Quantum-Dot Displays: Giving LCDs a Competitive Edge Through Color

Quantum-dot technology is bringing wide color gamut to LCDs, giving them a leg up on another advantage that once belonged to OLEDs.

by Jian Chen, Veeral Hardev, and Jeff Yurek

SIXTY YEARS AGO, well before color TVs became widely available in the late 1960s, the National Television System Committee (NTSC) agreed on one of the first broadcast standards for color TV – the NTSC 1953 color standard. This new standard was a significant achievement, bringing color to a black-and-white world with a clever encoding scheme that tracked color separately from luminance. While the standard was based on the capabilities of the best-available cathode-ray-tube (CRT) phosphor materials, mainstream devices never really supported the full-color capabilities of NTSC 1953. The color primaries established by the standard would become more aspirational than truly standard over the next 6 decades.

That's not the case in 2013. Today, millions of people around the world carry a mobile device in their pocket that can reproduce more color than the 1953 NTSC standard, thanks to AMOLED-display technology. While historically limited to smaller devices by reliability and process issues, AMOLED displays may soon find their way into larger and larger systems. In 2012, 55-in. AMOLED TVs garnered significant attention and won awards at SID's annual Display Week exhibition.

Despite the emergence of AMOLED displays, the technology has yet to capture a large share of the overall display market, as LCDs remain the standard in nearly all product categories. After more than a decade of explosive growth in manufacturing capacity by LCD makers, the cost of LCDs of all sizes is tough to beat for upstart technologies such as OLEDs. Beyond cost, LCDs have been able to match just about every feature that new technologies have offered over the years. Advances such as local dimming, in-plane switching (IPS), and in-cell touch, respectively, have brought great contrast, improved viewing angle, and reduced thickness to LCDs. In most cases, manufacturers have yet to find an OLED advantage strong enough to compel them to move beyond LCD.

One area where LCDs have thus far failed to match OLEDs is color performance. Conventional LCDs face a ceiling in color performance, at best reaching the sRGB color gamut, or about 70% of OLED's capability, because of the white LED light source used in most LCD backlights. While LCD makers have experimented with other wide-gamut backlight technologies, such as discrete RGB LED and CCFL, all have proven too costly, too power hungry, or too bulky to be viable. For some time, it seemed that high brightness, portability, and wide-gamut color performance simply could not be had in the same LCD package at the same time.

That was until a new class of phosphor material called quantum dots became available to LCD makers. First developed in the 1980s at Bell Labs, quantum dots have the unique ability to efficiently emit light at a single spectral peak with narrow line width, creating highly saturated colors. In addition, the emission wavelength can be tuned continuously based on the size of the quantum dots. This capability enables display designers to custom engineer a spectrum of light to maximize both the efficiency and color performance of their display.

The term "quantum dot" was coined by Mark Reed, a physicist from Yale University who contributed to some of the early work on the technology in the 1980s. The dots are so named because of the quantum-confinement properties that are exhibited by the material. Quantum dots are semiconductors whose electronic characteristics are governed by the size and shape of the individual crystal. The smaller the size of the crystal, the larger the band gap becomes. In lighting applications,

Jian Chen *is Vice President of Research and Development at Nanosys, where he is leading the development of a new generation of lighting technology based on quantum dots. He can be reached at jchen@nanosysinc.com.* ***Jeff Yurek*** *is the Product Marketing Manager at Nanosys. He develops long-term marketing and communications strategies for the company and also handles day-to-day public relations, investor relations, and marketing communications. He can be reached at jyurek@nanosysinc.com.* ***Veeral Hardev*** *is the current program manager for quantum-dot lighting at Nanosys. Since joining Nanosys in 2004, Veeral has led product development implementing Nanosys technology to a variety of fields including life sciences, medical devices, and military displays. He can be reached at vhardev@nanosysinc.com.*

0362-0972/1/2013-0??$1.00 + .00 © SID 2013

this means higher frequencies of light are emitted as the crystal size becomes smaller, resulting in a color shift from red to blue in the light emitted.

LCDs and Color

To better understand how quantum dots improve the color performance of LCDs, it is useful to know how LCDs work. A typical LCD consists of two major components: a light source called the backlight unit (BLU) and a liquid-crystal module (LCM) (see Fig. 1).

When an LCD is operating, the BLU provides white light to illuminate the LCM. The LCM contains millions of pixels, each of which is split into three subpixels, one each for red, green, and blue light. By controlling the amount of light each subpixel allows to pass through, a broad range of colors is created by mixing the individual red, green, and blue light. Thus, the fidelity of color in each pixel is a direct function of the subpixel color saturation. To determine the overall color gamut of the LCD, one must look at the

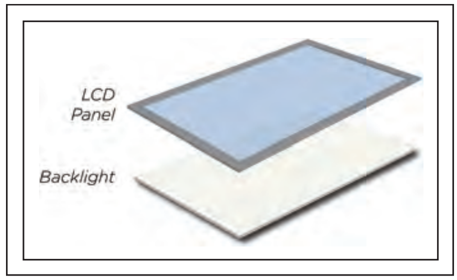

Fig. 1: A backlight unit, which these days generally uses LEDs as the light source, operates behind the LCD.

chromaticity of red, green, and blue light in each subpixel.

The color of each subpixel is determined by two factors: the spectral energy of the white light in the BLU and the effectiveness of the color filter at the subpixel. The color filter separates its component red, green, or blue color from the white light of the BLU. Thus, the red color filter on the red subpixels will cut off green and blue, attempting to let only certain wavelengths of red light though. To make a high quality red, the filter spectrum either needs to be very narrow, etting less undesired light through, or the red component in the white BLU light must be narrow and tuned to the desired peak red color wavelength in the filter. The same is true for the green and blue subpixels.

Unfortunately, narrowing the spectrum of the filters is expensive and results in substantial attenuation and loss of luminance.

Another solution to improving color fidelity might be to make a better white light. However, the LED light source at the heart of most BLUs in use today is not optimal for producing highly saturated red, green, and blue light, starving the subpixel filters of the colors that they really need to shine. While there are a variety of approaches to create white light from LEDs, YAG (yttrium-aluminum-garnet) phosphor combined with blue LED chips is the most common. This technology relies on a YAG-based phosphor to change the blue light from a GaInN (gallium-indium-nitride)

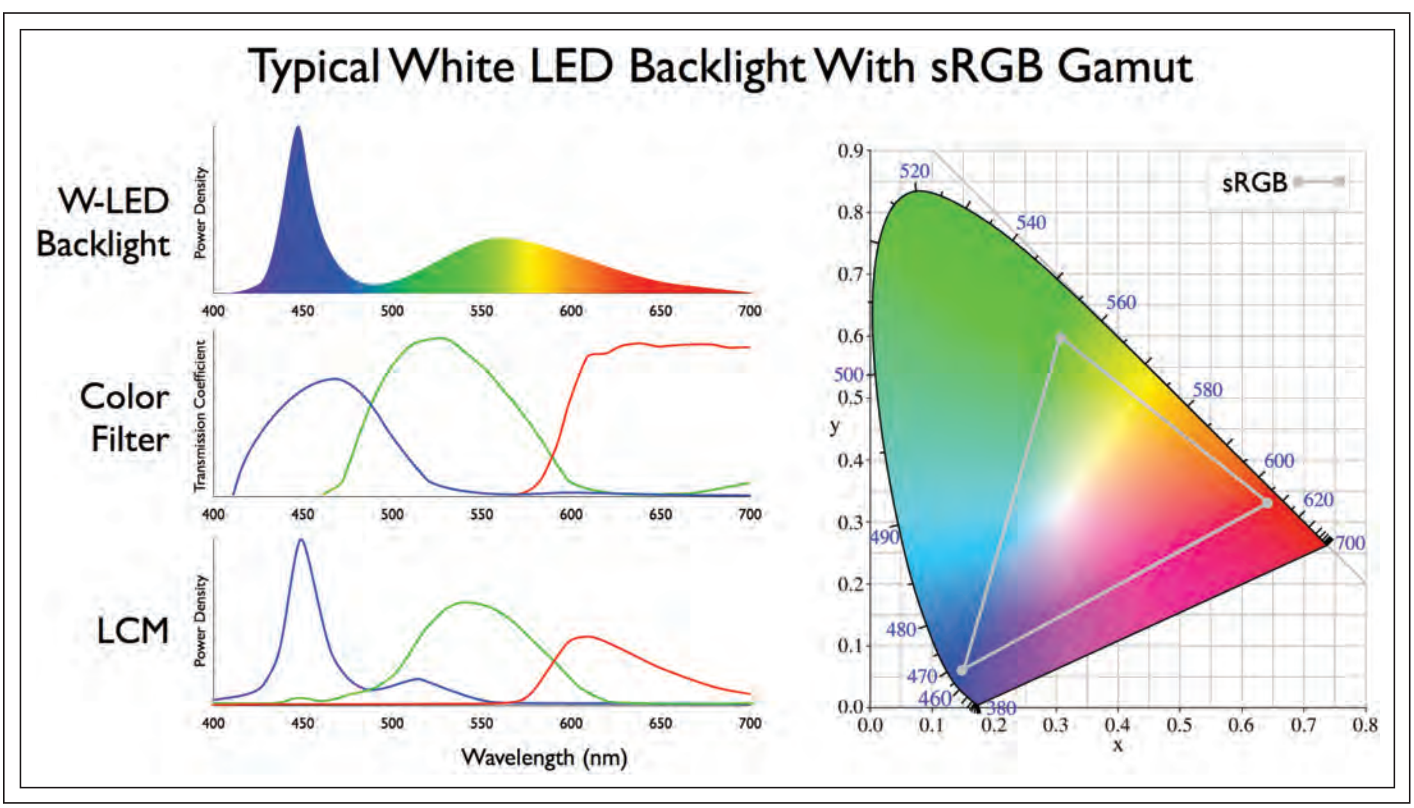

Fig. 2: Shown is the spectra from a conventional white LED (GaInN + YAG) backlight which does not provide a good match with red, green, and blue color filters in the liquid-crystal module (LCM). The resulting gamut, plotted in the CIE 1931 diagram on the right, covers a relatively small percentage of the total range of colors our eyes can see – only about 35%.

LED light source to a light that we perceive as white. This produces a spectrum rich in blue with a broad yellow component. It has a weak green and red content, and the spectrum is widely distributed from aquamarine through green, yellow, orange, and red (see Fig. 2). When this light is filtered into the component RGB filter colors in the subpixels, the primary colors are not pure enough to cover sufficient color space.

Knowing this, an ideal LED light source for an LCD should be capable of generating photons in the red, green, and blue wavelengths useable by the subpixel filters. For maximum efficiency, it should also not emit photons with wavelengths that are not matched to the red, green, and blue filters.

Quantum Dots

Quantum dots comprise a new class of material that can be tuned to emit light very efficiently at precise red, green, and blue wavelengths, thus creating an ideal light spectrum for LCDs. Unlike conventional phosphor materials, quantum dots, which are just nanometers in diameter, can be fabricated to convert short-wavelength light (*i.e.*, blue light) to nearly any color in the visible spectrum. The spectral output of a quantum dot is determined by its size. Bigger dots emit longer wavelengths, while smaller dots emit shorter wavelengths. It's a phenomenon of quantum mechanics called quantum confinement that describes what happens to electrons and holes when confined in nanoscale materials. Think of a guitar string – to use a classic physics analogy. When a guitar string is shortened, it produces a higher pitch, and, conversely, when it is lengthened, it creates a lower pitch. The tune of a quantum dot – the wavelength of the light it emits – behaves in a similar way.

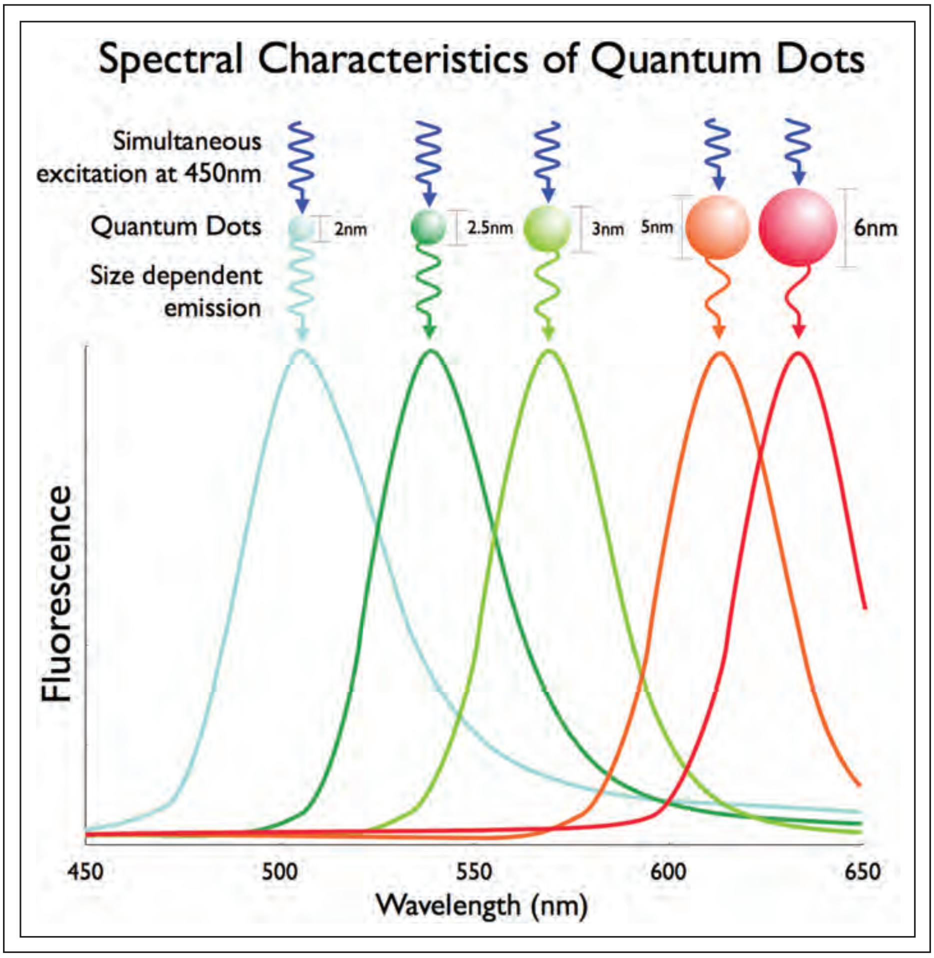

Fig. 3: Quantum-dot size relates to emission wavelength. Quantum dots absorb higher-energy/shorter-wavelength light and down-converts the light into lower-energy/longer-wavelength light. The smallest dot represented here, at 2 nm in diameter, absorbs the light from a 450-nm blue source and emits light at 500-nm green wavelength while a larger 6-nm-diameter dot emits at 630-nm red wavelength. Precise control of quantum dots at manufacturing enables the dots to emit light at any wavelength in the visible spectrum.

Figure 3 pairs quantum dots of different sizes with corresponding output wavelengths. The best dots available today emit light with over 90% efficiency and with very narrow spectral distribution of only 30–40 nm at full-width at half-maximum (FWHM). Ranging in size from 2 to 6 nm, quantum dots made from the same material emit light in the visible spectrum at different wavelengths based upon size.

Quantum dots for display applications are generally made from II-VI elements such as cadmium selenide or III-V elements such as indium phosphide. They are typically synthesized via solution chemistry in high-boiling-point solvents using precursors and ligands that bind to the surface of the dots. By controlling different synthesis conditions, *e.g.*, precursor and ligand concentrations and the temperature and time of the reaction, quantum dots of different sizes can be obtained.

Packaging for Existing Manufacturing Processes

The light-emitting properties of quantum dots make them a promising technology, but that is not enough to drive adoption in the display industry. Manufacturers are usually unwilling to risk altering processes they have invested billions in to try a new, novel technology. If quantum dots are going to have an impact in the display industry, they need to be packaged into a process-ready system that is compatible with existing standard LCD-manufacturing processes. Nanosys has aimed to achieve this goal in creating its Quantum-Dot Enhancement Film (QDEF) product (Fig. 4).

QDEF is designed to replace an existing film in the BLU called the diffuser. The film combines trillions of red- and green-emitting quantum dots in a thin sheet that emits finely tuned white light when stimulated by blue light. Each sheet of QDEF comprises three layers – two plastic barrier films sandwiching a layer of quantum dots suspended in a poly-

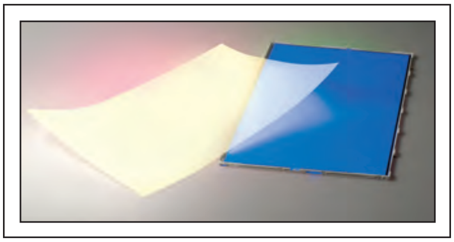

Fig. 4: *The quantum-dot enhancement film (QDEF) is designed to replace the diffuser in an LCD backlight unit (BLU) and is placed between the BLU and the LCM. The QDEF contains red- and green-emitting quantum dots that are tuned to each display system and is illuminated by blue LEDs in the BLU. In the above image, a sheet of QDEF (left) can be seen converting some of the blue light emitted by a BLU (right) into white.*

mer matrix. This deceptively simple optical system is enabled by two key breakthroughs aside from quantum dots themselves:

1. Surface functionalization, enabling reliable dispersion of quantum dots in solid matrix materials while maintaining brightness, and
2. The availability of high-performance optically clear oxygen/moisture barrier films.

In order to disperse quantum dots into a variety of different matrix materials such as epoxies, polymers, and UV-curable adhesives, Nanosys specifically tailored the surface functionality of the dots with a type of organic material, known as ligands. This surface functionalization keeps the quantum dots at a safe distance from each other, preventing adverse interaction. Keeping the quantum dots appropriately dispersed is important in maintaining both efficiency and reliability over long lifetimes. If the dots aggregate, the photon conversion efficiency degrades, resulting in a lowered output of green and red color. This leads to an undesired white-point change on the display. Stable and reliable dispersion into a matrix material allows quantum dots to be employed in manufacturing processes already in use throughout the optical-films industry, such as roll-to-roll coating, and helps to assure their long-term stability.

With the successful functionalization of quantum dots in matrix material, the final critical component of QDEF is the addition of a barrier film to protect the quantum dots from the outside environment. Similar to OLED materials, quantum dots are sensitive to oxygen and moisture. The dots will degrade and become less efficient over time with exposure to either. Therefore, the quantum dots must be kept in an environment in which they will not be exposed to such elements. Encasing the quantum dots in a high-quality oxygen/moisture-barrier film does just that.

The ideal barrier film for QDEF must prevent degradation from oxygen and moisture in a package that is optically clear to let light pass through, flexible for rolling and thin to allow a slim device profile. The authors' company used a film from 3M that had been developed for solar, display, and lighting applications, which fit this ideal profile. QDEF's barrier, based on a clear plastic material called polyethylene terephthalate (PET), is coated with a thin oxide/polymer barrier on the inside-facing side. This proprietary barrier provides the dots with oxygen and moisture protection that is orders of magnitude better than conventional barrier films, improving the lifetime and reliability of QDEF without impeding light transmission.

The result is a simple, ready-to-use product that manufacturers can directly integrate into existing processes. By adding QDEF, the display maker can immediately begin producing LCD panels with color and efficiency performance beyond OLEDs, without making any changes to established processes.

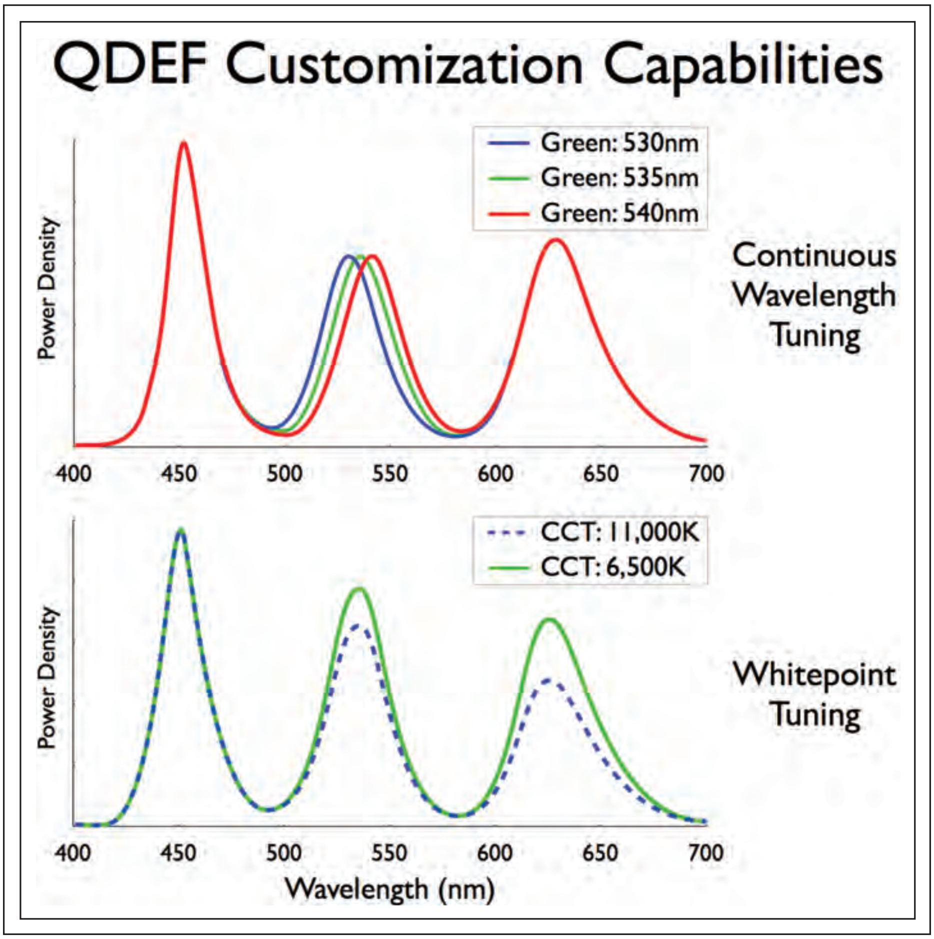

Fig. 5: *Various quantum-dot backlight customization possibilities exist. Top: Continuous-wavelength tuning enables display designers to target different color gamuts and/or optimize backlight emission for a given color-filter spectrum. Bottom: By changing the ratio of red to green and overall loading of dots in the film, different white points can be achieved to match the requirements of different display applications, i.e., mobile devices, tablets, and TVs.*

Customization

Using the size-dependent emission properties of quantum dots, QDEF can be custom formulated for different display applications – some for wide color gamut and some for energy/light efficiency. This allows display designers to tune the backlight spectrum to meet exact performance goals. For example, a display maker may want to target the Adobe RGB gamut and a D65 white point for a particular device. Each system is unique and a number of variables, such as color-filter cutoff frequencies, optical path length, and the amount of light recycling in the film stack, can affect the light as it passes through the LCD. Nanosys can design a sheet of QDEF with the precise color wavelengths and ratio of red to green to blue to account for each one of these variables to meet the designer's goals.

Figure 5 demonstrates the customization capabilities of QDEF. Matching red and green wavelengths to color filters enables precise reproduction of color-gamut standards and high efficiency. In the example shown in Fig. 5, the three green wavelengths represent the difference between hitting the sRGB, DCI-P3, and Adobe RGB color gamuts. Additionally, by controlling the ratio of red and green to blue by loading more or fewer dots into the film, QDEF can create any desired white point. More red and green makes a warmer white, while more blue creates a cooler white point.

The results can be seen in Fig. 6, wherein a sheet of QDEF was matched to a CF72 color filter that was designed to create the sRGB gamut when paired with a white LED. By using QDEF, this display can now generate over 100% coverage of the much larger Adobe 1998 color gamut with high power efficiency.

Commercial Viability

Reliability is a concern for any new technology. Quantum-dot R&D efforts are focused on creating products that will meet the increasing demands of product applications. Display products are getting brighter and larger and are now expected to last beyond 30,000–50,000 hours of operation.

To address these reliability demands, QDEF has been tested for tens of thousands of hours of operation under a variety of conditions, including high temperature, high humidity, and high light flux. In every case, QDEF has met or exceeded industry expectations. Because TVs are expected to last for many years and tend to be used in harsh environments, TV lifetime standards are one of the toughest tests for a new display component. Using accelerated lifecycle testing, QDEF is expected to surpass the 30,000-hour lifetime specification expected by TV makers, which translates to approximately 10 years of typical television-set usage (8 hours per day) (Fig. 7).

Quantum dots also face a challenge for mass adoption from competitive products based on OLED and other RG phosphor technologies that are likely to arrive in the future. QDEF's ability to leverage the existing infrastructure of the LCD industry provides an advantage against these other entrants.

Color is the Next Big Differentiator

Since the days of the first color TVs, a

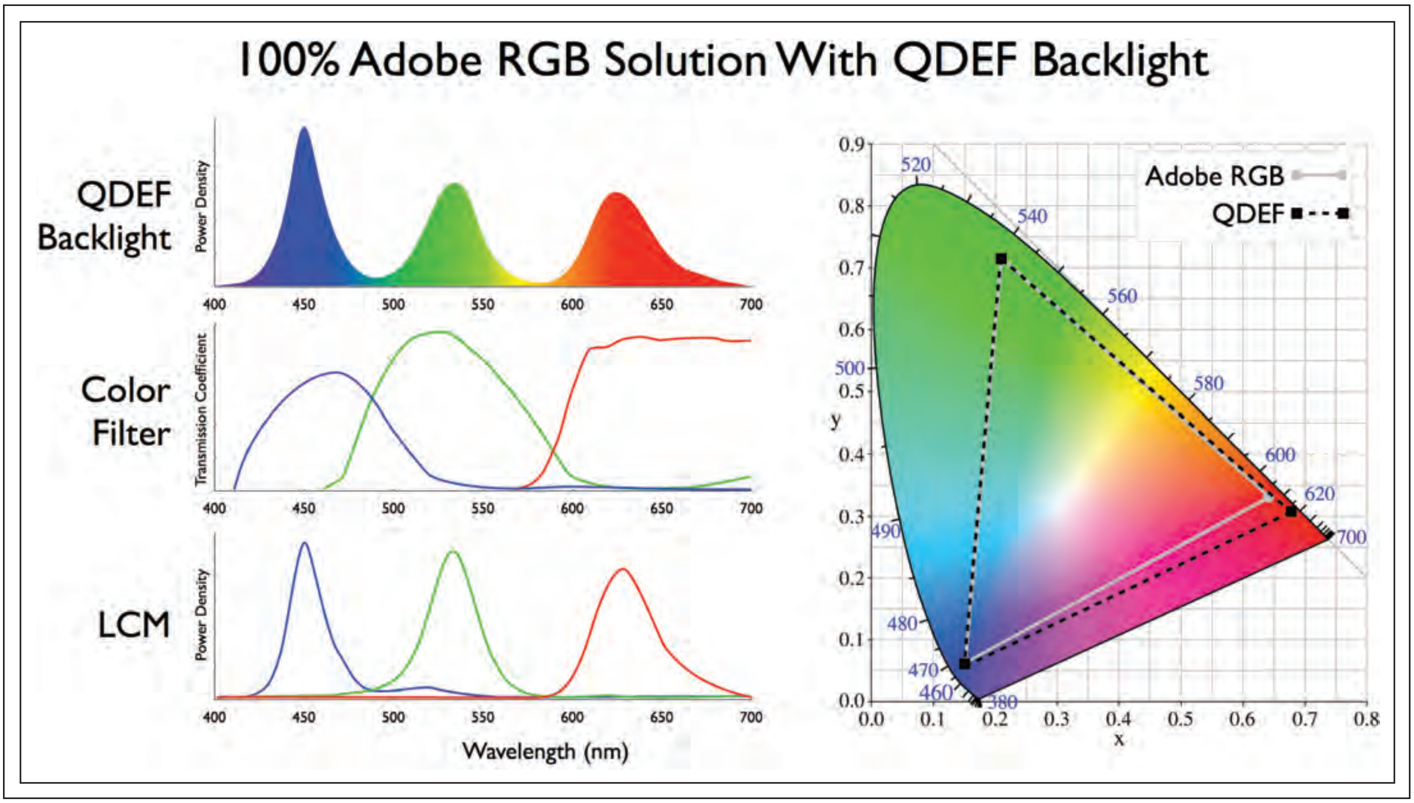

Fig. 6: A QDEF backlight using an off-the-shelf CF72 color filter is able to generate 100% coverage of the Adobe 1998 color gamut.

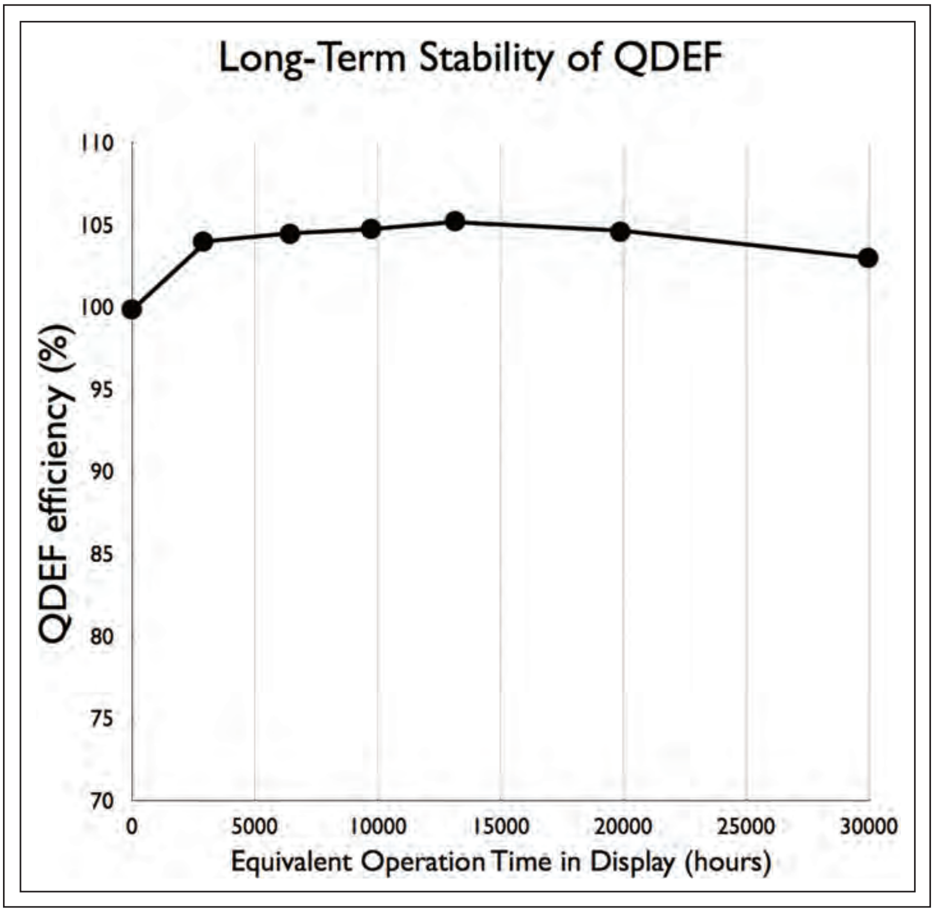

***Fig. 7:** Shown is 10x accelerated reliability data. The authors have tested QDEF at conditions that are 10x harsher than what a typical TV operates at, with a combination of more intense light and higher temperature. No degradation has been seen in this testing after 3000 hours of operation, which may be considered equivalent to normal operation after 30,000 hours.*

chicken and egg problem has prevented wide gamut from gaining mass-market appeal. Content creators have avoided wide gamut because devices that support it are typically expensive and not widely available – niche products at best. Likewise, display makers have historically felt that a lack of wide-gamut content limits the appeal of hardware.

QDEF is cost-effective, process-ready, reliable, and efficient enough to bring wide-color-gamut performance to all of the screens in our lives, from the smallest mobile device to the biggest TV. None of the wide-gamut technologies that preceded QDEF could claim to pull all four of these critical attributes together in one package. With broader availability of wide-color-gamut hardware enabled by QDEF, content creators can begin to take wide gamut seriously. This opens the door for Hollywood to create a stunning new visual experience for consumers, actually bringing a full cinematic viewing experience to our living rooms.

Color is the next big differentiator in the increasingly competitive consumer display market. Display makers that can bring the user experience closer to reality with lifelike colors, without sacrificing efficiency or cost, will establish a dominant market position. It may have taken several decades, but quantum-dot displays will finally deliver on the wide-color-gamut promise of the 60-year-old 1953 NTSC TV color specification. ■