The MicroLED Breakthrough: Shaping the Future of Near-to-Eye Displays

Expert Insights

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MicroLEDs Bring Exciting Promise to AR/VR Near-to-Eye Displays

At Display Week 2023, the buzz around emissive technologies, especially microLED, was hard to ignore. MicroLED displays offer a unique opportunity because they can be used directly in small formats to create incredibly bright, high-resolution solutions for several applications, especially in near-eye display (NED) applications – where the optics are highly inefficient, and weight must be minimized. A headset that weighs more than your normal eyeglasses or needs to be recharged more than your phone probably will not achieve mainstream consumer acceptance. But one that does meet these targets, which also provides a compelling visual experience, is likely to be as much of a success as the smartphone.

In this compilation, we feature authors from two very well-known display manufacturers, each with their own perspectives on the role microLEDs can play in the future of AR/VR NED displays. From Samsung, we learn about the many challenges of designing a truly compelling NED and what they have learned while evaluating the strengths and weaknesses of microLED solutions for this application.

From Jade Bird Display, we learn about the state of the art for microLED manufacturing and how the industry is experimenting with the best ways to design an optical system around this technology. Both sources will tell you that there are still problems to overcome – or "opportunities for improvement" as one of my colleagues used to say to correct me. But this technology offers a lot of promise and overcomes some important limitations of previous types of imagers.

One of the significant challenges for NED development is characterizing the results of your work. How do you know when you have hit the mark? Whether you are developing prototypes in the lab or setting up a pilot production line, the latest designs for NEDs impose unique challenges on the optical measurement equipment and accessories we are all used to working with. Speaking to this challenge, the engineers at Photo Research present their views on the evolving needs for AR/VR NED display measurement capabilities.

Soon, I predict, we will see rapid progress in designs around microLED displays as well as the necessary improvements in the devices themselves. Together, we could be on the verge of an iPhone moment in this industry.

Stephen P. Atwood
Executive Editor, *Information Display*

Advanced VR and AR Displays: Improving the User Experience

For VR/AR devices to reach full potential, we need user-friendly near-eye displays that can match the human vision system, while also increasing microdisplays' functionality.

by **Juhwa Ha, Sangho Kim, Daeho Song, Sangho Park, Jintaek Park, Jaebeom Choi, and Changhee Lee**

THE COVID-19 PANDEMIC ACCELERATED THE DESIRE FOR improved user experiences in the real and virtual worlds. The demand continues for high-resolution displays capable of realizing virtual and augmented reality (VR/AR) technology, and it is increasing rapidly.

Until recently, a satisfactory AR/VR experience was difficult because of non-ergonomic designs, an insufficient network ecosystem, poor image quality, and lack of effectual app content in the VR/AR market. Despite major advances to date, developing a user-friendly near-eye display (NED) system that can match the human vision system and meet high user expectations has many obstacles.

To provide possible solutions to such problems, this article reviews VR/AR technologies that let users interactively experience virtual objects in a three-dimensional (3D) world, or the metaverse. The authors review approaches for developing VR/AR displays, optical elements, and display engines that enable users to actively undergo a sense of reality in the metaverse.

Beholding Visions with Immersive IT

VR/AR devices, combined with a high-resolution display and optical elements, have emerged as the next generation of IT platforms that can create a 3D digital, interactive world. The VR system enables users to experience picturesque scenery and have an immersive presence (**Fig. 1a**). The AR system has the added requirement that synthetic 3D objects must be visible and properly rendered in the augmented view of the real world as seen through AR glasses (**Fig. 1b**).

Despite VR's and AR's different paradigms and requirements, both require an understanding of the human visual system's characteristics. The VR/AR display should be placed a short distance from the human eyes, and the rendered images (2D or 3D information from the device) should be transmitted to the eyes from the magnifying lenses. We must examine the performance of parameters in the human visual system for a better understanding of the ultimate goals and challenges faced in the VR/AR system.[1]

RECOGNIZING DETAILS AND TECHNICAL CONFLICTS

Human visual acuity is the technical term that rates a person's ability to precisely recognize small details with the naked eye. Perfect vision (20/20 ft., 6/6 m) and 1 arcmin correspond to 60 pixels per degree (PPD). In a VR/AR system, the display's 2D resolution is converted into an angular resolution in the 3D space of the optics. This resolution can be measured as PPD, which has a trade-off relationship with field of view (FoV), provided that the display's resolution is fixed. **Fig. 2** depicts the PPD tendency from 20 to 60 PPD in terms of display size and pixel density for 90 degrees FoV. If the PPD is not high enough, a screen door effect (SDE) occurs that disturbs the viewing experience. To overcome this technical conflict, researchers have proposed several types of high-resolution microdisplays.[2,3]

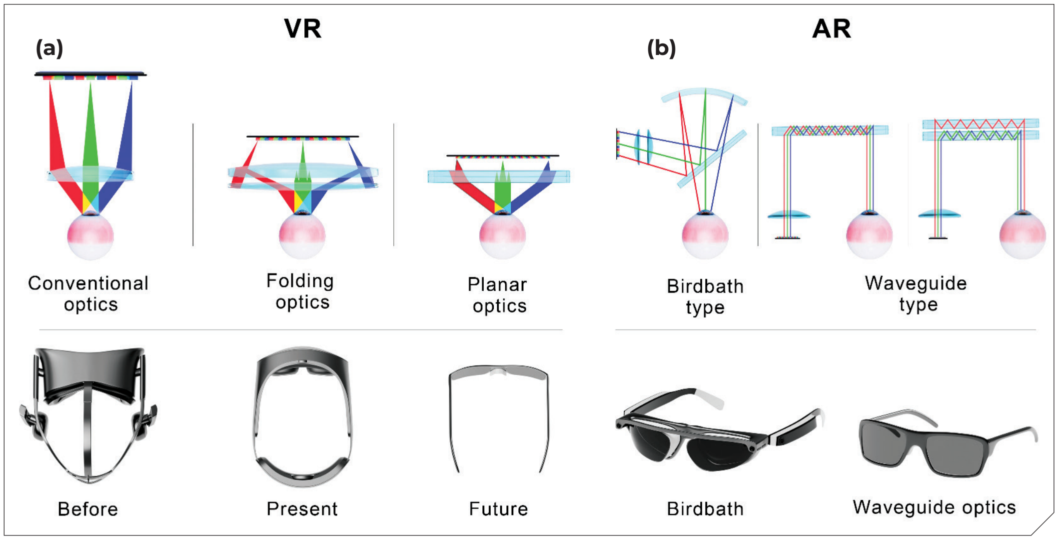


Fig. 1.

Illustrating (a) virtual reality (VR) and (b) augmented reality (AR) configurations with optical structures and product design.

VAC is a well-known cause of visual fatigue and headache.[4] This VAC phenomenon inhibits users from having a realistic VR/AR experience, often resulting in visually induced motion sickness (VIMS). Percival's and Sheard's zones of comfort can mitigate VAC.[5] We can reduce eye fatigue and VIMS by minimizing the difference of vergence and accommodation distances under 0.5 diopter using multifocal or variable-focal lens technology. Therefore, it is necessary to develop innovative optical elements that can mitigate VAC and increase the immersive presence in the natural 3D world.

MITIGATING VISUAL DIFFICULTIES

Depth cue is another important parameter to achieve a vivid 3D experience. Vergence is the natural rotation of both eyes in opposite directions to maintain single binocular vision. Accommodation involves simultaneously adjusting the movement of a crystalline lens in the eye to focus the image.

When viewing an object under natural light conditions, vergence and accommodation are neutrally coupled, as they interact with each other in the visual system and recognize the information at the same depth. When viewing an AR or VR display, the fixed image plane often is mismatched with the actual depth of the intended 3D image. The observer's eyes remain focused at the distance to the physical or virtual image plane, while their eyeballs rotate to converge the left and right eye images. This causes a conflict in the observer's natural visual processing system and leads to a phenomenon defined as the vergence-accommodation conflict (VAC) when viewing a virtual object displayed at a fixed plane in the VR system (**Fig. 3**).

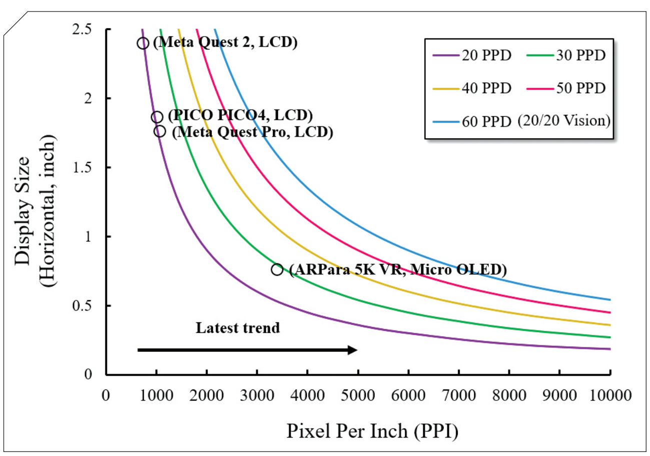


Fig. 2.

Display size versus pixel density (pixels per inch, PPI) for various pixels per degree (PPD), in the case of a fixed 90-degree field of view (FoV). Current VR products have ~20–30 PPD.

A Foray into Potential Solutions

Meta recently released a VR/mixed reality (MR) device called Quest Pro in succession of Quest 2. It adopts a 2.48-inch liquid crystal display (LCD) with 1,058 pixels per inch (PPI) and ~2,000 pixels per eye with 22 PPD and a 90-Hz refresh rate. Its improved image quality and reduced form factor use polarization-based folding optics called pancake lenses. However, regardless of improvements over previous products, critical challenges remain, such as SDE and VIMS, which cause visual fatigue.

To solve the visual fatigue and form-factor issues, efforts are underway to apply a small, higher-resolution display panel on the VR/AR system, more vivid color volume, higher luminance, and faster frame rates. These measures have accelerated microdisplays' rapid growth based on a silicon wafer. The silicon complementary metal-oxide semiconductor (Si-CMOS) can minimize the active area of a driving circuit owing to its higher carrier mobility and narrower linewidth, resulting in higher pixel density for microdisplays.

COMPARING OPTIONS

Compared with LCD and OLED based on a glass substrate, Si-based microdisplays—such as microLED, micro-OLED, liquid crystal-on-silicon (LCoS), digital micro-mirror devices (DMDs), and laser beam scanning (LBS) devices—are more efficient in meeting key performance requirements of the VR/AR system. **Fig. 4** compares microdisplay technologies in terms of six key evaluation criteria: pixel density, luminance, contrast ratio, compactness for design, color gamut, and maturity of technology in VR/AR applications.[6]

The compact form factor of an Si-based microdisplay makes the

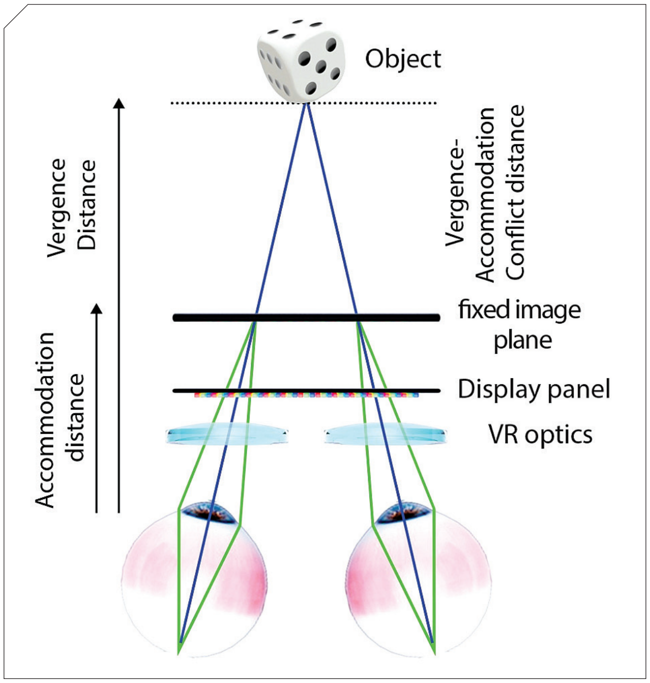


Fig. 3.

Configuration of the vergence and accommodation conflict (VAC).

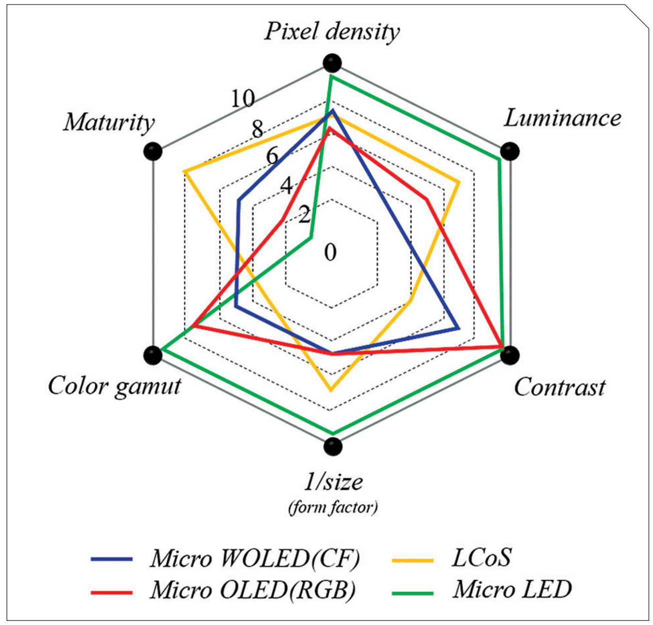


Fig. 4.

Comparison of microdisplay technologies based on six evaluation criteria for VR/AR applications. CF: color filter; LCoS: liquid crystal-on-silicon; WOLED: white OLED.

VR/AR device more attractive to users. To realize a compact VR system, the pancake lens—consisting of a half mirror and polarization configuration—usually is adopted, but it has low optical efficiency. Recently, Limbak demonstrated improved efficiency using a light-folding approach with multichannel lenses.[7] The micro-OLED and microLED devices, which are self-emissive, usually are more compact than LCoS and DMD devices because no illumination optics are required. Thus, these devices are strong candidates for future VR/MR/AR displays.

VR displays are starting to use micro-OLED technology to reduce the form factor and SDE. Micro-OLED displays can be classified into two types according to the color patterning method: white OLED (WOLED) with red, green, and blue (RGB) color filters (CFs) and patterned RGB OLED. In the WOLED microdisplay, the CF absorbs ~60–70 percent of the emitted light, limiting the luminance. The multi-stack tandem device structure is adopted to obtain higher brightness, but it requires a higher driving voltage. The luminance can be increased by matching the CF bandwidth with the OLED emission spectra and using the micro lens arrays (MLA) on the CFs.[3,6] In the RGB micro-OLED, the light from the separated RGB subpixel structures produces the desirable wavelength for a full-color display (**Fig. 5**).

By eliminating the need for CFs, high luminance can be achieved with lower power consumption, but it is challenging to make a high PPI panel. The organic material should be deposited onto the defined area of separated RGB subpixels using a fine metal mask (FMM).

It is challenging to apply current FMM technology on a microdisplay under 10-µm pixel pitch because of the shadow effect during the deposition process. Amal Ghosh and colleagues at eMagin introduced non-FMM, called direct-patterned display (dPd) technology, and demonstrated an RGB micro-OLED display with a resolution of 2,645 PPI built on a 1,920 × 1,200-pixel CMOS backplane.[8]

For AR displays, the most important parameters are brightness and glasses-like design, because AR displays are adopted in the optical see-through configuration. The basic configuration of AR displays includes a display unit, magnifying optics, and a combiner that superimpose digital content onto the physical world (**Fig. 1**). Therefore, ambient contrast ratio (ACR) is a critical parameter to achieve better image quality in AR systems.

TECHNICAL ISSUES OF MICROLEDS FOR AR DISPLAYS

To provide a superior see-through display function, AR displays should have high-resolution and high-brightness properties while maintaining low power consumption, because portability and long battery life are crucial in wearable devices. To meet these requirements, it is essential to develop high-efficiency RGB microLEDs with a chip size in the several micrometers scale.

Unfortunately, microLEDs become inefficient as the chip size shrinks because of non-radiative recombination losses at the surface states; the high surface-area-to-volume ratio makes these effects even more significant.[6,9] Recently, we demonstrated that this size-dependent external quantum efficiency (EQE) reduction problem can be alleviated by minimizing surface defects using an appropriate sidewall passivation structure and method.[9]

Another issue is that red microLED exhibits much lower EQE compared to blue and green devices and a large wavelength shift with increasing current density. In the InGaN LEDs, a higher indium content is required to realize red emission compared to blue and green LEDs. The increased indium concentration in the InGaN compound causes lattice mismatch and piezoelectric potential in the multi-quantum well (MQW), which inevitably causes wave-

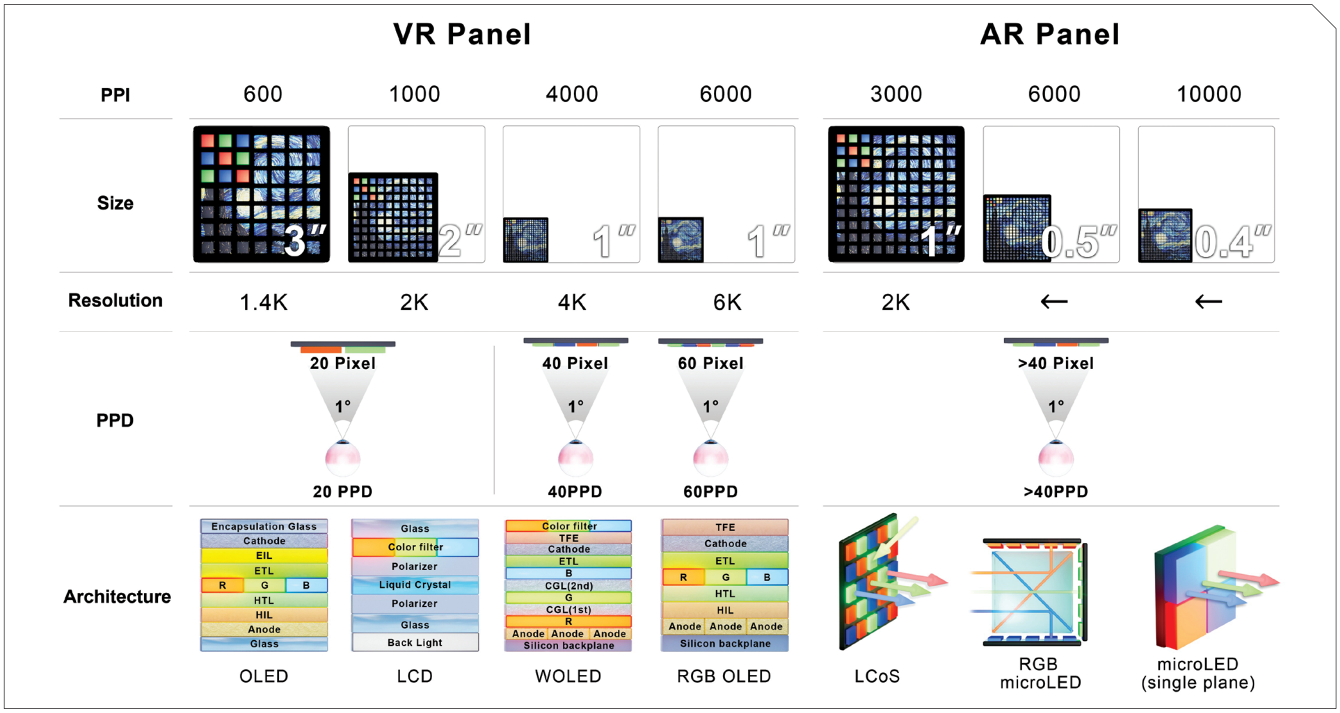


Fig. 5.

The display technology trend for AR/VR applications. A red, green, and blue (RGB) micro-OLED display with high pixel density (~60 PPD) and monolithic RGB microLED displays with high brightness of more than 6,000 PPI will provide an immersive experience in VR or AR devices.

length shift because of the quantum-confined Stark effect (QCSE).

Because of the EQE droop and wavelength shift with the current density for microLEDs, a driving method of pulse amplitude modulation (PAM), which controls luminance and gradation through the amount of current in the OLED display, is not suitable for the microLED display. A more effective method is to control luminance by fixing the current density and adjusting the current injection time (pulse width modulation, PWM). This method, in particular, can solve the wavelength shift problem of red microLEDs. Developing a device with high efficiency at low current density and combining it with an optimized pixel-driving circuit should achieve high image quality and low power consumption.

RGB LEDs still are fabricated by epitaxial growth on different wafers. Several research groups and companies are developing cross-sectional RGB and stacked vertical RGB to implement RGB on a single wafer, but the technology is not mature enough to be applied in mass production. Therefore, in the first step, three RGB panels will be commercialized using an optical combiner, and in the next step, AR products using a monolithic RGB panel are expected to be developed (**Fig. 5**).[3,6]

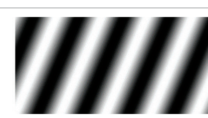
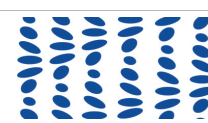
WAVEGUIDES FOR AR DISPLAYS

The waveguide is a key component in making the AR device as a glass-like form-factor.[10] The goal is to project the light efficiently from the display to the eye through the waveguide combiner.

First, the light from the display is collimated in front of an

Table 1.

Detailing the three developed waveguide grating technologies.

WAVEGUIDE	SURFACE RELIEF GRATINGS (SRG)	PHOTOPOLYMER GRATINGS (PPG)	POLARIZATION VOLUME GRATINGS (PVG)
Grating characteristic	Nanoimprinting replication Slanted features	Interference exposure Phase separation	Bragg grating LC Photoalignment self-assembly
Pros	High index modulation Spectral/angular bandwidth	Superior see-through quality Simple process	Birefringence material High efficiency Polarization selectivity
Cons	Difficulty in mass production	High spectral selectivity Narrow FoV	Color aberration
Architecture			
Company	Microsoft, Magic Leap, Dispelix, Sony	Digilens	—

in-coupler. The in-coupler should be highly efficient to collect all the collimated light from the light source. Second, the light coupled by the input grating is diffracted, satisfying the condition of total internal reflection (TIR). Finally, the light is coupled out of the glass by modulating light intensity when it encounters the folding and out-coupling grating. Through these processes, the light can be partially coupled out from the glass uniformly, and it helps to increase the exit pupil expansion (EPE).

Currently, three major diffractive coupler types—surface relief gratings (SRGs), photopolymer gratings (PPGs), and liquid crystal gratings (known as polarization volume gratings, PVGs)—have been developed (**Table 1**). They aid in creating a thin form factor, but there are still great challenges, such as VAC, increasing FoV, eyebox, and optical efficiency, in VR and AR. These details, regarding the current status of optical elements and microdisplays, will assist when rectifying these challenges while designing VR/AR displays.[1,3,6]

Conclusion

The desire to interact in the digital world has grown gradually during the past several years. However, Covid-19 has accelerated expectations and demands. The number of people using VR and AR in the workplace, private life, as entertainment, and in the medical sector has risen drastically because of social distancing and lockdown policies. This has led to increased opportunities to experience VR/AR in daily life and to interact in the 3D metaverse. The demand for high-performing display devices with small form factors and high pixel density has increased as well. To meet such expectations, emerging microdisplays—such as micro-OLED and microLED—will offer the possibility to render VR/AR devices with a more ergonomic design, high peak brightness, and good reliability by integrating new optical elements (e.g., polarization-based optical elements and waveguides).

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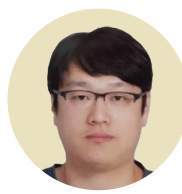

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MicroLED Microdisplays: An Invention Fueled by Augmented Reality

Soon manufacturers can use their acquired knowledge to release subsequent generations of their AR glasses with more advanced features.

by **Leon Baruah**

THERE IS TREMENDOUS ENTHUSIASM FOR AUGMENTED reality (AR) and numerous ongoing efforts to bring related hardware and software products to the enterprise and consumer mass markets. Most new and disruptive technologies have to transition from the early market fueled by innovators and early adopters to the mass market by "Crossing the Chasm."[1] With the presence of social media enabling a direct connection with end users, it is now possible for original equipment manufacturers (OEMs) to reach out to the mass market directly, without involving traditional distribution channels. Typically, this is accomplished by launching a minimally viable product and iterating it until it is widely adopted.

Developing an entry-level feature-set of AR hardware is dependent on multiple disruptive technologies coming to life in the form of displays, sensors, optics, batteries, systems on chip (SoCs), and other sub-components. MicroLED microdisplays, in particular, are critical components and tailor-made for AR glasses.

In this article, the role of microLED microdisplays in the development of AR head-mounted displays (HMDs) is described and the critical technical considerations, as well as business dynamics, are discussed that should be considered when developing a microLED microdisplay.

MicroLED Displays

As the name suggests, a "microLED" is a light-emitting diode (LED) fabricated in the scale of microns. There is no standardized definition, but with a microdisplay for AR, it often means the size of the microLED emitter is less than 5 µm. Similar to a larger-scale LED when a current is injected into a microLED emitter, light is emitted in a wavelength corresponding to the intrinsic properties (band gap) of the semiconductor material from which it is made.

Many thousands or millions of (inorganic) microLED emitters can be assembled together with the ability to control them individually. They can be used as a display by adjusting the on/off state and intensity of each emitter. Such displays, where the pixels generate light and do not require a separate illumination source, are commonly known as "self-emissive displays." OLED displays are a well-known example of self-emissive display technology. The advantages of self-emissive displays, when compared to LCDs, include unparalleled contrast; when a self-emitting pixel is off, no other sources of light exist to offset the true black state. These displays also can achieve higher efficiency, especially in images with low average luminance levels.

MicroLED technology can be applied in larger pixel-pitch displays such as TVs, but it also can be applied to manufacture extremely fine pixel pitch, ultrahigh pixel-density microdisplays. For larger pixel-pitch displays (e.g., TVs), a "mass transfer" technique is used. Individual microLED emitters are transferred from their native substrate to the display backplane, similar to a pick-and-place process for the surface-mount technology (SMT) of electronic components to printed circuit boards (PCBs). For ultrahigh pixel-density displays with a pixel pitch of a few microns, the displays are made on a wafer level by bonding the microLED wafer to the integrated circuit (IC) backplane.

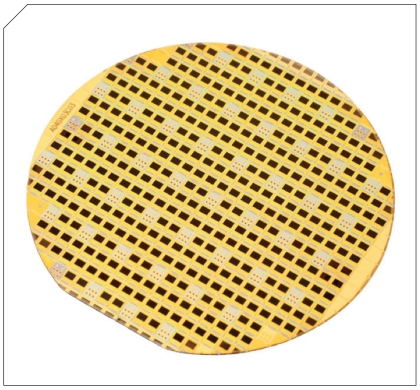


Fig. 1.

Illustration of pre-singulation Jade Bird Display (JBD) microLED displays on a CMOS IC backplane wafer.

Key Technology Enablers

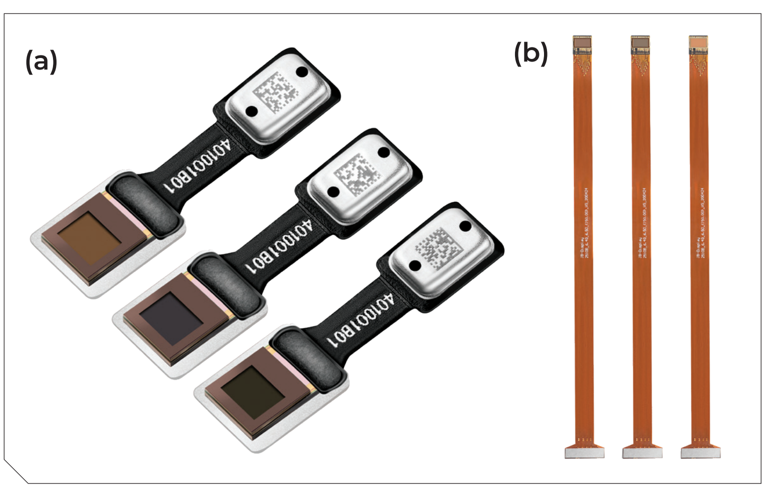
For microLED microdisplays, several organizations either focus on the development of microLED emitters or the design and development of the IC backplane driving the microLED emitters. Usually they only have expertise in one (not both) domains.

Successful partnerships are the building blocks in the adoption of any disruptive technologies, but generally they rely on expertise in completely different sciences for achieving a solution but not manufacturing a sub-component together. MicroLED microdisplays have a unique current drive, gamma, mura correction, and memory requirements compared to any other display backplane technology, including OLEDs, hence design considerations for developing the IC backplane are unique and challenging. Therefore, to be successful, an LED microdisplay manufacturer needs a broad array of skills in their toolbox; otherwise, they will not succeed. These include:

- methods for growing high-efficiency microLED epitaxial material (MOCVD);
- process to sub-divide the microLED material into pixels and subpixels only a few microns in size, while maintaining high wall plug efficiencies;
- process to design and fabricate microlens arrays (MLAs);
- ability to achieve high pixel yield and chip yield;
- process for integrating or bonding the microLED wafer with the IC backplane;
- design expertise for developing the IC backplane;
- ability to package the displays to be compatible and reliable under harsh operating conditions while maintaining a compact form factor; and
- ability to test displays for robust quality control.

Fig. 2.

(a) JBD's 0.13-inch diagonal active-matrix AmμLED display with a 4-μm pixel pitch and 640 × 480 resolution. (b) JBD's 0.22-inch diagonal active-matrix AmμLED display with a 2.5-μm pixel pitch and 1920 × 1080 resolution.



Jade Bird Display (JBD) is a vertically integrated manufacturer of microLED microdisplays (**Fig. 1**). It possesses proprietary device architecture and epitaxy technology for red, green, and blue (RGB) material, in-house device processing, testing and packaging facilities, and an extensive patent portfolio. Being vertically integrated enables faster learning cycles to meet the demands for custom design requests.

One of the main challenges facing microLEDs is the rapid degradation in external quantum efficiency when pixel size is reduced to less than 10 μm. This occurs because the ratio of perimeter to area increases and produces an edge effect that reduces the luminous efficiency. The so-called edge effect is more pronounced for red pixels using AlInGaP technology because of the higher surface recombination velocities, leading to higher efficiency loss. To date, red pixel efficiency remains the biggest challenge compared to its blue and green counterparts. The ability to mitigate edge effects is key toward enabling the adoption of this technology. To circumvent this, JBD has developed technology to engineer its epitaxy structure to be less susceptible to edge effects. Coupled with its sidewall recovery processes and MLA for beam shaping, this results in high-efficiency pixels down to a 2-μm pitch.

Applications

Every disruptive technology needs to address an application with an intractable problem, not solvable by conventional technologies. For AR glasses to achieve all-day use (with a single charge) in all ambient lighting conditions and eyewear form factors, the following are some of the requirements for the imaging source or display.

- **Ultrahigh luminance**: Millions of nits are required because of the low efficiency of see-through optical combiners. Assuming the whole optical stack, including WG and projection optics, is at best 0.5% efficient, at least 1 million nits from the display is required to generate 5,000 nits to the eye for all ambient lighting conditions.
- **Ultrahigh pixel density**: Achieved by pixel pitches less than 5 μm. The result is a high-resolution display with an ultra-compact form factor (**Fig. 2**).
- **High optical coupling efficiency**: Optical combin-

Fig. 3.

JBD's Hefei fab is under construction—a 79-acre site with a planned annual capacity of 120 million panels.

ers need collimated light from the display to capture and couple as much light as possible from the display to the see-through optics.
- **Excellent (on/off) contrast**: More than 100,000:1.
- **Excellent color gamut**: Capable of at least DCI-P3 for RGB or narrow spectral hardware for monochrome displays.
- **Excellent efficiency**: Need to consume milliwatts of power to deliver millions of nits.
- **Reliability**: Need to have stable operating characteristics in high ambient operating temperatures because of the limited envelope of space in which the display is housed.

When designed correctly, microLED microdisplays are the only display technology capable of meeting all the aforementioned requirements. Hence, it is the display of choice for AR applications.

Partnerships

For a problem as difficult to solve as AR glasses or headsets, a microdisplay forms a critical part of the hardware, but it is not a solution in its own right for the near-eye display (NED) system. A microdisplay needs projection optics (if required) and a see-through combiner. For JBD, it has taken years of working with partners developing optics and SoCs to understand what is required. Partnerships are the key to success for bringing disruptive technologies into the market, and this is mutually beneficial to all partners involved.

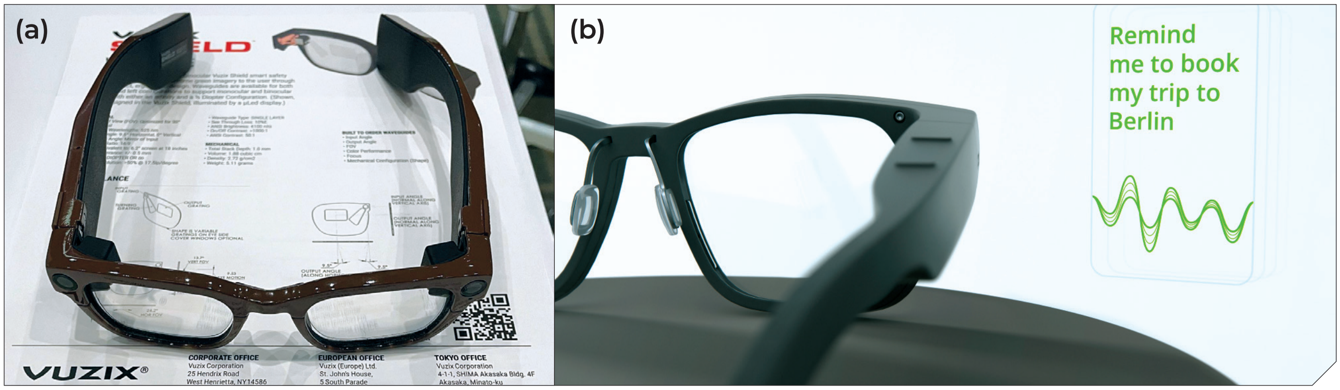
To expand on the partnerships, a brief description of the different components of a NED system, types of see-through optical combiners, how they work with microLED microdisplays, and the partnerships JBD has nurtured to develop reference designs and solutions are necessary.

JBD has established partnerships with the following optical combiner companies:

- Waveoptics: Diffractive waveguide FoV 27 degrees Katana (Asgard outline); custom 0.76 cc LE based on 0.13-inch green panel.
- Vuzix: Diffractive waveguide FoV 30 degrees; 0.35 cc custom LE based on a 0.13-inch green panel.
- Tooz: Reflective Fresnel combiner FoV less than 25 degrees; JBD's 0.13-inch polychrome X-cube 0.72 cc; and high efficiency (up to 5,000 nits to eye) + prescription.
- Dispelix: Diffractive waveguide FoV 30 degrees; JBD's 0.13-inch polychrome projector.
- HLDS: A-BSA optic (TIR) FoV 20 degrees; JBD's 0.35 cc monochrome green projector.

Manufacturing Model

Being a fabrication plant (fab) or fabless manufacturer is a business decision that is determined by multiple factors, including the capital available to build or operate a fab. Both models have benefits and challenges. Nonetheless, for a disruptive technology where there are no established foundries available or offering for the full suite of services, the benefits of having a fab is undeniable, as it leads to quicker R&D cycles and time-to-market (TTM) for launching a product (**Fig. 3**).



Economies of Scale

Introducing a disruptive technology to new customers and partners is challenging. Regardless of lean base manufacturing costs, manufacturers still must achieve economies of scale and thereby a suitable price for the marketplace. Bringing standard products to the market is one way of achieving economies of scale. Dedicated fab(s) to support and scale production follows next. OEMs developing AR glasses and HMDs often have a set of internal requirements for a display and are sometimes inclined toward developing a fully custom display from scratch. Because of the high investment required, judicious business and engineering studies must justify such a development; however, the industry is in its infancy, and volumes are not expected to be as high even if there is rapid consumer adoption. Sometimes oversights in thinking are that since some OEMs can make custom displays for their phones or tablets, then it must be an established business model. However, these companies often are both display and consumer electronics companies simultaneously, and usually they only make custom displays for mature technologies, not innovative new displays.

Fig. 4.

(a) Vuzix Shield and (b) tooz ESSNZ Berlin.

Voice of Customers

The success of a standard microLED microdisplay or for any product depends on one thing—the voice of the customer (VoC). As a non-captive manufacturer serving OEMs of all sizes, JBD understands the requirements of most OEMs for both standard products as well as custom displays. It incorporates the most important and common requirements from all the VoCs received for standard products. This has resulted in the successful incorporation of JBD's 0.13-inch video graphics array (VGA) display in many smart glasses, such as the Vuzix Shield and tooz ESSNZ Berlin (**Fig. 4**).

IMAGING SYSTEM (TYPES)
- MicroLED (μLED) display
- Micro-OLED
- DMD
- LCoS
- LBS

PROJECTOR
- Collimation/imaging lenses
- Color combining optics

OPTICAL COMBINER (TYPES)
- Waveguides (SRG/HOE/reflective)
- Prism combiner
- Lightguide with partial mirror
- Birdbath

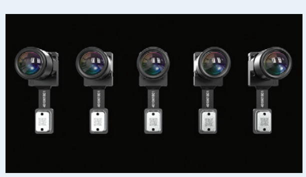


Fig. 5.

Components of a near-eye display system and how they interact.

Fig. 5: Source: JBD.

Components of a Near-Eye Display System

There are many components of a NED system. The microdisplay is the imagining source. The principle of how a microLED microdisplay operates and its inherent features that solve the problems for AR systems is described previously. For the projector or light engine, the primary function is to funnel the light from the microdisplay and couple it with the optical or see-through combiner. With the optical combiner, the optics form the virtual image and lay it on top of the real-world view (**Fig. 5**).

With the microLED projectors and light engines, the primary function is to collect the light from the microdisplay and efficiently couple it with the optical combiner. The light distribution from a microLED display is near Lambertian. JBD microLED displays have a collimating MLA called Pixel Optics, which results in 3× more optical coupling efficiency with the projection optics in the microLED projector (**Fig. 6**).

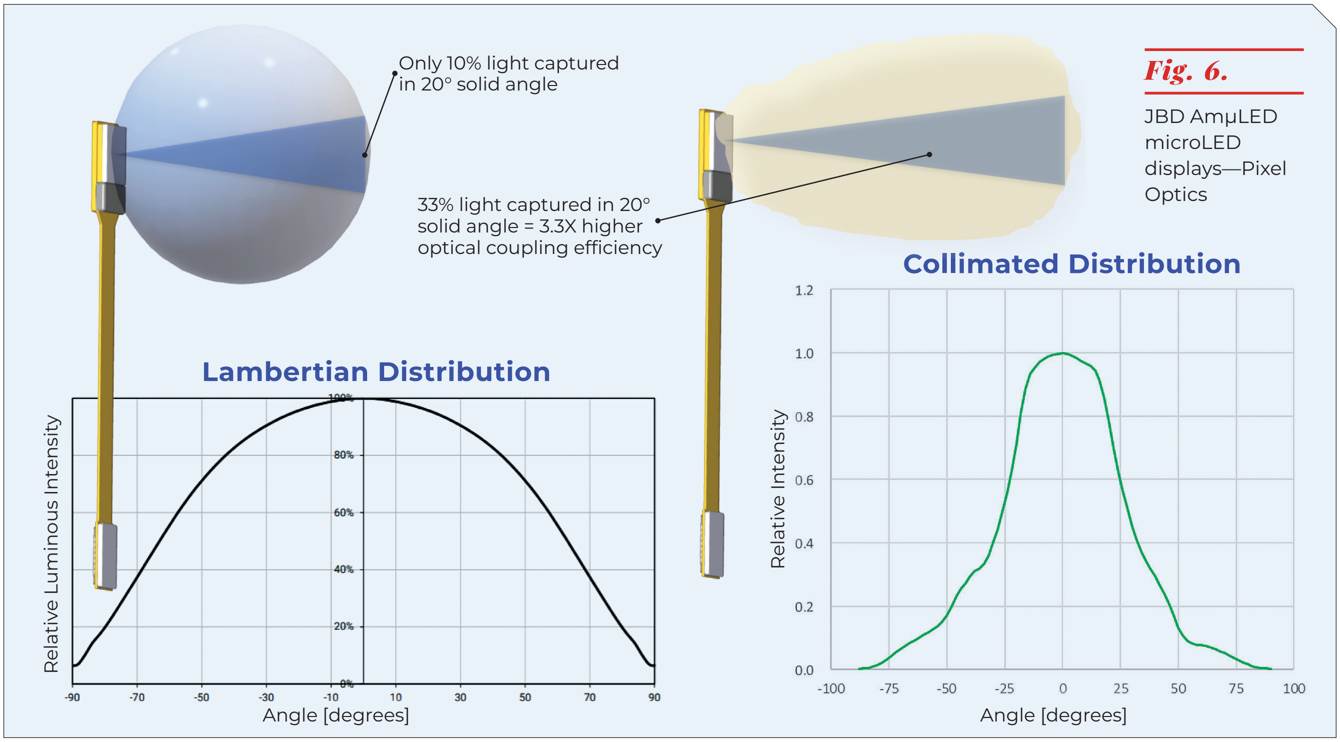


Fig. 6. JBD AmμLED microLED displays—Pixel Optics

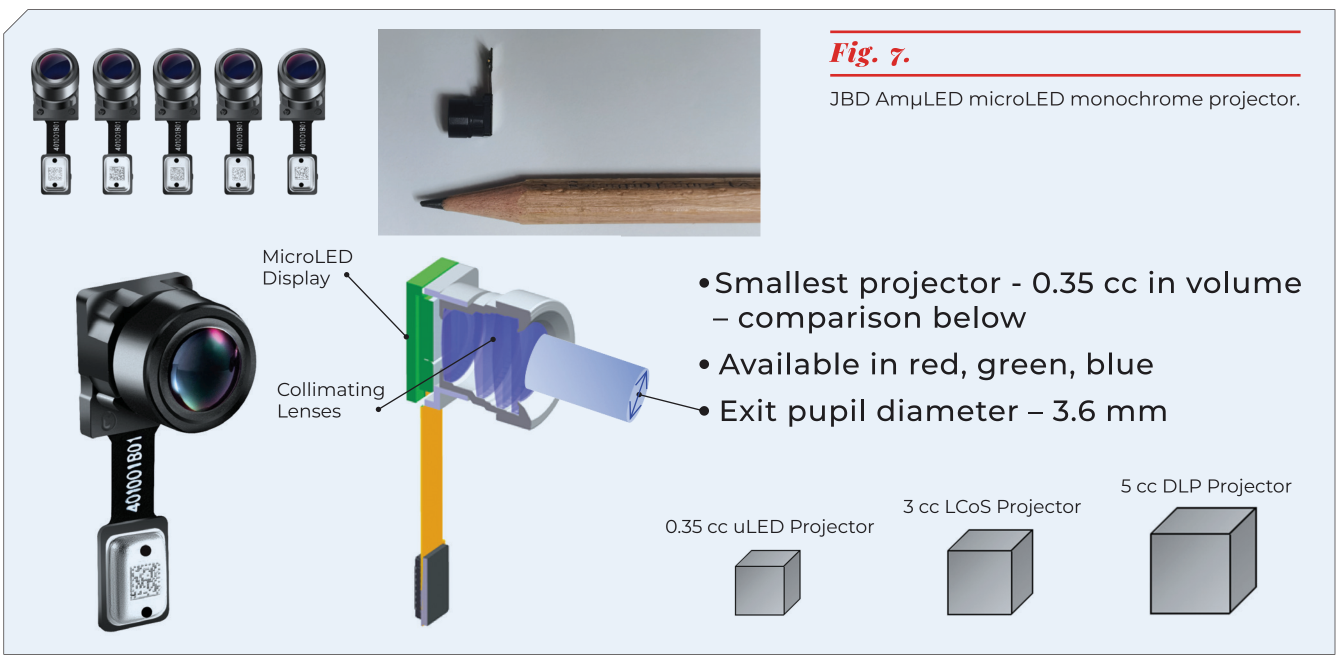


Fig. 7. JBD AmμLED microLED monochrome projector.

Figs. 6-7: Source: JBD.

MicroLED Displays with Prism Combiner	MicroLED Displays with Light-Guide and Partial Mirror	MicroLED Displays with Waveguides
- Very small FoV ~10-degree image occupies most of FoV - Image quality—okay but small FoV and eyebox—poor visual comfort - Moderate optical efficiency: microLED display operating at ~10 percent max brightness - No EPE. Small eyebox. With eye movement, projected image is easily missed. - Non-eyewear form factor. W × D > 10 × 10 mm - Suggested applications: sports AR; sports optics	- Small FoV ~20 degrees—limited content - Image quality—good, but small eyebox = moderate visual comfort - High optical efficiency: microLED display operating at ~5 percent max brightness - No EPE. Small eyebox. With eye movement, projected image is easily missed. - Non-eyewear form factor. W × D > 10 × 10 mm - Suggested applications: sports AR, helmet HUDs	- Eyewear form factor thickness = 1 mm - Pupil expansion = large eyebox - Image quality—moderate + large eyebox = good visual comfort - Moderate to large FoV ~30–60 degrees - Low optical efficiency (only applicable for diffractive waveguides, not reflective): microLED display operating at ~50 percent max brightness - Suggested applications: smart glasses, AR headsets

Table 2.

MicroLED displays with optical combiners.
EPE = exit pupil expansion

The microLED projectors have a stack of lenses that collect the light from the microLED display and collimate it into a parallel bundle of light that is fed to the input coupling of the optical combiner. Because of the ultra-compact form factor and MLA of JBD's microLED displays, JBD has developed compact and light-weight projectors that are only 0.35 cc in volume and weigh approximately 0.6 grams. JBD has developed both monochrome and polychrome projectors (**Fig. 7**).

There are several types of optical combiners, as detailed in **Fig. 5.** The optical combiners receive the image from the microLED projector, and it magnifies it either through a system of lenses or through pupil replication via a waveguide and overlays the virtual image on top of the real-world view. **Table 2** details the operation of JBD's microLED displays with the featured optical combiners.

Crawling Before Walking

MicroLED microdisplays are here, but they are not suitable for all use cases in AR. Immersive AR glasses require a number of disruptive technologies to mature, and in terms of a microdisplay, it requires a full-color ultrahigh resolution (>2K × 2K) microdisplay. The availability of a full-color single-chip microLED microdisplay is still a couple of years away. It is dependent on achieving higher efficiency at smaller pixel pitches (≤2.5 µm) and subpixel sizes for monolithic RGB displays or developing color-conversion materials, such as quantum dots, that can be applied in the aforementioned pixel pitches and remain stable over time. While JBD currently is shipping monochrome panels, development of monolithic RGB panels is underway, and prototype samples will be available in the near future.

Hardware developers working in the field of AR headsets are not pragmatic, so the adoption of microLED microdisplays is apparent. Smart glasses are aimed at being used as information-based head-up displays to show notification and navigation alerts. In addition to Vuzix and tooz, other consumer electronics OEMs have demonstrated products (soon to be launched), such as the Oppo air glass, Xiaomi Smart glasses, and Thunderbird Smart Glasses Pioneer Edition, and all of them use microLED microdisplay light engines—both monochrome and color. The resolution of the displays in these glasses are 640 × 480 (VGA) and are perfectly adequate for being used as information displays. They meet all other requirements of a microdisplay for AR, such as high-energy efficiency (all day use), ultrahigh brightness, ultra-compact form factor and excellent contrast.

MicroLED display technology is new and disruptive, and OEMs are learning about integrating microLED microdisplays with the launch of their products. As the resolution of the microdisplays increases, without increasing the form factor, and full monolithic RGB microLED displays become available, OEMs will be able to use their acquired knowledge to release subsequent generations of their AR glasses with more advanced features.

This is a light bulb moment. In comparison, factories that did not adapt quickly from incandescent or fluorescent light bulbs to LEDs ceased to exist, and early adopters that were quick to see the inevitable benefits of LEDs came out as clear winners. In the field of consumer electronics, smart watches did not turn out to be the Star Trek-style watches that could control a spaceship. Instead, they turned out to be useful as a health, fitness, and notification companion. Rome was not built in a day, and we must learn to crawl before we can walk.

Reference

[1] Moore, G.A. (2006). *Crossing the Chasm*. Harper Business (New York).

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WHITEPAPER:

Growing consumer demand for new display types challenges inline color measurement production

Why speed and accuracy are critical for color and light measurement

When you want to track the color and light measurement industry, a good place to start is the digital display industry. The display industry is innovating, and to keep up, so too is color and light measurement. Photo Research, a leader in color and light measurement, has raised the bar for its new products to meet the emerging color measurement challenges in the display industry for the coming years.

Trends impacting color and light measurement products

The trends in the display markets today, of course, influence those in display color measurement. As it turns out, 2020 was a, in a way, good for the display industry which quickly ran into shortages, thanks to those consumers purchasing for televisions, VR headsets, and such during lockdown. This renewed demand, after a previous run of low panel prices before and into 2020 that hurt display manufacturers, has only further pushed forward invention and innovation while supply chains have rallied to meet pace. It has resulted in new displays which have brighter whites, deeper darks, a wider color gamut, with resolutions that offers the crispest experience yet available.

The big players have taken to their technological paths, some have thrown their weight behind OLED or MiniLED, others vested in LCD are innovating to compete (borrowing from MiniLED, the use of many local dimming zones for high dynamic range (HDR) can improve LCD screens and reduce costs), while others (Samsung) are pushing the envelope with visually superior, but expensive, MicroLED technology, which has the future promise of overcoming those limits.

Photo Research has identified two key factors energizing future color measurement trends underlined by a invigorated display industry:

Growth of Applicable Uses of Electronic Displays — The electronic display markets show steady growth and are projected to double to more than $1.0265 trillion by 2028.[1]

While reduced costs for higher quality components plays a factor in display growth, the display industry is known to keep an innovation first mindset to prevent industry consolidation and markets stifling. Fortunately, a growth in the number of display applications for high-quality displays is helping to drive innovation. This market will be filled with an increase of displays for video walls, TVs, and digital signage applications, as well as interactive displays in various applications, including rising demand for display-based medical equipment.

Moreover, these technologies are expected to penetrate further into foreign and emerging markets in the expectation that high-speed connectivity spreads, followed by streaming services. Keeping up with this style of innovation and production to meet demand will challenge inline color measurement of products during production—as display resolution enlarges and improves, so do the difficulties in accurately

[1] https://www.prnewswire.com/news-releases/at-cagr-of-10-9-global-electronic-display-market-size--share-2022---2028--projected-to-surpass-at-usd-1-026-5-billion-industry-trends-value-analysis--forecast-report-by-zion-market-research-301548035.html

measuring the increasing variability in the growing number of pixels, while increasing production speed only compounds the issue of performing the task.

Adoption and Growth of Applicable Uses of Near-eye Displays (NED) — In 2021, the growth of VR/AR headsets hit a CAGR of 56.1%, reaching an astounding 81.2 million units of production.[2] Astonishing growth since the first primetime ready VR headset hit markets in 2016.

This achievement was made possible by exceptional reduction in component costs, improvements in VR applications, and customer curiosity turned to adoption. But also, because VR headsets are finding greater application in a number of industries. They're used in product design for automotive and aerospace. They're used to help imagine spaces in architecture, interior design, and real estate. And in healthcare they're used in surgical operations to help visualize the operating field better. Greater demand and the unique virtual quality of the NED headset display, namely targeting and measuring the VR ghost image, will challenge its color measurements in production.

Trends in color measurement devices

The primary production concern with these newer display technologies is achieving microscopic accuracy at mass-production speeds. Emissive displays have innate variability, extremely high resolutions, and elevated quality expectations, so, the most important innovation design factors are to design products that fulfill:

- Greater color and luminance accuracy that overcomes variability and resolution
- Faster measurement and readout speed capable for inline production speeds
- Increasing solution flexibility for application fit and future adaptability

Based on the before mentioned trends and these design focuses, PRI has identified six key trends in color measurement devices:

1. **Stand-alone Capabilities** — A key improvement in the general spectroradiometer is the uncoupling of external computers from the measuring device. Now, spectroradiometers can measure spectral values on the device itself, and often using familiar interfaces like touch screens.

2. **Miniaturization of Form Factor** — The miniaturization of spectral measurement equipment is a key area of development. Miniature field spectroradiometers have an exceptional range of applications, not only on the manufacturing line where high speed color measurements are needed, but in other exotic areas, like in underwater remote sensing, or in greenhouse plant production.

3. **Expanded Connectivity** — While new devices are smaller and ready for more applications outside and inside the factory or laboratory, so follows the need to make connectivity more accessible. Color measurement devices are being equipped with new interfaces, including Bluetooth, NFC, USB, and WiFi, making them adaptable components in larger more complex systems.

4. **Multi-channel Measurement Capabilities** — Multi-channel spectroradiometers are some of the most advanced, capable of measuring multiple points in a single pass. Many are equipped with extended measuring capabilities into the near-infrared and ultraviolet bands. Multi-channel spectroradiometers have applications such as rocket motor exhaust efflux analysis or the examination of gun flashes that are beyond the capabilities of other spectroradiometers.

5. **Custom Algorithms** — Algorithms improve the capabilities of light and color measuring devices and help to analyze base measurements to produce properties such as irradiance, illuminance,

[2] https://www.azooptics.com/Article.aspx?ArticleID=1668

chromacity, peak and dominate wavelengths, and much more. They can also be used in custom applications to overcome visibility challenges, for instance by applying custom algorithms to accurately detect aerosol in a given airspace.

6. **AR/VR/MR Color Measurement Capabilities** — Augmented Reality/ Virtual Reality/ Mixed Reality applications, collectively Near-Eye Display (NED) devices, have developed to serve many new applications, in medical, military, education, and more, and have entered into mass consumption. Adoption has embroiled the call for virtual experiences to match reality with greater fidelity, a key factor in devising spectroradiometers capable of measuring virtual images accurately.

Photo Research anticipates that these trends will likely not slow anytime soon, nor will the demand for high-quality displays from consumers abate.

Color measurement solutions

With an optimistic outlook, and design insight from the prevailing production trends, Photo Research has expanded their color and light measurement solution suite, which is now capable of accurately measuring AR/VR headsets. New enhanced models will replace stalwart flagship solutions, addressing the new challenges in R&D, inline production, and field applications.

- **SpectraScan PR-1050** with enhanced features for R&D
- Introduction of **ATAKT Velocity 7-HS** for inline manufacturing
- **SpectraScan PR-670** an enhanced economic portable solution
- **AV/VR SpectraScan Lens Adapter** for NED headsets

SpectraScan PR-1050 for Research and Development

The Photo Research SpectraScan PR-1050 is their most advanced and versatile R&D spectroradiometer. The PR-1050 has undergone several key future-proof enhancements that ensures it will be an indispensable tool throughout many successive product development lifecycles.

SpectraScan PR-1050

Feature improvements include:

- Sensitivity Improvements — allowing more accurate color measurements of OLED, and other emissive displays
- Mitigation of Residual Bulk Images — allowing for greater speeds
- Improvement of Luminance and Color Accuracy on Narrowband Sources
- Introduction of Higher Quality Diffraction Gratings

SpectraScan PR-1050 detailed improvements

FEATURE	DETAILS	KEY BENEFITS
Mitigation of Residual Bulk Images (RBI)	• Proprietary firmware algorithm removes RBI from measurements	Improved accuracy and sensitivity (down to 1.71×10-5 cd/m²)
Introduction of Higher Quality Diffraction Gratings	• Optimized blaze wavelengths for more neutral spectral responsivity • High cosmetic quality of new grating replicas and strict quality requirements	Improved stray light levels (up to 10 - 50%)
Optimized internal neutral-density (ND) filter	• Spectrally optimized internal ND filter, improved transmission in the blue and green	Luminance error less than 1%, CIE x,y 0.0015
Display optimization mode	• Auto display setting function with 16ms min exposure	Ideal for display customers, reduces setup errors
Improved sensitivity & speed	• Adopt PR-740 optics and relocated internal ND	Improved sensitivity from 1.37E-4 to 6.8E-5 cd/m2

ATAKT Velocity 7-HS for Inline Color Measurements

Manufacturers of displays and other similar equipment must test the accuracy of their products before they leave the factory. To address this, JADAK offers a high sensitivity inline production spectroradiometer, the ATAKT Velocity 7-HS. The V-7HS prioritizes speed and accuracy, measuring 0.5 cd/m² at 250ms total measurement time (tested for LED backlit LCDs). Other spectroradiometers can take up to 14 seconds to complete this same task. This means that it is possible to conduct in-line production testing with exceptional spectral accuracy nearing real-time speeds.

ATAKT Velocity 7-HS

Feature benefits include:

- Easy-to-use application SDK for custom developments
- Built-in CCD target acquisition camera cuts the need to manual target through an eye-piece
- Multiple connectivity interfaces, including USB and RS232
- Highly durable designed built for production environments
- Mountable through ¼-20 SAE threaded mounting holes
- Compatable with specialized lens to reduce unwanted light

AV/VR SpectraScan Lens Adapter for NED Headsets

The challenges presented by AV/VR headsets stem from the idea that the target to measure is a ghost image, however, there are also structural challenges as well, which include:

- Target image is viewed extremely close up
- Target image is viewed with a wide field of view (immersive)
- Target image is viewed within head-mounted devices (goggles, glasses, and headsets)

To overcome these challenges, JADAK has designed an AR/VR lens adapter for SpectraScan units that easily attaches and allows the measurement of light within the range of 0.3-6mm. The adapter point-and-measure feature allows headsets to easily align into measurement position, but also to allow units to be quickly switched out during quality checks.

AV/VR SpectraScan Lens Adapter

SpectraScan PR-670 for Mobile Color Measurement

Color measurement applications extend into the real-world too, and JADAK addresses these color measurement situations with their SpectraScan PR-670 model. The PR-670 is a portable, economical, battery powered unit for precisely measuring a range of light sources in the physical world, including displays, projectors, electronic signage, reflective surfaces, and industrial applications.

SpectraScan PR-670

About Photo Research

Photo Research, a Novanta brand, has been developing products that have been the gold standard for the cinema business since the early 1940's. Since that time, the products have won numerous Academy Awards and continued to raise the bar in light and color measurement. Today, Photo Research offers a wide range of luminance and color measurement solutions including the Photo Research SpectraScan® Spectroradiometer series for spectral based photometric and colorimetric light measurements.

About Novanta

Novanta is a leading global supplier of core technology solutions that give medical and advanced industrial original equipment manufacturers a competitive advantage. We combine deep proprietary technology expertise and competencies in precision medicine and manufacturing, medical solutions, and robotics and automation with a proven ability to solve complex technical challenges. This enables Novanta to engineer core components and sub-systems that deliver extreme precision and performance, tailored to our customers' demanding applications. The driving force behind our growth is the team of innovative professionals who share a commitment to innovation and customer success. Novanta's common shares are quoted on Nasdaq under the ticker symbol "NOVT."