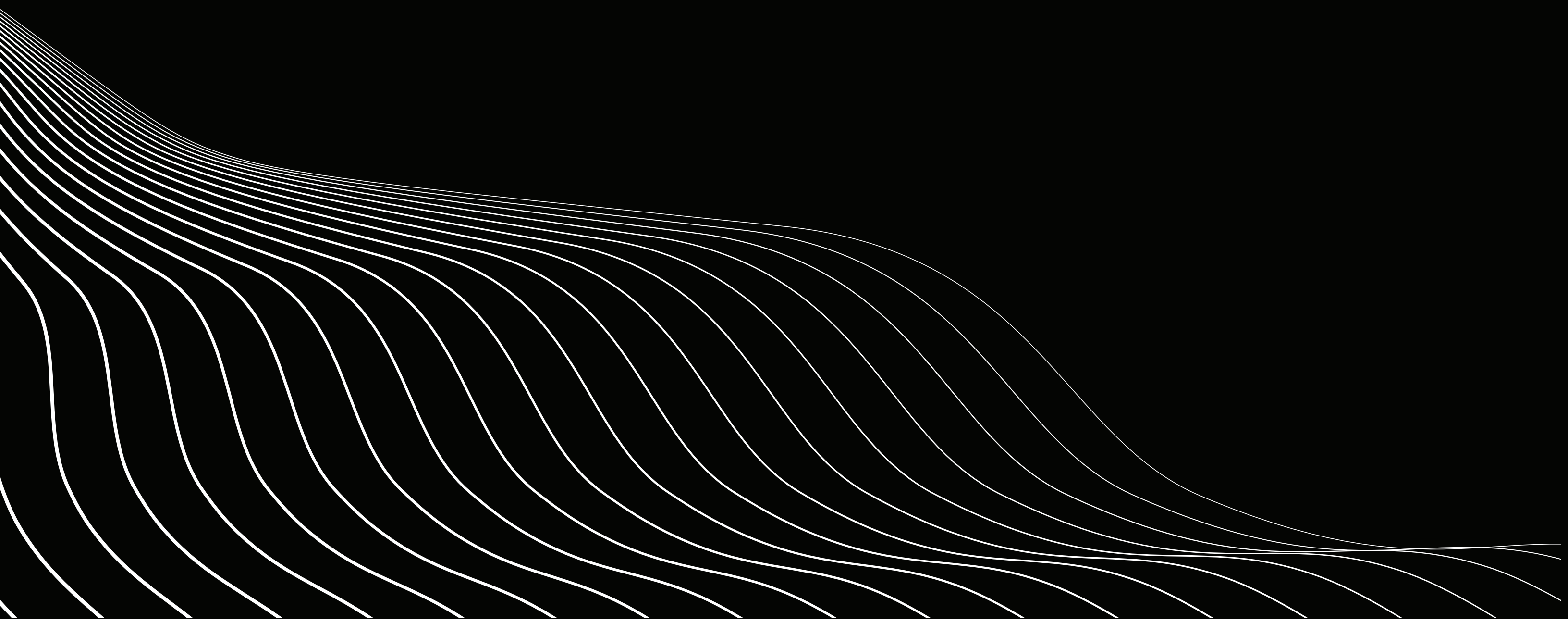
BRIGHTVIEW
TECHNOLOGIES

Creating Uniform, Bright Displays Using Micro Lens Arrays in 2D Mini-LED Backlight Units



Whitepaper

New 2D mini-LED backlight architectures for liquid crystal displays offer improved contrast and brightness performance over other backlight designs. Creating a uniform 2D mini-LED backlight that meets demanding thickness and efficiency requirements is challenging. This whitepaper discusses backlight design considerations and how BrightView's Micro Lens Array technology fits into this new architecture.

Summary

- Micro lens arrays (MLAs) create highly uniform light output from 2D mini LED backlight units for LCDs that are thin and efficient
- Every 2D mini LED backlight design requires a unique film stack depending on several factors including the LED pitch, reflector type, LED type, color conversion film, and desired thickness
- The MLA stack configuration should be considered early in the design cycle to ensure performance is optimized

Introduction

Liquid Crystal Displays (LCDs) are a highly successful, pervasive display technology used in myriad electronic devices such as televisions, computer monitors and notebooks, smartphones, tablets, and automotive displays. After many years in the market, new innovations still continue to drive performance and feature improvements. 2D mini-LED backlight architecture is a recent major innovation that dramatically increases contrast and brightness compared to existing backlight designs. These new LCDs demonstrate similar contrast performance to emissive displays, including organic light emitting diode (OLED) displays, with contrast ratios on the order of 1,000,000:1. They also feature high levels of continuous and peak brightness of >1000 nits, depending on the display model, without the drawback of burn-in which often plagues OLED devices.

Figure 1. Mini-LED displays improve contrast compared to edge lit displays.

New Design Challenges

The new 2D mini-LED backlights demonstrate a dramatic performance increase but pose new design challenges for display engineers as it differs from current LCD backlight technologies in significant ways. LCD backlights in the market today usually consist of a row of LEDs aligned along one edge of the backlight unit, which are directed into a light guide. Called edge lit displays, these devices typically use a single diffuser film in conjunction with crossed brightness enhancement films (xBEFs) to manage and direct the light to the user, see Figure 2. The diffuser film, or down diffuser, ensures a smooth, uniform light output from the light guide, while the xBEFs narrow the viewing angle of emitted light and increase its intensity outward. Edge lit LCDs are a mature, cost-effective display technology, but they are unable to create high dynamic range (HDR) high-contrast content like OLED displays and cannot efficiently reach brightness levels customers demand.

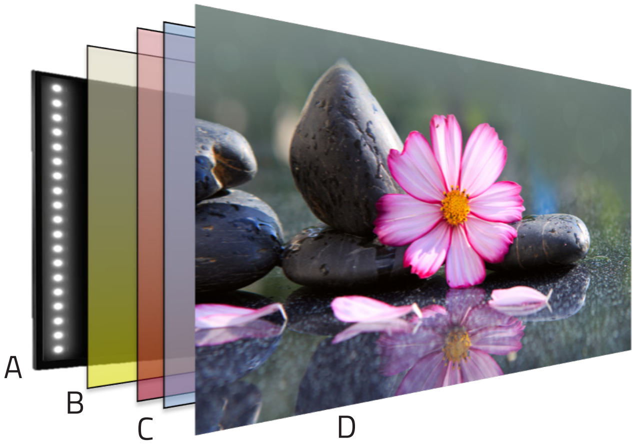


Figure 2. The layers in an example edge lit BLU configuration. The edge lit light guide (A) is at the back, followed by the down diffuser (B, yellow), xBEFs (C, red and blue) and LCD panel (D).

2D mini-LED backlight units consist of an array of LEDs bonded to a PCB that turn on and off, or adjust to a specific brightness, individually or in clusters of a few LEDs. These single or clusters of LEDs, called local dimming zones, can number from a few hundred to many thousands depending on the design. Local dimming zones solve an inherent drawback that limits an LCD's contrast performance. An individual liquid crystal cell in the panel acts as an on/off switch. This switch is unable to fully turn off and allows some light to leak through, so dark colors and blacks are not well reproduced resulting in a relatively low contrast ratio. 2D mini-LED backlight units, hereafter referred to as 2D BLUs, circumvent the light leak issue by dimming or turning off specific zonesin the backlight itself, so there is little to no light to leak through when the liquid crystal cell is in its off state. This enables the LCD to reproduce truer blacks and dark colors dramatically increasing the contrast ratio. Note that an edge lit backlight must constantly remain on when displaying content. Figure 3 shows an example of a 2D LED backlight array board, from Rohinni (www.rohinni.com), which consists of 1,920 LEDs on a 2 mm pitch with 480 dimming zones (4 LEDs per zone). Depending on the board design, the LED pitch can vary as well as the number of LEDs in a dimming zone. Increasing the density of local dimming zones reproduces smaller areas of high contrast, further improving the display quality.

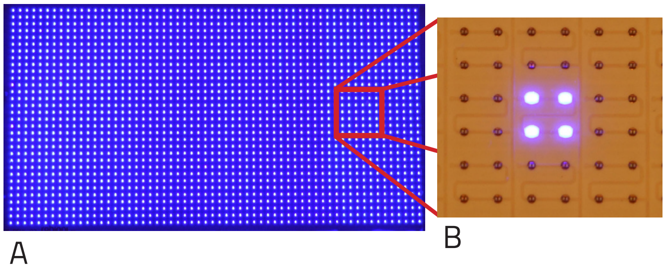


Figure 3. 2D mini LED backlight architecture. A) shows an LED board and the array of blue LEDs arranged in square pattern. This Rohinni board has 1,920 individual LEDs with a 2 mm pitch and 480 dimming zones. B) a close up of an individual zone, comprised of a group of 4 LEDs.

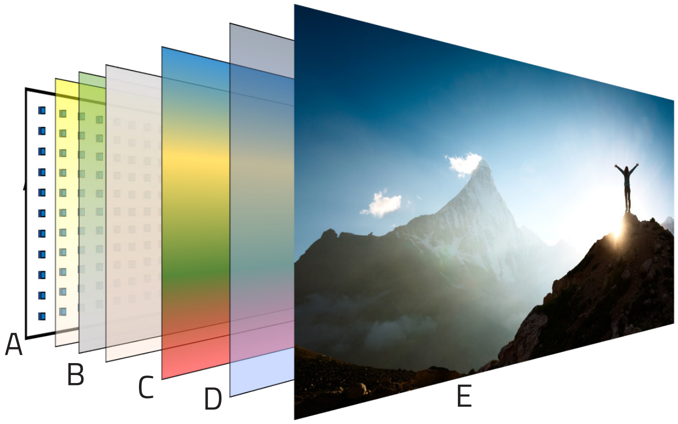


Figure 4. The layers in an example 2D BLU configuration. The LED array (A) is in the back, followed by MLAs (B, yellow, green and tan), the color conversion film (C, rainbow color), a edge mura correction film (D, blue), xBEFs (not shown), and the LCD panel (E).

In a 2D BLU, each individual LED in the array acts as a point source of light. These point sources must be hidden, or smoothed out, to produce uniform light output. The display must also be thin and energy efficient - crucial requirements for mobile devices such as smartphones, tablets, notebook computers, and displays in electric vehicles. 2D BLUs often use blue LEDs due their wide availability in the supply chain and cost considerations (these details are beyond the scope of this whitepaper). Blue LEDs require a color conversion film to convert some blue light to red and green to create white light for the LCD to work properly. Figure 4 shows an example film stack configuration in a 2D BLU. The LED array is located at the back of the stack, followed by the films used for LED hiding, the color conversion film, xBEFs, and LCD panel.

The new architecture offers exciting opportunities in display designs but requires innovative solutions for LED hiding to meet performance requirements. Therefore a departure from current diffuser film designs is needed. This whitepaper discusses the main BLU components, how they interact, and important design tradeoffs, as it applies to the film stack, when bringing a new 2D BLU to market.

Design Considerations for 2D Mini-LED BLUs

When designing a high performance 2D BLU display there are several factors to consider:

- LED spacing or pitch: 2D BLUs have an array of LEDs, arranged in regular square matrix array or checkerboard pattern. The LEDs can be spaced differently, depending on the design. Fewer LEDs saves costs, but usually do not perform as well as backlights with more LEDs.
- LED type: DBR and non-DBR LEDs. LEDs can have a Bragg reflector that directs light to the side of the LED, as opposed to in a Lambertian distribution: non-DBR.
- LED packaging and encapsulation: LED arrays use a bare die and are encapsulated directly onto the PCB verses traditional packaged LED format. The way LEDs are packaged can have an effect on hiding performance.

- LED color: Blue LEDs are often used for the backlight, but white LEDs (CSPs) have also found use. Blue LEDs require a color conversion film; white LEDs do not.
- Color conversion film: There are two types of color conversion film available today: quantum dot (QD) and phosphor. This film converts some blue light to red and green to create white light.
- Color Edge Mura: 2D mini-LED displays often have color non uniformity around the perimeter of the display, which can effect the color quality of images and video. It can be corrected with a film or through software. This is important as LCD designers move to bezel-less displays.
- Reflector: A reflector can be used behind the LED array to help direct and recycle light out. It can consist of different materials and reflective properties, which affects the performance of the films in the stack.
- BLT: Blue layer transmission films enhance transmission of blue light from the LED array and reflection of red and green from the color conversion film. This adds cost and thickness to the backlight but offers a performance boost.
- Thickness: The thickness of the display depends on the design of the BLU and can be a function of the LED spacing, type, and encapsulation among other factors.
- Cost: Perhaps the most important consideration, the cost depends on the number of LEDs, type of LED (blue or white, DBR vs non DBR), thickness (thinner displays are more challenging), film choice, encapsulation, rigid or flex PCBs, among several other factors.

The components of the BLU are interdependent and changing one can have meaningful performance and cost impacts on others. The design must factor in these components and interdependencies to determine which LED hiding solution is optimal. Figure 5 shows a simple example of how each component can affect another; the thicker arrows indicate a stronger dependency. Due to the sheer number of design combinations, every 2D BLU requires some level of film stack customization.

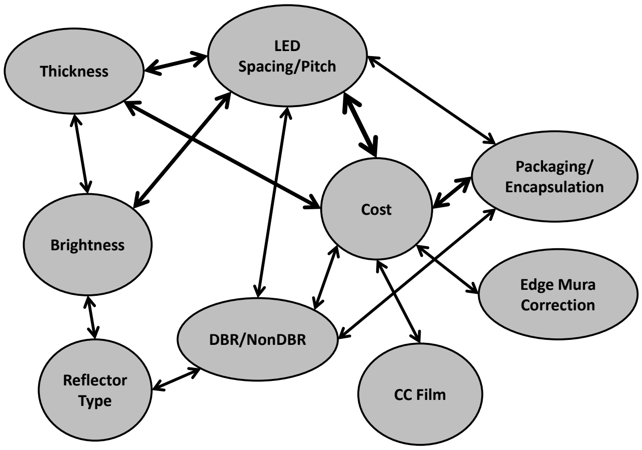


Figure 5. Schematic showing interdependencies in design factors. Thicker arrows indicate a stronger dependency.

LED Hiding with Conventional Volumetric Diffusers

Edge lit LCDs often rely on volumetric diffusers or simple coated diffusers (coating on a film) as the down diffuser to create a uniform backlight. While volumetric diffusers can work well in edge lit displays, and are widely used in LED lighting for hiding, they are not well suited for 2D BLU applications. They cannot create the required light uniformity and meet stringent performance requirements, primarily thickness and efficiency, needed to take full advantage of the new architecture. Figure 6 shows an example film stack configuration in a 2D BLU using a volumetric diffuser. The diffuser sits on or just above the LED array, followed by the color conversion film, xBEFs and LCD panel.

A strongly scattering, thick volumetric diffuser is required to sufficiently hide LEDs in a 2D BLU. If the volumetric is too thin, mura appears, which manifests as uneven luminance across the display and individual LEDs remain visibly distinct. Figure 7 shows the results of LED hiding performance using a 105° volumetric diffuser with three different thicknesses. The volumetric film was placed directly on the LED

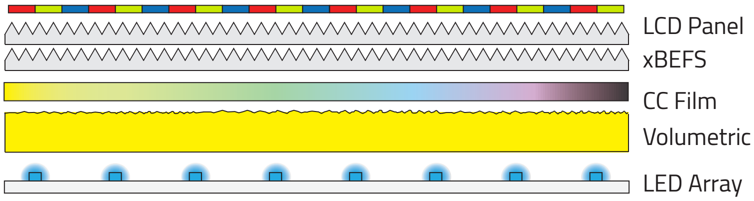
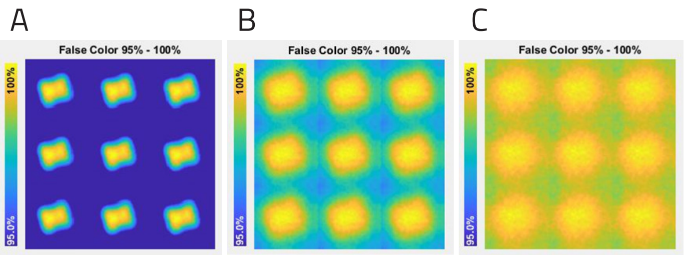


Figure 6. Example schematic of the layers in a mini LED display using a volumetric diffuser. The diffuser sits on or just above the 2D LED array, followed by the color conversion film, xBEFs and LCD panel.

array (zero optical distance), followed by a quantum dot color conversion film, and xBEFs. At a film thickness of 0.36 mm, Figure 7A, the LEDs are clearly visible with a range/mean (brightest point vs dimmest point) of 14.6%. As the thickness increases to 1.14 mm, Figure 7C, the range/mean is reduced to a more acceptable level of 1.75%. However, the mean energy (brightness) is reduced to 64.6%, an efficiency level unacceptable for most 2D BLU design specifications.

2D BLUs have LEDs arranged in a square or rectangular array. However, volumetric films diffuse light radially, which can create hot spots due to overspreading. As the volumetric film thickness is increased to create sufficient hiding, light from adjacent LEDs begin to overlap making an optimal, homogeneous light spreading configuration very challenging. Figure 8 illustrates this effect. The thinner film, Figure 8A, shows under spreading, while the thicker film, Figure 8B, exhibits overspreading.



T = 0.36mm
Mean Energy = 83.1%
Range/Mean = 14.6%

T = 0.76mm
Mean Energy = 72.8%
Range/Mean = 3.7%

T = 1.14mm
Mean Energy = 64.6%
Range/Mean = 1.75%

Figure 7. A) 0.36 mm thick 105° volumetric diffuser, B) 0.76 mm thick diffuser, C) 1.14 mm thick diffuser on a 2D BLU. LED hiding increases as the volumetric film gets thicker, but efficiency is reduced. Mean energy and range/mean measurements are relative and meant for comparison only.

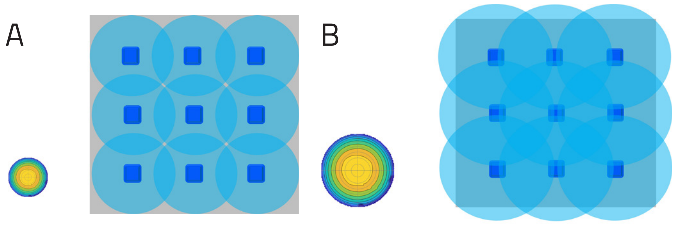


Figure 8. Light spreading as a function of film thickness. As thickness of a volumetric film increases, it can lead to over spreading and hot spots. A) shows a thinner film, B) a thicker one.

LED Hiding with Micro Lens Arrays

Micro Lens Arrays (MLAs) use customized engineered optics to steer and shape light in a variety of applications, and can be specifically engineered to hide LEDs in 2D BLUs more effectively than volumetric diffusers. They feature micron-scale lenses that are embossed, etched, or molded onto or in optically clear substrates such as PET and polycarbonate films. BrightView MLAs are manufactured in a high volume, roll-to-roll production process, which uses an embossing tool created on a unique digital gray scale lithography system. This process enables a unique lens design that can be tailored to hide the 2D LED array efficiently, with high uniformity, and zero optical distance (OD). MLAs achieve this using three methods: beam shaping, image splitting, and film thickness.

Beam Shaping

MLAs can create distinct beam shapes, in effect reversing an LED's emission profile, to steer the zero-order emission into the dark regions between LEDs. For example, a Lambertian LED source can be shaped into various intensity profiles with different symmetries using specific lens shapes, which can be tailored to match the geometry of a 2D LED array. Figure 9 shows some examples beam shapes made possible using MLAs.

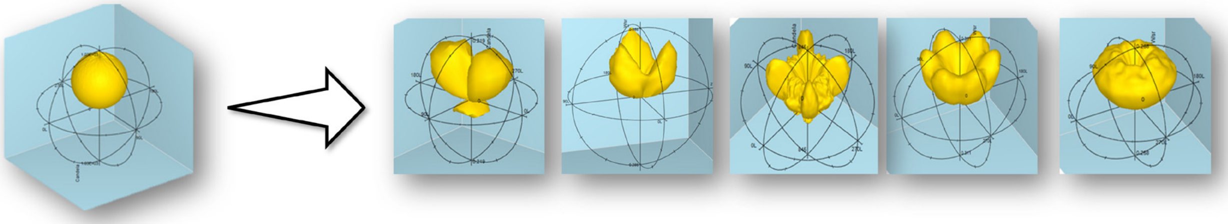


Figure 9. Simulated LED emission profiles. The left most image shows the emission profile (Lambertian) of an individual LED. The series of images on the right show the different intensity profiles possible using BrightView MLAs.

Image Splitting

Image splitting takes a single LED and splits the profile to simulate multiple points of light. In this way, a single LED acts as multiple sources that are closer together achieving higher LED packing density optically. The lens shape of the MLA determines how the light is split, see Figure 10.

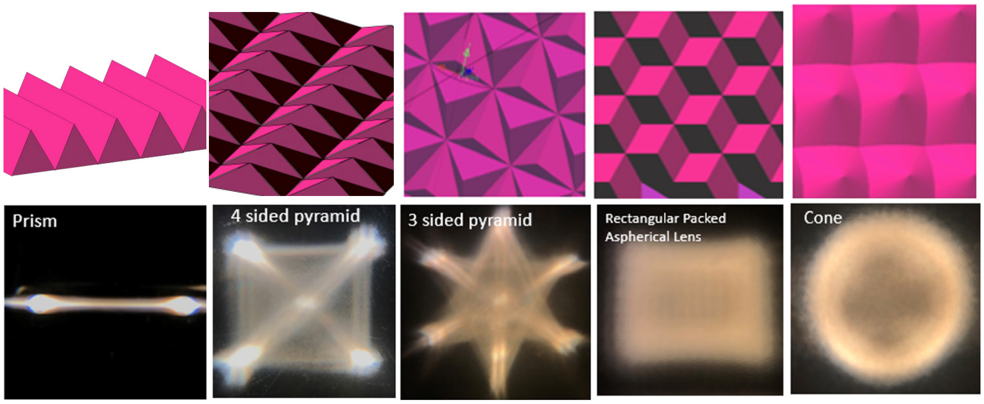


Figure 10. Different MLA lens types can split LEDs into various shapes. The top row shows illustrations of lens shapes, including prism, 4 sided pyramid, 3 sided pyramid, rectangular packed, and cone shaped lenses. The bottom row shows actual measurements of a single LED using the above lens shape.

Film Thickness

Thickness, like with volumetric films, plays a role in optimizing LED light spreading and hiding. Beam spread increases proportional to the film thickness. Thus, it is important to choose the proper film thickness to avoid over or under spreading, which can create hot spots, see Figure 11. In general, LED arrays with a larger pitch require thicker films.

Many film stack configurations are possible depending on the 2D BLU design. Figure 12 shows one possible film stack configuration. A stack of three MLAs situated on top of the LED array work together to hide the LEDs and create a uniform light output, followed by a color conversion film, xBEFs, and LCD panel. In some cases, the color conversion film is placed directly above the LEDs followed by the MLA film stack, and a BLT may be added. Microstructures can also be pattered directly on the color conversion film for added functionality.

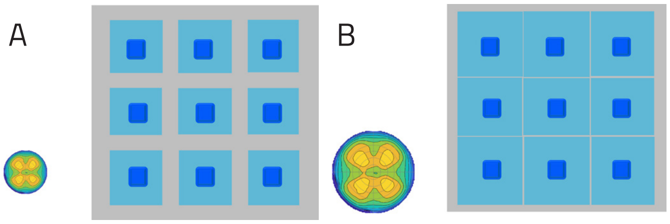


Figure 11. Light spreading as a function of MLA thickness. A) shows a thinner film under spreading the LED light. B) shows a thicker film with optimal spreading.

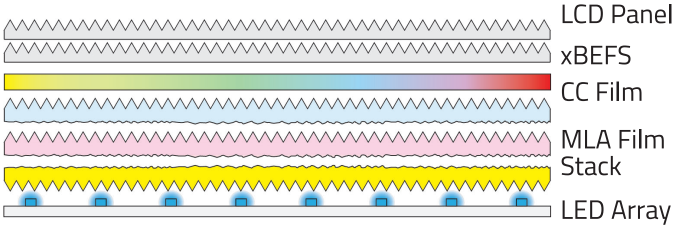


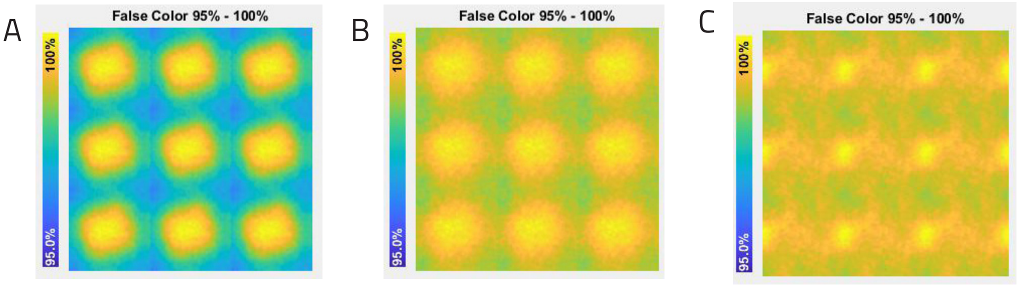
Figure 12. Example schematic of the layers in a 2D display using MLAs. A stack of 3 MLAs sits on top of the LED array, followed by the color conversion film, xBEFs and LCD panel.

Volumetric vs MLA Films

By making use of beam shaping and image splitting, MLAs can improve the LED hiding performance in 2D BLUs when compared to conventional volumetric diffusers. Figure 13 shows results of a direct comparison between an MLA stack and volumetric diffusers of different thicknesses. In figure 13A, a 0.76 mm thick volumetric diffuser had a mean energy, a measure of efficiency, of ~73%. However, the range/mean, a measure of light uniformity, was high at 3.7%: the individual LEDs are easily distinguished in the image. In Figure 13B, the volumetric film thickness was increased to 1.14 mm and the range/mean is improved to 1.75% indicating good hiding. The mean energy drops to 64.6%, which is below the acceptable value for efficiency. Compare these results to the BrightView MLA film stack in Figure 13C. At a thickness of 0.6 mm, the mean energy is 73.4% and the range/mean of 1.67%. This result shows an that MLA film stack can outperform a volumetric diffuser in both LED hiding and efficiency performance while maintaining a thin stack.

Color Edge Mura

Color edge mura, or just edge mura, is a deviation in color at one or more edges of the display. It is a consequence of the 2D LED array and a move to very thin or bezel-less designs. To reduce the edge mura and improve color uniformity, a gradient film with microstructured features, or a phosphor coating, around the perimeter of the display is placed below the xBEFs. Software algorithms can also correct for edge mura, but come at a performance cost and can be more challenging to implement.



T = 0.76mm
Mean Energy = 72.8%
Range/Mean = 3.7%

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Mean Energy = 64.6%
Range/Mean = 1.75%

T = 0.6mm
Mean Energy = 73.4%
Range/Mean = 1.67%

Figure 13. Direct comparison between volumetric diffusers and an MLA film stack. A) is an image of a 2D BLU with a 0.76 mm 105° volumetric film. B) shows the same BLU with 1.14 mm volumetric. C) shows a 3 film MLA stack on the same BLU. Mean energy and range/mean are relative and for comparison purposes only.

Blooming

When displaying bright images with very high contrast, such as bright white features on a black background, blooming can occur. It appears as a halo surrounding the bright areas and is due to light leaking into neighboring zones. MLAs can mitigate blooming effects so graphics appear sharper and truer to the original intent. Blooming can be quantified with a point spread function (PSF), where a single dimming zone is illuminated and the luminance measured radially outward. To obtain an accurate PSF, the dimming zone must first be made sufficiently uniform. Figure 14 shows a comparison of the blooming effect with BrightView's MLAs and a competitive MLA film stack. The test was done using a Rohinni 2D LED board as described earlier. The graph in Figure 14 is a measure of the light spread: a steeper slope indicates less blooming, which results in sharper images. The BrightView MLA stack performs better at hiding the LEDs compared to the competitor, and exhibits less blooming. These results can vary depending on the design of the BLU and MLA stack.

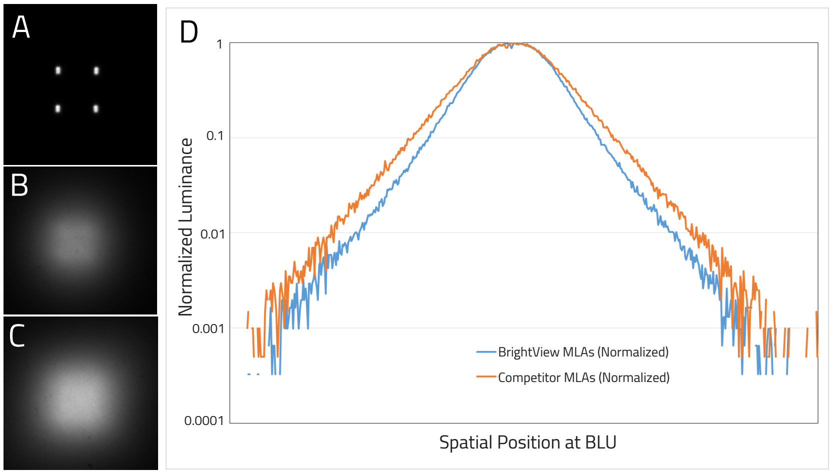

Figure 14. The results of a halo measurement using the point spread function (PSF). A) Single dimming zone (4 LEDs). B) Hiding using competitor's film stack. C) Hiding using BrightView film stack. D) Point spread function: blue line is the BrightView film stack, the orange line is the competitive film stack.

Conclusion

2D BLUs are quickly becoming a mainstream display technology poised to breathe new life into LCDs. They now compete with OLED displays in contrast ratio without burn-in issues, generate higher peak and sustained brightness levels, and may become the display technology of choice for many applications. The 2D BLU architecture presents several new challenges in creating a highly uniform backlight that remains thin, efficient, and cost effective. Micro lens array (MLA) technology is well suited to address these challenges through more sophisticated and clever use of light management compared to conventional volumetric diffusers, and ensures the new BLU takes full advantage of its potential. When the LCD design parameters are chosen carefully, such as the LED pitch, LED type and LED encapsulation, early in the design cycle in conjunction with the MLA stack design, the display can be optimized more quickly and brought to market faster while meeting the performance customers now demand.