

Micro-Optical Systems for Micro-LED Displays

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Abstract

Since 2008 Optovate have been innovating in Micro-LED technology and micro-catadioptric optical systems for display and environmental lighting applications. Results are reported, for the first time, of early demonstrations of array extraction of GaN Micro-LEDs onto a TFT substrate using a proprietary patterned laser lift-off process. Techniques to overcome the unique tooling challenges of micro-catadioptric arrays and example fabricated components are reported. New display implementations are presented that leverage the precise optical beam control of Micro-LED catadioptric technology and include switchable privacy, outdoors and night mode directional displays; flexible HDR-LCD backlights; and AR/VR and projection HUD display illumination.

Keywords

Micro-LED; Mini-LED; micro-optic; catadioptric; LCD; backlight; directional; privacy; flexible; free form; zero bezel; HDR; laser lift off.

1. Introduction

Since the 1970s the flat panel display industry has evolved to meet successive image quality and cost challenges. These have been achieved through substantial investments in backlit LCD and emissive OLED technologies.

However, both TFT-LCD and TFT-OLED appear to be approaching limitations for maximum luminance (cd/m^2) and efficiency ($\text{cd/m}^2/\text{W}$). Further demands including the super high resolution needed for Light Field and AR displays; flexibility; free-form shapes; and ultra-low thickness present new challenges.

The inorganic LED industry has made similar progress, driven by the needs of environmental lighting; and of the LCD industry for long lifetime, high luminance, high efficiency wide colour gamut backlights.

Micro-LED display technologies seek to combine the proven materials technology of highly efficient inorganic LED light sources with the massively parallel pixel manufacturing technologies developed for TFT displays. With a luminous emittance (lm/mm^2) that is of order 10^4 greater than OLED, and the ability to provide pixel dimensions of less than $5\mu\text{m}$, Micro-LED technology offers the potential for a step change in display performance. Many companies are now engaged in developing Micro-LED backplanes^[1,2,3].

Directional displays with switchable and/or controllable viewing angles add value to displays. The Nintendo 3DS observer tracking autostereoscopic display^[4] and Sharp Dual View^[5] displays are successful examples, each combining switchable liquid crystal parallax barriers with high resolution LCD panels to enable electrical switching of viewing angle. Another example using switchable birefringent microlenses^[6] is in the Toshiba Qosmio F750 3D autostereoscopic laptop. More recently the use of directional backlight technologies that image an array of LEDs through a light guide plate and LCD towards the user has been reported^[7] for autostereoscopic 3D and privacy applications. In this paper the underlying technologies to bring directional light control to Micro-LED display and environmental lighting will be discussed.

2. Micro-LED backplane fabrication

The multi-millions of Micro-LEDs necessary for direct emission displays mean that serially picking and placing individual emitters from a wafer to a sparse array on a display substrate will take too long to be economical.

A parallel pick and place, or array transfer technique is therefore highly desirable. Since 2008^[8,9] the authors have been researching and demonstrating the underlying technologies for directional Micro-LED displays based on sparse array Micro-LED backplane fabrication as illustrated in Figure 1.

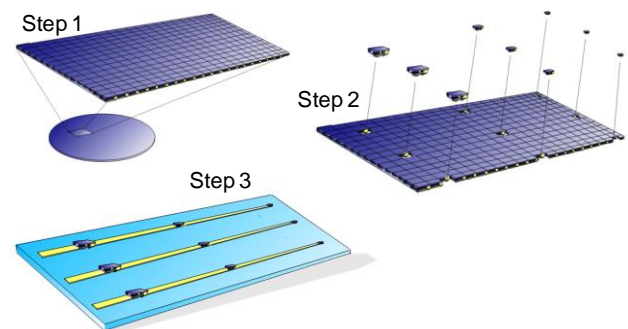


Figure 1. Micro-LED backplane fabrication. (Step 1) LEDs are grown in a dense array on a GaN wafer. (Step 2) Micro-LEDs are simultaneously extracted in parallel as a sparse array, preserving their precise relative separation. (Step 3) The array of Micro-LEDs is then mounted in one step onto a thermal and electrical substrate

The array transfer approach illustrated in steps 1-3 has recently become more widely appreciated and is now the focus of much R&D worldwide. Multiple techniques have been suggested for array transfer including elastomeric stamps^[10,11] and fluidic self assembly^[12].

A sparse Micro-LED array extraction technique has been demonstrated using a proprietary patterned laser lift-off (p-LLO) process. A 194nm ArF excimer laser selectively removed multiple $100\times 100\mu\text{m}$ patches of a GaN LED semiconductor grown on a sapphire wafer. After extraction the LEDs were transferred in parallel to a TFT backplane as a size reference, shown in Figure 2. Other investigations included development of strategies for yield optimisation, area colour correction, fault correction, Micro-LED array addressing and backplane re-working methodologies.

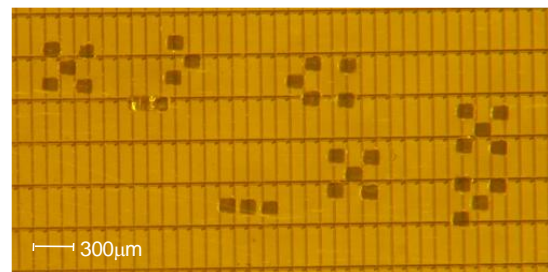


Figure 2. Early demonstration of extracted Micro-LEDs after transfer onto a TFT backplane.

3. Directional Illumination & Catadioptrics

The very high luminous emittance of Micro-LEDs means the emitting elements need cover only ~1% of backplane area to achieve required luminance levels. Such a sparse array enables unique functions from optical elements, superior thermal management and in-plane sensors in the intra-LED regions. Micro-LEDs combined with novel optics enable new classes of directional display with compelling benefits.

View angle control of a Micro-LED display requires efficient capture and redirection of the substantially Lambertian light output cone from each Micro-LED. Three approaches using different classes of optical elements are illustrated in Figure 3.

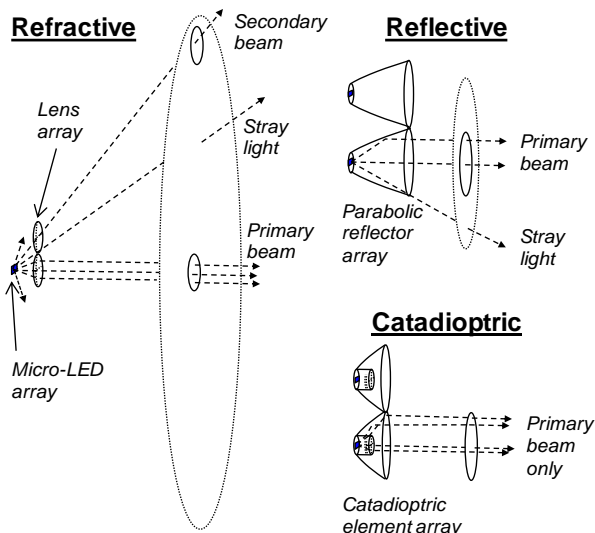


Figure 3. Options for capture of Micro-LED light output.

Refractive arrays such as microlenses capture small solid angles. Secondary beams or lobes create unwanted stray light at off-axis locations that is problematic.

Reflective arrays such as parabolic reflectors capture light more effectively than lenses, however light that is not reflected by the walls of the optic exits the device directly as stray light.

Catadioptric arrays combine refractive surfaces (dioptrics) and curved mirrors (catoptrics). Catadioptrics can capture the full 2π steradian solid angle of Micro-LED light output by refraction at inner walls and reflection by TIR (total internal reflection) at an outer surface, or by refraction in a central microlens; and are capable of providing highly collimated output from moulded optical components. Catadioptric elements can also combine metal coated and light guiding surfaces, particularly in applications which require very low thicknesses and large area illumination.

In an example design, Figures 4 and 5 show raytraces for a catadioptric optical system with a $30\mu\text{m}$ Micro-LED and $600\mu\text{m}$ width output aperture. Light rays from the Micro-LED that are incident on the central lens surface are imaged by refraction, while rays at higher emission angles are directed by refraction at inner walls and total internal reflection at outer aspheric collimating surfaces.

Figure 6 shows simulation results of output light fields for different Micro-LED widths and Gaussian profile diffusers. The high effective numerical aperture of catadioptric non-imaging systems can provide light cones with full width half maximum (FWHM) of $<6^\circ$ in very thin form factors.

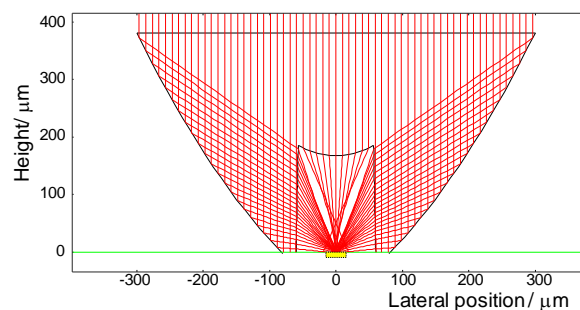


Figure 4. Catadioptric geometric raytrace-to-source for head-on output.

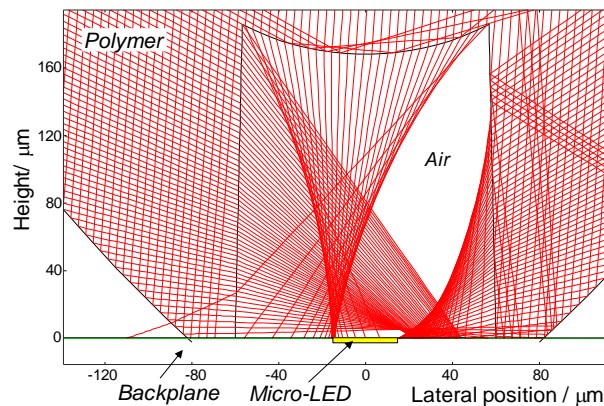


Figure 5. Detail of geometric raytrace-to-source for 5° off axis output direction and $30\mu\text{m}$ Micro-LED width.

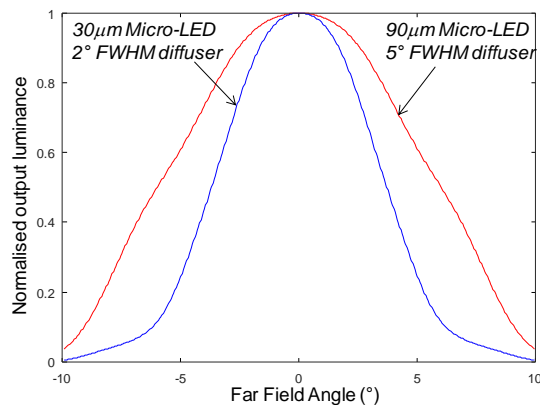


Figure 6. Simulated output angular characteristics of micro-catadioptric optical elements and aligned Micro-LEDs for the design of Figure 4.

Figure 7 illustrates the variation of output luminance against position across the catadioptric element output aperture. As Micro-LEDs decrease in size, the proportion of forward emission reduces because light guiding within the GaN chip (refractive index ~ 2.5) increases the relative edge emission as illustrated in Figure 8. In conventional Micro-LED structures, this effect reduces device efficiency and creates unwanted stray light. However, catadioptric optical elements efficiently capture this increased edge emission and direct it to the primary beam. Figure 7 additionally illustrates the impact this additional light has on output uniformity.

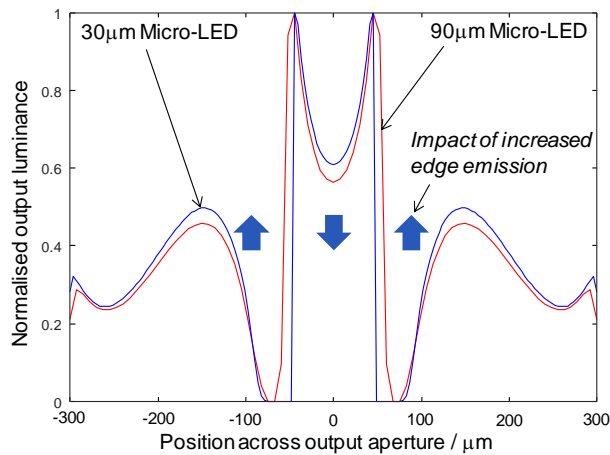


Figure 7. Simulated spatial output luminance variation across the output aperture of a micro-catadioptric optical element and aligned Micro-LED.

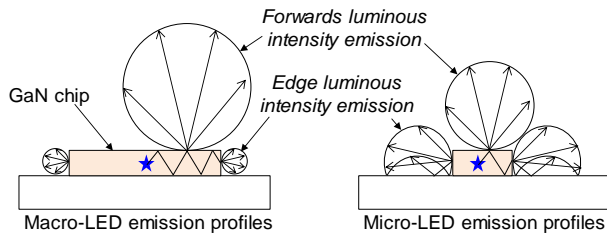


Figure 8. Increased edge emission from Micro-LEDs can be used to increase both efficiency and uniformity.

4. Catadioptric Micro-LED system fabrication

Continuing with the display manufacture process of Figure 1, in Figure 9 steps 4-5 illustrate attachment of an array of catadioptric optical elements and dicing that leverages glass and flexible mothersheet substrate processing techniques from LCD and OLED manufacturing. The preservation of the original spatial locations of the Micro-LEDs in the p-LLO array transfer process shown in Figure 1 means that very precise alignment of Micro-LED backplanes with catadioptric optical element arrays can be achieved over large areas while providing uniform control of output directionality.

Mothersheet dicing can deliver Micro-LED displays with free-form shapes, enabling applications including “all screen”, zero bezel smartphones and wearables.

Environmental lighting catadioptric designs are typically based around 1x1mm sized LEDs with output aperture diameters of 10~20mm; such elements can be formed by diamond machining of macroscopic molding tools. Scaling to the dimensions suitable for display applications creates new challenges and opportunities for optical tooling and moulding, as the same techniques are not readily applicable.

A proprietary process for fabrication of tools for large area array replication of micro-catadioptric optical elements has been developed by the authors. A fabricated demonstration element is shown in Figure 10 with an aperture width of 2mm, designed for use with the 100μm micro-LEDs of Figure 2. This process is expected to be scalable to the micro-optic pitches of less than 100μm needed for future direct display devices described below.

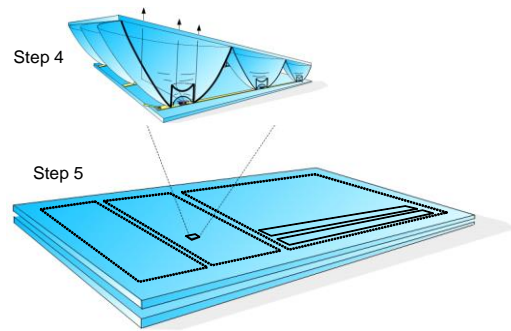


Figure 9. Catadioptric Micro-LED array fabrication. (Step 4) A monolithic array of catadioptric optical elements is aligned to the Micro-LED backplane using large area mothersheet assembly techniques. (Step 5) the array is thinned, diced and finished including electrical and thermal interfaces (shown with exaggerated perspective)

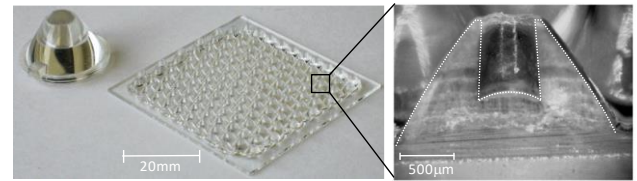


Figure 10. Comparison of proprietary fabricated micro-optic element array with standard optic (left); enlarged cross section of element from the fabricated array (right).

5. Catadioptric Micro-LED display

5.1 Switchable direct Micro-LED display

Figure 11 shows an example of an optical stack design for a direct view switchable directionality Micro-LED display.

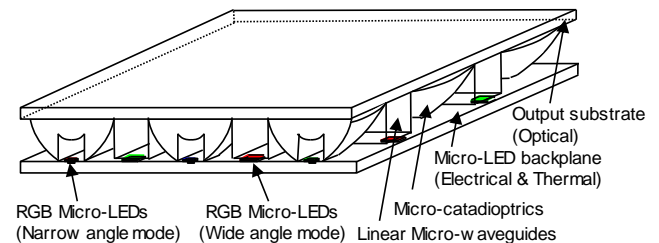


Figure 11. Catadioptric optical element array for a switchable privacy direct Micro-LED display application.

A first Micro-LED array aligned to a catadioptric array creates a narrow beam for directional operation while linear micro-waveguides between the catadioptric optical elements provides Lambertian illumination from a second interspersed Micro-LED array – switching between the two arrays controls directionality. Switchable View Angle display technology provides control of the angular light field from the display between two or more different angular luminance distributions.

Such displays can provide:

- Wide-angle operation similar to conventional displays.
- Privacy displays that are not visible to adjacent viewers.
- Reduced stray light for night time operation.
- Reduced power consumption as energy is not directed unnecessarily away from the user.
- For outdoors use, very high head-on luminance for the same power consumption as the wide-angle mode.

Micro-LED displays that use catadioptric optical systems to control optical output offer many advantages over other types of switchable directional displays including:

- High luminance ($>10,000$ cd/m²) & high uniformity ($>95\%$)
- Low power consumption: $<30\%$ of conventional Micro-LED display & $<1\%$ of conventional LCD/OLED
- Low bezel width (<0.1 mm) & Low total thickness (<0.5 mm)
- Flexible substrates & free-form shapes
- Low stray light leakage at high angles
- Controllable angular output from Lambertian to $<6^\circ$ FWHM

5.2 Mini-LED backlights for HDR-LCD

As a precursor to the direct Micro-LED displays of Figure 11, LCD backlights can use LEDs of size $\sim 100\mu\text{m}$ (sometimes referred to as “Mini-LEDs”). Catadioptric optics offer a thinner backlight with fewer Mini-LEDs than direct diffusion methods, and have less complex optical stacks than conventional waveguide systems.

Catadioptric designs similar to Figure 4 combined with diffusion optimisation and polarisation recirculation schemes can remove the non-uniformities of Figure 7, minimising unwanted Moiré and mura artefacts. By relaxing the collimation cone angle, modified designs can also target highly uniform flexible backlights with total thickness $<250\mu\text{m}$ and pitch >1 mm (reducing the total number of Mini-LEDs needed).

Early catadioptric Mini-LED backlight applications are expected to include high dynamic range (HDR) LCD displays, one example of which is shown in Figure 12. By incorporating addressing on the Mini-LED backplane the halo effect, for example in “star field” images can be reduced and provide performance that is similar or superior to flexible OLED.

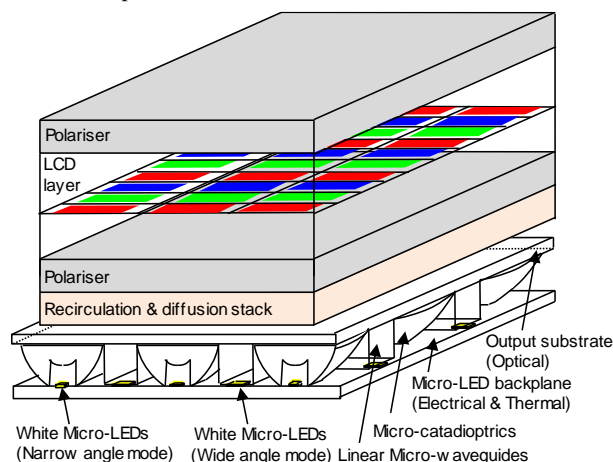


Figure 12. Catadioptric optical element array for a flexible high resolution HDR-LCD backlight.

5.3 AR/VR and HUD display applications

In head-mounted Augmented Reality (AR), Virtual Reality (VR) optics and automotive projection Head-Up-Display (HUD) applications, the narrow light cones from catadioptric Micro-LED arrays can be used to illuminate micro-displays efficiently while delivering low levels of stray light and thus reducing image cross talk and substantially increasing image luminance. Further, numerical aperture of collection optics can be reduced, minimising projection system aberrations to increase field-of-view and resolution without loss of efficiency.

In direct view AR display applications, ultra-high brightness operation will be essential for effective operation in outdoor

environments – the directional micro-LED displays described here can achieve very high luminance levels to compete with the brightest ambient illuminance of ~ 25 klux, while maintaining low power consumption.

6. Conclusion

A new paradigm for both direct Micro-LED display and LCD display backlighting has been proposed. Arrays of Micro-LEDs are aligned in a single step to a high precision array of catadioptric micro-optical elements.

Technology demonstrators have shown the scalability of the optical fabrication processes required for fine pitch directional Micro-LED display. Combined with the progress now being made with Micro-LED backplanes based on GaN LED technology, key building blocks for a new generation of high performance displays have been established.

Applications include ultra-thin switchable Privacy display, LCD backlighting including high resolution HDR-LCD, AR/VR display system enhancement and automotive projection HUD.

7. References

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