DISPLAY WEEK 2015 REVIEW AND METROLOGY ISSUE

Information DISPLAY

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Sept./Oct. 2015
Vol. 31, No. 5

China Display Manufacturers Dazzle Display Week

Keynote address

Exhibition opening

Plus

Best-in-Show and I-Zone Winners

Latest Advances in Imaging Colorimetry

Characterizing Visual Performance under Ambient Conditions

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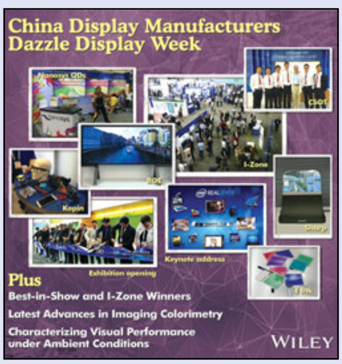
SEPTEMBER/OCTOBER 2015
VOL. 31, NO. 5

ON THE COVER: *Scenes from Display Week 2015 include, clockwise starting at upper right: 110-in. curved 4K TV from China Star Optoelectronics Technology (CSOT) (photo courtesy Steve Sechrist); Innovation Zone at Display Week; Sharp's free-form LCD technology (photo courtesy Ken Werner); color E Ink samples; slide from keynote address by Intel's Brian Krzanich; ribbon-cutting ceremony for Display Week exhibition; applications for Kopin microdisplays (photo courtesy Steve Sechrist); 82-in.10K display from Best-in-Show winner BOE; and quantum-dot LCD exhibit with acrobats from Nanosys.*



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In the Next Issue of *Information Display*

Lighting and Imaging Technologies and Applications

- Light-Field Imaging
- Indoor Scene Understanding with RGB-D Images
- Melanopsin Receptors
- Human Productivity and Lighting
- OLED Panels with Low Blue Current
- History of *Information Display* Magazine

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editorial

Down the Path of Display History

by Stephen P. Atwood

Some of you may have noticed that the 2015 issues of *Information Display* are labeled "Volume 31." This denotes the 31st year of the modern era of *Information Display*. I say "modern era" because prior to 1985 (Volume 1 of *ID*) there was apparently a previous incarnation of SID's "*Information Display*," subtitled "*The Journal of Data Display Technology*" and published by a separate company beginning sometime around 1964. If you count this period, then the publishing history of *ID* actually covers some 50 years of the display industry by now. One can easily imagine the depth of evolution our industry has experienced in that time and what we might find by looking back at older volumes of *ID*.

I found this idea particularly intriguing and started looking at older issues to see what was there. I was very pleased to see the rich technical landscape of our industry documented by some great contributors, some of whom are still active today. Each issue is a great read covering various topics that you may remember or that may fill in some missing information about the innovation steps that led to something that is commonplace today. Together these issues form an immensely valuable history of our industry that I want to see preserved and made available for everyone to enjoy. So, we have embarked on a project to digitally scan and archive all the available back issues of *ID*. As these become ready we will be posting them on the Informationdisplay.org website. Thus far, we have close to 30 back issues digitized, and they are slowly being uploaded to the website as time and resources allow, so check back often to see what gets added each month as we work through this project.

As an example of how interesting these back issues can be, let's take a look at what was happening in January 1995, roughly 20 years ago.

January 1995 Issue of *Information Display*

A very young looking editor named Ken Werner wrote about some of the presentations at a recent Japanese technology conference where the focus was on developing the LCD manufacturing infrastructure in Japan and how the current production yields were not yet adequate. Well-known companies such as Toshiba and NEC were optimistic that this could change soon and were making sizable investments as a result. They were also very bullish about Japan's ability to dominate the market share in LCDs for the foreseeable future. Ken chronicled the familiar concerns about prices, supply and demand swings, and margins for notebook manufacturers, who were one of the main application targets for the young LCD industry at that time. One interesting data point was the push towards larger-sized motherglass sheets in manufacturing, with the goal being something around 500 × 600 mm. This would enable 6-up 10.4-in. panels or 9-up 9.4-in. panels and was expected to help bring costs down significantly. Contrast this to today's LCD industry, in which people continue to worry about prices, supply and demand swings, and margins but are now manufacturing on motherglass formats over 2 m in length on a side and making many units of large HDTV panels on a single sheet! Obviously, today's LCD panels are radically more advanced than they were in 1995, but that time frame was the nascent period of growth for both portable computing and LCDs.

(continued on page 43)

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Leyard Optoelectronic to Acquire Planar Systems

In August, Oregon-based display manufacturer Planar Systems announced that it would be acquired by a U.S. affiliate of Leyard Optoelectronic, a Chinese electronics manufacturer specializing in LED-based products. The transaction is still subject to regulatory approval and a shareholder vote by Planar, but is expected to occur in the fourth quarter of 2015. Planar's board unanimously approved the merger.

Gerry Perkel, president and CEO of Planar, said, "The acquisition by Leyard will provide our investors with a 42% premium to market based on our latest closing price and a 51% premium based on a 7-day volume-weighted average price of Planar common stock of $4.35 and will position the Planar business for continued growth and innovation."

DisplayMate Nods to Galaxy Note 5 in Shoot-out

DisplayMate recently reviewed the Galaxy Note 5 and S6 edge smartphones – in typical exhaustive fashion. Its conclusion, based on weeks of testing early production units sent to DisplayMate from Samsung Headquarters in Korea: "… the Galaxy Note 5 is the best-performing Smartphone display that we have ever tested. It takes over from the Galaxy Note 4, which was the previous record holder for mobile-display performance." For more information, see: http://www.displaymate. com/Galaxy_Note5_ShootOut_1.htm.

Qualcomm Develops Update to Mirasol Technology

Using a structure comprising a mirror and an absorbing layer to take advantage of the wave properties of light, researchers at Qualcomm MEMS Technologies, Inc., a subsidiary of Qualcomm Incorporated, have developed a display technology that harnesses natural ambient light to produce what it claims is an unprecedented range of colors and a superior viewing experience. An article describing this approach recently appeared in The Optical Society's journal *Optica*.[1]

This technology, which is the latest version of an established commercial product known as Qualcomm Mirasol, is designed to reduce the amount of power used in multiple consumer-electronics products. Based on a new color-rendering format its creaters call Continuous Color, the new design may help solve problems affecting mobile displays, such as how to provide an always-on display function without requiring more frequent battery charging and a high-quality viewing experience anywhere, especially in bright outdoor environments.

[1] http://www.osa.org/en-us/about_osa/newsroom/news_releases/2015/mirror-like_display_creates_rich_color_pixels_by_h/

Futaba Announces Flexible PMOLEDs

Futaba Corporation has announced production availability of its flexible, passive-matrix OLED display. The product is now being made at Futaba's plant in Kitaibaraki, Japan. It is ultra-thin – 0.3 mm in overall thickness – with a 1.4-in.-diagonal black-and-white format, supporting a resolution of 128 × 16 pixels at a minimum luminance of 600 cd/m^2. The display can be formed around any curved object with a radius of 40 mm or larger. Other notable benefits are that it is shatterproof – thereby easier to handle in assembly production lines – and very lightweight, an advantage for wearable devices. Wearables is one of the major intended markets for the product.

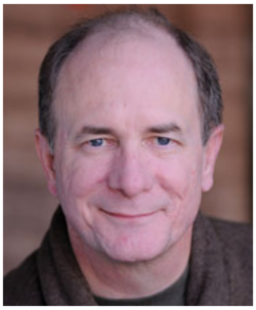
Philips Introduces New 55-in. TV

Philips has added another quantum-dot-based display to its portfolio. The new 55-in. 4K TV is based on QD Vision's Color IQ optics and complements Philips' existing lineup of quantum-dot displays, including a 27-in. LCD monitor.

Gooch & Housego Has New 6-in.-Diameter Veiling Glare Integrating Sphere

The new Veiling Glare Measurement System from Gooch & Housego was designed for performing veiling-glare test measurements on sensor samples in accordance with VESA 2.0, IDMS1, and other applicable standards on measurement solutions. The sphere consists of a sample port, light trap, and two illumination sources, all located on the sphere's horizontal axis. The sphere assembly also comes mounted to a rugged base plate. Its internal surfaces and baffles are coated with Gooch & Housego's Optolon2 high-reflectance coating, which has an effective wavelength range of 300–2500 nm. ■

guest editorial



Technical Progress Should Not Overwhelm Common Sense

by Tom Fiske

Welcome to the metrology issue of *Information Display* magazine. Technical progress is inexorable. As time goes on, photon-catching detectors get more sensitive. Sensor arrays get more pixels. Computers process more data than ever before. What we often need more of, however, is common sense. That is not to say that detector sensitivity, numbers of sensors on a chip, or computational power are not important. But they are not the only important things. For these advancements to be useful, one has to know what to do with the extra sensitivity and the additional data. Our contributions this issue help us along the way of optimizing that extra data and computer power.

We have two articles this month describing advances in metrology. The first one, from NIST scientists John Penczek and Paul Boynton and consulting display-metrology expert Ed Kelley, recommends a standardized method for finding the optical performance of displays in any ambient lighting environment. They describe a common-sense extension of the principles in the Information Display Measurements Standard (IDMS) that cover emissive, reflective, and transparent displays. With straightforward characterization of the reflective and transmissive properties of a display, one can use these principles to account for how ambient lighting will affect the visual performance of almost any display. These authors show us how to use these principles to report the optical properties of transparent displays in a variety of common lighting environments.

The second article is by Đenan Konjhodžić, Peter Khrustalev, and Richard Young of Instrument Systems, GmbH. They report on a new technique for extending the usefulness and accuracy of an imaging colorimeter. There are a few different paths one can take to increase the accuracy in such a system: Optimize the accuracy of the "CIE" filters, increase the number of filters used for the colorimetric measurements, or use a set of accurate spectroradiometric measurements of a typical spectral power distribution (SPD) to construct a transformation matrix. There will always be some deviation in the CIE matching filters. Increasing filters adds time and cost. Matrices increase accuracy, but limit the system to measuring accurately only a narrow range of SPDs. Konjhodžić and colleagues propose a method that uses six filters and a range of training spectra. Optimization and appropriate choice and weighting of the training spectra improve the transformation matrices and increase the accuracy of the system for a general range of SPDs.

I had the privilege of reporting on Display Week for *Information Display* magazine. Along with several others, we covered various aspects of the event by writing blogs (http://idmagazinedisplayweek2015.blogspot.com/) and articles for this edition of *ID*. Although not strictly part of the metrology issue, my article covers image quality and metrology for Display Week 2015. In it you will find my take on high-dynamic-range and extended-gamut displays as well as on recent offerings from display-measurement system providers. ■

***Tom Fiske** is currently a consultant specializing in display technology, image quality, and optical metrology. He has been on the technical staff at Qualcomm, Rockwell Collins, Philips Electronics, dpiX LLC, and Xerox PARC. He can be reached at tgfiske@gmail.com.*

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Chinese Displays, Light-Field Displays, and Automotive Technology Lead Trends at Display Week 2015

Chinese display companies showed up in force this year, adding excitement to an already dazzling exhibit hall of displays in sizes ranging from micro to downright huge. A couple of futuristic table-top displays and a wealth of automotive displays also commanded attention. Information Display*'s roving reporters were on the scene to describe these and other advances.*

by Jenny Donelan

ONE OF THE BEST aspects of Display Week is discovering how much progress has been made from one year to the next. Sometimes this progress is expected or hoped for – remember when the big OLED TVs finally hit the show floor a couple of years ago? Sometimes it is surprising – be sure to read about micro-LEDs in contributor Ken Werner's Display Week review on materials in this issue. This year, the editors of Display Week compared notes after the show about what really impressed us. We came up with three major themes: working light-field demonstrations, an aggressive ramp-up in the area of vehicle displays (they were everywhere at the show), and, last but not least, some major demos of large-area displays from Chinese manufacturers.

Our team of roving reporters blogged from the show about what they saw: Tom Fiske alerted us to what was going on in metrology; Steve Sechrist covered microdisplays, near-to-eye, and 3D; Ken Werner looked at new materials; and Geoff Walker wrote about touch. If you missed these blog entries before, you can read them again now. Check out our writers' impressions on *Information Display*'s show blog at: http://idmagazinedisplayweek2015.blogspot.com/. And you can read their full articles on metrology, microdisplays and 3D, and materials in this issue.

As always, we are indebted to our contributors. Here's a quick look at highlights from their pieces in this issue, accompanied by a few of our own notes. Here are the technologies that caught our eyes and our imaginations at the show, starting with some notable displays from China.

Jenny Donelan *is the Managing Editor of* Information Display. *She can be reached at jdonelan@pcn411.com.*

China Rises

Everyone in the industry knows that Chinese display manufacturing is now a powerhouse in terms of overall production. This was the first year at Display Week, however, that products from China made such a strong appearance at the show. These companies have made real progress in recent years in terms of innovation. Among the many worthy Chinese firms in the exhibit hall (including the Innovation Zone) were certain standouts, including BOE, CCDL, CSOT, and SuperD.

As noted in the Best-in-Show article in this issue, BOE Technology Group won an award in the Large-Exhibit Category for its 82-in. 10K display. With its vibrant imagery, this panel was one of those products that stopped many showgoers in their tracks. Although the 10240 × 4320 pixel display was a prototype created to demonstrate how high high resolution can go, the company says that mass production of similar products is not far off. It's amazing to think that we might have TVs of this resolution in our living rooms in a couple of years – hopefully with some worthy content to go with them.

Another display that had showgoers pausing to admire it was a huge (20 square meters) LED-based 3D display from CCDL (Central China Display Laboratories) that showed life-size and larger imagery – pretty arresting when extremely large objects looked like they were coming right at you (Fig. 1). This HD stereoscopic display for indoor use required glasses, but presented a fairly wide central viewing area for the 3D effect and could certainly be viewed by multiple people. The pixel pitch of the demo display was 6 mm, with a resolution of 960 × 576. CCDL also offers these indoor displays in 8- and 10-mm pixel pitches.

Shenzhen-based China Star Optoelectronics Technology (CSOT) was also at Display Week

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Fig. 1: *The team from CCDL stands in front of the company's LED-based 3D display, providing an idea of how large this 3D display really was. In the center is company president Chao Li. Image courtesy CCDL.*

with its 110-in. curved 4K TV (Fig. 2), claiming it as the "world's largest" curved LCD TV, with dimensions of 2.4 × 1.4 m. The set includes a 3840 × 2160 (4K × 2K) pixel display with 10-bit color at 60-Hz refresh, and a 50K:1 contrast. CSOT product engineer Yuming Mo told *Information Display* contributing editor Steve Sechrist that at its thinnest point (the edges), the curved set is only 20 mm thick, with a curve radius of 5500 mm total.

SuperD, based in Shenzhen, China, has developed a second-screen mobile display monitor it calls 3D Box, which shows 2D content from smartphones or tablets in autostereoscopic 3D via a wireless connection with the help of its eye-tracking software. (For more about CSOT and SuperD, see Sechrist's Display Week review on microdisplays and 3D in this issue.)

Next-generation Displays in the I-Zone

Light-field and other 3D displays have thus far belonged to the "fairly futuristic" category of displays, but there are signs that this is changing – something we have been covering in *ID* for quite a while now. Two companies in the Innovation Zone (Display Week's special exhibit space for cutting-edge display technology in development) had table-top displays that went a good way toward bringing the future to us – or the other way around. Zebra Imaging showed a holographic light-field 3D display with a self-contained real-time spatial 3D generator device incorporating a table-top display that it called the ZScape. This was a full-color table-top display that did not require special eyewear and offered compatibility with most software platforms as well as interactivity with off-the-shelf peripherals such as 3D tracking wands and gloves and gaming devices including pointers.

Another exciting table-top display created a 3D image that multiple users could see and manipulate. HoloDigilog's display, from Korea's Human Media Research Center, modified a conventional direct-view system with sub-viewing zones, a lenslet array, and light-field technology, with a QXGA (3840 × 2160 pixel resolution) flat-panel display as the base. This display enabled multiple viewers to see a 3D image projected onto the 23.8-in.-diagonal table-top panel (Fig. 3). According to Sechrist, who also wrote about this technology and the Zebra Imaging demo in his Display Week review on microdisplays and 3D in this issue, the product looked surprisingly good for an early table-top demonstration.

Automotive Displays at Display Week

Display manufacturers, especially those companies dedicated to medical and industrial customers, have long shown vehicle displays at Display Week. But where there used to be two or three such displays per exhibitor, there are now whole rows or sections of booths devoted to this application. This year, Display Week also featured a special technical session track on vehicle displays and trends. According to a recent report from IHS Technology, automotive displays are projected to grow 29.1% in 2015, and from what we saw at Display Week that figure sounds reasonable.

3M was one of the companies with a new emphasis on vehicle display. The company

Fig. 2: *The CSOT team at Display Week (shown here with Display Week contributing editor Steve Sechrist, third from right) is justifiably proud of its 110-in. 4K curved LCD TV. Image courtesy Steve Sechrist.*

Fig. 3: *Holodigilog's table-top panel display projected 3D imagery that could be seen and manipulated by multiple users. Image courtesy Steve Sechrist.*

was showing a line of films designed to enable brighter displays, reduce glare, and eliminate windshield reflection – all issues involved with integrating LCDs in vehicles.

Other companies with designated automotive display areas this year included Fujitsu, JDI, and Tianma Microelectronics USA, which shortly before the show rolled out two high-bright LCD panels with touch aimed at the automotive market. Mention must also be made of Sharp for their free-form display technology that allows panels to be cut with curves and other novel shapes. This will certainly open up dashboard design possibilities in the near future. Read how the company arrived at this technology in Ken Werner's review of materials in this issue.

These examples are but several of all that could be seen at Display Week this year. Be sure to read our contributing editor's offerings to find out more, and don't miss Tom Fiske's excellent update on metrology progress. Display metrology may not make headlines in the mainstream press, but it underpins everything that display manufacturers do and is a vital piece of our industry.

Now that Display Week 2015 is behind us, it's exciting to think about what next year's top trends are going to be. It seems safe to say that Chinese manufacturers will continue to make progress in terms of innovation and new products. And we certainly look forward to more novel types of displays, such as those based on light fields and micro-LEDs. We do know that next year will feature special session tracks on augmented and virtual reality as well as digital signage. No doubt there will be surprises as well. You will have to attend the show to discover them first hand. ■

I-Zone and Best-in-Show Winners

The Society for Information Display honored six exhibiting companies at Display Week 2015 in San Jose last June. These companies were Ubiquitous Energy for best prototype in the Innovation Zone and AUO, BOE, Fogale Sensation, Nanosys, and Nippon Electric Glass for Best-in-Show winners on the main exhibit floor.

Compiled by Jenny Donelan

EACH YEAR, a committee of experts travels the show floor at Display Week in search of the exhibits that most deserve SID's Best-in-Show awards. These awards honor the most significant advances in display technology and systems, products, prototypes, and manufacturing processes as presented by exhibitors. Winners are chosen for their ability to generate excitement not only within the display industry, but among members of the general public as well as the global media and analyst communities. The awards committee considers not only a product's significance, but how effectively it is presented on the show floor. This year's five winners were selected from more than 200 exhibitors.

Also spotlighted in this article is the winner of the Best Prototype Award, bestowed by SID's Innovation Zone (I-Zone) committee on the most outstanding product in the I-Zone, Display Week's special exhibit area for early-stage technology.

I-Zone Best Prototype

This year's winner of the I-Zone award for Best Prototype at Display Week was Ubiquitous Energy for its ClearView Power Energy Harvesting technology. ClearView's technology incorporates a transparent solar cell that can be used to coat any surface to harvest ambient light and generate electricity (Fig. 1). The transparent film covers the display area of a range of products – including wearables, tablets, and digital signage – transmitting light visible to the human eye while selectively converting ultraviolet and near-infrared light into electricity to power the devices. The company states that its mission is to eliminate the battery-life limitations of electronic devices with this technology. Spun out of MIT, Ubiquitous Energy is a Silicon Valley company producing solar cells in its pilot-production facility in Redwood City, CA.

Best-in-Show Winners

Five companies – AUO, BOE, Fogale Sensation, Nanosys, and Nippon Electric Glass – won Best-in-Show awards at Display Week 2015. These awards are presented in three categories of exhibit size: large, medium, and small.

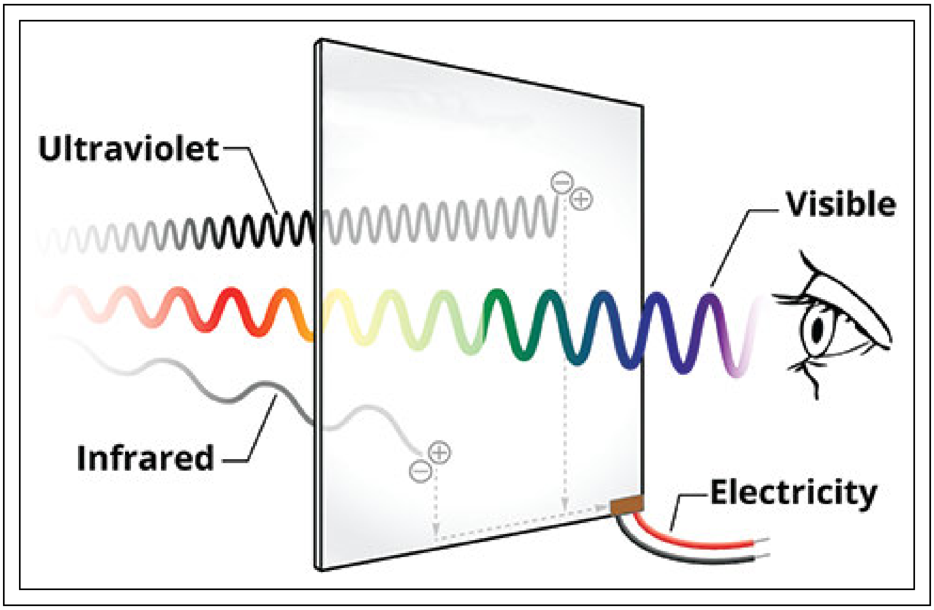

Fig. 1: Ubiquitous Energy's ClearView film product is a solar cell that captures UV and IR light to power electricity, while allowing visible light to travel to viewers' eyes.

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Fig. 2: BOE used imagery from a variety of European settings to show off the capabilities of its 10K LED-backlit display.

Large-Exhibit Category: BOE Technology Group won an award in the Large-Exhibit Category for its 82-in. 10K display (Fig. 2). This is the second year in a row the company has won in the large exhibit category – last year BOE received the award for an 8K display.

According to *Information Display* Contributing Editor Steve Sechrist, this year's 10240 × 4320 pixel display (in 21:9 format) was a one-off created to demonstrate the cutting edge of high-resolution capabilities. The panel uses a direct-LED-backlit scheme. Pixel addressing is done from both top and bottom, using a standard a-Si backplane. The end result, notes Sechrist, is stunning imagery. BOE says work is on-going to modify the technology and prepare it for commercial release in the (not too distant) future.

Medium-Exhibit Category: AUO won an award in the medium-exhibit category, also for the second year in a row, but this time for its 1.4-in. full-circle AMOLED (Fig. 3). This ultra-slim and light display, which features a resolution of 400 × 400, wide color gamut, and low power consumption, was acknowledged for its ability to meet upcoming trends in wearable devices.

AUO has successfully mass produced these circular displays, applying special cut and driver-IC designs to create a full circular shape. To help meet demand for low power consumption in wearable devices, AUO is leveraging the self-emissive nature of AMOLED displays in combination with its self-developed driver circuit to achieve more than two times the duration of other smartwatches currently on the market. AUO has also designed 1.5- and 1.6-in. square AMOLED displays as well as many other types of LCD products to meet ongoing wearable demands.

Fig. 3: AUO's 1.4-in. full-circle AMOLED display features a lightweight low-power design.

Also winning in the medium-exhibit category was Nippon Electric Glass (NEG) for its ultra-thin G-Leaf glass (Fig. 4). G-Leaf is less than 0.2 mm (200 µm) thick. It is created through overflow technology and maintains the advantages and reliability of glass but in a film state. By reducing thickness and weight, NEG has created an environmentally friendly design option in terms of material conservation, smaller carbon footprint, and green processes. This is a material with a great deal of potential for the next generation of applications including electronics, energy, medical supplies, and lighting.

Fig. 4: Nippon Electric Glass's G-Leaf glass is less than 0.2 mm thick and, as a result, is extremely flexible.

Small-Exhibit Category: Fogale Sensation won an award in the small-exhibit category for its simultaneous touch and high-range hovering technology (Fig. 5). This technol-

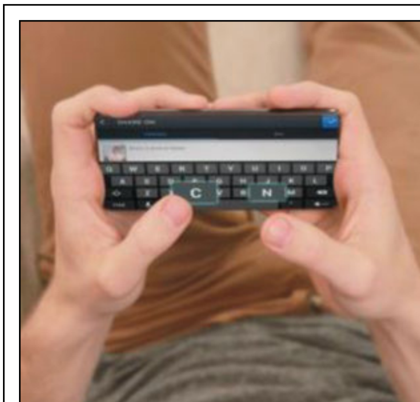

Fig. 5: Fogale Sensation's hovering technology allows accurate input without touch.

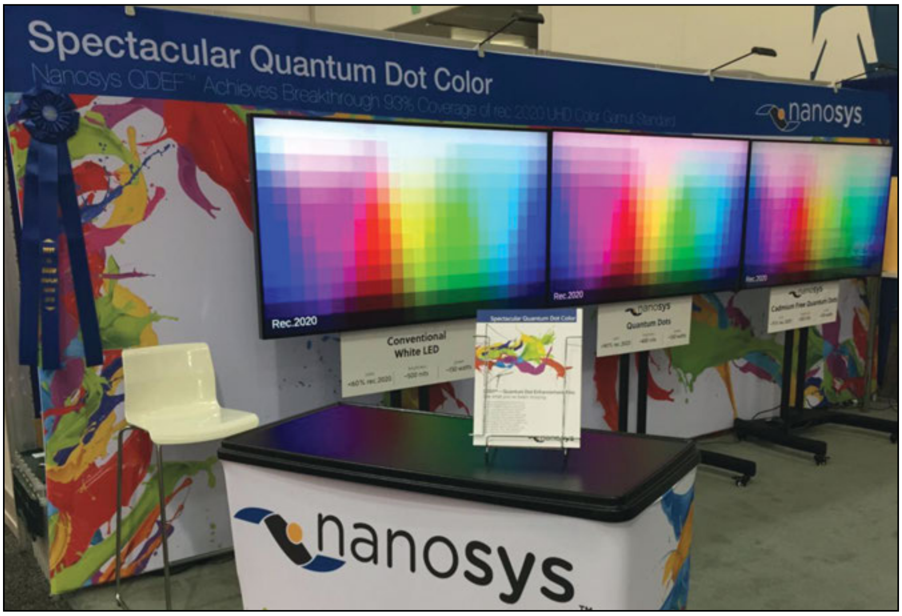

Fig. 6: Nanosys featured a side-by-side comparison of televisions using (from left to right) white LEDs, cadmium-free quantum dots, and quantum dots.

ogy brings additional functionality to the human–machine interface by adding multi-hovering capabilities (detection of fingers above the screen) and edge interaction capabilities (detection of fingers on the side of devices) to state-of-the-art multi-touch technology, without the need for any extra sensor. By combining the power of an integrated circuit with extremely accurate signal-processing software, the Sensation platform enables a new world of interactions, first with portable devices such as smartphones and tablets and soon with any connected surface. This z-dimension works up to 5 cm away (10 cm for hand gestures) from the touch screen or pad.

Nanosys also won an award in the small-exhibit category for its quantum-dot TVs. Nanosys's Display Week demonstration included three matched 65-in. UHD TVs (Fig. 6). Each of the sets used the same color filters, underlying LEDs and direct-lit backlight structures. They were also driven at the same settings from the same content. The only difference was in the phosphor used to create white light in the backlight. These were: conventional white LEDs, Nanosys's Quantum-Dot-Enhancement Film, and Nanosys' Cadmium-Free Quantum-Dot-Enhancement Film. The differences in color performance without noticeable brightness loss were striking. Rec.2020 color-gamut coverage ranged from <60% for the white LED set to ~75% for the set with cadmium-free quantum dots to >90% for the set with quantum dots. This demonstration showed that cadmium-based quantum dots have a significant performance advantage over other phosphor materials and that Rec.2020 is achievable today. ■

Image Quality and Metrology

Display technology delivers the photons to the front of the screen; the human vision system detects the photons and perceives an image. Measurement devices capture and analyze image characteristics and deliver objective quantities that engineers use to inform optical designs and monitor manufacturing processes.

by Tom Fiske

DISPLAY WEEK is all about the presentation and demonstration of visually stunning displays – and this year's event was no disappointment. Set in the middle of Silicon Valley in the first week of June, the show had an energy that was demonstrably high, as evidenced by the 10–15% increase in attendance across all events. Display Week is full of opportunities to network, learn, make deals, and feast your eyes on all the shiny new displays. Eye candy is a big part of the draw of Display Week – with various claims and demonstrations of the biggest, the brightest, the thinnest, and the best. Complementary to all the hoopla on the exhibit floor, and the biggest draw for engineers and researchers, are the opportunities to report on and learn about the latest technology required to create all that eye candy.

One important field of endeavor that touches all the various visual display technologies is the application of human vision concepts to the systematic evaluation of display image quality. Critical to this application are the devices and techniques that we use to measure display optical performance. Display technology delivers the photons and images to the front of the screen (or to the exit pupil); the human vision system (HVS) is there to perceive and appreciate them. Measurement device companies create systems to capture and analyze those photons and images and then deliver objective quantities that engineers use to inform optical designs and monitor manufacturing processes.

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High Dynamic Range

One of the more compelling topics around display image quality this year was high dynamic range (HDR) and extended color gamut. For HDR, there was a Monday seminar,[1] an invited paper in the Imaging Technologies and Applications track,[2] and a presentation at the International Committee for Display Metrology (ICDM) meeting on Tuesday evening. Dolby Laboratories, Inc., is a strong proponent of HDR, given the company's long incubation of HDR display and the Dolby Vision architecture for the capture, distribution, and display of HDR content. Scott Daly and Timo Kunkel delivered a Monday seminar that covered the basics of HDR display technology and human vision considerations. Daly and Kunkel described how the technology delivers more than 6 orders of magnitude of luminance dynamic range – yielding bright highlights and good shadow detail simultaneously. One way to do this is with a dual modulation display. In Dolby's case, at least for the consumer market, it uses an array of LEDs in the LCD backlight that is independently controlled and in synchrony with the image on the LCD. The result is an HDR image created by a low-resolution luminance-only image on the backlight that is combined by the high-resolution image on the LCD. This type of backlight is also known as a local-dimming backlight.

Dolby's studies show that 90% of subjects prefer images rendered with 6+ orders of magnitude of luminance dynamic range (from less than 0.01 cd/m^2 to more than 10,000 cd/m^2 (see Fig. 1).[3] Typical LCDs can only deliver about 3.5 orders of magnitude of dynamic range and a peak luminance of several hundred cd/m^2. Dolby Vision also accommodates expanded color gamut, high bit-depth gray scale (10–12 bits per color channel), and high frame rate (up to 120 Hz). Luminance dynamic range consistently ranks at the top of the list of those image-quality parameters that most people prefer, followed by color gamut, frame rate, and resolution. In other words, if you want to spend your gold on making your image look better, spend it on improving luminance dynamic range.

HDR and wide color gamut enable greater creative choices by making a larger color volume available. However, care must be taken throughout the image capture, transformation, color grading, and mastering processes to preserve luminance and color information so that the intended image can be presented in either cinema or video contexts. James L. Helman of MovieLabs delivered an invited paper[2] describing the background and

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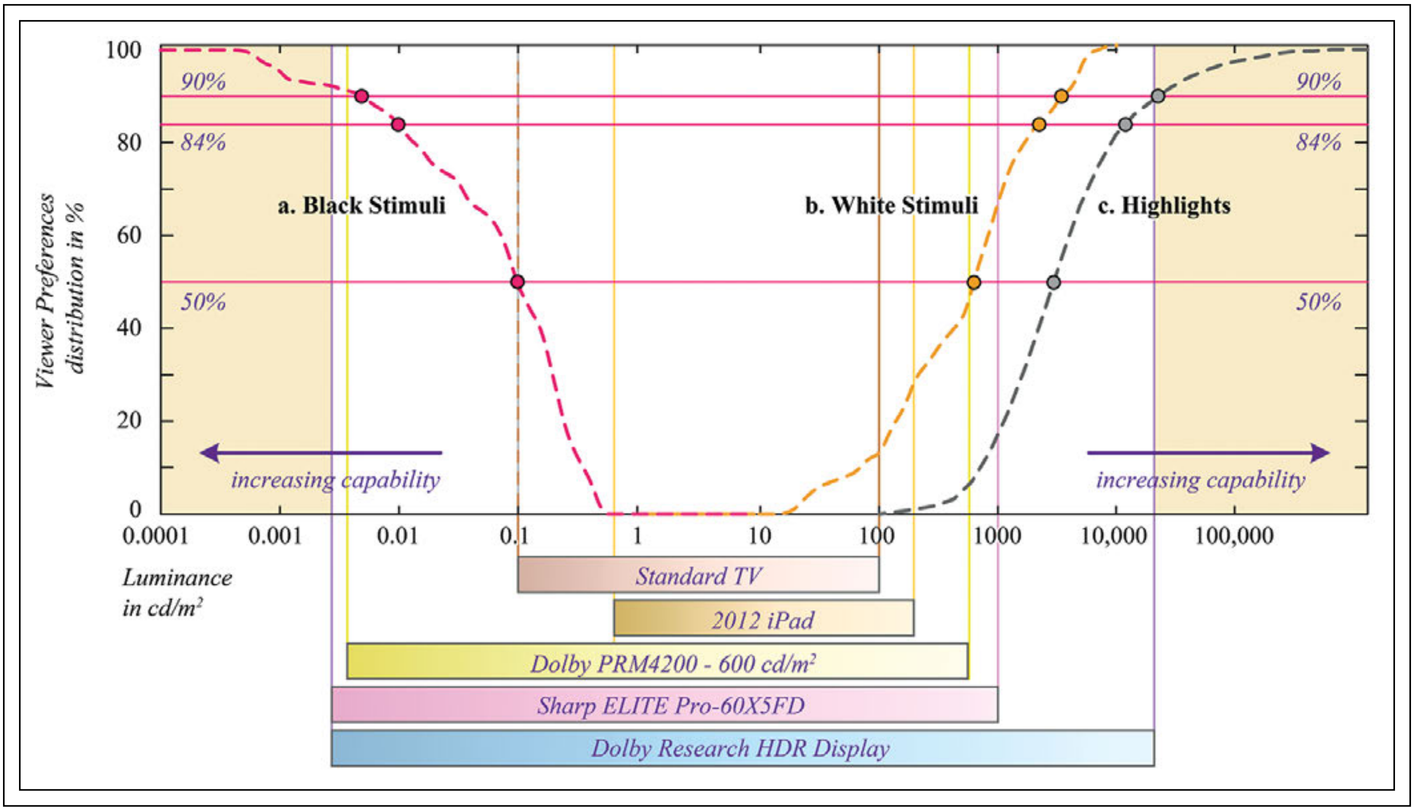

Fig. 1. *Studies from Dolby show that 90% of subjects prefer images rendered with 6+ orders of magnitude of luminance dynamic range.[3] Image courtesy Scott Daly, Dolby Laboratories, Inc.*

reasoning behind some of the standards and architectures in the capture, mastering, and rendering tasks that take advantage of HDR. One process this paper focused on is the adoption and standardization of a perceptually based gray level to absolute luminance transfer curve to replace the traditional gamma curves used since the early days of video production. A 12-bit gray ramp as embodied in SMPTE ST 2084:2014 results in no gray-level banding artifacts and handles the wider primaries proposed for use in BT.2020.

Helman reported that the Academy of Motion Picture Arts and Sciences has developed an advanced color system and digital framework called the Academy Color Encoding System (ACES). ACES promises to simplify and improve the handling of multiple cameras, films, and mastering display devices through the definition of formats and standard color transforms. This will help manage the burden of adding and preserving HDR to content as it makes its way to various display devices. While it is still early, the infrastructure is being put in place to deliver HDR-enabled content in wide distribution. The goal is to realize a video system that delivers images below perceptual thresholds with a full-gamut-color system that matches the capacity of the HVS.

ICDM Tackles Contrast and Dynamic Range

At the ICDM meeting on Tuesday evening of Display Week, Daly and Darin Perrigo reviewed various ways that luminance contrast and dynamic range have traditionally been characterized and reported. Perrigo's presentation focused on problematic issues when characterizing contrast in front-projector systems. Daly suggested extensions of current methods from the Information Display Measurements Standard (IDMS)[4] that will give more relevant and useful information. Sequential contrast ratio (luminance of full-screen white divided by luminance of full-screen black, IDMS Section 5.10) is not adequate to fully describe the dynamic-range behavior of modern displays. This is especially true in regards to emissive displays (*e.g.*, OLEDs), for which the black state is too dim to measure accurately as well as displays that use global or local backlight dimming. ANSI (aka black and white checkerboard) contrast (IDMS 5.26), another popular dynamic-range metric, has an average luminance that is not representative of most imagery (too high), overestimates internal display flare, and underestimates perceived contrast capability.

Daly reviewed several other extant methods for characterizing contrast, including full-white-signal contrast (IDMS 5.9.1), peak contrast (IDMS 5.11), starfield contrast (IDMS 5.12), and corner-box contrast (IDMS 5.13). He concluded his remarks with a description of an extension of the corner-box contrast method by adding measurements of images in which the position and gray level of the bright boxes are varied. These have the advantage of including in the characterization some of the beneficial effects from local-dimming displays in a relevant and realistic way. He also mentioned some potential ways to account for the spatio-temporal characteristics of the HVS. High-spatial-frequency-contrast detection is limited by glare and the MTF of the human vision system.[5]

Fig. 2. The Nanosys booth at Display Week featured three displays (from left to right: a conventional LCD, with quantum dots, with Cd-free quantum dots) – and acrobats. Image courtesy Nanosys, Inc.

Fig. 3. Photo Research displayed its Tru-Image 2D Imaging Colorimeter. Image courtesy Tom Fiske.

Extended Color Gamuts

Another aspect of adding to the color-volume capability of displays is extending the color gamut by making the red, green, and blue color primaries more saturated. The SID exhibit floor offered examples of one of the main methods for realizing this technology. The two most common methods for achieving extended-color-gamut displays are laser (or laser/hybrid) projection or LCDs illuminated by backlights using blue LEDs and quantum-dot technology. Two of the most prominent implementations of quantum-dot backlights are from Nanosys and QD Vision. Both methods use blue LEDs as the light source to illuminate quantum dots that down-convert some of the blue light to green and red light. The result is narrow spectral bands of blue light (from the LEDs) and green and red light (from the quantum dots). The narrow spectral bandwidth of the resulting light – putting spectral power only in the red, green, and blue portions of the backlight spectra – is what enables the wider primaries and extended color gamut. The Nanosys approach uses a blue-LED-backlit light guide coupled with a quantum-dot-impregnated film (supplied by 3M) to deliver the uniformly distributed blue, green, and red light to the back of the LCD panel. The QD Vision approach is exclusively an edge-lit design. The light from a linear array of blue LEDs is coupled with a strip that contains quantum dots, and the resulting blue, green, and red light is uniformly distributed to the back of the LCD panel via a light guide. The QD Vision method has a cost advantage, but may be somewhat less efficient than the Nanosys/3M approach. Nanosys claims better efficiency due to effective light recycling, and its method is compatible with HDR displays because it can more easily accommodate a local-dimming backlight.

QD Vision has announced that its Color IQ technology is in sets from Philips, Hisense, TCL, and Konka. Nanosys quantum-dot-enhanced sets are also available from Samsung and AUO. Both quantum-dot companies were well represented on the Display Week exhibit floor, with stunning demonstration sets. The images in each booth effectively highlighted the visual power of wide-color-gamut displays. Nanosys won a Best-in-Show award (for the second year in a row). It was also the only booth at the exhibit that featured performances by acrobats (!) – see Fig. 2.

The exhibition also highlighted several advances on the metrology hardware front. One example is the new Tru-Image series of 2D imaging colorimeters (Fig. 3) from Photo Research. These instruments feature a thermoelectrically cooled 8- or 16-Mpixel CCD with a high-speed CIE color wheel. They come with Windows-based VideoWin 3 Pro software to control the instrument and analyze the data. Measuring capabilities include 2D-based luminance, chromaticity, correlated color temperature, and CIELAB analysis.

Radiant Vision Systems showed off its line of automated-visual-inspection solutions. The company has been working on fielding configurations that reduce takt time, for example, with its ProMetric I series imaging colorimeter coupled with multiple spectrometers for testing smartphone displays. Their lineup also includes imaging spheres and imaging goniometers for angular measurements.

At the Gamma Scientific booth, we saw the company's Robotic Display Measurement System that combines a 6-axis robot and high-performance spectroradiometers for fast, accurate display measurements (Fig. 4).

Gamma Scientific fields a large array of optical measurement tools including spectrometers, integrating spheres, calibrated light sources, goniophotometers, and LED testers.

Display Week is an important venue for the presentation of new display technologies and applications. A significant goal of display technology is the continuous improvement of front-of-screen image quality. The chief method used to monitor progress and verify image-quality goals is by using proper display optical-measurement methodologies and tools. Display Week 2015 highlighted the advancements of HDR and extended color gamut and how the standards community is beginning to address these features. The exhibit featured examples of extended-gamut displays and several new display measurement tools designed to aid the engineer, technologist, and manufacturer in the pursuit of image-quality improvement.

References

[1]S. Daly and T. Kunkel, Seminar M-2, "High-Dynamic-Range Imaging and Displays," *SID Seminar Lecture Notes* (2015).

[2]J. L. Helman, "Delivering High Dynamic Range Video to Consumer Devices," *SID Symposium Digest of Technical Papers* **46** (2015).

[3]S. Daly, T. Kunkel, X. Sun, S. Farrell, and P. Crum, "Viewer Preferences for Shadow, Diffuse, Specular, and Emissive Luminance Limits of High Dynamic Range Displays," *SID Symposium Digest of Technical Papers* **44** (2013).

[4]International Committee for Display Metrology (ICDM), Information Display Measurements Standard (IDMS), ver. 1.03 (2012); http://www.icdm-sid.org/.

[5]E. H. A. Langendijk and M. Hammer, "Contrast Requirements for OLEDs and LCDs Based on Human Eye Glare," *SID International Digest of Technical Papers* **41** (2010). ■

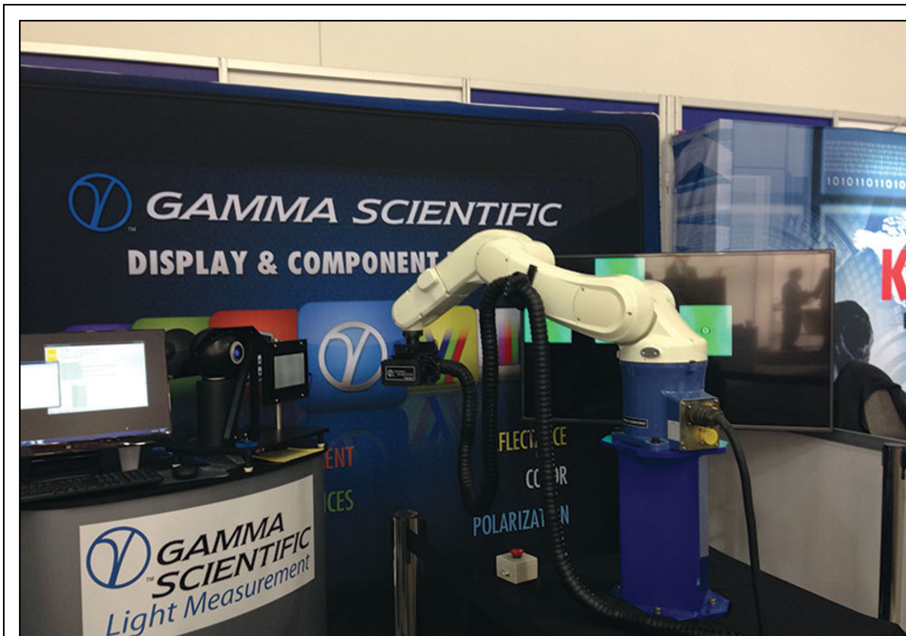

Fig. 4. This Robotic Display Measurement System from Gamma Scientific featured a six-axis robot (at right). Image courtesy Tom Fiske.

Display Materials and Processes

In addition to three major categories of new and evolving display materials – display glass, flexible transparent conductors, and quantum dots – a potentially disruptive material-and-process combination appeared at Display Week this year.

by Ken Werner

WITHOUT new materials and new manufacturing processes, progress in display technology is limited to evolutionary rather than revolutionary changes. On the show floor at Display Week this year, we saw three major categories of new and evolving materials: display glass, flexible transparent conductors, and quantum-dot products. In addition, both on and off the show floor, Sharp was talking much more than previously about how it has implemented gate drivers on a display's image area to create its attention-grabbing free-form displays. Off the show floor, there was considerable discussion about micro-LEDs. Candice Brown-Elliott, Nouvoyance CEO and creator of the Pentile matrix configuration widely used in Samsung OLED displays, said this was the only truly disruptive technology she saw at Display Week this year. And there were additional interesting materials developments that did not fit into any of these categories.

Glass

The three leading manufacturers of display glass – Corning, Asahi Glass Company (AGC), and Nippon Electric Glass (NEG) – along with glass fabricator Cat-i Glass Manufacturing (Elgin, Illinois) were all on the show floor. Also in the exhibit hall were LCD re-sizer Tannas Electronic Displays (Orange, California) and Litemax Technology (Fremont, California), which resizes LCDs and fabricates custom-sized signs and monitors using its resized panels. In an aisle, I also ran into Larry and Like Linden of glass-cutter TLC International (Phoenix, Arizona). I have known TLC as a scriber of straight, curved, and circular lines in glass, but I did not know until this meeting that it also cuts complete LCDs.

Corning was showing several technologies, including its Iris Glass designed to replace polymer light-guide plates in television displays, its flexible Willow glass, two types of Gorilla Glass, and NXT Glass, its "next-generation" product. Each of these varieties is designed to fit specific design needs, although in some cases their capabilities overlap.

According to Corning, an Iris light-guide plate "eliminates space and components, features excellent transmission, and enables thinner, brighter TVs with accurate colors." Also on display was the second generation of 100-mm-thick Willow glass on a carrier of conventional display glass. This allows the glass to be processed on a conventional manufacturing line and then separated from the carrier. The display is now on a very flexible sheet of glass that can be rolled to a rather tight radius, while the expensive carrier can be resurfaced and re-used. If used as the substrate for a flexible OLED display, the Willow glass blocks moisture and oxygen, unlike polymer substrates.

Corning had an extensive display of Gorilla Glass for automotive demonstrations, including "cold form," in which a flat piece of Gorilla Glass is bent to fit the application, and pieces that are hot-formed for applications requiring 3D surfaces or a localized bend – bends that vary in curvature across the sheet (Fig. 1).

Gorilla Glass 4 was announced at CES. Corning reps were happy to explain that it has been engineered with increased fracture resistance if a phone (for instance) is dropped on the display side, while Gorilla Glass 3 is engineered for maximum scratch resistance and scratch concealment. Since the two versions optimize different characteristics, both will be produced. Corning discovered that dropping a Gorilla 3 phone face down on a slightly rough surface such as concrete, asphalt, or sandpaper is more likely to produce fracture than a similar drop onto a smooth surface such as hardwood, granite, or steel. The design of Gorilla 4 resolves that issue, says Corning.

Lotus NXT Glass, Corning's next-generation display glass, is described by the company as "stable glass for high-performance displays." Under typical display processing, this glass exhibits a significantly lower "total pitch variation" – less variation in the pitch of the TFT array relative to the color-filter array. A glass poster showed the improvement to be significant. Lotus NXT is available in thicknesses as low as 0.4 mm.

In its booth, Asahi Glass Company (AGC) featured Dragontrail, its competitor for Gorilla Glass. New was a flexible version called Dragontrail X (Fig. 2). AGC also showed soda-lime glass as thin as 0.23 mm and "Spool," an ultra-thin developmental glass that is 0.05 mm thick. Two or three years ago

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at Display Week, AGC showed its own version of thin glass on a carrier, along the lines of Corning's Willow, but I did not see it this year.

AGC also showed its new "Glass Plus" glass-resin composite component. Glass Plus is a display cover glass (which may contain a touch-panel sensor) bonded to a surrounding polymer frame that can be flush to the glass on one or both sides. The component can therefore do away with the separate frame or bezel that often surrounds the cover glass, decreasing product thickness and removing both a component and an assembly step.

Nippon Electric Glass (NEG), which won an award for best medium-sized exhibit on the show floor this year, featured its own 0.2-mm glass called G-Leaf. NEG's Ted Shimizu highlighted G-Leaf's roll-to-roll processing and possible use as a flexible OLED substrate with inherent barrier qualities. He also mentioned heat shields for laboratory and industrial workers as a possible application that would leverage G-Leaf's impressive transparency.

When it comes to ultra-thin glass, glass-makers are ahead of their display-making customers. Rollable display glass is available now or will soon be available from the three leading fabricators, but display-makers have not yet developed the processes needed to make use of it. LCD manufacturers may not feel justified in spending a lot of money to make major changes to plants and processing to incorporate roll-to-roll, especially since there are difficult problems to solve. One of these is maintaining cell thickness when a flexible LCD is rolled to even moderate radiuses. (Merck KGaA thinks it has a solution for this problem and is looking for development partners. You will find more details later in this article.)

A nearer-term application of ultra-thin glass is OLED displays, even though this application requires a transition to printed OLED front planes. That has been a subject of serious R&D for years. At the beginning of Display Week, DuPont Displays and Kateeva announced they would collaborate to optimize ink-jet printing for the mass production of OLED TVs. "With Kateeva and DuPont combining their considerable expertise in ink-jet printing and OLED materials, the industry is poised to take a significant step forward in achieving low-cost mass production of OLED TV," said Steven Van Slyke, CTO at Kateeva.

Fig. 1 Corning Gorilla Glass can be formed with a "local bend" for automotive applications. Photo courtesy Ken Werner.

From another source that might sound like standard commercial puffery. From Van Slyke (co-inventor of the practical OLED display), it deserves to be taken seriously.

Quantum Dots

A lot of the conversation about quantum dots at Display Week this year revolved around the European Commission's rejection of its own technical committee's recommendation that cadmium-based quantum dots continue to be exempt from prohibition because cadmium is on the European list of dangerous substances.

Initially, this generated some angst in the cadmium contingent and some jubilation in the non-cadmium (mostly indium phosphide) crowd. But a consensus soon emerged that the EC's rejection was based on one minor technical and one procedural matter and that the technical committee would certainly correct the minor issues, after which the exemption would be continued. EC exemptions are often based on there being no alternative solution available, so the issue revolved around the current availability of indium phosphide. However, indium has also been added to the EU's list of hazardous substances. It was generally regarded as irrelevant to the regulators that neither cadmium nor indium is biologically available when encased in a quantum-dot shell.

Nanosys, which won an award from SID for best small exhibit at the show, had three side-by-side TVs that clearly showed why indium-phosphide quantum dots (QDs) are a poor substitute for cadmium. The typical conventional LCD TV with white-LED backlighting in the Nanosys booth had a measured color gamut of less than 60% of Rec.2020, a luminance of 500 nits, and a power consumption of 130 W. The same model of TV modified with blue LEDs and a cadmium QD sheet in the backlight measured greater than 90% of Rec.2020, 400 nits, and a power consumption of 130 W (with the original color-filter array) (Fig. 3). And another example of the same model TV with an indium-phosphide QD sheet measured about 75% of Rec.2020, 350 nits, and 130 W. Clearly, if the goal is to get close to Rec.2020, indium phosphide is not the way to go. Subjectively, the difference between the cadmium QD-enhanced TV and the standard model was dramatic. The difference between the indium-phosphide-enhanced set and the standard one was visible, but sufficiently subtle that consumers might not be strongly motivated to pay a premium for it.

Nanosys Corporate Communications Manager Jeff Yurek wanted me to know that Nanosys has now reached a level of manufacturing volume such that the EPA required it to submit a pre-manufacturing notice, which was accepted. He also announced a follow-on investment from Samsung Venture Investment Corporation. The new funds will be used to expand production capacity as demand increases.

Also at Display Week, Nanosys partner 3M Display Materials and Systems Division showcased LCDs in several sizes with color gamuts of up to 93.7% of the Rec.2020 color gamut. Among the demos was a 4K monitor with 93.7% Rec.2020, which demonstrated, as the booth signage read, "one of the largest known color gamuts in an otherwise commercially available 4K LCD monitor."

QD Vision was exhibiting available commercial products using its IQ Color linear QD element. Among these were a Philips 29-in. monitor, a TCL 65-in. TV, and a Hisense 65-in. curved TV. This is the first curved TV, said CMO John Volkmann, and it uses one edge light and one IQ Color element on each of the left and right edges.

I asked Volkmann if he was concerned that an increasing percentage of TV sets are using direct backlighting for local-area dimming and therefore cannot use QD Vision's linear array. His answer: "There will be a lot of edge-lit TVs made for the foreseeable future." He also said the company was looking at other form factors. As previously stated, the company is working on a QD-on-chip approach and is closer than its competitors. There was a 94% Rec.2020 demo in the booth. To get higher than that, Volkmann said, wide-gamut color-filter arrays as well as high-quality QDs (such as QD Vision's) are required. Volkmann was confident that cadmium would remain legal in the EU and did not mention any fall-back materials for QD Vision.

If Nanosys, 3M, and QD Vision are among the leading QD companies, Quantum Materials Corp. (San Marcos, Texas) is one of the hopefuls. Although not exhibiting at Display Week, QMC announced in a June 1 press release that it had "launched their new QDX class of high-stability cadmium-free quantum dots…." The release continued, "QDX quantum dots have been tested to withstand heat resistance to 150°C for 4 hours with no oxidation performance degradation in an open-air environment." When I asked him, QMC PR person Art Lamstein told me the company is in a "pre-revenue" stage. In addition to the company's original cadmium-based quantum tetrapods based on a Rice University patent, QMC is now also making indium-phosphide dots based on a Bayer patent the company purchased in 2014.

Nanoco (Manchester, UK) was not on the show floor, but I spoke briefly with COO Keith Wiggins and Business Development VP Steve Reinhard. Since Nanoco has for some time emphasized that its QDs are free of not only cadmium, but also of other heavy metals,

***Fig. 2** AGC's Dragontrail X is a flexible version of its Dragontrail product, which competes with Corning's Gorilla Glass. Photo courtesy Ken Werner.*

the company has been almost gleeful in welcoming the European Parliament's decision to turn down the RoHS exemption for cadmium despite its approval by the technical committee. However, as mentioned above, the majority opinion is that this potential gift to Nanoco is likely to be short-lived. As is well known, Nanoco has licensed its technology to Dow Chemical for volume manufacturing.

Transparent Flexible Conductors

Transparent flexible conductors (TFCs) provide added value based on their thinness, light weight, and ruggedness even when they are being applied to displays with rigid substrates. Now that flexible displays are entering the marketplace in significant numbers, that value becomes even more pronounced.

TFCs compete on a combination of cost (low is good), sheet resistance (measured in ohms per square; low is good), transmittance or transparency (high is good), lack of coloration (none is good), haze (the lower the better for most but not all applications), degree of flexibility (measured by the diameter of a mandrel around which the film can be bent), and maintenance of sheet resistance with repeated flexing.

The first technologies in the market were fabricated metal matrices and silver nanowire (AgNW) inks. AgNW inks have taken the lead because metal matrices have a regular pitch that produces moiré interference with the pitch of the pixels unless the matrix is especially designed for each display, and their relatively large feature size means they cannot be used with displays having very fine pixel pitches. AgNW patterns are random and can be used with virtually any pixel pitch, with the silver wires from some makers now so fine that they produce very little haze in bright sunlight. Cambrios is the current AgNW leader.

However, as we saw at Display Week, other ways to play the game have already escaped from university labs and corporate skunkworks. Here, in no particular order, are the entries that appeared on the show floor.

Richard Jansen, VP of Sales and Marketing at SouthWest NanoTechnologies (SWeNT; Norman, Oklahoma), said his company uses both AgNW and carbon nanotubes (CNTs) in two layers. The CNTs are screen-printed on top of the AgNWs, where they serve as a patterning mask. The unprotected AgNWs are washed away with water and then reclaimed. When AgNWs are used by themselves and adhered to the underlying film, Jansen said, they require laser patterning or photolithography. Thus, SWeNT offers an easier and quicker patterning process. The company is several months away from customer sampling.

Fig. 3 Shown is the cadmium quantum-dot-enhanced example from the comparison shown in Nanosys's prize-winning booth. The demo made it very clear that cadmium quantum dots deliver a much greater color gamut than indium-phosphide dots. Photo courtesy Ken Werner.

Canatu Oy (Helsinki, Finland) uses carbon nanobuds for its conducting medium. These budlike structures appear on the exterior walls of CNTs when they are grown, said Canatu marketing and sales VP Erkki Soininen, but Canatu forms its nanobuds directly through the reaction of gasses. The nanobuds, said Soininen, literally fall out of the reacting gasses onto a film in a roll-to-roll process. There is enough adhesion between the buds and the film so the product can be shipped in this form. The customer patterns the film and adds an overcoat and any other films needed for his application. The Canatu process produces TFCs with sheet resistances as low as 100 Ω/□ at 95% transparency. Canatu has just announced its first design win, a flexible consumer product. What product? Soininen can't say. Not yet.

Kelly Ingham, COO of Cima NanoTech (St. Paul, Minnesota and Singapore), told me the company is currently making a major transition to manufacturing and is ramping up high-volume film production in China. Cima NanTech spent 10 years in R&D mode, so this is a very significant change. Ingham and two other members of the strong senior management team are former 3M employees and presumably familiar with high-volume films.

The company's SANTE technology applies proprietary nanoparticles on PET or other polymer film in a wet roll-to-roll process. The nanoparticles then self-assemble into a random metal mesh with 3–6-µm conductors. The process can produce films with a 25-Ω/□ sheet resistance at 87% transmissivity (including the PET). The SANTE's "shading" – the transmissivity loss caused by the metal mesh alone – is only part of the total loss. NanoTech's first app is a game table with 10-finger touch from a U.S. company, in which the large display size and requirement for 6-msec response time demands very low sheet resistance. The technology can go as low as 10 Ω/□ for large sizes.

At Display Week, Stanford spin-out C3nano (Hayward, California) culminated a string of major announcements this year by introducing its highly flexible ActiveGard hardcoat for its AgNW TFC product. C3nano deposits an ink containing silver nanowires that overlap each other in a loose web. The wire web is open enough so light can pass through but dense enough to provide good conductivity. C3nano's wrinkle is "Nanoglue" technology, a catalyst-mediated process that causes the AgNWs to fuse where they cross. This results in greater conductivity for a given wire diameter, which can be used to deliver lower sheet resistance, less haze, or a combination of the two, said CEO Cliff Morris.

These are the TCFs that were on the show floor. Still in laboratories are carbon nanotubes, graphene, and who knows what else. For a category often thought of as simply "ITO replacements," TCFs have become very interesting indeed.

Off the Show Floor

It took five contributors to produce the reporting for *Information Display*'s coverage of Display Week, and we did not come close to seeing and hearing everything. There were many, many technical and business presentations at Display Week, some of quite general interest, some by specialists for a handful of their fellow specialists. Here are short summaries of a very few materials-and-process-oriented presentations I was smart enough to seek out or lucky enough to stumble upon.

For some time, Sharp has been showing examples of its "free-form" displays, which do both the "row" and "column" driving through one edge of the display, leaving the rest of the display to be cut in curves or other unusual shapes (Fig. 4). But until this Display Week, Sharp had not been willing to describe in detail how it distributed the gate drivers throughout the display so that conventional row drivers mounted on a vertical display edge are not necessary.

In the Sharp booth, Automotive Marketing Director for Display Products Thomas Spears did his best to explain the situation but it was hard for him to do so in any detail amidst the cut and thrust on the show floor. More detail was available from the invited paper by Hidefumi Yoshida and 13 colleagues from Sharp in Nara, Japan. The paper, "Flexible Flat-Panel-Display Designs with Gate Driver Circuits Integrated within the Pixel Area," described Sharp's truly clever approach.

Fig. 4 This recent demo of Sharp's "free-form" LCD technology has a curved top and almost no bezel on the top three sides. The display incorporated touch on the outside edges of the display, not the surface. Photo courtesy Ken Werner.

Yoshida and colleagues began with a well-known method, gate-driver monolithic circuitry (GDM). With GDM, the shift registers and output transistors of the gate drivers are deposited on the vertical edge of the display at the same time as the switching transistors are fabricated. This is an alternative to the more conventional approach of using ICs for the gate-driver circuitry. Since GDM circuitry can occupy significant real estate at the vertical edge of the display, especially when implemented in amorphous silicon, it requires a wide bezel, which is not compatible with current display preferences or with gracefully curved display contours.

Here is where Sharp's cleverness comes into play. First, instead of putting the GDM circuitry on the vertical edge(s) of the display, Sharp locates it in one or more vertical "bands" within the display area (Fig. 5). I've put "bands" in quotes because Sharp has done far more than simply shifting the left-edge circuitry into the image area. Sharp disperses the transistors of the GDM circuitry so individual transistors are located at individual pixel locations and interconnected via additional surface connections and a large number of through holes in the display. Thus, the gate-driver control signals enter through the bottom edge of the display, which is also where the source drive ICs are located. The gate signals travel from the dispersed GDM circuits horizontally to the pixels, but entirely within the image area. This allows the left, right, and top edges of the display to have very thin bezels, which can be shaped with great freedom. Sharp has widely shown a triple curve that is appropriate for the tachometer, speedometer, and combined temperature/gas gauge in a primary automotive instrument display. This is a significant innovation in display architecture that is, as Yoshida *et al*. carefully note, just as applicable to OLED displays as to LCDs.

Dow Corning's EA-4600 HM RTV hot-melt adhesive was initially developed as an alternative to double-sided tape in the assembly of cell phones and other electronic devices. In this role, it can be 20% of the cost of DS tape in large-volume applications. But because the material requires dispensing equipment that

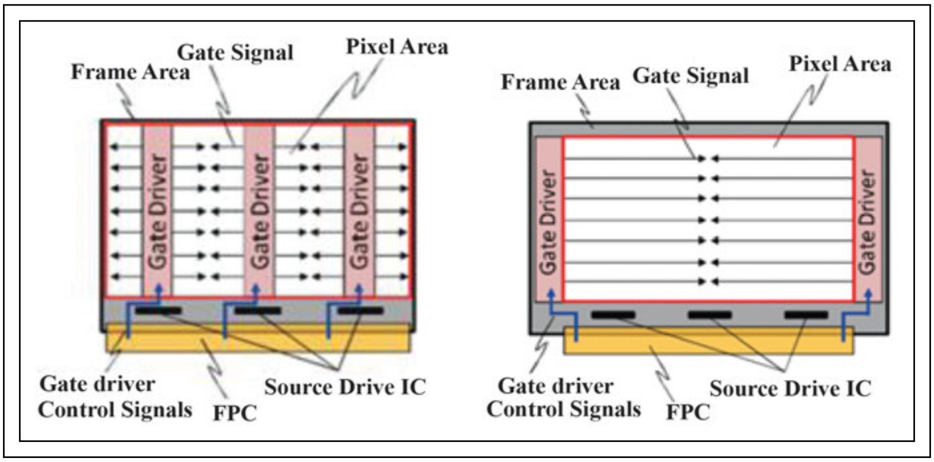

Fig. 5 At right, a conventional display has gate-driver circuits located in the bezel area. At left, the Sharp display has gate drivers integrated within the pixel area. (Graphics: Yoshida et al.).

costs in the vicinity of $100,000, it takes high volumes for the much lower material cost to deliver maximum savings.

In a poster paper entitled "Silicon Hot-Melt Adhesive Providing Protection, Waterproofing and Reworkability for Precision Assembly of Electronic Devices," Ryan Schneider, Glenn Gordon, and colleagues from Dow Corning explained that one advantage of the silicon hot melt is that it can be used to make to make beads of 0.5 mm or less when, for example, making a peripheral seal on cell-phone window glass, where maximum screen area is crucial. It is, said Gordon, impossible to cut DS tape that finely.

Although the original conception was to use the hot melt as an adhesive for assembly, if you deposit a peripheral bead on only one surface and allow it to cure, it forms a gasket that can be used to provide water- and dust-proofing for a snap-on cover – and the cover can be removed and re-snapped indefinitely while still retaining its water-proofing characteristics. This approach was used to waterproof the back cover of a recent, popular smartphone model. Although Schneider and Gordon would not identify the model in question, reliable industry sources tell me it was the Samsung Galaxy S5 (Fig. 6). Dow Corning is talking to other manufacturers about adopting the technique.

Merck KGaA (Darmstadt, Germany) offered a substantial number of technical presentations. Two were particularly interesting. In an invited paper, Merck's Martin Engel and colleagues discussed the company's ultra-bright fringe-field-switching (UB-FFS) formulation, which provides 15% more transmittance than standard FFS. The product is currently available but various parameters – including switching speed and reliability – still need to be improved, said Engel.

Engel noted that in both UB-FFS and FFS, transmittance depends on the polarity of the applied voltage, and this produces flicker. The reason is not fully understood, but some formulations can reduce the flicker/switching-speed trade-off.

In the Q&A, Facebook/Oculus VR executive Mary Lou Jepsen asked if the diffraction seen at the edge of the fringe field is any less than in UB-FFS. Engel speculated that there would be less diffraction because there is less tilt at the edge of the fringe with UB-FFS.

In "Opening the Door to New LCD Applications via Polymer Walls," another invited paper from Merck KGaA, Nils Greinert and his colleagues revealed a practical way of making LCDs with internal polymer walls. Currently, most of the interest in flexible displays is focused on OLED displays, which are amenable to being bent if they are fabricated on a flexible substrate. It's harder with LCDs, which depend on a precisely maintained cell gap for proper operation. Bending a conventional LCD decreases the cell gap. (Current curved LCD TVs side-step this problem by bending the LCD so slightly that cell-gap reduction and substrate misalignment remain insignificant.)

The problem could be solved by fabricating walls between the flexible substrates (and in between the pixels) to stabilize the cell gap when the display is bent. This is not a new idea. NHK showed a simple ferroelectric LCD with walls in the early 2000s, and the Merck authors cite other early efforts. But there was not a process for fabricating the walls that was efficient and compatible with

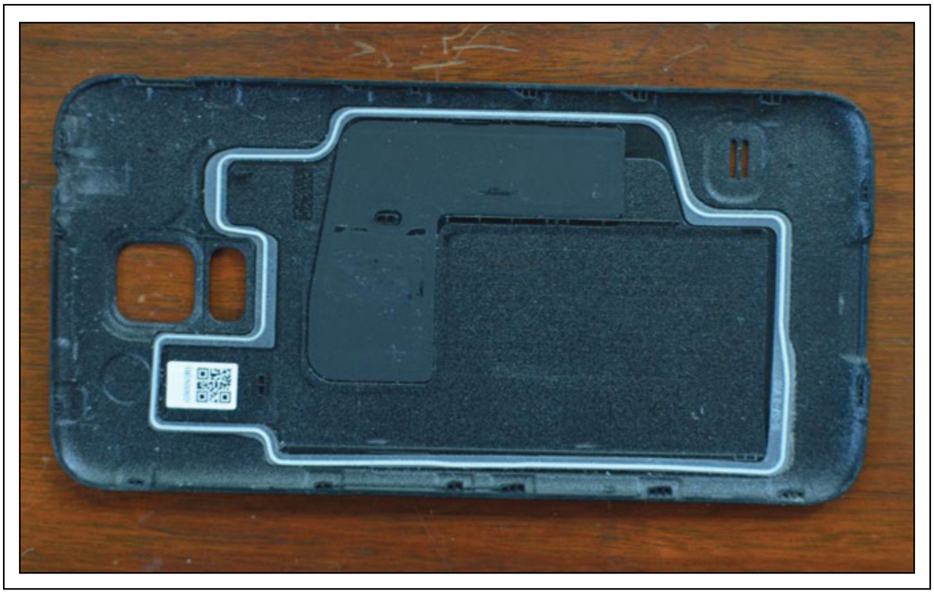

Fig. 6 Dow Corning's EA-4600 HM RTV hot-melt adhesive (presumably) forms this waterproof gasket in the author's Samsung Galaxy S5 phone. Photo courtesy Ken Werner.

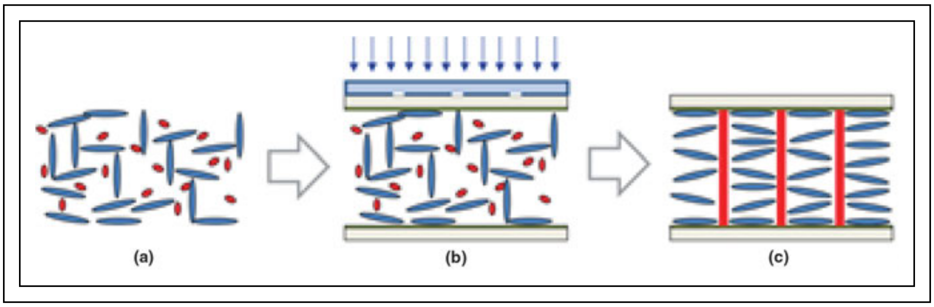

Fig. 7 (a) The "wall LC" mixture consists of the LC host (blue rods) and polymer precursors (red dots). (b) The mixture is deposited in the display and exposed to UV radiation through a photomask, which results in polymerization-induced phase separation. (c) Polymer walls form in the irradiated regions. The liquid-crystalline phase is restored and, equally important, has aligned itself with the polyimide layer. (Graphic: Greinert et al.*)*

standard LCD fabrication techniques. That is the problem Merck KGaA has solved.

Greinert and his colleagues mix polymer precursors together with the LC host and homogenize the mixture by heating it above the liquid-crystal clearing point. The authors call the resulting mixture a "polymer wall LC mixture." The mixture is enclosed between the two substrates and UV-irradiated through a photomask. The walls form and the LC host settles down to its expected orientation and tilt angle. Remarkably, if the proportion of precursor to LC material is chosen properly, all of the monomers are incorporated into the polymer walls and the LC characteristics are very, very close to what they are in a conventional process (Fig. 7).

The authors note that "total monomer concentration, photomask, cell, and UV equipment have to be considered and optimized in order to produce the desired polymer-wall pattern." However, they also say, "We have found that commercially available monomers do not satisfy the simultaneous requirements of good mask reproduction and mechanical stability." Merck KGaA is currently developing tailor-made monomers to solve this problem.

Following the paper, Robert Miller (Senior Business Manager, LC and Advanced Technologies at Merck's U.S. subsidiary EMD Performance Materials) told me, "We feel we have demonstrated the effectiveness of the basic materials and process, and we are now looking for development partners."

Last but Certainly Not Least: Micro-LEDs

John Rogers (a professor at the University of Illinois and co-founder of and technology advisor to X-Celeprint) presented a Monday seminar entitled "Microscale LEDs for Multifunctional Display Systems." You may recall that this is the technology Candice Brown-Elliott called disruptive. Microscale LEDs (or micro-LEDs or µ-ILEDs) were not well known outside the relatively small community of people who work on them before Apple acquired LuxVue last year, at which point a much wider community started scrambling to learn about them.

It would be very attractive to make phone, tablet, and TV displays from inorganic LEDs, but there has been no inexpensive way to assemble LED chips into dense RGB arrays. If it were possible, such displays could be several times as efficient as OLEDs and have longer lifetimes.

What Rogers and colleagues, along with a handful of micro-LED companies, have learned to do is to initiate the epitaxial growth of AlInGaP LEDs on recyclable GaAs wafers. Rogers described a process for making multiple layers of LEDs with sacrificial layers in between that allow the layers to be lifted off. That's impressive, but solves only half the problem. If we went no farther, we could make no more than wafer-sized displays (Fig. 8).

The second part of the solution was covered by Chris Bower, CTO of X-Celeprint (Cork, Ireland), who described the company's technology for performing transfer printing of the chips using elastomeric stamps utilizing peel-rate-dependent adhesion. To oversimplify shamelessly, if you place the stamp on the layer of chips and peel it off quickly, the chips adhere to the stamps. By impressing the stamp on the target substrate and peeling it off slowly, the chips adhere to the target. This is also impressive, but it still does not create LED arrays any larger than the original lattice-matched array.

As it turns out, it is relatively simple to impose patterns on the stamps that result in picking up every 10th, 20th, or nth LED before depositing them on the substrate. In this

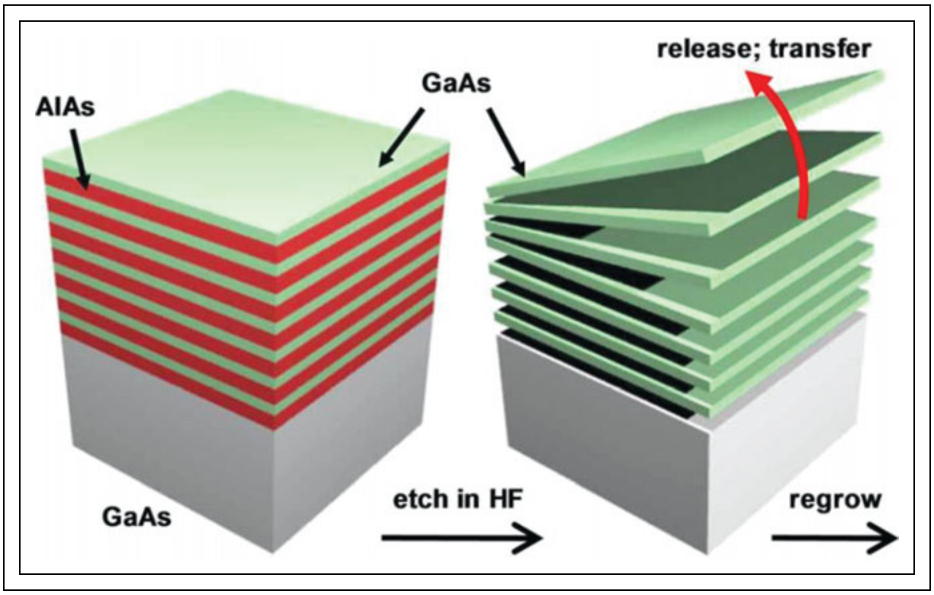

Fig. 8 This diagram shows a multilayered epitaxial lift-off. (Graphic: John Rogers).

way, you can go from the dense array of the original wafer to a sparse array on the target substrate. In principle, this allows you to make μ-ILED displays of virtually any diagonal. Bower said that X-Celeprint has made 150-mm stamps. Making larger ones is just a matter of engineering, he said, not science.

Now, obviously, if you can transfer-print u-ILEDs you can also transfer-print CMOS switching circuits and no longer worry about the instability issues of a-Si and IGZO TFTs or the scalability issues of LTPS. In fact, you can transfer-print many types of "chiplets" and even assemble them in three-dimensional structures. Displays are only one application of the technology.

Some experts have speculated that the first μ-ILED display we see in a commercial product may come from LuxVue and appear in an Apple iWatch as early as next year. While that may be a touch on the early side, it will be interesting to see if and when the technology starts to make inroads. Is it possible that μ-ILED, not OLED, will become the universal display that replaces the LCD? That is a question that should be commanding the attention of all of us in the display community.

We led off this article by saying new materials and new manufacturing processes are basic to major display developments. That becomes very clear in the context of μ-ILED and transfer-printing technology. ■

Microdisplays, Near-to-Eye, and 3D

New display technologies, including some new twists on tried-and-true display technologies, are helping displays integrate ever more seamlessly with the devices we use every day.

by Steve Sechrist

AT THIS YEAR'S Display Week in San Jose, California, we saw a growing renaissance of some tried-and-true display technologies – including and especially new-use models for microdisplays in both the consumer-wearable and automotive markets, the latter in the form of head-up displays (HUDs). These use models included applications created by size and weight breakthroughs and lower power requirements, and enhanced, in part, by new semiconductor material compounds – all discussed below. This technology trend even goes beyond displays, with some microdisplay companies now targeting industrial optical inspection and sensing in very-high-tolerance manufacturing. Some companies are now obtaining more than half of their revenue from non-display-related applications.

Near-to-eye (NTE) and 3D displays are also experiencing a resurgence, particularly when empowered by eye-tracking sensors and algorithms that boost system understanding of "user intent." These technologies are being used to help generate autostereoscopic 3D solutions and light-field holographic displays that begin to push the boundaries of current display capabilities.

Meanwhile, in the HUD space, we discovered new film technologies that transform simple glass (in the car and elsewhere) into next-generation displays that, when combined with the latest sensor technology, can bring to reality visions of a display future only dreamed about in sci-fi film and literature just a few short years back. It's exciting to see these older technologies rising again with some new twists.

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NTE Technology for Wearables

Wearables are one of the fastest growing markets in the microdisplay category. This fact is not lost on headset-maker Kopin, a company that was in the wearable-display business before it was even called that (see Fig. 1 for some examples of its applications for various devices). Kopin's Dr. Ernesto Martinez-Villalpando presented at Display Week's IHS-sponsored Business Conference, explaining how augmenting the human visual system with HUD or NTE devices offers the

Fig. 1: Kopin demonstrated a table-top of display applications for its small display components.

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opportunity to move beyond simple data interfaces such as display monitors or smartphones. Much like bionic prosthetic limbs, HUD and NTE technology begin to address the possibility of true augmentation.

As an example, Martinez outlined the design goals of Kopin's "Pupil" display module. These include size, weight, battery life, and display resolution. The technology empowers augmented-reality applications that have already proven valuable in supporting and documenting complex service and maintenance operations in the field. For instance, rather than carrying a thick operations manual to a tower antenna or wind turbine needing maintenance, service personnel can call up specific operational procedures with the added benefit of documenting the maintenance that took place. Beyond B2B, other applications include enhanced situational awareness and even the ability to see through buildings to know what is on the next street – the next-best thing to X-ray vision.

We see the Kopin NTE device as a technology milestone in the space developed by other leaders in the field, including Google, with its Glass prototype project that pushed the limits of wearable (OK, "geeky") technology and Apple, with its "taptic" version of a haptic feedback engine that notifies users with a slight tap on the wrist. What will be interesting in this space is just how we begin to adapt and take advantage of new sensory input that moves us beyond the audio and visual cues we have previously relied on.

At the same conference, Margaret Kohin, Senior VP of eMagin, said her company was looking to use its emissive OLED-XL (on silicon) microdisplay technology with resolutions as high as 1920 × 1200 pixels to bridge the gap between the consumer space and military applications in HUDs. She said eMagin's consumer applications initiative has been in place since late 2014. The latest advance in this area is a 4-Mpixel OLED microdisplay that offers a luminance of 6500 cd/m^2 and a 90° FOV (field of view) while delivering greater than 75% color gamut with 85% uniformity. Sizes range from 0.86 in. (WUXGA) to 0.61 in. (SVGA). There is even a 15-µm VGA version that weighs less than 2 grams.

Kohin also made the point that the mid-term wish list for AR and VR markets is a very good fit for OLED microdisplays. She said the wish list includes benchmarks such as high luminance in the 20,000–30,000 cd/m^2 range and high contrast (true black), low power consumption (OLEDs require no backlight), and small form factor.

Fig. 2: These ForthDD high-resolution microdisplays shown at Display Week are now used in machine-vision projects well as high-end viewfinders.

If the Google Glass pull-back has discouraged some companies in the consumer NTE industry, eMagin is not among them. At Display Week, Kohin was clearly bullish on the space and said she believes that along with continued B2B and government clients, the consumer space is ready to move.

Meanwhile, in the exhibit hall at this year's Display Week, Greg Truman, CEO of ForthDD (now part of Kopin), talked to us about the company's high-resolution LCoS microdisplay business (Fig. 2) and the applications opening up in the non-display space. One example of the latter is in spatial light modulation, with applications for its liquid-crystal–on–silicon (LCoS) chips in QXGA resolutions used for automated optical inspection equipment. "The big win comes in improved accuracy on the production line," Truman told us, "in what is now a cubic micron accuracy business." While the NTE business is still contributing up to 50% of Kopin's revenue, the new field of automated optical inspection is helping diversify the business, lowering dependence on the display market alone. This technology is now empowering machine vision with a highly discrete ability to "see" flaws in solder or other assembly operations. This goes well beyond the visual acuity of human inspection.

Parent company Kopin has a long history of making HUDs for pilots, and the firm supplies display components including the complete optics package, driver software, a software development kit, and test and development platforms for its military and B2B customers, which include Thales, Elbit, and Rockwell Collins.

Elsewhere in the exhibit hall, another microdisplay designer, Fraunhofer Institute for Organic Electronics, showed off its new full-color SVGA bi-directional microdisplay OLED (Fig. 3) that serves double duty as both a display and eye-tracking scanner. An embedded image sensor is used to track eye movements with algorithms designed to target the center of the pupil. This greatly enhances the system's ability to discern user intent, offering some huge benefits in head-worn mobile personal electronic devices. The design includes a four-color (RGBW) pixel arrangement that adds an embedded photodiode image sensor used to detect light. The display is based on a 0.18-µm CMOS process chip that delivers an SVGA resolution display with a luminance of 250 cd/m^2. This idea of embedding sensors into the microdisplay to enhance the overall user experience is encouraging and will likely continue. Early applications include video or data goggles, augmented-reality eye wear, and even machine-to-machine applications. Once the resolution is enhanced beyond 720*p*, Fraunhofer anticipates suitability for biometric and security applications that can benefit from discrete iris detection algorithms, but there is more fundamental chip development work to be done before those become a reality.

Fig. 3: Fraunhofer's bi-directional OLED microdisplay appears in the bottom left side of this image.

Participating in Display Week's Innovation Zone this year was Korea-based Raontech, demonstrating a new 720*p* HD LCoS microdisplay module (0.5 in., 1280 × 720 pixels) in a super-compact 8 mm × 8 mm optical package using an LED light source (Fig. 4). This was shown with applications proposed for automotive HUDs, wearable smart glasses, and pico-projectors moving to HD. Dual-display (two-eye) support for display goggles was also on the Raontech product offering list. We were told a full-HD version is on the design roadmap.

In a technical session devoted to microdisplays, Dr. Brian Tull from Lumiode, a Columbia University start-up company, presented a paper titled "High Brightness Emissive Microdisplay by Integration of III-V LEDs with Thin Film Silicon Transistors." He also showed the company's next-generation microdisplay, a photolithographically pixelated LED (think LED-based digital signs shrunk down to microdisplay size.) The Lumiode team uses a type III-V semiconductor compound material that creates an emissive microdisplay using TFTs that act as both the light source and the image component. Creating a high-brightness emissive LED microdisplay using TFTs that is based on proven methods used in both LCD glass substrates and OLED display manufacturing represents a significant technological achievement. According to the company, "Our transistor process flow follows a conventional thin-film process with several modifications to ensure process compatibility with LED epitaxial wafers." The result is a monolithically integrated thin-film device using standard GaN-based LEDs from a combined process flow.

Tull claims several advantages for his modified conventional thin-film process over traditional liquid-crystal or micromirror devices, and even over "low light" emitting OLED-based microdisplays. He believes that LEDs are the best choice for miniaturization of wearable applications as they offer significant advantages in the most important display metrics; a luminance of 20 × 10^6 cd/m^2, the highest efficacy (100 lm/W), and the most robust lifetimes (50 khours and up). This new approach using type-III and type-V compound silicon has the potential to shift the direction of small-display technology, perhaps for generations to come.

3D Moves to Eye Tracking at SID

Using eye tracking, along with software, core display hardware, and a complex set of optics, a company called SuperD that is based in Shenzhen, China, has developed a second-screen mobile-display monitor it calls 3D Box. The "Box" shows 2D content from smartphones or tablets in autostereoscopic 3D via a wireless connection with the help of its eye-tracking software.

Content in 2D and user (via touch) control are provided through a wirelessly connected mobile device for, say, mobile game interaction that can be made viewable on the SuperD display in autostereoscopic 3D. Previous versions of this technology surfaced as far back as 2011, using a laptop screen for input, but recent eye-tracking improvements have made the 3D effect much more compelling. This is because when the eye position is known, the image can be rendered in 3D in real time by sending the 3D pixel data through a lens located on the device's LCD panel. This autostereo content is then reflected to the user's eyes.

SuperD also sponsored three papers at the Display Week symposium, including work on a polarizer-free LCD lens and highlights of a study on the relationship between driving voltage and cell gap in a two-voltage driving structure. In the poster session, SuperD also showed contrast enhancement using an electrically tunable LC lens performing a focusing function by electrically varying the focal length to achieve contrast. The advantage is no change to image magnification due to focusing, so contrast is enhanced merely by controlling focusing and defocusing of images through simple arithmetic operations.

Another 3D technology found in the I-Zone came from Polarscreens, Inc., from Quebec, Canada. This company also makes use of advanced eye tracking by providing full-resolution stereo vision without 3D glasses, goggles, or other worn apparatus by using a camera-based eye-tracking system. It tracks both the head and eyes to create what it calls "eye gaze data" using motion prediction algorithms. Eye rotation speed and the point of eye focus are calculated from this gaze data and then used to create the 3D effect.

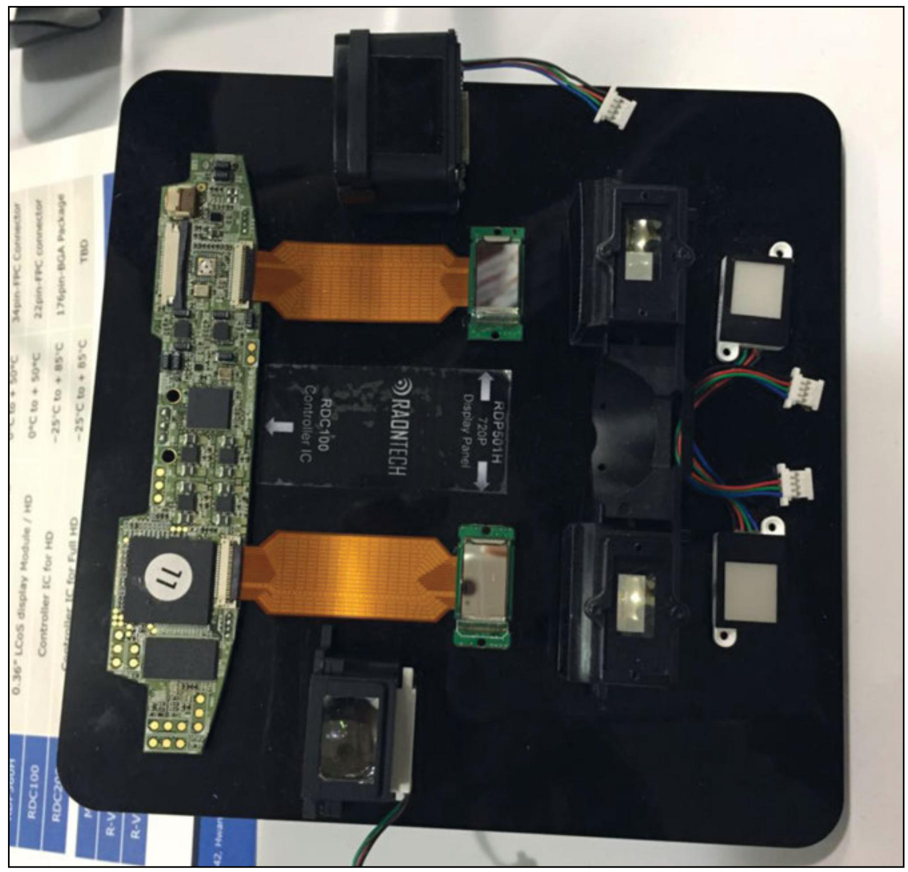

Fig. 4: This Raontech working prototype board shows wearable LCoS MD modules.

Here, a stereoscopic video is constructed using three fields (one common and two alternated parallax barriers.) They are displayed in sequence but at different times; consequently, each field does not register on the eye's retina at the same location due to eye rotation between each field. Eye tracking and head tracking are used to determine eye rotation speed in both the x and y directions, and that data is used to shift the video content of each parallax-barrier field to match the rotation speed, reconstructing a perfect image on the user's retina.

In essence, a computer-generated image is rendered based on the user's viewpoint using two virtual cameras and the motion-prediction information, re-aligning each parallax field's video content with the common field at the user's retina. It works for both still images and 3D objects and video.

One other benefit from this approach, since the object of focus is known by the system, is that the data can also be used to improve the sharpness of the fixed object while blurring the background data, creating a depth-of-field illusion that is quite compelling. The FOV ranges from just 6 in. to a whopping 7 ft., the group said. Eye tracking is disengaged if the head tilts out of range or 2D content is selected for display. This technology was originally developed to counteract the effect of eye rotation during virtual-reality sessions in glasses-free autostereoscopic systems.

A Light-Field-Display Approach to 3D

Zebra Imaging was in the I-Zone with a holographic light-field 3D display with a self-contained real-time spatial 3D generator device incorporating a table-top display that it calls the ZScape. On display were applications in simulation awareness and "visitation," so the group was clearly targeting the military but was also able to create dynamic and interactive images from diverse data sources including LIDAR, CAD, biometric, and bathymetric (ocean topography) – all in real time. This is a full-color auto-viewable (no special eye wear) table-top display offering compatibility with most common software platforms as well as interactivity with off-the-shelf peripherals (gesture, 3D tracked wands and gloves, multi-touch, and gaming devices including pointers.)

The images are made from an array of "hogels" or holographic elements, created in the light-field display. According to Zebra Imaging's I-Zone application: "The display plane is modeled as a 2D array of microlenses that correspond to camera positions on the display surface, defining a mathematical model of the physical emission surface of the display in model space. Hogels are computed at the center of every microlens from the perspective of the holographic-display plane. 3D operations such as pan, scale, zoom, tilt, and rotate are accomplished by transforming the modeled display plane through the scene's model space. Thus, the modeled display plane becomes a window into the 3D scene which translates into the projected 3D light-field visualization." My personal impression is the technology is yet one more milestone in moving toward holographic displays with some useful (even critical) military or security applications. For example, it can provide vital, real-time data to planners, decision makers, and perhaps even for medical apps. That said, we are still a bit far away from consumer-level displays of this type.

University of Seoul 3D Table-Top

Another table-top 3D display in the I-Zone was from the University of Seoul's Human Media Research Center in Kwangwoon, Korea. This immersive table-top 3D display system is called "HoloDigilog." It is a modified conventional direct-view system that cleverly uses sub-viewing zones and a lenslet array and light-field technology, and a QXGA display (3840 × 2160 pixel resolution) flat panel as the base (floor of the hologram if you will.) It allows for multiple viewing of a 3D image that can be projected on to the 23.8-in.-diagonal table-top panel. It looks surprisingly good for a table-top 3D display. The group said it had (but did not bring) a 20- and 30-in. version of the display in Korea as well.

HoloDigilog consists of a four-part system that includes (1) a real-time pick-up of a 3D scene by capturing its intensity and depth images, (2) depth compensation used to co-ordinate between the pick-up and table-top display, (3) an elemental image array (ELA) that is created through image processing using compensated intensity and depth mapping, and (4) the EIA displayed on the immersive table-top 3D display system. Total "boxels" in the existing system are limited to 300 × 200 × 256 vertical and to increase the object projected, an even higher-resolution panel is required. There is also an optical projection layer (patent pending, so few details were given.)

On the application side, the group mentioned a table-top display for sporting events, *etc*., but creating content for this display, then mass distribution, may still be a long way off. Even a simple application like the one shown in *Star Wars*, a "Princess Leia" version of FaceTime with 360° viewing for the entire family to see, would be an awesome "killer app." But don't mind me – I'm just dreaming here. The Korea-based group said it is possible to do real-time streaming content, but that it was highly processing intensive. In short, this technology is still in its very early days, but, that said, it is exciting to see the progress.

Fig. 5: Sun Innovations creates color-sensitive RGB films and excites them with a projector to create full-windshield HUDs.

HUD Wavelength-Selective Excitation

Sun Innovations was at Display Week in the exhibit hall with a full-windshield HUD system that renders objects in color using a novel emissive projection display (EPD). Remarkably, images in multiple wavebands between 360 and 460 nm will be projected onto a windshield coated with Sun's fully transparent emissive films using a UV light projector. The process is called projective excitation and uses a laser or LED-based HUD projector for what company namesake and founder Ted Sun calls wavelength-selective excitation (WSE).

On the materials side, specially treated color-sensitive films are made in optically clear sheets <50 μm and stacked in an RGB configuration (Fig. 5).

This luminescent material is added to standard automotive glass with polyvinyl butyral (PVB) based resin films embedded (used to create shatterproof windscreen glass in cars). Sun stacks these color-sensitive RGB films and excites them using a display engine powered with a UV light source, each film with distinctive absorption and emission characteristics to excite the red, green, or blue layer. Sun insists there is no extra coating step or added change to the primary manufacturing process used to create the film. Best yet, Sun said these films can be produced in a roll-to-roll process that is low cost and haze-free (no pixel structures to interfere with light transmissivity). If this sounds like the Holy Grail for the automotive display industry, we agree.

For automotive applications, Sun combines this material with a HUD projector based on blue-ray laser and x-y laser image scanners. The group is working on a separately designed palm-sized full-windscreen HUD projector with integrated control and interface boards to speed adoption and design flexibility. In principle, the projector encodes the original color image into three excitation wavebands, which excites the corresponding film layer, generating the RGB. The trick is to do this without interfering with the excitation or emission from other two layers. In full implementation, this system can display information on any window in the car. Other horizon milestones include embedded sensor integration, touch and gesture control, and voice commands for hands free operation.

Display Evolution Empowers a New Wave of Devices

So there you have it, a primer on microdisplays, NTEs, and 3D displays at this summer's Display Week. And while we see these examples of new film-based displays and table-top holograms are still a bit far out, it is exciting to see what may be the beginnings of our future car, window, living room, and mobile experiences, as seen on the Display Week show floor. Some milestone NTE technologies have finally reached size, weight, and battery-life thresholds that will empower the next wave of wearable AR and VR devices. These will push us toward an ever-tighter integration of virtual and augmented reality with real life. In addition, displays are becoming ubiquitous, as sensors and microprocessors did before them. Displays that provide easy access to information are becoming the norm in virtually all parts of our lives. Look for displays to melt into the background, only to emerge when needed and perhaps when anticipated by the smart objects all around us. Until that time, the industry continues to work, integrate, and iterate toward fulfilling our dreams of ever more efficient and seamless devices. ■

A General Framework for Measuring the Optical Performance of Displays under Ambient Illumination

The growing diversity of the display landscape requires a unified approach to characterize visual performance under realistic lighting conditions.

by John Penczek, Edward F. Kelley, and Paul A. Boynton

AS displays continue to evolve while manufacturers seek to provide users with improved image quality and greater utility, there is a tendency for each manufacturer to develop measuring methods that are specific to each display technology, even for the same application. These disparate methods can make it difficult to compare performance among different display technologies. This is especially true when displays are characterized under ambient illumination, where display performance is often quoted for inconsistent lighting conditions.

For example, the ambient contrast ratio may be specified with a display at 200 cd/m^2 under 500 lx of illumination. However, that lighting information is often insufficient for the user to confirm the performance or determine if it is applicable to their environment. The laboratory measurement may have been performed with a single light source, but typical indoor and outdoor illumination conditions have two or more lighting sources. And each of these light sources could have different illumination levels, spectra, and directionality. All this can affect how light is scattered to the viewer. Therefore, simply citing display performance at a specific illumination level and viewing condition is usually not sufficient to describe the range of use cases. A more systematic approach is needed to manage the complexity posed by the range of ambient illumination conditions that may be used.

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The General Lighting Environment

Although a display may be viewed under a large number of lighting scenarios, the display's ambient performance is typically evaluated by a common set of observed photometric and colorimetric characteristics, which are largely independent of the display technology. From the optical-metrology perspective, the net photometric and colorimetric quantities measured at the observation point are usually indifferent to the source or multiplicity of the light. In addition, since the detectors employed to measure the light are fundamentally linear radiometric instruments, we can employ linear superposition to determine the

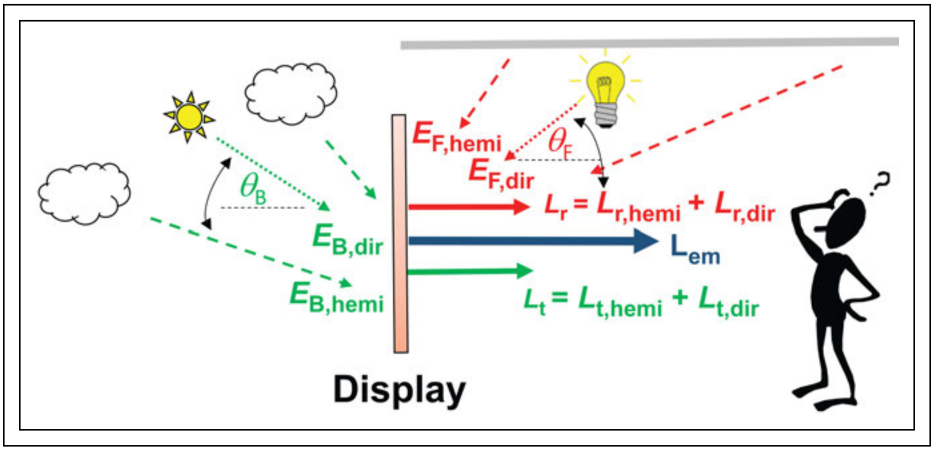

Fig. 1: This general viewing scenario of a display shows front- and back-illumination from hemispherical diffuse and directional light sources.

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magnitude of the optical signal from multiple light sources by summing up the individual contributions. However, it should be noted that the presumption of linear superposition in the detection of the optical signal does not mean that the human visual system is linear. Vision science has demonstrated that our perceived sense of brightness and color is sensitive to adaptation mechanisms.[1]

There are extensive vision models to simulate these mechanisms if more accurate perceptual results are necessary. However, these visual models still rely on the photometric and colorimetric data as inputs, which are taken by linear optical detectors. We can leverage the concept of linear superposition for luminance and spectral radiance (or absolute tristimulus values) to simulate complex lighting environments from individual source measurements.

Figure 1 illustrates the situation of a general display under arbitrary illumination. In the case of an emissive or transmissive display (*e.g.*, OLED or LCD) in a dark room, the viewer only observes the emitted luminance (L_{em}) or color. If the display is observed in an illuminated room, or in daylight, the illumination from hemispherical diffuse ($E_{F,hemi}$) and directional ($E_{F,dir}$) light in front of the display would produce a net reflected luminance (L_r) that would add to the emitted light. And in the case of a transparent display, the illumination from hemispherical diffuse ($E_{B,hemi}$) and directional ($E_{B,dir}$) light in back of the display would produce an additional transmitted luminance (L_t) to the viewer.

In general, the total luminance perceived by the viewer would be the sum of the three contributions ($L_{em} + L_r + L_t$). If a spectroradiometer was used to measure the spectral signal at the viewer's position, the total spectral radiance would add up on a wavelength basis. The spectral information could then be used to calculate both the luminance and color of the signal. This model can also be applied to a reflective display, which would only have a reflected contribution (L_r) if it was opaque.

The use of linear superposition in this model may appear simplistic, but as we will show shortly, the extension of this concept into the display metrology can yield valuable

The general equation uses linear superposition to combine the light emission, along with the reflective and transmissive components scattered by the display from each type of light source, to estimate the total luminance of a transparent display. The reflected specular and transmitted regular components can be arranged to come from either the hemispherical diffuse or directional contributions.

Scatter mechanism: Reflection (first two terms), Transmission (last two terms)

$$L = L_{em} + \frac{R_{F,hemi} \cdot E_{F,hemi}}{\pi} + \frac{R_{F,dir} \cdot E_{F,dir} \cdot \cos\theta_{F,s}}{\pi} + \frac{T_{B,hemi} \cdot E_{B,hemi}}{\pi} + \frac{T_{B,dir} \cdot E_{B,dir} \cdot \cos\theta_{B,s}}{\pi}$$

Light source: Hemispherical diffuse, Directional, Hemispherical diffuse, Directional

Here,
L_{em} = display emission in a darkroom,
$R_{F,hemi}$ and $R_{F,dir}$ = front hemispherical diffuse reflectance factor and directional reflectance factor,
$E_{F,hemi}$ and $E_{F,dir}$ = desired front hemispherical diffuse illuminance and directional illuminance,
$T_{B,hemi}$ and $T_{B,dir}$ = back hemispherical diffuse transmittance factor and directional transmittance factor,
$E_{B,hemi}$ and $E_{B,dir}$ = desired back hemispherical diffuse illuminance and directional illuminance.

Fig. 2: *The above represents the general formalism for simulating the ambient performance of displays.*

benefits. Our analysis will also assume that the focus of the viewer is on the display screen. In some situations, such as specular images or viewing objects behind transparent displays, the viewer's focus may be at a different position. In those situations, the content on the screen will interfere with the off-screen image. We will, however, limit our discussion to the display's on-screen performance.

When evaluating the performance of a display under ambient lighting conditions, there are numerous possible lighting configurations. However, for daylight conditions, there are two main light sources. The hemispherical skylight provides omni-directional illumination, and sunlight illuminates the display with rather directed rays. The illuminance levels from both of these components are a function of the display orientation, its position on the earth, the season, time of day, *etc*. The Illumination Engineering Society of North America (IESNA) has developed an empirical model to estimate the illuminance levels for both the hemispherical diffuse illumination of the skylight and directional illumination of the sunlight.[2] However, the IESNA model does not provide color information, which is necessary to predict the resulting color. Alternatively, the National Renewable Energy Laboratory (NREL) in the U.S. has collected a substantial amount of spectral irradiance data for solar energy research and developed a spectral model for skylight and sunlight.[3] Both of these daylight models were found to yield similar illuminance levels for the test cases we explored. But the spectral data available from the NREL model provides the complete information needed to calculate both luminance and color results.

Indoor illumination can be more varied than outdoor. There may be several luminaires (or directional sources) in a room, but we can consider there to be only one hemispherical diffuse source. The hemispherical illumination may originate from luminaire light that diffusely scatters off indoor surfaces or the light from windows. For the example shown in Fig. 1, we limited the indoor lighting scenario on the right side of the display to one luminaire. The relative amount of hemispherical diffuse to directional illumination on the screen depends greatly on the lighting conditions. However, for offices with windows, the hemispherical diffuse illumination originating from window light can be a dominant contributor.

A General Display Formalism

As suggested in Fig. 1, the luminance (or spectral radiance) that is measured at the observation point will be the sum of all the contributing light sources. This can be expressed mathematically by the expression in Fig. 2, where the contribution of each external light source can be represented by their front reflection ($R_{F,hemi}$ and $R_{F,dir}$) and back transmission ($T_{B,hemi}$ and $T_{B,dir}$) coefficients and their relative illumination levels. The geometric dependencies of the reflection and transmission coefficients on the light source and detector configuration have been omitted for simplicity. When the measurements are made in terms of photometric units (*i.e.*, luminance), we refer to luminous reflection and transmission coefficients. The general equation can also be expressed in its spectral form, with equivalent spectral reflectance and transmittance factor distributions. The original concept was put forth by Kelley *et al*. to take into account ambient reflections, but has been recently generalized to include transparent displays.[4,5]

The reflection and transmission coefficients are fundamental display characteristics that describe how light is scattered when measured at a given illumination and detection geometry. Displays will usually exhibit a linear response to the incident light, which means that the reflection and transmission coefficients will remain constant for typical levels of illumina-

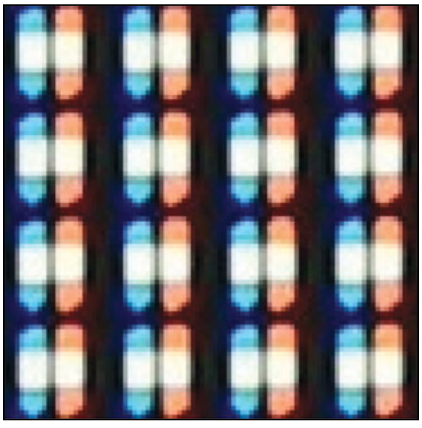

Fig. 3: *The above close-up image of a transparent LCD pixel structure shows a rendering of a magenta color (green pixels off). This design uses a clear section in the middle of each subpixel.*

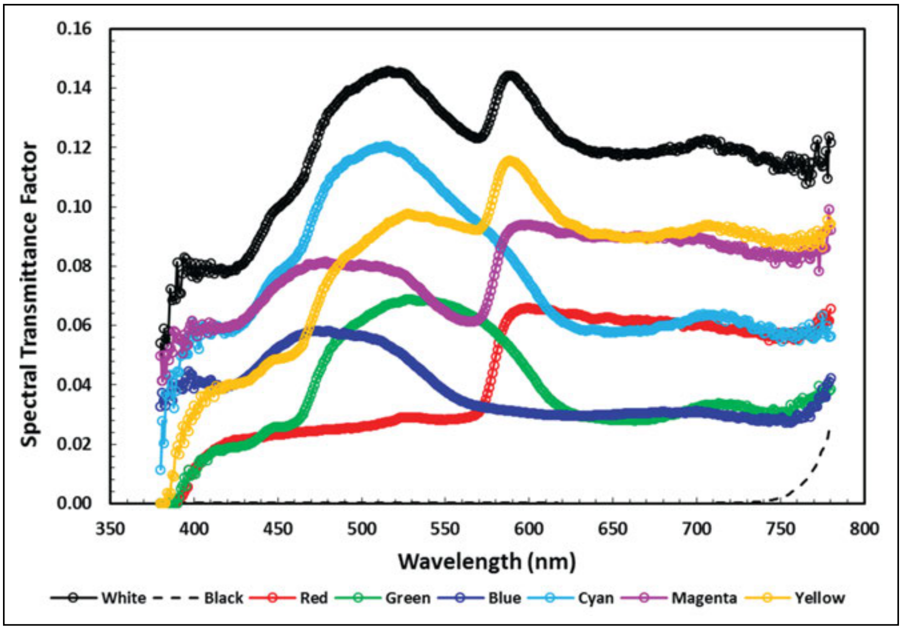

Fig. 4: *Spectral transmittance factor distributions for the transparent LCD are measured with back-illumination from a hemispherical diffuse light source. The legend at the bottom indicates the color the display was rendering during the measurement.*

tion. This invariance enables the reflection and transmission coefficients to be measured at modest illumination levels, and the general equation then allows the display luminance to be calculated at low or high illumination levels. The illumination scaling property yields even greater benefits when performing spectral measurements. In that case, the spectral reflection and transmission distributions can be measured with a convenient light source (*e.g.*, tungsten lamp), but the reflected or transmitted spectra can be calculated for an ideal source such as CIE Illuminant D65. Using the spectral form of the general equation also allows us to calculate the effective color observed from the combined sources. The detailed methods for measuring the reflection and transmission coefficients are given elsewhere.[6,7] However, we highlight the utility of this method by applying it to several lighting scenarios.

Applying the Formalism

We demonstrate the value of the proposed formalism by simulating the ambient performance of a commercial transparent 22-in.-diagonal TN-LCD panel under various application scenarios. A photograph of the pixel structure used by this LCD is shown in Fig. 3 with hemispherical diffuse white back-illumination. Since this is not an emissive device, the RGB color-filter array must be externally illuminated in order to be visible. The spectral distribution of that illumination will also impact the resulting color gamut of the device. Therefore, this structure is strongly affected by the illumination conditions.

The response of the transparent LCD to ambient illumination was characterized by using a white hemispherical diffuse light source (with specular included, $d_i/0$, detector at normal incidence) and a directional source at 45° inclination to the display. Since the periodicity of the active-matrix structure tends to induce diffractive scatter with discrete directional sources, a ring light source was used instead. These illumination sources were employed in front and back of the display to measure the reflection and transmission characteristics. In our tests, a spectroradiometer was used in order to measure the spectral reflectance and transmittance factor distributions. This allowed us to accurately model the color response of the display to a variety of other (ideal) light sources. If photometric characteristics (*e.g.*, contrast ratio) were of primary concern, then photometers could be used.

The measured front spectral reflectance factor distributions, for both hemispherical diffuse and directional illumination, were measured to be fairly consistent for the rendered red, green, blue, cyan, magenta, yellow, white, and black (RGBCMYWK) colors. However, the spectral transmittance distributions measured by back-illumination strongly depended on the rendered color. Figure 4 shows the measured spectral transmittance factor distributions for the transparent LCD with back-illumination from a hemispherical diffuse light source. The red, green, and blue distributions resemble the transmission curves for typical RGB filters. However, in this device design (see Fig. 3), each color subpixel has a clear middle section that transmits broadband light. Therefore, when the display is rendering a red color (for example), the measured spectral transmittance in Fig. 4 indicates that green and blue wavelengths are also transmitted. The spectral reflectance and transmittance factor distributions can be weighted by the photopic response of the eye and expressed as scalar values. The front luminous reflectance and

Table 1: Reflection and transmission coefficients are used to evaluate the transparent LCD performance. Corrected to a CIE Illuminant D65 white light source.

Light source	Front reflection coefficient	Back transmission coefficient
Hemispherical diffuse (di/8)	white: R_F,hemi = 0.025	white: T_B,hemi = 0.13
	black: R_F,hemi = 0.023	black: T_B,hemi = 0.00018
Directional (Ring light, 45/0)	white: R_F,dir = 0.00061	white: T_B,dir = 0.00061
	black: R_F,dir = 0.00059	black: T_B,dir = 0.000078

Table 2: Ambient illumination conditions are shown for several lighting environments where transparent displays may be used.

Lighting Environment	Directional light			Hemispherical diffuse light	
	Illuminance [lx]	CIE Illuminant	Incident angle	Illuminance [lx]	CIE Illuminant
Indoor (office)	200	D50	45°	300	D50
Showcase or Kiosk				1500	D50
Outdoor (daylight)	65,000	D50	45°	15,000	D75

Table 3: Ambient optical performance of the test transparent LCD is measured in various viewing scenarios.

Back/Front lighting conditions	Contrast ratio	Percent sRGB gamut area
Indoor/indoor	6.6	1.7
Showcase/indoor	28	3.2
Outdoor/indoor	138	4.5
Showcase/outdoor	3.8	0.9

back transmittance factor coefficients for the transparent LCD are summarized in Table 1.

The performance of the transparent display was evaluated for the three ambient illumination environments listed in Table 2. The indoor and outdoor conditions replicate the ambient lighting conditions used by several standards.[6,8,9] The showcase lighting conditions are typical of how transparent LCDs are currently used in point-of-sale situations.

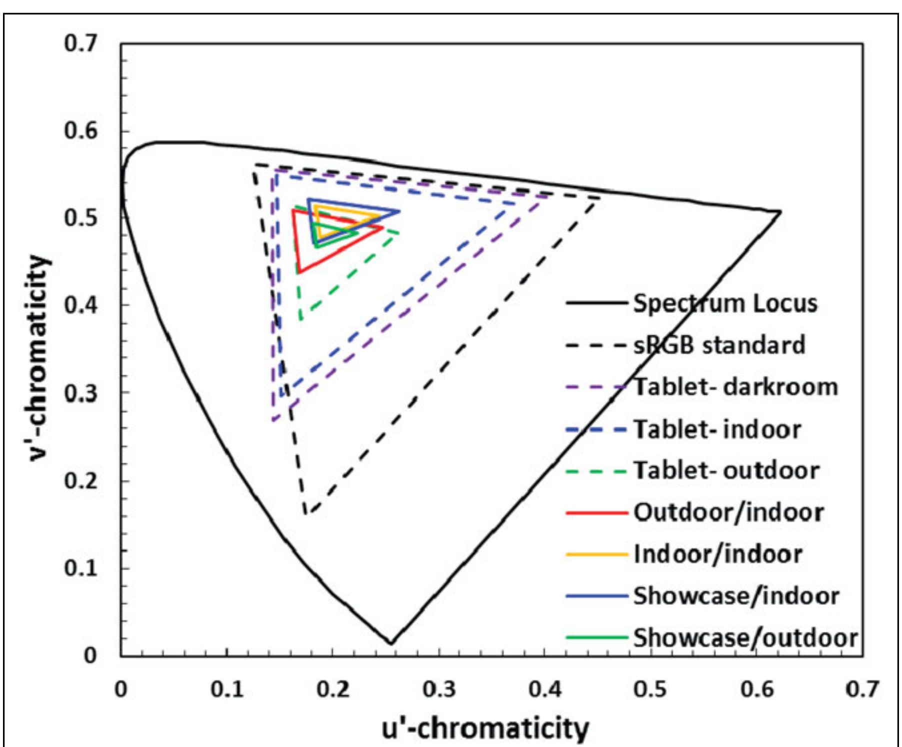

Fig. 5: The CIE 1976 chromaticity diagram illustrates the color gamut of the transparent LCD and tablet display under the various scenarios listed in Table 2.

Note that the illumination level, geometry, and light-source spectra are specified in order to accurately represent the lighting environment.

The ambient lighting conditions were applied in four viewing scenarios. These scenarios are tabulated in Table 3 using the back/front notation to identify which illumination conditions are used in back and in front of the display, relative to the viewer. The indoor/indoor scenario simulates the lighting environment when the display is used in an office setting. The showcase/indoor scenario estimates the lighting conditions when the display is the front face of a lighted booth inside of a building. The outdoor/indoor configuration approximates the case when the display is mounted in a window, with the indoor viewer looking outside. And the showcase/outdoor setup simulates the situation where the display is a window to a storefront and the viewer is outside.

Each of the viewing scenarios listed in Table 2 was evaluated following the expression in the equation box, using the coefficients in Table 1 and the lighting levels in Table 2. The ambient contrast ratio can be obtained using the photometric form of the expression in the equation box. In this case, the color dependence of the transparent LCD transmission coefficients did not produce a significant impact on the ambient contrast ratio calculation for the illumination levels used in our scenarios. However, the actual spectral transmittance factor distributions were needed to determine the effective colors and, consequently the color gamut area. The color gamut area listed in Table 2 was calculated as the percent area covered by the effective ambient RGB colors on a CIE 1976 chromaticity diagram relative to the sRGB gamut area (see Fig. 5).

The previous example illustrated how the display ambient performance can be predicted by using the general model for the complex case of a transparent display. The simpler situation of a conventional opaque display can also be evaluated. We demonstrate this by only measuring the hemispherical diffuse and directional reflection coefficients of a commercial tablet display and evaluate the display indoor and outdoor performance using the illumination conditions given in Table 2. The contrast ratio and color gamut area for the tablet display at 200 cd/m^2 is summarized in Table 4. The color gamut of the tablet display is also compared to the transparent LCD in Fig. 5.

Table 4: The ambient optical performance of a commercial tablet device with a 200 cd/m^2 LCD is charted under the indoor and outdoor illumination conditions given in Table 2.

Front lighting conditions	Contrast ratio	Percent sRGB gamut area
Darkroom	883	57
Indoor	25	44
Outdoor	5.5	9.6

Table 4 illustrates the sharp reduction in the contrast ratio of the tablet display as the illumination is increased to full daylight levels. It is interesting to compare this with the transparent LCD. In both cases, the contrast ratio is constrained by the reflected ambient light, which raises the black level. But the transparent LCD can utilize the high back-illumination levels to achieve on-screen contrast ratios that can sometimes exceed the tablet display under similar conditions. However, Fig. 5 illustrates that even the high back-illumination levels cannot substantially improve the relatively narrow color gamut of the transparent LCD. The clear mid-section of this subpixel design washes out the transmitted colors by allowing broadband light through the color-filter array and severely limits the display's color gamut. Other transparent LCD designs have since been introduced and are expected to have significantly better performance. Transparent OLED displays are also expected to enter the market. The proposed methodology is capable of fairly evaluating either of these technologies.

This example illustrates how the new generalized framework for display ambient performance can be used to simulate many lighting scenarios from a basic set of reflection and transmission measurements. By framing the analysis in terms of the intrinsic reflection and transmission characteristics of the display, we can estimate the display performance without physically assembling and measuring the actual lighting environment. Since some lighting scenarios can be complex, with special spectra and high illumination levels, they are difficult to replicate and tend to produce unstable measurements. The linear superposition concepts employed in our method breaks that paradigm in favor of simple well-controlled transmission and reflection measurements with single light sources. This approach will yield reliable measurements that can be applied more broadly than legacy methods.

References

[1] G. Wyszecki and W.S. Stiles, *Color Science: Concepts and Methods, Quantitative Data, and Formulae*, 2nd ed. (John Wiley & Sons, 2000).

[2] *The IESNA Lighting Handbook: Reference and Application*, Illumination Engineering Society of North America, 9th ed. (2002).

[3] ASTM G197-08: Standard table for reference solar spectral distributions: Direct and diffuse on 20° tilted and vertical surfaces (2012).

[4] E. F. Kelley, M. Lindfors, and J. Penczek, "Display Daylight Ambient Contrast Measurement Methods and Daylight Readability," *J. Soc. Info. Display* **14**, 1019–1030 (2006).

[5] J. Penczek, E. F. Kelley, and P.A. Boynton, "General metrology framework for determining the ambient optical performance of flat panel displays," *SID Digest of Technical Papers* **46** (2015).

[6] International Committee for Display Metrology (ICDM), Information Display Measurements Standard (IDMS), ver. 1.03, section 11 (2012); http://www.icdm-sid.org/.

[7] J. Penczek, E. F. Kelley, and P. A. Boynton, "Optical measuring methods for transparent displays," *SID Digest of Technical Papers* **46** (2015).

[8] IEC 62679-3-1 Ed1.0 Electronic paper displays - Part 3-1: Optical measuring methods, International Electrotechnical Commission, April 24, 2014.

[9] IEC 62341-6-2 Ed1.0 Organic light emitting diode (OLED) displays - Part 6-2: Measuring methods of visual quality and ambient performance, International Electrotechnical Commission, Jan. 24, 2012. ■

Advanced Imaging Colorimetry

Implementing advanced methods of display metrology enables highly accurate luminance and color-imaging measurements to be performed. The next generation of high-accuracy imaging colorimeters benefits from a combined approach of recording additional data and utilizing a matrix-based optimization algorithm.

by Đenan Konjhodžić, Peter Khrustalev, and Richard Young

A colorimeter comprises at least three opto-electrical detectors, each in combination with a filter to match the overall spectral sensitivity of these combinations to those of the CIE 1931 color-matching functions. The electrical output of each of these color channels is proportional to the tristimulus values X, Y, and Z. When the detectors deliver output signals according to the sum of the light intensity across the field of measurement, the device is called a "spot"-meter. When two-dimensional arrays of detector elements are used instead – again in combination with appropriate filters – a corresponding array of area elements on the object of measurement can be analyzed with respect to luminance ,Y, and chromaticity, *e.g.*, x, y.

Instruments of the latter type are called imaging colorimeters because the color channels can analyze the surface area of objects and scenes and generate data arrays (of luminance and chromaticity levels) just like cameras deliver RGB images. The detector arrays can be provided with color filters on the individual elements (*e.g.*, RGB filters) or a filter wheel with at least three filters can be in front of the array for time-sequential color analysis, usually in terms of the tri-stimulus values X, Y, and Z. Imaging colorimeters also require a suitable optical system for projection of a region of the surface of the object of measurement through the filters on the detector array. Imaging colorimetry has gained popularity due to its convenience and potential for making sophisticated automated analyses.

Instruments for colorimetric analysis *via* spectral measurements (spectral power distribution) are currently of the spot-meter type, so they have to be carefully aligned in order to make sure that the field of measurement is correctly positioned on the object to be measured. Incorrect positioning can cause severe measurement errors, especially in the case of objects with complicated display structure and layout (*e.g.*, automotive dashboards and displays). Such complex display devices can be analyzed much more easily with imaging colorimeters because the actual colorimetric analysis can be performed after recording of the image, and identification of the regions of interest can be automated. This ease of use is the motivation for development and implementation of techniques that increase the precision of colorimetric analysis for arbitrary spectra as described in this article.

Objective and Background

The measurement accuracy of imaging colorimeters crucially depends on the quality of the optical filters in use. Enhancing the fit of the filters with the human eye's color-matching functions (CMFs) improves the accuracy of the measurements. As a result of the unavoidable spectral mismatch of the colorimeter response functions relative to the CMFs, the accuracy of measurement varies with the spectrum of the device being tested. Usually three filters are used, one for each CMF. More advanced devices use four filters, since one of the CMFs exhibits two disjunctive spectral regions that can be more accurately matched with two filters. In technical terms, even the best filters available will still not perfectly match the corresponding CMF, and this will inevitably generate measurement errors, most prominently at both ends of the spectral range of human vision. One approach to improving results is the use of additional filters to collect more information in these spectral regions. However, simply extending the number of filters, *i.e.*, the number of data-acquisition channels, will not necessarily improve measurement accuracy. A negative side effect is the significant increase in the measurement duration with the number of filters in use.

Measurement accuracy will increase according to the spectral match of the device under test and of the calibration source. Since calibrations are frequently made using white incandescent sources, LEDs and colored sources often create large errors in measurement. Matrix correction methods are used to correct display measurements and reduce such errors. There are generally three primaries of the display that are mixed to give the test color, and hence there is a limited variation in spectra. The matrix method of correction is now commonly applied to such measure-

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ments, but it cannot be used if the spectrum is completely unknown. Matrix methods can still be applied to improve results in specific cases.

Here, we present a combined approach for extending the number of color filters from four to six, together with advanced matrix-based optimization methods. A matrix operation can derive the three tristimulus values from the six measurement values. This correction matrix can be optimized across a large set of sources so that no inherent assumption of spectrum is required. Only combining both methods yields more accurate results for practically all sources compared to standard methods of today. This article develops the theoretical proposals given as references to include practical implementation and performance tests of actual devices. The goal of this work is to produce a better colorimeter that also works well when you need to measure an arbitrary or unknown spectra source.

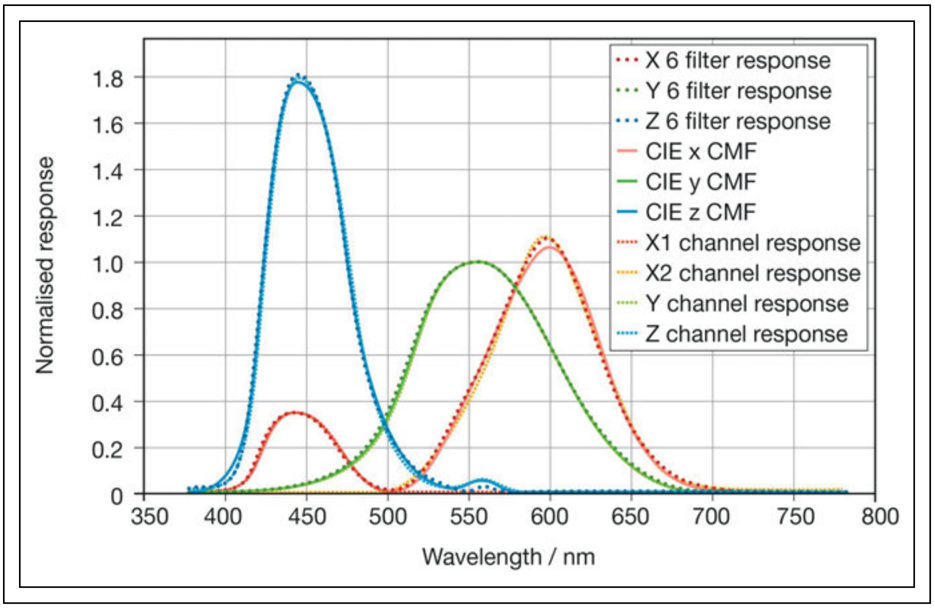

Fig. 1: Color-matching functions and examples of implementation appear in the above chart. CIE CMFs are solid lines; four-channel colorimeter examples are dashed lines; and six-filter colorimeter examples are dotted lines.[7]

Optimizing Spectral Responses

Color-matching functions, which form the basis for most measurements of color quantities, are shown in Fig. 1 as solid lines. A typical colorimeter aims to reproduce these spectral response functions using a combination of filters and detectors, and although the match can be close, it is never exact. An example of a four-filter colorimeter is shown as dashed lines in Fig. 1. The CIEx color-matching function is realized using two channels on the colorimeter (X1 and X2) for the two peaks. This example shows that regions of mismatch occur around specific wavelengths. Significant errors are expected for such sources because LEDs may have narrow-band emissions in these regions.

Combining the channels is one way of improving the match. However, if the response is improved in one region, the response in another region is likely to be worse. There are many possible optimizations and each depends on the spectrum of the source to be measured. The source spectrum is generally unknown, so a compromise combination is required that minimizes the errors from each source.

Adding a 5th or 6th channel greatly increases the possibilities for optimization and reduces dependence on the source spectrum. Figure 1 provides an example of using six channels to conform with the CIE CMFs more exactly. The match here is dramatically improved in both the 530- and 560-nm regions. This can be represented mathematically by a matrix product of six channel responses with a 3 × 6 adaptive matrix **M** of factors for the combinations of channels resulting in three tristimulus values.

The response of these extra channels would typically be single peaks at appropriate wave-

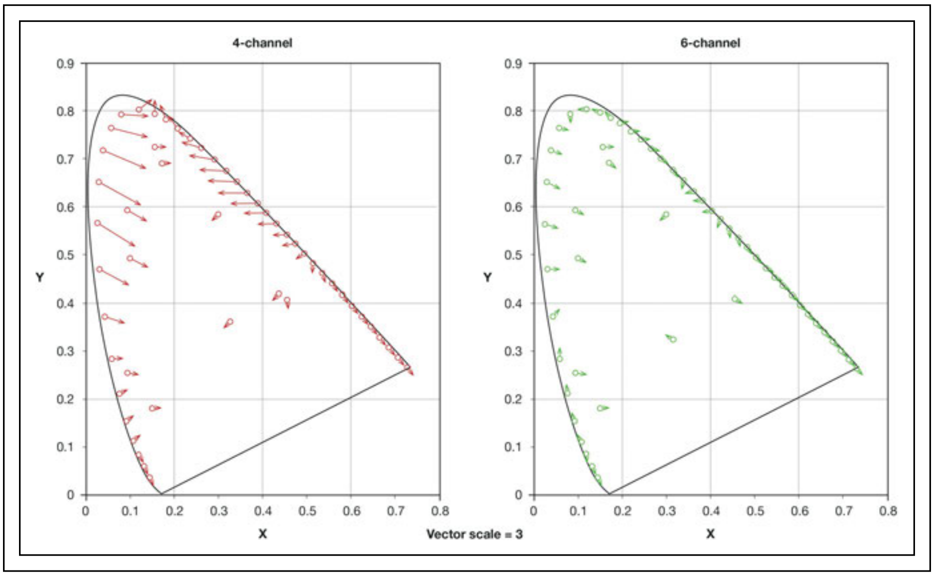

Fig. 2: Shown are color-difference vector plots in the CIE 1931 x,y color space illustrating the errors in the measurement of various sources using four- (left) and six-channel (right) imaging colorimeters. The vectors point from the true value to the measured value reported by the instrument. The vectors are enlarged by a factor of 3 to improve visibility.[7]

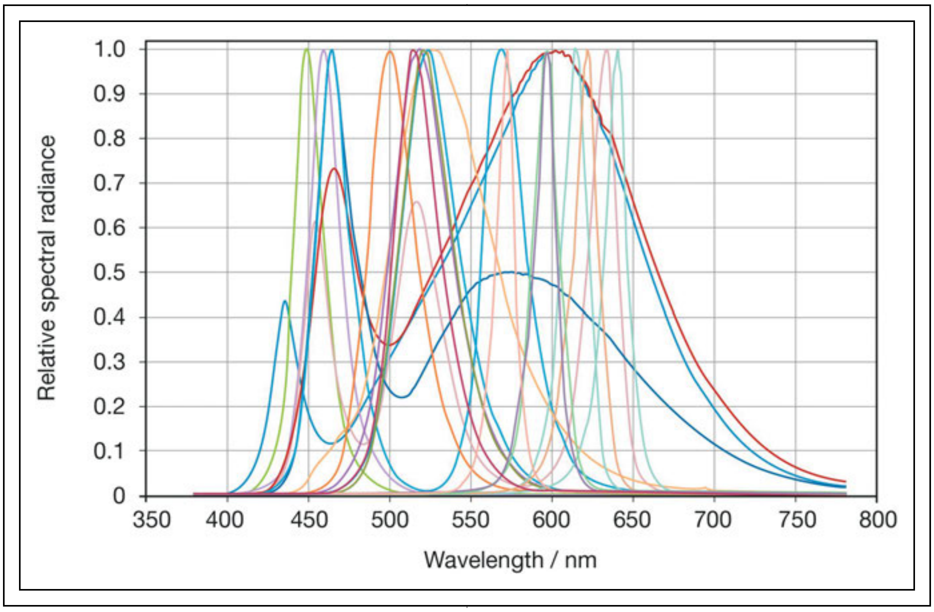

Fig. 3: Above are spectra of three white and 16 colored LEDs used as a training set covering the entire spectral range. The spectra are measured with a spectroradiometer and provide precisely determined x,y color coordinates as references for matrix optimization.

lengths to correct errors in the other four channels, but this is not a strict requirement. Narrow-band responses may introduce local corrections but be of limited general use. The optimum responses of these extra channels should therefore be matched to the errors in the basic four channels. It is useful to look at color errors for general matching. Color-difference vector plots, such as those shown in Fig. 2, illustrate the errors with vector arrows and this conveys an immediate visual impression of distinct characteristics. The true coordinates (measured using a high-quality spectroradiometer for real sources or calculated for simulated sources) are shown as circles and the colorimeter-measured coordinates are at the tip of an arrow originating in the circle. The length of the arrow indicates the magnitude of the error and the direction of the arrow gives the direction of change. The arrows are too short to be seen clearly for use in quality systems, so they are magnified by a scaling factor to highlight the differences. For example, the vector scale is 3 in Fig. 2 and displays the arrows three times longer than they actually are. When comparing errors, the shorter the arrow the lower the error.

The sources represented in Fig. 2 include real and simulated sources. A set of 20-nm FWHM Gaussian distributions represents pseudo-monochromatic sources such as LEDs. In the CIE diagram, these are located around the outer edges close to the monochromatic locus. A further set of 20 colored and white LEDs plus four white and filtered incandescent sources are included. These are distributed at the edges and toward the middle of the diagram.

There is a clear general improvement resulting in lower errors for all sources when going from a four-channel to a six-channel colorimeter. The only limitation is that those spectral components lying beyond the wavelength range of the filters cannot be corrected in this general way so the errors are the same for both systems. The color-difference vector plots in Fig. 2 are calculated by least-squares optimizations to the CMF spectra and as such they are perhaps the most general. However, this requires knowledge of the spectral responsivities of each channel.

Optimizing Color Errors between Sources

If specific types of spectral sources are anticipated in the measurement, typical sources can be used (a training set) to minimize errors across the set. This procedure no longer requires knowledge of the spectral responsivities of the channels, but instead the tristimulus values of the training set must be known. The optimization can be for any specific derivative

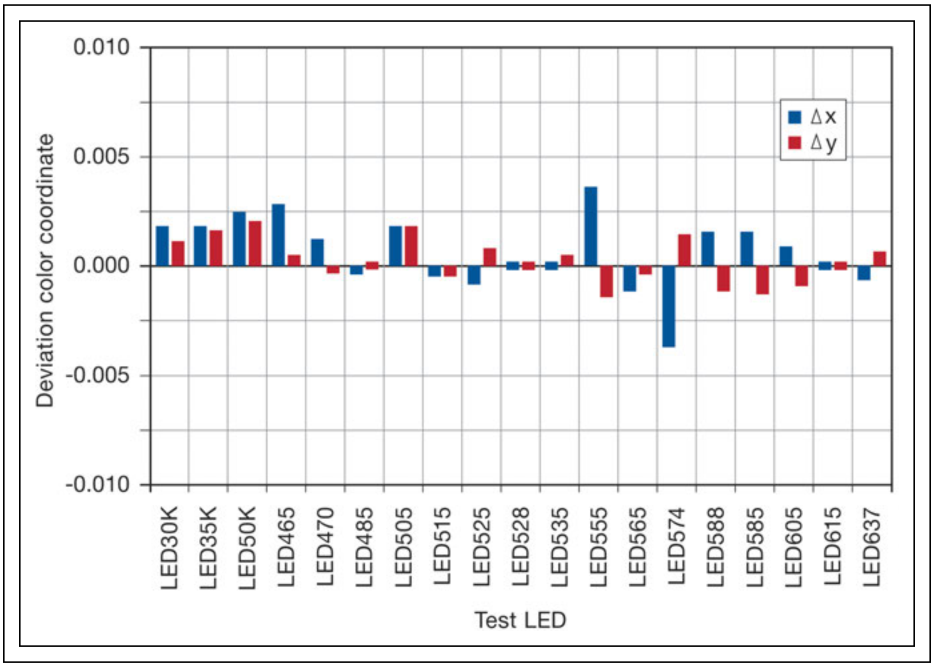

Fig. 4: The chart shows color-coordinate deviations of test LEDs for measurement with a six-filter imaging colorimeter.

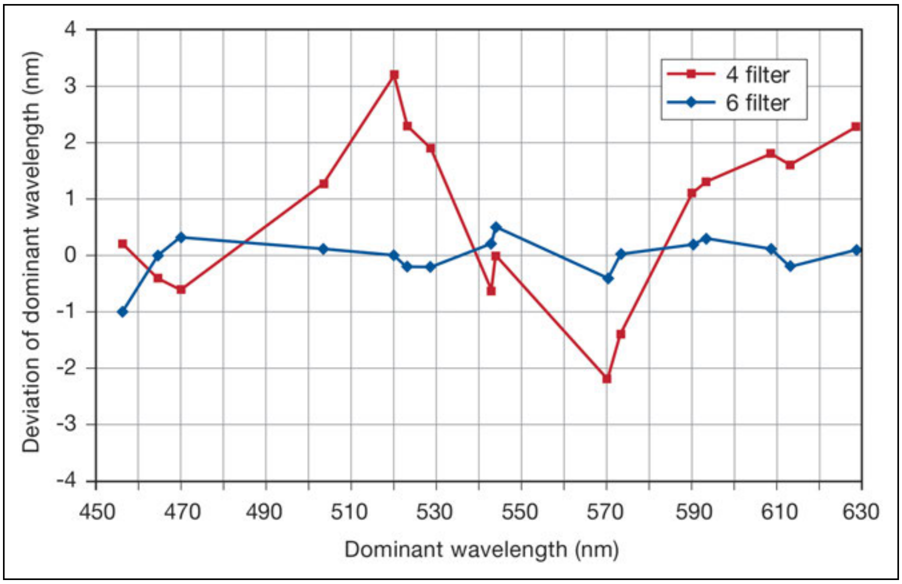

Fig. 5: The chart shows a comparison of deviations in the dominant wavelengths for different test LEDs for four-filter (red) and six-filter (blue) imaging colorimeters.

color space or output quantity, *e.g.*, CCT or x,y color coordinates.

The training set should represent the typical variation in measured sources, such as those shown in Fig. 3. An entire spectral range needs to be covered and several white sources included. Figure 4 shows an example of measurements for which a training set of three white and 16 colored LEDs was used. After completing the calibration and application of matrix optimization for x,y color coordinates, the training set is used for verification. The diagram shows that color-coordinate deviations Δx and Δy are below 0.005 for all LEDs. Improved all-round performance is obtained for the whole set.

The higher accuracy of the optimized six-filter imaging colorimeter for determining the color coordinates is also reflected in the calculation of the dominant wavelength, as shown in Fig. 5.

It is important that the training set includes all the required sources to be measured. However, some sources might be considered more important than others in terms of accuracy, and this can be accommodated using weighting factors in the optimization.

Obviously, there can be as many adaptive matrices as there are output parameters, so each can be individually optimized. However, if this is the case it should be noted that measurement results obtained with different optimization matrices are no longer related by normal transforms and cannot be interconverted.

Practical implementation requires the chosen matrix to be robust and stable during normal use so that multiple matrices are avoided, depending on conditions or the display being measured. Figure 6 shows that the matrix can be used at different distances, indicated by the measurement points plotted close to the "equivalence" line. Although each lens used has its own matrix, they all give equivalent results. Similar analyses of temperature changes and *f*/number changes show they too exert a generally insignificant effect. Results on different systems show close correlation with those obtained using a quality spectroradiometer.

Study of Different Test Sources

Another study was made consisting of 22 samples, including LEDs and filtered incandescent sources that were not included in the training set. Each source was measured using a high-quality spectroradiometer as a reference and a colorimeter possessing the basic four filters (normal) or six filters (advanced). The six-filter system was optimized for minimum x and y differences.

Figure 7 shows the results of the study as color difference vector plots. Note that the vector scale is 10 to clearly show the errors involved. Although white sources are accurately measured with the four-channel system, colored sources give large errors. In contrast, the errors for all sources are small using the six-filter system.

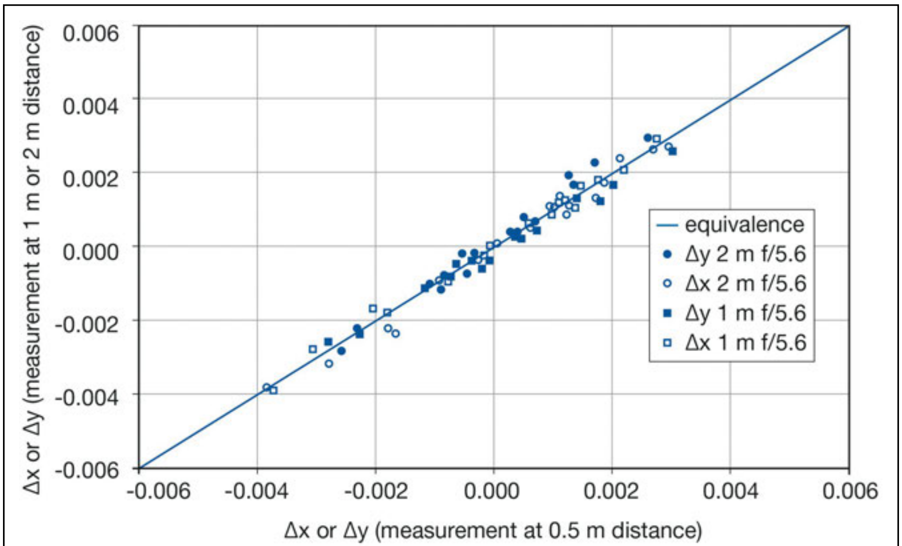

Fig. 6: Shown are equivalence plots for use at different distances for a wide range of white and colored incandescent sources and LEDs.

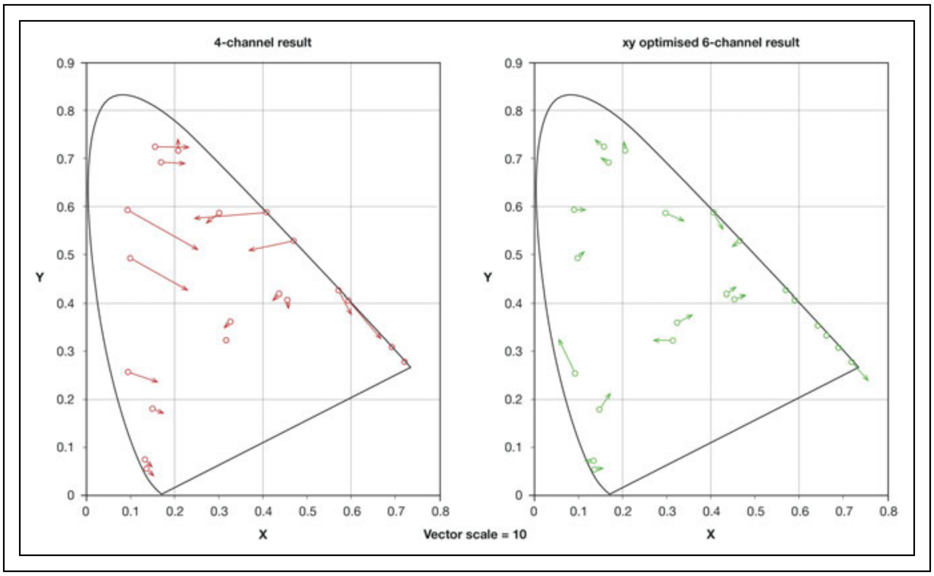

Fig. 7: Final study results show a four-channel filter (left) and six-channel optimized systems (right).

The Case for Colorimeters

The convenience of imaging colorimeters for performing complex characterizations of displays has made it the technology of choice in many applications. However, the accuracy of color and luminance values obtained has limited their reliability. The study has demonstrated that a six-channel imaging colorimeter utilizing a matrix-based optimization algorithm gives a significant accuracy improvement compared with traditional three- or four-channel systems. The colorimetric accuracy of this method approaches that of high-quality spectroradiometers while maintaining the benefits of imaging technologies.

Optimization of the adaptive matrix can be generalized for all sources by a least-squares fit to CIE color-matching functions. This optimizes the effective responsivity of the system and does not require prior knowledge of the source to be measured. However, it does necessitate knowledge of the channel spectral responsivities.

Nevertheless, if knowledge of the tristimulus values for sources is available, the adaptive matrix can be optimized to a specific output parameter, *e.g.*, CIE color coordinates x and y. The spectral responsivities of channels are no longer required. Optimization using a training set and a target algorithm will generally reduce errors inside the wide range of the training sources. Optimization can include weighting if some sources are more important than others in terms of accuracy.

This study of 22 samples, including LEDs and incandescent sources, verified the benefits of using an advanced (six channel) instead of a normal (four channel) imaging colorimeter.

References

[1]J. J. Jensen, "Advantages and Applications for the Use of Imaging Colorimeters" *Proc. CORM Conference* (2013).

[2]G. P. Eppeldauer, "Spectral Response Based Calibration Method of Tristimulus Colorimeters," *J. Res. Natl. Inst. Stand. Technol.* **103**, 615, (1998).

[3]Y. Ohno and J. E. Hardis, "Four-Color Matrix Method for Correction of Tristimulus Colorimeters," *Proc. IS&T Fifth Color Imaging Conference*, 301–305 (1997).

[4]J. D. Schanda and Z. T. Kosztyán, "Industrial colorimetry with image resolution," *Proc. Bulg. Color Conference*, 1–5 (2008).

[5]Z. T. Kosztyán, G. P. Eppeldauer, and J. D. Schanda, "Matrix-based color measurement corrections of tristimulus colorimeters", *Applied Optics* **49**, 12, 2288–2301 (2010).

[6]R. Young and J. Neumeier, "High accuracy imaging colorimetry," CIE x039:2014, 461–469 (2014). ■

International Display Workshops to Take Place in Otsu, Japan

The 22nd International Display Workshops (IDW) will be held December 9–11, 2015, in Otsu, Japan. These workshops, sponsored by the Society for Information Display and the Institute of Image Information and Television Engineers, include oral presentations by invited and contributing speakers as well as poster presentations, discussions, and special R&D updates. Exhibits by universities and display-industry-related businesses will also be featured in parallel with the workshops.

This year's event will feature 15 technical topics in various fields of importance to the information-display industry. Four special topics of interest — Oxide-Semiconductor TFTs, Augmented and Virtual Reality, Lighting Technologies, and Printed Electronics – will be highlighted this year. The three-day conference will feature 365 papers. This year, IDW will present an "IDW Best Paper Award" and an "IDW Outstanding Poster Paper Award" based on originality and technical significance to information displays. In addition, Nobel Laureate (2014 prize in physics) Professor Hiroshi Amano of Nagoya University will give a special address on Wednesday, December 9. IDW 15 should be of interest to not only researchers and engineers, but also managers of companies and institutions in the display community.

The event takes place at the Otsu Prince Hotel, on the south edge of Lake Biwa, the largest lake in Japan (Fig. 1). Otsu is about 10 km from Kyoto and is rich in history and nature. Numerous historical sites, such as the Mii-dera and Ishiyama-dera temples, are located in the city.

For more information, visit https://www.idw.or.jp/. ■

Fig. 1: The city of Otsu stands on the shore of scenic Lake Biwa, the largest lake in Japan.

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Also in the January issue was a review of the recently held IDRC (International Display Research Conference) in Monterey, CA. Hot topics included new research into polycrystalline-silicon TFTs and the possibility of a making a projection engine from TFT-LCDs using this technology. Progress in many other technologies such as color plasma display panels, electroluminescent displays, single-crystal-silicon TFT arrays, CRTs, and diamond field emitters for field-emission displays (FEDs) were also reported on. It's clear by this point that CRTs were the mature technology and much of the ongoing research effort was on the many other growing technology options.

Another milestone from January 1995 was the announcement of the "The Video Processing Laboratory at NIST, Gaithersburg, MD," where interested researchers could use the considerable computer resources available to simulate various aspects of display visual performance including image quality and human visual perception issues. Also discussed was the planned development of the NIST Display Measurement Laboratory, which we now know led to the creation of a whole family of display-metrology standards and whose work was eventually taken over by the SID-supported International Committee of Display Metrology (ICDM).

Browsing through the rest of the 1995 issues reveals interesting work in medical imaging with CRTs, news of INFOCOMM's Projection-Display Shootout, early developments in LCD-based projection engines, innovative developments in touch technology, advances in both field emission and plasma technologies, improvements in materials and manufacturing processes such as ITO sputtering, and, of course, some nice articles about CRTs.

One other interesting story we came across during our digitizing work was another article by Ken Werner, this time in the December 1995 issue heralding the launch of the SID Display of the Year and Display Product of the Year awards. In the article is the story of the origin of the awards, the names of the committee members, and, of course, the first winners. Who were they? Display of the Year went to the Texas Instruments' Digital Light Processing (DLP) engine incorporating the Digital Micromirror Device (DMD), with an honorable mention to Fujitsu's 21-in. color plasma display. Display Product of the Year went to Casio for the first digital camera to have a 1.8-in. TFT-LCD built into it. Can you believe this was 20 years ago? This is all just a taste of the rich history of display technology you can find in each of the back issues of *ID* we are slowly resurrecting.

Our current issue this month covers our review of Display Week 2015 from San Jose in June as well as a couple of great articles on display metrology. We lead off with the Display Week coverage grouped into several key topical categories covering the gamut of things on display and presented at the conference. We can do this because of the dedicated effort of our contributing authors Ken Werner, Tom Fiske, and Steve Sechrist. We have also developed our own overview for you to see how all the pieces seem to fit together and explain more about the significant themes of the event, including the huge presence of China-based display manufacturers this year. Whether you were there with us or not, I think the comprehensive reports from each of these contributors will help you gain a better appreciation for where the industry is going today. A fun project would be to look back at the *Information Display* show review issues for 2010, 2005, 2000, 1995, and so on to form a long-range view of the major themes of the display industry. You can do this today back to 2004 on our website, where there are already a few issues dating back to the mid-90s and even earlier.

One of the highlights for me at Display Week each year is the chance to participate in the selection of the Best-in-Show award winners chosen from all the great exhibitors in three size categories. This year the field was great and the choices really hard but I think the committee did an excellent job capturing the most innovative and informative exhibits. Our own Jenny Donelan has compiled these results for you along with the story of the winner of the I-Zone award as well. I won't steal the headline or the unveiling of the winner from her so you need to go to her article to get it all first-hand.

Our technology theme for this month is display metrology, and Guest Editor Tom Fiske drew double-duty between his efforts to develop the next two great Frontline Technology stories as well as provide his coverage of Display Week 2015. The field of optical metrology is still very alive, vibrant, and staunchly supported by some great people with whom I was privileged to hang around in San Jose at the ICDM (International Committee for Display Metrology) meeting. The people on this committee are truly passionate about their work and are looking at very important topics in metrology, especially as related to emerging display capabilities such as transparency. Transparency is certainly the right word both in terms of the measurement results themselves as well as the new considerations brought about by the developments in transparent displays. As Tom explains in his guest editor's note, authors John Penczek, Edward F. Kelley, and Paul A. Boynton describe a common-sense approach to the characterization of the reflective and transmissive properties of displays in their Frontline Technology article titled "A General Framework for Measuring the Optical Performance of Displays under Ambient Illumination."

In order to make good measurements, you need good instrumentation and there is certainly no shortage of that in the marketplace today. But, just like in any field, the range of options includes trade-offs in terms of cost, performance, accuracy, *etc*. Colorimeters are a class of instrument that give you good results for a reasonable investment but generally rely on three or four tri-stimulus color filters for computation of chromaticity. Imaging colorimeters are an especially useful instrument because they combine the ability to capture and analyze spatial information as well as color and luminance information all at the same time. However, for some measurement applications their color accuracy may not be enough because of the well-known limitations of tri-stimulus color filters. As authors Đenan Konjhodžić, Peter Khrustalev, and Richard Young from Instrument Systems explain, by developing a six-channel (six-filter) imaging colorimeter as well as utilizing a matrix-based optimization algorithm, they can demonstrate significant accuracy improvements making colorimeters even more attractive options for display-metrology applications. I learned a lot about their work and the general challenges of this technology from their Frontline Technology article "Advanced Imaging Colorimetry" and I am very pleased they were willing to share it with us.

Having started down the path of exploring *ID*'s history, I think even more about what people 20 or more years from now might think about what we write today and I'm glad this issue offers so much in terms of industry insight and technical depth. I hope you feel this way as well and we welcome your comments and feedback as always. ■

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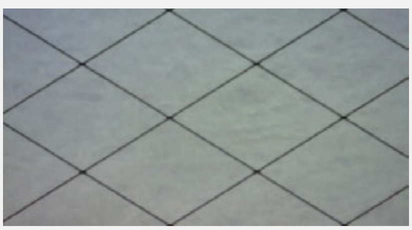

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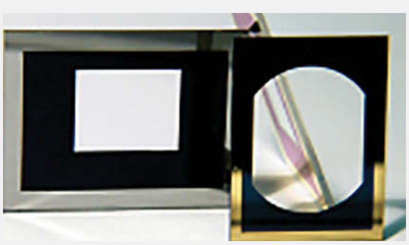

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