The Future of Compact AR Displays: LCoS vs Micro-LED

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Abstract
The success of Ray-Ban Meta and the release of Meta Orion have drawn tremendous attention to the wearable AI devices. To be integrated into such applications, LCoS (liquid-Crystal-on-Silicon) and Micro-LED are redeemed as the most promising micro-display candidates for their unprecedented high PPI and image quality. In this digest, we would comprehensively compare the key metrics of LCoS and Micro-LED panels and the optical architecture of light engines built for them. By exploring design and process limitations, Goeroptics sketch the road map to the commercialization of these miniaturized AR displays.

Author Keywords
Micro-LED; LCoS; Augmented Reality; Micro-display; AI Glass

1. Introduction
The development of next-generation AR glasses hinges on the advancement of display technologies that can deliver high brightness, high resolution, low power consumption, and compact form factors. Current solutions include Organic Light-Emitting Diodes (OLEDs), Liquid Crystal on Silicon (LCoS), and Micro-Light Emitting Diodes (Micro-LEDs), with the latter two emerging as the most viable options for consumer-grade AR devices.

LCoS, a reflective display technology, has been widely adopted in projection systems and is now being adapted for AR due to its high brightness and mature manufacturing processes. However, its reliance on external light sources and optical inefficiencies in waveguide-based AR systems present challenges. In contrast, Micro-LED, an emissive display technology, promises superior contrast, higher brightness, and better energy efficiency but faces significant hurdles in mass production, particularly in achieving high yields for micron-scale pixel arrays.

This paper provides an in-depth comparison of LCoS and Micro-LED for AR applications, examining their technical merits, industry adoption, and future trajectories. Additionally, we introduced the compact optical solutions from GOS to facilitate their future integration into AI/AR glasses.

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2. Technical Overview of LCoS and Micro-LED
LCoS Technology: LCoS operates by reflecting light off a liquid crystal layer deposited on a silicon backplane. The liquid crystals modulate light polarization, which is then converted into visible images through polarizing optics. Key advantages of LCoS include:

- High Resolution: Silicon backplanes enable dense pixel arrangements, making LCoS suitable for compact AR displays requiring high pixel-per-inch (PPI) densities.
- Mature Manufacturing: Leveraging existing semiconductor and LCD fabrication processes, LCoS benefits from lower production costs and scalability compared to emerging technologies like Micro-LED.[1]
- High Brightness: LCoS light engines utilize Köhler illumination, polarization recycling and illumination cone matching with imaging optics, which are highly efficient compared to self-emissive displays (e.g., exceeding 3 million nits D65)

However, LCoS has several drawbacks:

- Complicated optics: LCoS light engines necessitate polarization beam splitter (PBS) and illumination optics, which hinders miniaturization. Although PBS-free light engines partially solve the volume and cost issue, the slanted optical path would double the aperture and thus deteriorate the contrast ratio.
- Limited Contrast: Reflective LC modulation cannot achieve true blacks, unlike self-emissive technologies such as Micro-LED.
- Color Performance: Sequential color illumination (field-sequential color) can introduce motion artifacts and reduce color accuracy.

Micro-LED Technology: Micro-LEDs are inorganic, self-emissive displays with micron-scale pixels. Each pixel emits its own light, eliminating the need for a backlight. Key advantages include:

- Ultra-High Brightness: Micro-LEDs can theoretically exceed 10 million nits, far surpassing OLED and LCoS.
- Energy Efficiency: Each pixel emits light independently, reducing power consumption compared to backlit systems.
- Longevity & Stability: Unlike OLED, Micro-LEDs resist burn-in and degradation, making them ideal for always-on AR applications.

However, Micro-LED faces significant challenges:

- Manufacturing Complexity: Mass transfer of micron-scale LEDs remains costly, with low yields for high-resolution displays.
- Pixel Shrink Limitations: Efficiency drops as pixel sizes decrease below 10µm, complicating high-PPI designs.
- Color Conversion: Monolithic full-color Micro-LED displays often require quantum dot color conversion or vertical stack structure, which introduce additional complexity. In Fig. 1, we summarized and compared the current monolithic solutions.

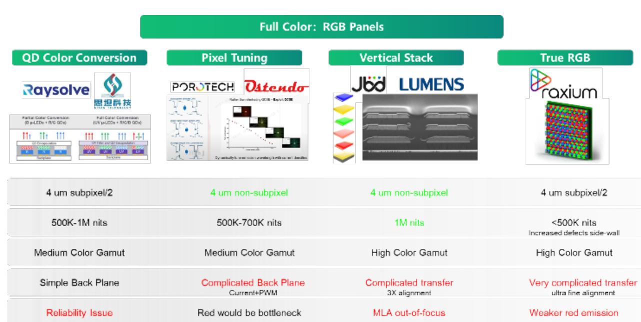

Figure 1. Comparison of Monolithic RGB Micro-LEDs

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3. Optical Architecture Comparison of LCoS and Micro-LED

The fundamental differences between LCoS and Micro-LED optical architectures stem from their distinct approaches to light generation and modulation. These architectural variations lead to significant performance tradeoffs that directly impact their suitability for augmented reality applications. This section provides a detailed technical comparison of their respective light engine implementations, waveguide coupling characteristics, and color generation methodologies. The results were summarized in Table 1.

Light Engine Architectures

The LCoS optical system employs a reflective architecture with three key components:

- Illumination Module: Typically uses high-brightness Mini-LED arrays (up to 3M nits) or laser sources with field sequential color (FSC) operation
- Polarization Optics: Includes PBS (polarizing beam splitter) and quarter-wave plates to manage light polarization states
- LCoS Panel: Silicon backplane with liquid crystal modulation layer and aluminum reflector

The light path follows: light from the source is collimated and polarized. Then, PBS directs polarized light to the LCoS panel, where light polarization state is modulated pixel-by-pixel and light passes back through PBS to projection optics. Recent innovations like Himax's front-lit LCoS and GOS 0.7cc engine demonstrate ongoing miniaturization efforts.[2]

On the other hand, Micro-LED systems feature a direct-emissive architecture:

- Panel: monolithic or transferred micro-scale LEDs (typically <10μm pitch) working with Micro-lens arrays or meta-surfaces to control emission angles
- Color Conversion/Combining: Traditional X-cube is still the most efficient way to combine the 3 color light. While, quantum dot layers or native RGB pixels for full color monolithic panels
- Projection lens: Small lens assembly similar with fixed focal length camera system collimates the light to the waveguide system.

The key optical advantage over LCoS lies in the elimination of external illumination components and favors for ultra-compact light engine design. Currently, the most compact micro-LED is demonstrated by GOS 0.15 cc with Jade Bird Display. Yet due to the limited EQE of micro-LED, especially <5% red pixel EQE, the heat management and thermal drifting become very important considerations in designing compact light engine system. Also, ongoing evolution to 10000 PPI would further impose loads on color uniformity and mura.

Waveguide Coupling & Module optimization

The waveguide coupling efficiency is fundamentally determined by the interplay between display optical properties and waveguide physical architectures. LCoS polarization-dependent reflection characteristics and Micro-LED's unpolarized emission exhibit markedly different coupling behaviors in geometric waveguides (GWG) versus diffractive waveguides (DWG). The linear polarization state of LCoS output (typically >95% polarization purity) perfectly matches the s-polarization requirement of GWG out-coupling dielectric mirror coatings, achieving desired light distribution and better color uniformity. On the other hand, polarization optical system is sensitive to birefringence in the system. The novel material, $LiNbO_3$, is very favorable for DWG due to its high refractive index. However, consider its strong anisotropy in dielectric constant, the LCoS incorporation with such kind of waveguide should be treated very carefully.

The DWG suffers from poor color uniformity due to its strong dispersive nature. Recently, a new technology merging in Micro-LED industry which enables pixel level demura to facilitate module level optimization of the overall optical performance. Through careful measurement and calibration on waveguide output, part of the waveguide color aberration could be compensated by emission intensity modulation of different color micro-LEDs, of course, at the sacrifice of peak brightness. While, due to the current semiconductor process limitations, the driver circuit of LCoS is not compatible with this kind of functionality. The key suppliers in this field is planned to support mesh based demura in next year.

Optical Color Combing Scheme

The color combination strategies for Micro-LED and LCoS displays employ fundamentally different optical architectures, each presenting unique advantages and technical challenges. Due to limited technical maturity, monolithic full-color micro-LED is not covered in this section. Micro-LED systems primarily utilize waveguide-based color combination or X-cube prism approaches, while LCoS displays conventionally adopt field sequential color methods, with each technique exhibiting distinct performance characteristics in augmented reality applications.

Waveguide-based color combination for Micro-LED displays represents the most efficient approach for power demanding AR systems, achieving greater than 85% color gamut coverage through sophisticated optical integration of three separate monochromatic micro-display panels. This architecture couples red, green, and blue light channels into shared optical paths that are combined either using waveguide stack or single blade waveguide with three separate in-couplers. Especially the recent release of META Orion prototype, which demonstrates superior optical efficiency by utilizing high refractive index SiC waveguide and enabling remarkably slim form factors under 1 mm thickness. However, this method demands extraordinary precision in optical alignment, requiring high angular alignment accuracy between different light engines.

The X-cube prism alternative is more mature technologically and currently considered as a concrete solution for compact light engines. This conventional approach employs precisely engineered dichroic coatings on four internal surfaces to combine color channels, achieving excellent 80%-95% theoretical combining efficiency and exceptional color uniformity with only ±2% variation. Now with the improved processing capability, the minimum 5×5×5 mm^3 volume X-cubes could be mass produced, which proves more suitable for eyewear form factors than PBS.

LCoS systems employ field sequential color methods that time-division multiplex RGB illumination synchronized with the display frame rate. This mature technology achieves 72-78% system optical efficiency and 95% color gamut coverage, but requires liquid crystal response times below 2ms and minimum 180Hz operation (60Hz per color channel). The approach suffers from inherent motion artifacts causing 0.5-1.2° visual displacement during rapid eye movements. Also, the inherent difference reflectance and wave retardance among different colors hinders achieving saturated light in LCoS system.

Table 1. Comparison of LCoS and Micro-LED Light Engines

Key Merits	LCoS	µLED
Full-color Scheme	1or 2 channel LED Field sequential	X-cube: 2M-5M nits Monolithic<0.5 M nits
Brightness	2-6 lm	X-cube: 2-6 lm Monolithic<0.5 lm
Highest Resolution	2K*2K	1080P
ANSI Contrast	50-80:1	>100:1
Volume	>0.5 CC	<0.2 CC
10% APL Power	250 mW/lm	30-50 mW/lm

4. GOS progress on compact AR Displays

GOS, a subsidiary of Goertek Inc., has established itself as a pioneer in XR optical solutions through continuous technological development. As one of the earliest entrants in the field, the company has built comprehensive capabilities spanning optical design, light engine development, optical testing, manufacturing, and automated module assembly.

At last year's Optical Expo, GOS unveiled its 0.7cc ultra-compact LCoS module, currently recognized as one of the smallest, lightest, and mass-producible full-color LCoS display modules in the industry. The detailed performance specification is enclosed in Fig. 2. This technological achievement demonstrates the company's expertise in miniaturization while maintaining optical performance.

Item	Design Value
Display	OV 03011
Resolution	648*648 (1:1)
Angular Resolution	32.7 PPD
Brightness(lm)	1.6 lm@0.37W (LED)
FOV	28°
Uniformity 9 point	85%
Pupil distance /mm	0.3
TV Distortion	H: 0.46%; V: 0.46%
Pupil Size /mm	Φ 3.3mm
MTF /@all field	≥0.58@132lp/mm
ANSI contrast	60:1
LE Size	12.3*10.6*7.8 (0.7cc)

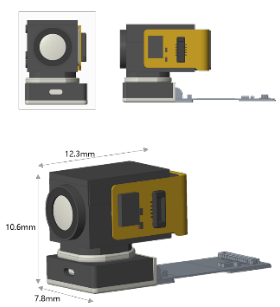

Figure 2. Performance specification of GOS 0.7 cc LCoS Light Engine

Furthermore, the company has developed a mass-production-ready solution based on monochromatic green Micro-LED technology combined with resin diffractive waveguide optics. This system incorporates their proprietary Star E-P1 resin diffractive waveguide lens, achieving an impressive optical efficiency exceeding 1000 nits/lumen. The module delivers an eye-box brightness of 5000 nits, meeting the demanding requirements for outdoor augmented reality applications.

Through integration with GOS ultra-compact lens solution, the Micro-LED light engine achieves an exceptionally small form factor of just 0.15cc with a mere 0.3g weight. This represents the smallest volume Micro-LED optical module currently available in the industry. The combination of high brightness output and extreme miniaturization positions this technology as a promising solution for next-generation wearable displays.

These technological advancements highlight GOS leadership in developing compact optical systems for XR applications. The company's vertically integrated approach, from optical design to mass production, enables rapid iteration and optimization of display modules. Both the LCoS and Micro-LED solutions demonstrate practical pathways toward achieving the critical balance between optical performance, power efficiency, and form factor that is essential for consumer AR devices.

The 0.7cc LCoS module particularly stands out for its full-color capability in such a compact package, while the Micro-LED solution showcases the potential of emissive display technology when combined with advanced waveguide optics. These developments contribute significantly to addressing the key challenges of brightness, efficiency, and miniaturization in AR displays.

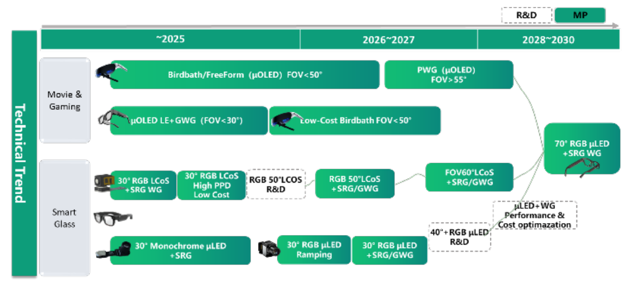

Figure 3. Technical Trend of Compact AR Displays

5. Conclusions

In Fig.3, We predicted the on-going technical evolution of compact light engines. GOS advancements highlight the ongoing competition between LCoS and Micro-LED for AR displays. Their 0.7cc LCoS module demonstrates LCoS maturity for compact, full-color solutions, while their 0.15cc Micro-LED light engine showcases superior efficiency and miniaturization potential. While LCoS remains dominant for near-term applications due to manufacturing readiness, Micro-LED offers long-term advantages in brightness and power efficiency—once full-color and yield challenges are resolved. For now, the choice depends on application priorities: LCoS for color performance and scalability and field-of-view, or Micro-LED for efficiency and ultra-compact designs. Both paths will drive AR display innovation in coming years.

6. References

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