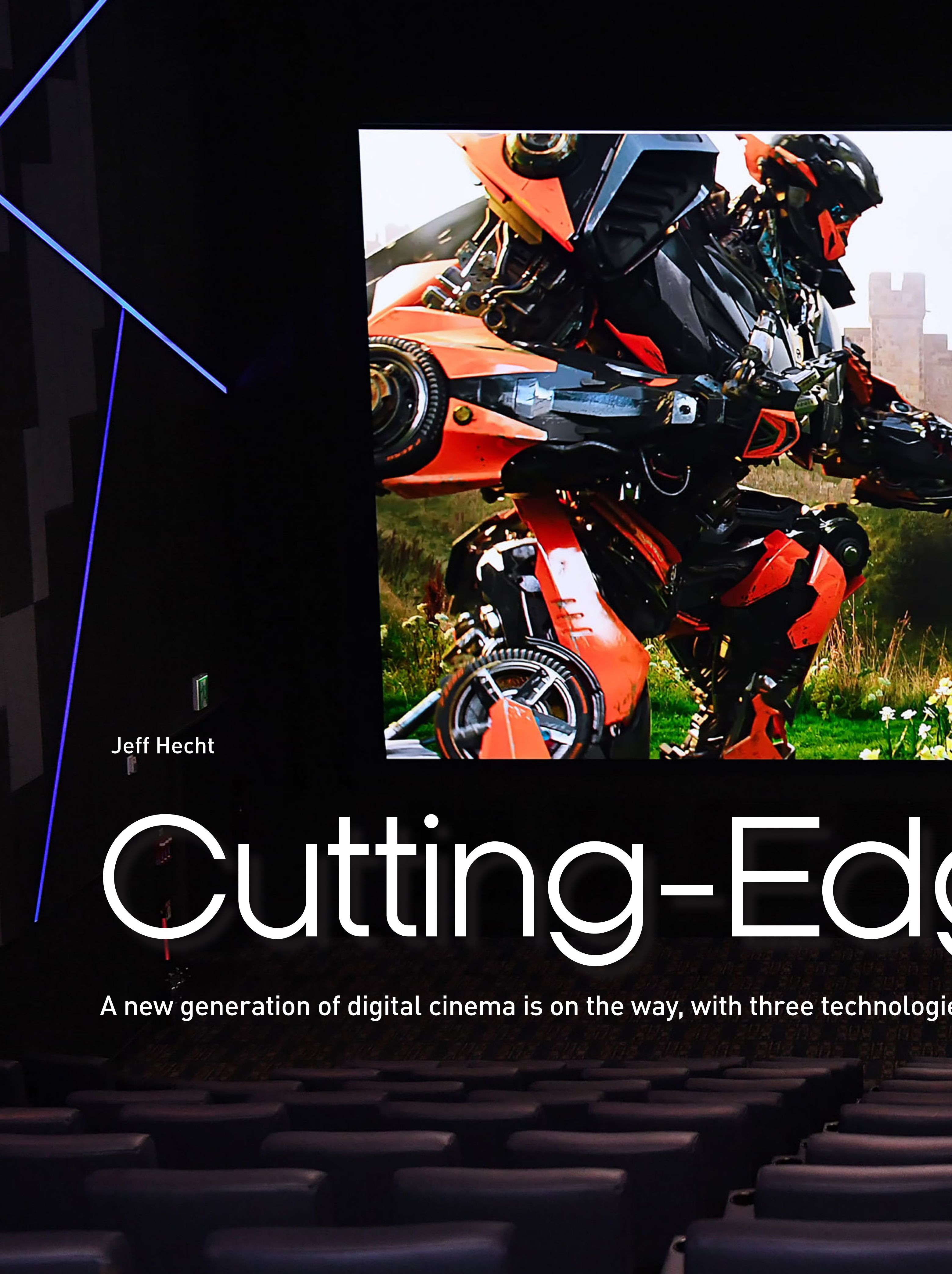


Jeff Hecht

Cutting-Edg

A new generation of digital cinema is on the way, with three technologie

ge Cinema

es offering a wider dynamic range, more vivid colors and darker darks.

Samsung's high-resolution LED cinema screen.
Samsung Electronics

The spread of analog television in the mid-20th century pushed theaters to upgrade their projection optics. They experimented with wide screens, eventually settling on aspect ratios of 1.85 to 1 in North America and similar ratios elsewhere (see "New Visions of Movies," *Optics & Photonics News*, April 2016, pp. 40-47). Hollywood also began producing most movies in color, so 35-mm film projectors with xenon lamps could light up theaters with images that home analog televisions could not match.

Movies had to step up their game after the U.S. Federal Communications Commission decided in 1990 to replace the venerable U.S. National Television System Committee (NTSC) standard for broadcast television—which included a nominal 525-line resolution designed for cathode-ray-tube TVs—with a digital standard. The new high-definition television (HDTV) digital standard offered wide-screen resolution up to 1920×1080 pixels, approaching the image quality of 35-mm film. Hollywood welcomed the chance to improve theater projection quality and avoid the cost of distributing hefty, expensive multi-reel 35-mm prints that had to be shipped to up to 3,000 screens for major film.

The crucial breakthrough toward improving projection quality was the commercialization of digital micromirror devices (DMDs) by Texas Instruments, says Howard Lukk, director of standards at the Society of Motion Picture and Television Engineers (SMPTE). Individual micromirrors bend back and forth extremely fast to modulate light intensity by changing the ratio of off and on time, using a 10-bit code to generate up to 1,024 intensity levels. Light from a xenon lamp is split into red, green and blue bands, each of which illuminates one of three micromirror arrays. Then the colors are combined to produce a full-color image on the screen. Micromirror arrays are complex, but their performance is very stable over long periods, and digital files don't wear out like film prints that degrade each time they're run through a projector.

The first generation of digital DMD projectors wowed audiences at the opening of *Star Wars 1: The Phantom*

Widening the color gamut in digital cinema

The sweeping arc of the chromaticity diagram shows all the colors the human eye can see, and the triangles inside represent the ranges of colors produced by mixing three primaries, i.e., color gamuts. The larger the area inside, the wider the color gamut and the better the color quality.

○ Pointers Gamut

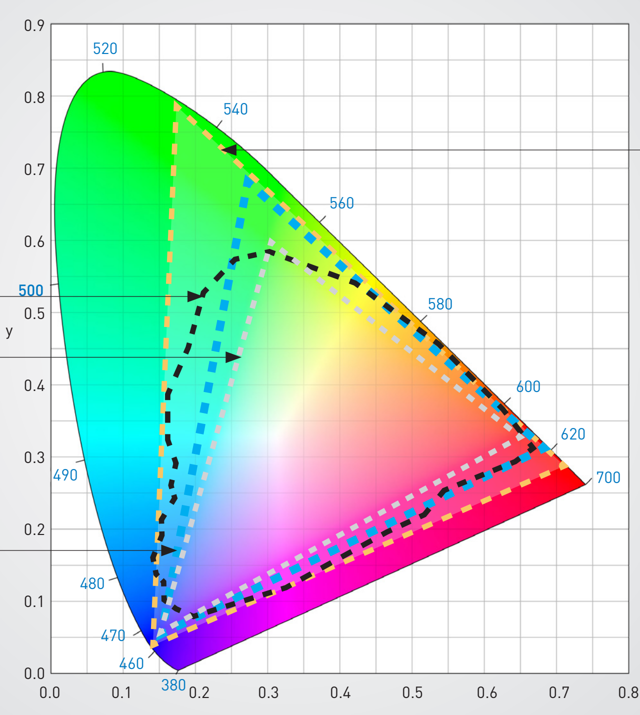
Represents the colors we see about us in the natural world—some colors outside of this area, such as neon shades or the pure monochromatic emission line of a laser, can only be produced artificially

▲ Rec 709 Gamut

The International Telecommunications Union (ITU)-specified range for HDTV

▲ DCI-P3 Gamut

The minimum standard color range in first-generation digital cinema



▲ Rec 2020 Gamut

Expanded target range for second-generation digital cinema and ITU recommendation for UHDTV

Meeting Recommendation 2020 requires laser sources with linewidth of 1 nm, which puts them on the arc of the chromaticity diagram. The other standards described use less-pure colors with broader linewidth, which put them inside the arc and reduce their gamut

1047-6938/18/05/28/8-$15.00 ©OSA

Today's digital theater projectors can't match the contrast, color palettes and luminance of the latest home HDTVs with high dynamic range.

Menace in 1999. But theater adoption of those projectors was slowed by initial prices of around US$150,000, five times that of a film projector. In 2005, film distributors stepped in, agreeing to pay cinema owners "virtual print fees" to help pay for new digital projectors. The 3-D boom that followed the blockbuster success of James Cameron's 2009 film *Avatar* added another push because the digital projectors can display higher 3-D quality.

Time for a new generation

Now, further advances in home television are challenging cinema owners again. "The theatrical experience has historically been the highest quality, but it's in danger of falling behind. HTDV today is incredible," says Chris Chinnock, president and founder of Insight Media in Norwalk, Conn., USA. Today's digital theater projectors can't match the contrast, color palettes and luminance of the latest home HDTVs with high dynamic range. Theater owners are upgrading seating and food service, but they must also keep up in image quality.

The dynamic range of conventional imaging systems is limited, making it hard to read a smartphone screen in sunlight or see into the dark corners of a film noir on television in a lit room. First-generation digital cinema had a dynamic range of 2,000 to 1, says Chris Kukshtel, director of product marketing for Dolby Cinema, but the human eye has a range of about a million to one, which lets us see in environments ranging from a moonless night to the bright midday sun, although the eye needs time to adapt to changes. Re-creating the high dynamic range we see when looking out a window on a sunny day "is a big thing" because it simulates vivid scenes in the real world, according to Michael Karagosian, head of MKTE Consulting in Calabasas, Calif., USA.

Another goal for new projectors is a broader color gamut, the range of colors produced by mixing three primaries, which is represented as the area inside a triangle on a 2-D chromaticity diagram (see sidebar). Greatly expanding the dynamic range effectively adds a third dimension to the flat chromaticity diagram, producing what some call a volume of color. "The color of a rose changes with the illumination," says Lukk. "Purples get deep and rich in low light, and by reaching down to that low level you can increase the colors. The volume of color is where high dynamic range combined with a wide color gamut gives you spectacular images, and lets you see things in nature that we hadn't been able to see in cinema."

Competing technologies

Three technologies have emerged for next-generation cinema. One is a projector that uses separate red, green and blue lasers to illuminate three micromirror arrays with projection optics combining the images and projecting them onto a screen. A second, also a projector, uses blue lasers to illuminate phosphors generating red and green, and also to provide the blue light for three micromirror arrays, with projection optics combining the images and focusing them on the screen. The third eliminates the projector and replaces the reflective screen with a super-sized emissive LED screen.

Both laser-based projectors replace the single, short-lived lamp in first-generation digital projectors with three brighter, longer-lived primary color sources that provide the light projected onto a reflective cinema screen. That gives these technologies a big head start because they work with the same micromirror arrays used in first-generation digital cinema. The arrays come in two standard sizes: 2K with 2048×1080 mirror elements, and 4K with 4096×2160 mirrors, which produce images slightly wider than the HDTV and UHDTV digital television standards.

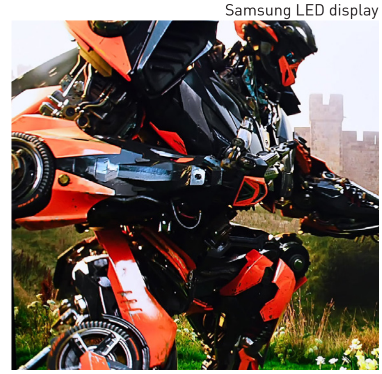
RGB projectors require separate red, green and blue lasers, each emitting a single wavelength, with pure colors that expand the color gamut beyond that achieved by traditional film projectors. The brightness of laser beams helps them provide the intense light needed for a theater screen, and the projectors use laser light more efficiently than the light from phosphors or lamps. Like xenon lamps, the lasers emit continuously, with the micromirror arrays modulating their output to produce the red, green and blue images overlaid on the screen.

Laser-based illumination is not new, but the ability to implement it in projectors at a cost comparable to lamps certainly is, says Brian Claypool, vice president of product management and global cinema for

Christie RGB display/projector

Epson phosphor display/ Christie projector

Samsung LED display



RGB laser light source

- + Excellent color gamut
- + High brightness
- + Contrast: 1,000,000 to 1
- – High cost

Laser phosphor light source

- + Low capital cost
- + Very good color gamut
- + Much longer lifetime than lamps
- – Quality similar to lamps

Emissive LED screens

- + High peak luminance
- + Excellent color gamut
- + Blackest blacks
- + Excellent contrast
- – Very high cost

Christie Digital, a projector manufacturer with roots going back to 1929. Christie has already supplied RGB laser projectors—currently used in some theaters—that use frequency-doubled neodymium lasers at 532 nm as green sources, along with diode lasers for red and blue, with the laser light fiber-coupled into the projector. Now, Christie is about to begin mass production of 4K RGB projectors using diode lasers emitting all three colors, with the light delivered to the projector head directly by the laser rather than transmitted through an optical fiber. This direct-coupling technique is believed within the industry to enhance image quality.

Image-degrading laser speckle was an early concern with RGB projectors, but speckle can be limited by using multimode lasers or other mitigation techniques. Green diode laser power has long been limited, and remains only about 80 mW in single-mode lasers. However, Nichia now offers a 1-W multimode diode with output centered at 525 nm. Fortunately, multimode output is desirable for laser projectors because its low coherence reduces laser speckle. Necsel also offers green diode sources emitting directly at 525 nm, with output to 3.5 W. Both companies' green laser diodes are used in RGB projectors.

RGB projectors are the top of the line for cinema, says Chinnock. "They are much more expensive, but you can get much higher contrast, much wider color gamut, and you can get much brighter projectors as well." Claypool says Christie has focused on direct-coupled RGB projectors because they have the most impact on improving the cinema experience. Others offering RGB projectors include Barco, Dolby, IMAX and NEC Display.

Dolby has taken advantage of RGB lasers to double luminance to 108 nits (108 cd/m^2) on screen, more than twice the 48 nits of standard lamp-based digital cinema projectors. "Where the magic happens is in producing a contrast ratio over one million to one," more than 500 times higher than standard lamp projectors, says Kukshtel.

Phosphors

Prices of laser phosphor systems are considerably lower than those of RGB laser projectors. As in LED lamps, a blue laser illuminates phosphors that absorb blue light and emit a yellowish light at longer wavelengths. For projectors, the phosphors are selected for their emission of red and green primaries that can be added to the blue laser light. The phosphors are mounted on a spinning wheel so no single spot gets overheated during operation and damaged.

In practice, laser phosphor systems use two blue laser wavelengths. One is at the 465-nm wavelength of the blue primary in the color gamut used in current

Laser-based illumination is not new, but the ability to implement it in projectors at a cost comparable to lamps certainly is.

digital cinema, to give a good color response. The other is at a shorter wavelength, typically 445 nm, to excite the phosphor more efficiently. Filters then separate the red and green phosphor outputs, and the three colors illuminate separate micromirror arrays to produce the images combined in the projector to give full color. Because the phosphors emit incoherent light, they avoid speckle. However, their emission spans a broader range of wavelengths, which limits color gamut to lower ranges than laser sources. In addition, most phosphors emit strongly at yellow wavelengths, which must be filtered out to avoid degrading color, reducing brightness and efficiency.

Laser phosphor systems share some important features with RGB projectors besides their brightness. Phosphor source lifetimes don't quite match those of RGB lasers, but typical ratings are 20,000 hours to degrade to 50 percent luminance, far longer than the typical lifetime of a xenon bulb. Phosphor sources got off to a faster start in the market because they were not hobbled by poorly performing green laser sources. But their main attraction has been a combination of lower capital cost than RGBs and much longer lifetimes than xenon lamps.

That may be changing, however. "Laser phosphor technology itself does not improve qualities such as contrast and color gamut. Performance-wise, it's more similar to a lamp," says Claypool. He thinks lamp-based projectors still offer a lower total cost of operation because mass-produced lamps are cheap enough to offset their short lifetime. That's why Christie is focusing on direct-coupled RGB projectors, which offer a substantial improvement in performance.

The LED alternative

Emissive LED displays are new contenders on the digital-cinema scene. Once limited to small phone displays, they have become common on televisions. Now, manufacturers such as Samsung are scaling up to cinema-size screens for the theater market. Projectors retain a cost advantage because they use a single bright source to illuminate a large reflective screen in a dark theater. However, emissive screens offer a better viewing experience, including

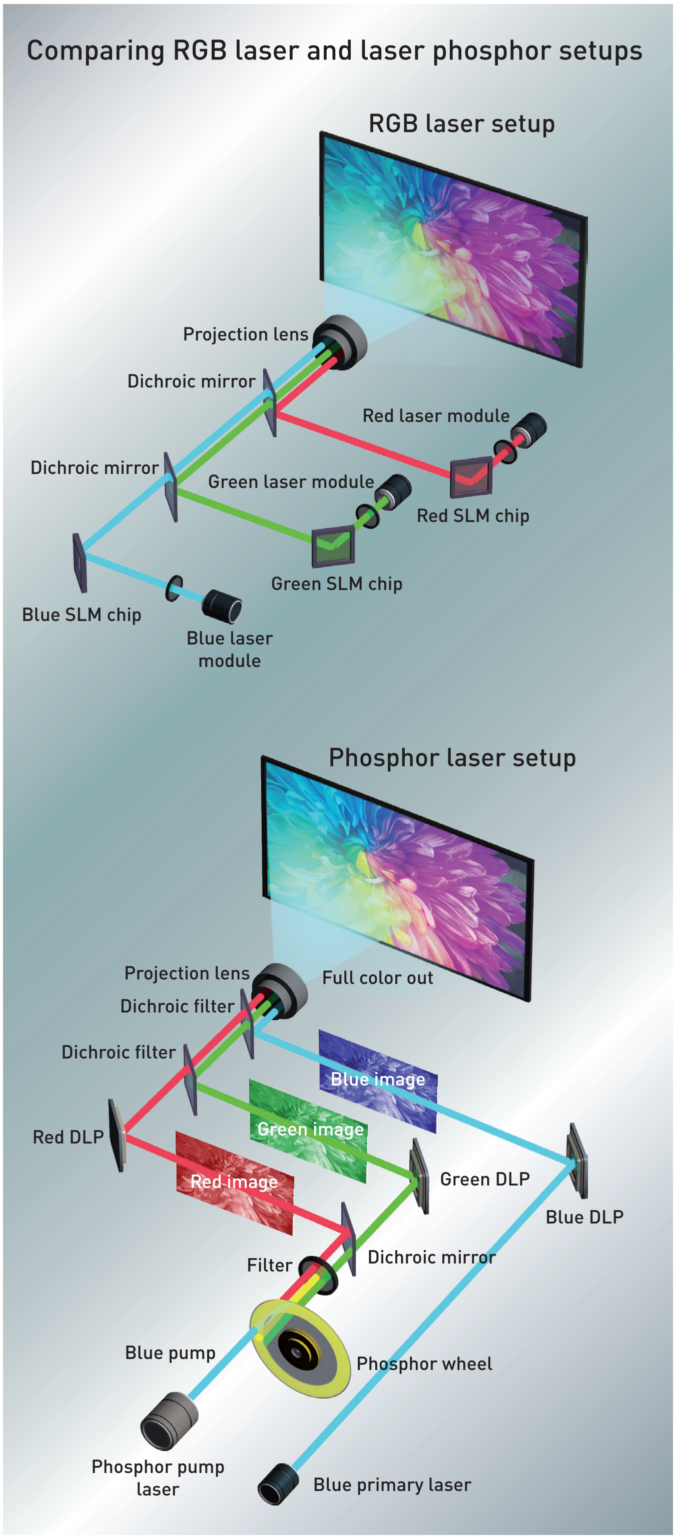


Illustration by Phil Saunders

A Dolby Vision image rendered in standard range (left) and high dynamic range (right) illustrates how much an image can be enhanced with the high dynamic range that is possible with RGB projectors. Courtesy of Dolby Vision

a broader viewing angle, higher dynamic range and darker blacks, and their economics will get better as prices decline.

Emissive screens have benefitted from the development of microscopic indium-gallium-nitride LEDs, called micro-LEDs (μLEDs). Like organic LEDs (OLEDs), inorganic μLEDs emit visible light and offer higher contrast, faster response and better efficiency than ordinary LEDs. However, μLEDs are more efficient and much brighter than OLEDs, producing better large displays and offering a high dynamic range.

Samsung impressed analysts in 2017 with a 10-m (measured diagonally) μLED "cinema screen" with full 4K resolution of 4096×2048 pixels. "The peak luminance is only 500 nits, but that's 10 times higher than the standard luminance for theaters," says Chinnock, who watched a feature film on the 10-m screen at a Seoul theater. "Many people believe this is the future of cinema," he added. He was impressed by the screen's color gamut and the "wonderful" uniformity of the light across its surface.

Karagosian was likewise impressed by the Samsung screen. "You get rich blacks because the emitting surface is mounted on a non-reflective screen ... It was amazing. All the things that had annoyed me [with cinema] had suddenly gone away." Lukk extols LED image quality and notes that emissive screens avoid the need to design theaters around projectors throwing light from the back of the room.

Emissive screens require rethinking sound systems that are traditionally placed behind the middle of a reflective screen, so the audience hears voices coming from where the actors seem to be. But Chris Buchanan of Samsung says that a new sculpted sound system from its recently acquired JBL Professional group can solve that problem.

The most serious issue preventing the adoption of emissive technology may be price, which increases sharply with screen size. Buchanan says cinemas pay US$300,000 to US$500,000 for 10-m emissive screens and associated audio systems. That's comparable to high-end laser projectors that can illuminate the 20-m reflective screens used for the largest one or two screening rooms in theater multiplexes. Samsung is considering targeting that range, but it would require four of the 10-m screen panels, multiplying the price.

Instead, Samsung is focusing on the 10-m screens considered mid-sized in multiplexes. Many theater owners are upgrading those mid-sized venues with luxury seating and better food. Adding a high-end screen to improve the viewing experience would help operators justify higher ticket prices to pay for the renovations and would also enhance their profits. Europe is moving toward smaller cinema sizes with upgraded amenities, so they can offer a greater variety of movies. Asia has also become an important market. In February 2018, Buchanan said Samsung had just installed its fifth 10-m LED screen for commercial cinema, giving it two in South Korea, and one each in China, Switzerland and Thailand. "This is going to be a very premium product," he said.

3-D and 8K

All three next-generation cinema technologies can support 3-D, and interest is strong in Asia. But 3-D is no longer the hot new thing in the United States, where interest in 3-D has dropped and viewers complain about dim screens and flicker.

RGB lasers offer a unique approach to 3-D made possible by the narrow bandwidth of the laser sources. The systems use two projectors, with two distinct sets of primary colors, placed close enough together to look

The new generation of cinema projectors and screens are getting extremely close to what the human visual system can support.

like the same shades of red, green and blue to the viewer, but spaced widely enough apart to be easily separated by the dichroic filters of the viewers' glasses. The lens for the right eye transmits the wavelengths used in the right projector and blocks colors from the left projector, and vice versa.

Dolby chose that approach because it produces superior images, says Kukshtel. The glasses' lenses are passive, and the system loses less light than conventional polarizer-based 3-D, so viewers get the same brightness as they would for 2-D shows, not the lower levels of 3-D. On the other hand, Christie is abandoning the six-color 3-D for its next generation of RGB projectors because of limited interest and the high cost of the special lasers required.

Emissive LED cinema screens, like HDTV, produce 3-D effects by using shutter glasses, which block light to each eye half of the time and don't become completely transparent, but Buchanan says Samsung's bright emissive screen "gives us a lot of brightness to play with" to make up for the losses. Shutter glasses can also be used with laser and phosphor projectors, if desired.

Screen resolution has been a big selling point in television, and manufacturers are now producing screens with 8K resolution, which for TV is 7680×4320 pixels, four times the resolution of HDTV and twice that of UHDTV. Yet when the cinema industry analyzed the prospects, it decided 4K was good enough for its viewers. The reason is that theater screens are set so far back that viewers can't see the extra resolution, says Lukk. Cinema standards call for seats being no closer than 1.5 times the screen height, or at least 7.5 m from a 10-m screen. At that distance, the eye can't see the pixels in a 4K display, so 8K resolution would serve no useful purpose. Home television is a different matter because viewers may sit closer to the screen, where they can see 4K pixels.

Cameras with 8K resolution could be valuable in cinema production because oversampling improves image quality at lower resolution, says Lukk. That high resolution could also be useful in theme parks and virtual reality because their screens are close to the eye. But he adds, "I think 16K would be ridiculous."

Looking to the future

The near-term choice of projectors will be affected by the upscaling of many screens to premium cinema, with deluxe seating, full meal service and top-notch audio and viewing. Barco, Christi and Dolby are targeting that market with RGB laser projectors, and Samsung is targeting it with emissive cinema-scale LEDs. Other companies will also offer premium projectors and LEDs, and operators will pay premium prices in hopes of boosting their sales proportionally.

Yet not all screens are going premium, and those owners that choose not to upgrade are focusing on the total cost of ownership and weighing the tradeoffs of the new technology in both up-front costs and consumables. Phosphors and RGB lasers last 20,000 to 30,000 hours, compared to 750 to 1500 hours for lamps. But, with 150,000 digital projectors using them, "lamps have never been more affordable, and we believe that lamps are still a better economic solution to the total cost of ownership," says Claypool. So operators may keep running many first-generation lamp projectors until they need replacement, especially for smaller screens.

Cinemas will need careful design adjustments to get the most out of their premium projectors and screens. Exit lights can wash out the darkest blacks of premium projectors and screens, so operators will need to move them accordingly, taking care to avoid compromising safety. Dolby already takes pains to reduce reflections and stray light, and to cover as much of the room as it can with matte black. Even audience clothing matters, says Kukshtel. If everyone wore white shirts, it would affect performance.

The new generation of cinema projectors and screens "are getting extremely close to what the human visual system can support," says Lukk. One big hurdle that cinema still faces is glasses-free 3-D, but that poses big challenges in manipulating light into the eye in the right way to provide the desired effects. It may take us beyond cinema into virtual reality and holographic mode, and that technology is not here yet, he adds. So there's more to look forward to in the next thrilling sequel. OPN

Jeff Hecht (jeff@jeffhecht.com) is an OSA Fellow and freelance writer who covers science and technology.