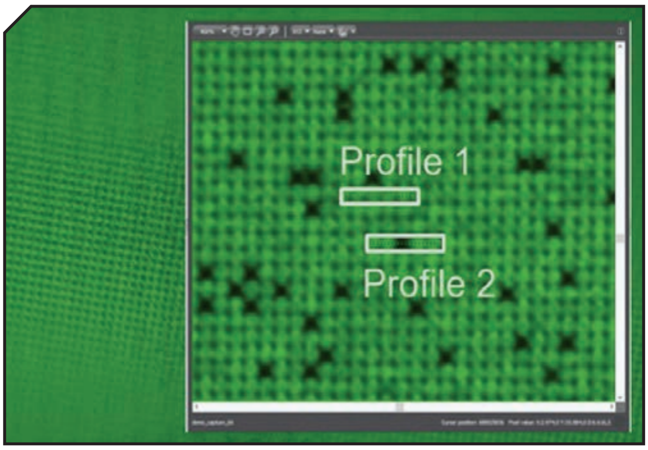

Fig. 1.

One-shot, all-pixel measurement of a monochrome 0.57-inch microLED display. Inlet: A close-up of the display for luminance profiling.

can be performed on such data's basis.

So, what's the best way to do this? For speed and resolution, a high-resolution camera is the preferred option, because display pixels can be measured parallel and fast in a single shot. (Most of us know this from using our multimegapixel [MP] digital cameras.) For absolute color, however, spectroradiometry is the most accurate method, because all of the spectral information—and hence the color—of the source is measured. Consequently, both techniques must be combined: Using a high-resolution camera and a spectroradiometer in the camera system at the same time achieves high speed and unprecedented accuracy. LumiTop devices feature this exact concept.[2,3]

In this article, we use the ultra-high resolution model LumiTop X150[3] for the subpixel metrology of microLED displays, OLED microdisplays, and OLED smartphone displays. This imaging light measurement device (ILMD) merges a 150-MP red, green, and blue complementary metal-oxide semiconductor (RGB-CMOS) camera with the high-end spectroradiometer CAS 140D. The production-optimized design enables concurrent data collection from both sensors by rapidly switching the optical path to bring light to the camera and the spectroradiometer. This guarantees high measurement speed and, equally important, allows the extremely accurate spectral information of the instrument's measurements to act as a live reference, which guarantees spectroradiometric test accuracy across the camera's whole image.[4] This is an established concept frequently used in display production lines. To test various kinds of displays, from flat panels and wearables to AR/VR headsets and even microLED-wafers, the LumiTop concept is adaptable to many different light sources, device under test (DUT) sizes, and applications. Resolution options range from 1.5 MP to full 150 MP per color channels and beyond, employing pixel shifting.

There is an additional benefit to combining a camera and spectroradiometer. LED production processes allow a certain variation of the LED's color—about 5 nanometers (nm)—across a wafer. All conventional imaging light measurement devices depend on calibration to the measured source to produce adequate measurement results. However, when the light source changes by typically up to 5 nm across the wafer, some light measurement devices may produce inaccurate results. This is because they do not "know" that the light source changed and the calibration is no longer valid. This can be handled with the special setup of the LumiTop, because a spectroradiometer always measures the light source's spectrum in the center of the camera image. Based on this information, sophisticated algorithms are used to adapt the factory calibration on the fly for color drifts or variations on the wafer or display.

EXAMINING EACH PIXEL

The LumiTop system takes high-resolution and accurate images of displays, where each DUT pixel is oversampled sufficiently by many camera sensor pixels. As a result, a well-resolved image of all display pixels becomes rapidly available. Then these data are processed using a method known as single-pixel evaluation (SPE) that derives pixel maps of the DUT with values of luminance and color for each display pixel. The pixel maps contain all relevant display data and act as a source for all desired quality tests. SPE requires optimized and fast evaluation algorithms to fulfill demanding production requirements.

Fig. 1 shows a monochrome 0.57-inch microLED display. The full display screen is captured in one single measurement using a five-fold

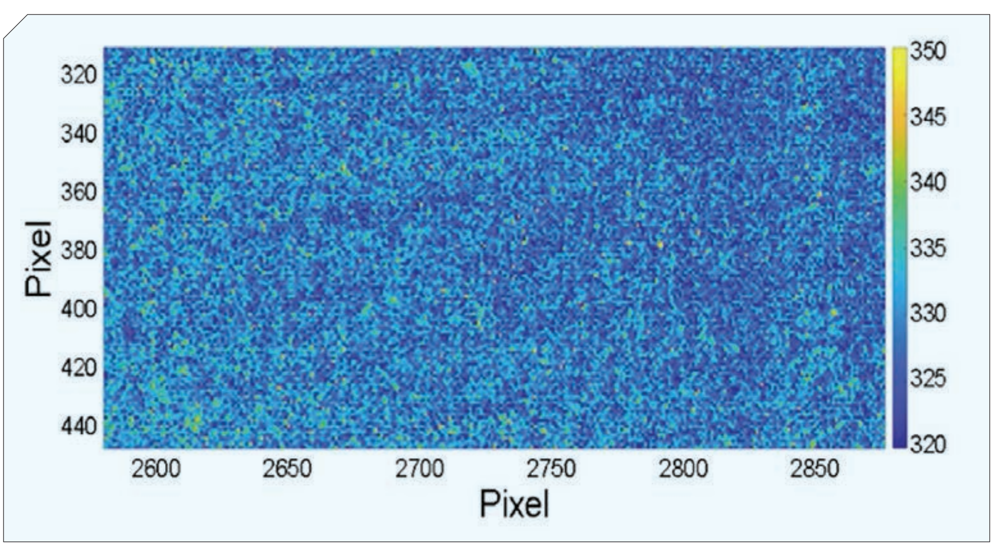

Fig. 2.

Up-close view of the luminance pixel map of an OLED phone display, where each dot represents a device under test subpixel (pseudo-color).

Figures 1-5: Data produced by Fabienna Arends, Mansur Kaan Demirci, Lea Grimm, Nina Mauser, and Roland Schanz of Instrument Systems GmbH

QUICK TAKE

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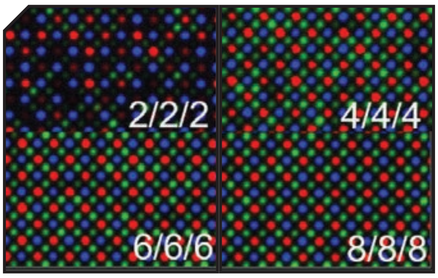

Fig. 3.

Pixel-level zoom into an OLED smartphone display at four different gray levels.

magnifying lens, and the gaps between the pixels are only approximately 2 micrometers (µm) wide. The highly resolved image clearly shows strong pixel defects of the microLED display as well as luminance variation.

Fig. 2 shows the close-up image of an OLED smartphone display as a luminance pixel map. The variations are far more subtle than the microLED display, and the individual pixel deviation of luminance can be seen in high resolution. Now we can use the pixel maps to detect dark, bright, or dead pixels automatically, depending on the user's quality criteria.[5] Then deviant pixels can be corrected electronically within the limits of the driver electronics to provide a highly uniform display.

Uniformity is an important display quality property, because the eye is quite sensitive to changes in luminance and color. Especially at low luminance, it is challenging to measure small variations of luminance and color to test and correct uniformity in LED displays. **Fig. 3** shows a pixel-level close-up of an OLED smartphone display at four different gray levels using our highly sensitive ILMD. It is easy to see that gray level 2/2/2 is significantly nonuniform, while uniformity increases at brighter gray levels. Clearly, the display has not been adjusted for uniformity at low luminance levels. An ILMD equivalent to ours is necessary to provide the sensitivity and high dynamic range needed for testing, and hence, correcting display properties.

Paying attention to every single display pixel increases production quality and yield, because every display can have its individual correction on the pixel level to meet the required specifications.

EVALUATING DISPLAY UNIFORMITY

The millions of pixels on a display come with a lot of information that can be used to find individual pixel defects and color errors. However, with this data basis, we also can use the power of statistics to evaluate display uniformity more easily and with greater detail.

It is useful and usually necessary to test the display's uniformity before and after correction. Additionally, modern displays may have edges, punch holes, and notches, where luminance might be systematically or even intentionally different from the rest of the display. In these cases, a statistical analysis of the luminance and color value distribution can help avoid errant correction and give a fast and sensitive means to rate the display's uniformity as a pass/fail criterion.

A simple way to measure uniformity is to divide the display image into equally spaced and sized areas and simply compare ratios of minimum and maximum luminance or these areas' color values. With a pixel map of the DUT at hand, we have the power to test not only the average luminance and color values of certain areas of the display, but all pixels of the display.

Fig. 4 gives an intuitive representation of the statistical distribution of the pixel luminance of the phone display under investigation. In the main figure frame, the number of pixels for different luminance ranges are plotted against luminance. The result is a smooth distribution of the pixels' luminance values. The distribution's center and shape can provide detailed insight into the origin of the pixels' luminance variations. Now different production techniques, corrections, and driving conditions easily can be judged with respect to display uniformity, because the goal always is to have as narrow as possible distribution around the center of the desired luminance value.

The statistical approach gives exact criteria for the users' pass/fail decisions, while at the same time fast standard algorithms for statistical evaluation can be employed to analyze the data more rapidly. A close look at the luminance distribution in **Fig. 4** (inlet frame) shows that there is not only one distribution of luminance around the central luminance at 330 candelas per square meter (cd/m^2), but also one at 165 cd/m^2 and another at 55 cd/m^2. In this experiment, these pixels correspond to pixels at image edges that are dimmed deliberately to allow for a more comfortable perception of the transition. SPE gives us the optical and spatial information on a pixel level, so that we immediately know where the low luminance pixels are. We can use this information to localize these pixels.

To differentiate defects from systematic deviation that may result (for example, from edges), it is extremely helpful to analyze the shapes and positions of pixels' luminance distributions. As a rule, normally distributed luminance is a result of production tolerances, while randomly distributed luminance stems from defects. By considering the intentional contributions (such as from the edges) separately from the main luminance distribution,

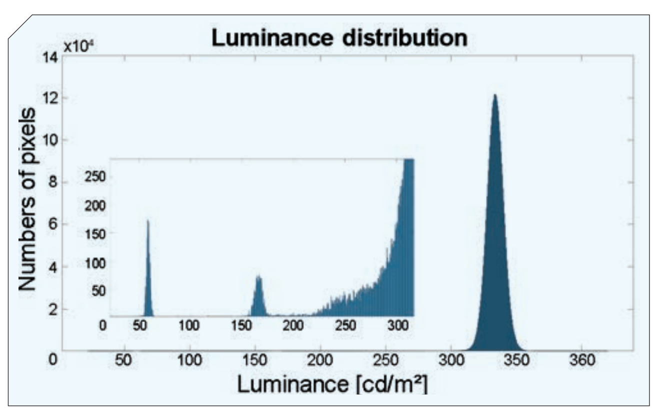

Fig. 4.

Distribution of luminance of all display pixels. Inlet: A close-up of distribution at low luminance.

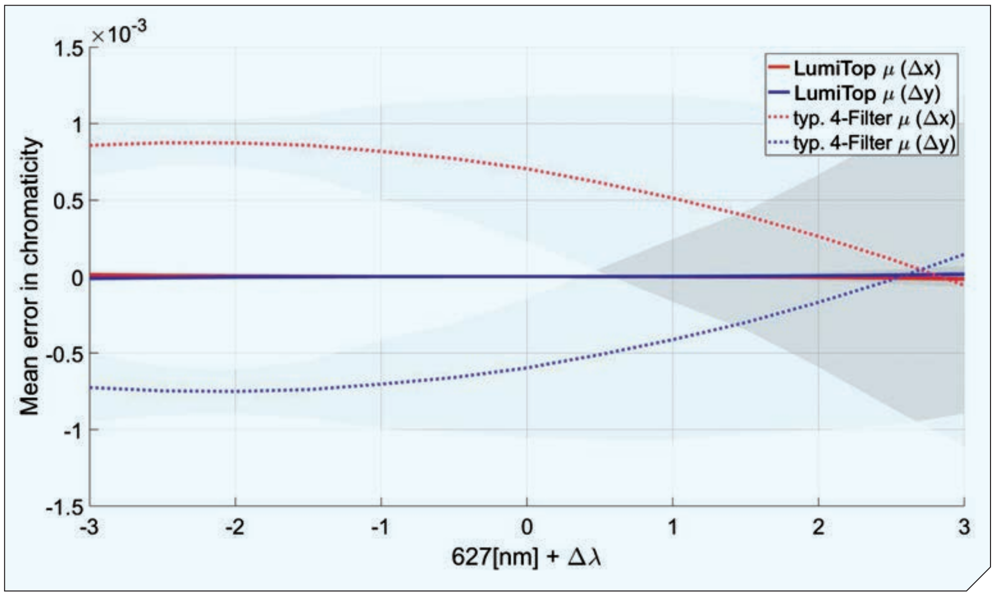

Fig. 5.

Mean chromaticity error and error distribution of a spectrometer-based and 4-filter-based color measurement device for a red microLED spectrum shifting by +/- 3 nm.

we obtain a more accurate and meaningful quantification of display uniformity.

ENSURING COLOR ACCURACY

New display technologies such as microLEDs can be challenging with respect to accurate color measurement, because LEDs' emission spectrum varies with environmental or production conditions. Quality tests in wafer production usually allow a variation of about +/- 3 nm of the emission spectrum. This means color measurement devices that usually are calibrated to a well-defined expected spectrum or golden sample are not optimally calibrated anymore when the DUT's spectrum is changing. With the advent of microLEDs, color calibration also must be robust to substantial drifts and changes in the DUT's emission spectrum. Also, mass production usually requires multiple sources for LEDs and display modules. Variations in the respective production locations prohibit the use of local golden samples, because the equality of different golden samples cannot be assured. Therefore, our light and color measurement device LumiTop copes with these challenges by taking a spectrum with a highly accurate spectrometer at each measurement. These spectra contain the full spectral information of the DUT and are used to obtain a robust calibration and enable high accuracy even under changing spectral conditions.

Fig. 5 shows the extent of errors introduced by variations of the DUT spectrum. The chromaticity error of color coordinates x and y are displayed for a spectrally enhanced measurement (LumiTop: solid red and blue line) and a state-of-the-art 4-filter-based measurement as performed by filter-wheel imaging light measurement devices (dotted red and blue lines) for a real spectrum of a red microLED (by lumens). The chromaticity error is negligible for the LumiTop system, while a 4-filter-based system not only shows a mean error of approximately one color point, but also shows a large error distribution (gray-shaded area). This means that even if a 4-filter-based ILMD is user-calibrated to the specific emission spectrum, the error margin for color location xy under ideal conditions is still around 3 color points across a typical wafer.

We find that our measurement instruments run 24/7 around the world in production environments, many for years without downtime. Reliability and accuracy arise from a mix of excellent hardware, software, and auditing. For the highest-quality requirements and distributed production scenarios, optical testing profits tremendously from an efficient auditing and service strategy that improves testing limits and reduces factory downtimes. Our auditing light sources are very accurately defined light sources traceable to national standards. Regular audit of the measurement instruments against those light sources guarantees absolute measurement accuracy at any time and at any production site throughout the supply chain. This assures the same high display quality of the product no matter where and when it is produced. Moreover, our auditing tools are optimized for quick inline instrument checks that minimize the downtimes. Local partners and service subsidiaries ensure swift response and provide rapid recalibration, instrument repair, and technical support. Therefore, auditing and service is a key requirement to bring true color displays into mass production and consumer markets.

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INVOKING SMART MONITORING AND SERVICE

In closing, microLED displays offer promising new technology that poses challenges to metrologists. For application in production lines, modern measurement devices must improve in terms of absolute measurement accuracy and analysis speed. This essentially means higher camera resolutions, sophisticated evaluation algorithms, and a product-optimized calibration, all incorporated into a smart monitoring and service concept. This article describes how to utilize an instrument that combines a 150-megapixel RGB sensor and a high-end spectroradiometer to cope with those challenges.

We particularly emphasize subpixel-level tests of displays that provide many new exciting ways to analyze display quality by leveraging a comprehensive data basis.[6] SPE algorithms create a digital twin of the display under test, with the luminance and color values of each pixel right at hand and ready for any evaluation. For example, a statistical approach to analyze display uniformity provides an easy and intuitive way to define and apply pass/fail criteria in display testing. The key to all pixel information, however, lies in the quality of the subpixel image and accurate luminance and color measurement, which is guaranteed by optimized calibration and spectroradiometric referencing.

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