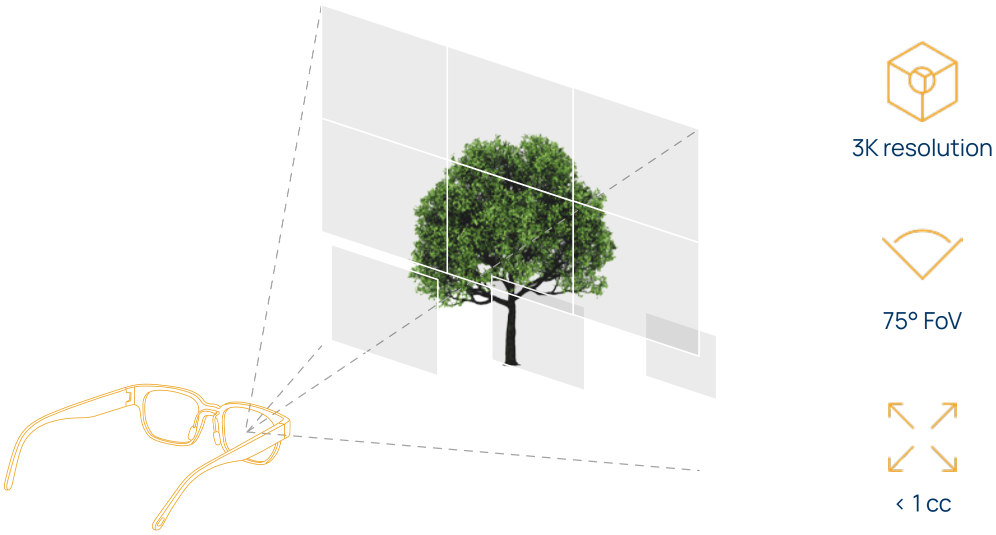
The Killer AR Light Engine: Waveguide-Compatible Laser-FLCoS

Enabling foveated 3K resolution in a 75° Field of View from a sub-1 cc engine, with unmatched power efficiency, brightness, and cost in a mature platform.



Context: This paper introduces CREAL's new waveguide-compatible foveated AR display system. By rearranging our Light Field architecture "inside-out," we deliver a Time-Sequential Pixel Replication engine, providing a short-term AR display solution for today's critical requirements in a waveguide-dominated ecosystem, while simultaneously offering a path toward the ultimate AR display: full Light Field, with focus depth and native prescription correction.

Executive Summary

Most AR displays today are essentially miniaturized monitors. They inherit properties developed for seated viewing of dense, high-fidelity content, in a narrow Field of View (FoV), namely: uniform pixel grids, high color resolution, and relatively low frame rate.

AR is different.

AR needs displays that are more dynamic, sparse, brighter, spanning a significantly wider FoV, and that must fit into an extremely constrained engine. This creates fundamentally different requirements on the display engine: speed, high brightness density, and extreme pixel and power efficiency.

The classical brute-force approach of optically magnifying a uniform pixel grid hits a hard barrier: a tyrannical link between resolution and FoV. Both cannot be maximized at once without unrealistically small and bright pixels, and/or paying an unacceptable price in pixel count, display volume, compute, and power density.

Laser-FLCoS system breaks this barrier through its **"speed" and optical efficiency**.

FLCoS (Ferroelectric Liquid Crystal on Silicon) is an ultra-high frame-rate reflective Spatial Light Modulator (SLM), similar to LCoS, but inherently binary, with some of the smallest high-quality RGB pixels ever demonstrated, and produced using mature, scalable, and low-cost processes.

Its framerate enables a new type of foveation: **Time-Sequential Pixel Replication**, a method that sequentially **replicates physical pixels** across FoV to dynamically allocate image detail where it matters. This dramatically increases **pixel efficiency**, making >3K perceived resolution in >75° FoV from a sub-1 cc engine readily feasible. Combined with highly efficient light coupling of a laser-modulator system, FLCoS achieves brightness, power efficiency, and production cost beyond the reach of conventional µLED or LCoS systems.

This paper outlines how the time-sequential projection nature enables a new kind of pixel economy, unlocking a step-change in display miniaturization by delivering higher perceived resolution from fewer physical pixels.

Key Challenges for AR that Classical Display Approach Fails to Address

Speed

Unlike conventional screens, AR displays move with the head, while the eyes remain locked on the zero-latency real-world [1]. This inversion of motion dynamics makes classical display parameters: 60–120 fps refresh rates, 8–16 ms frame durations (necessary to build up brightness), and typical latencies above 10 ms, fundamentally inadequate. As the head rotates, even static content blurs across the retina, Fig. 1a.

To reliably anchor virtual objects to the real space without motion blur, AR displays must combine higher framerate, shorter frame duration, and lower latency, Fig. 1b.

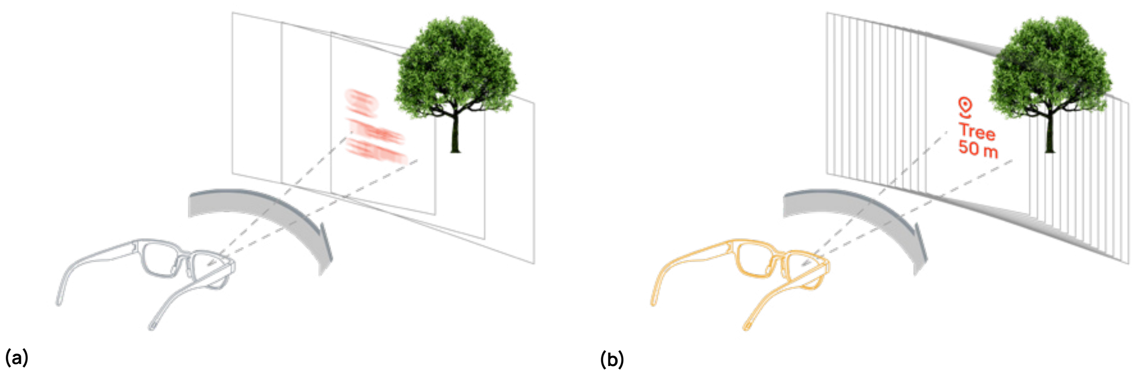


Figure 1: Low framerate, long latency and long image duration lead to instability and motion blur of world-locked content, (a). AR requires a significantly higher rate of shorter frames with low latency, (b).

The Pixel Efficiency

Full-scale AR systems are expected to deliver all of the following display KPIs:

- **Field of View**: >70°
- **Resolution**: >40 ppd
- **Brightness**: >2000 nits
- **Engine Volume**: <1 cc
- **Battery life**: >8h
- **Price**: <$100

This section shows why reaching these parameters is impossible with brute-force emissive pixel grids, and why the solution requires two principles: (i) **display foveation** to reduce the number of physical pixels while maintaining high perceived resolution, and (ii) **highly efficient light generation and coupling** to overcome brightness-per-watt limits, enabled only by laser/modulator-based architectures.

Each KPI target is demanding on its own, but combined, they form a set of mutually prohibitive constraints leading to a "**pixel efficiency trap**" for conventional displays:

1. Too Many Pixels in a Too Small Volume

Achieving high resolution across a wide FoV drives pixel count up with the square of FoV and engine volume with its cube. For example, 40 ppd over 75° requires >3000 × 3000 pixels. With even a 3 µm pixel pitch, this implies a 9 × 9 mm² active area, already beyond what fits in a 1 cc engine once optics and packaging are included.

This brute-force path quickly becomes unviable, blowing past volume, power, and thermal limits. AR displays must instead allocate resolution non-uniformly, matching the eye's acuity profile to deliver a high-resolution impression with fewer real pixels.

2. Too Much Light from a Too Small Pixel

As FoV increases and pixel size shrinks, each pixel must emit proportionally more light to maintain perceived brightness. This makes raw luminance insufficient; what matters is how efficiently light is emitted and delivered to the eye.

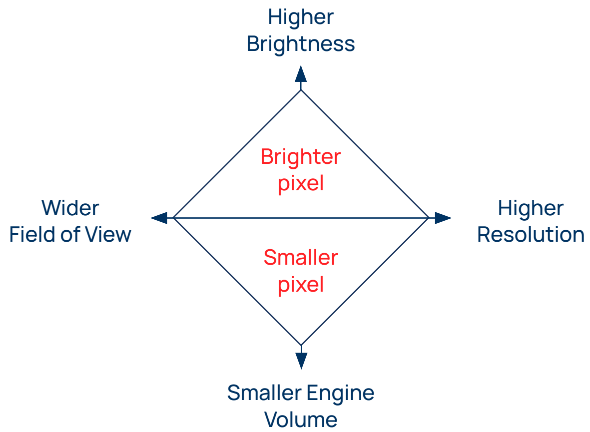


Figure 2: Key requirements on AR display engines boil down to the need for exceedingly small and bright pixels.

Emissive displays, such as µLEDs, struggle on two fronts. First, their near-Lambertian emission spreads light broadly, wasting most of it outside the collection optics (bad etendue matching). Second, at the µm scale, their luminous efficiency collapses, too, often falling below 1% wall-plug efficiency, especially for red µLEDs.

Reflective Spatial Light Modulators (SLMs) like LCoS, FLCoS, or DMD (Digital Micromirror Device), waste light on dark pixels, but their highly directional illumination and superior light coupling (better etendue matching) result in overall higher optical efficiency at higher than 12% scene fill ratio [2,3]. After all, wall projectors have directionally similar requirements and ended up with SLM solutions. Combined with segmented illumination, SLM systems can outperform emissive approaches in brightness-per-watt already at 3-5% scene fill ratio, ultimately compensating for the extra volume needed for the illumination system [4].

What's Overengineered for AR

- **Color Resolution**: AR content overlays real-world light, reducing the importance of color detail in the first place, while most of it appears in our near-color-blind periphery (Fig. 3b). A high color-resolution pixel grid spread uniformly across the FoV adds cost with no perceptual benefit.

- **Peripheral Spatial Resolution**: Peripheral vision has vastly lower acuity than the central fovea (Fig. 3c). Delivering full spatial resolution uniformly wastes pixels, bandwidth, and power where the eye can't meaningfully perceive it.

Key Takeaway: AR isn't a monitor on the face. It requires a fundamentally different display system built on foveation, efficient light coupling, and speed to meet the uncompromising constraints of size, power, and cost.

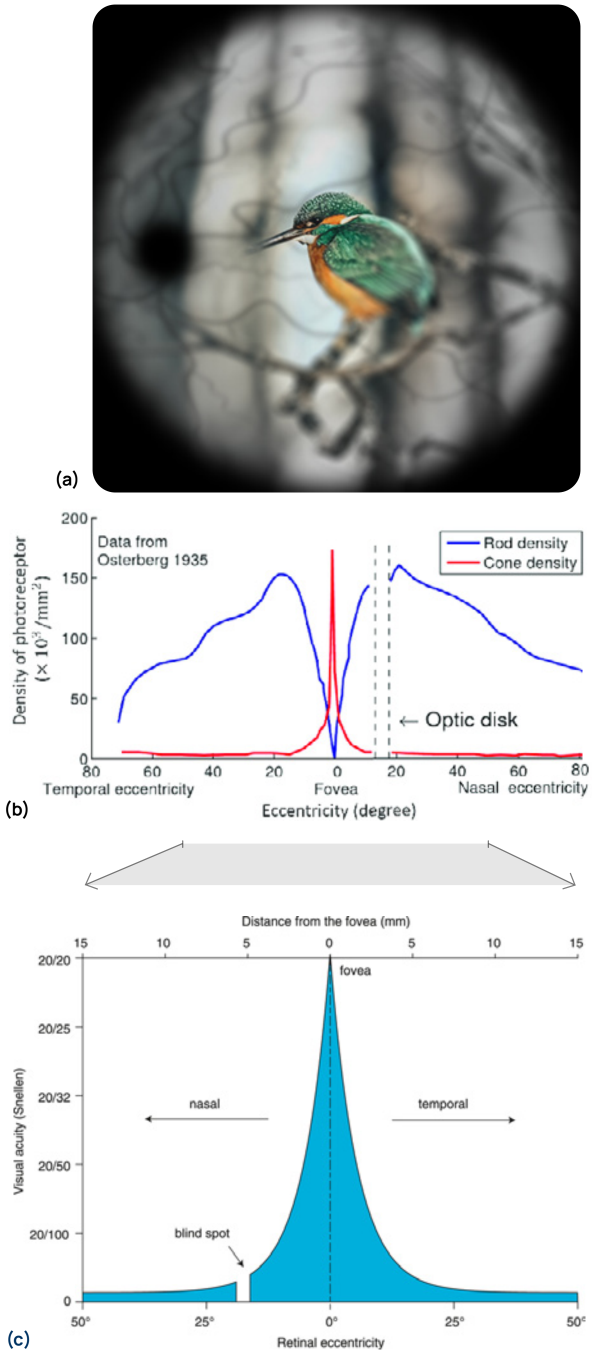


Figure 3: Retinal image illustrating non-uniform spatial resolution, (a), density of color (cone) and black-and-white (rod) receptos [5], (b), and visual acuity, (c), versus retinal eccentricity [6].

FLCoS

FLCoS is a microdisplay technology that modulates reflected light rather than emitting it. Each pixel consists of a 700 nm thin Ferroelectric Liquid Crystal (FLC) layer sandwiched between a transparent top electrode and a reflective bottom electrode deposited on a silicon backplane. The backplane circuitry applies an electric field across the FLC layer to rapidly switch its optical properties between two distinct states that determine the polarization of the reflected light. This modulated light is then converted into brightness through polarization filtering in the optical system.

FLCoS combines the benefits of LCoS and DMD without inheriting their main drawbacks. FLCoS is simple, low-cost, and scalable like LCoS, and fast and high-contrast like DMD. But it goes even further in miniaturization, cost, and power efficiency than either of the two.

Historically, FLCoS remained in the shadow of LCoS, offering similar performance for contemporary applications such as wall projection and viewfinders. Its smaller pixel pitch and high binary framerate become critically important only now with AR.

Compared to LCoS, FLCoS has smaller, higher-contrast, and cheaper pixels. It uses 10-100 times faster liquid crystals in a 4-10x thinner LC layer, and has simpler, binary, lower voltage driving circuitry - together enabling 2-3x smaller pixel size with cheaper production processes.

Though DMD has excellent contrast, it is not commercially viable in AR. FLCoS shares the binary mode of operation with DMD, but is significantly simpler, power efficient, cheaper, and smaller (including optics). For this reason, DMD will be excluded from the following comparison.

Key Highlights:

- **Extreme Speed**: Binary switching speeds exceed 8 kHz[1], with frame durations below 1 μs. This speed is essential for sharp, stable imagery that remains locked to the real world without motion blur.

- **Low Latency**: The binary nature of the FLCoS operation allows delivering the first pixels (first bit plane) to the eye without waiting for the full frame to stack, resulting in fundamentally lower latency (~200 μs) of the display pipeline compared to multi-bit-color displays.

- **Small Pixel Pitch**:Thanks to its thin FLC layer (<700 nm) and simple binary lower voltage backplane circuitry, **pixel sizes below 1.5 μm** have been demonstrated [7]. 2.8 μm pixel pitch is achievable with a low-cost 180 nm CMOS process used by CREAL. This is smaller than typical μLED or LCoS pixels (>3 μm). The main pixel pitch reduction to effectively <1 μm, however, comes from sequential pixel replication enabled by the FLCoS framerate. See the next section.

- **Dynamic Flexibility**: Frame timing and color depth can be adjusted on-the-fly, trading color

1 The 8 kHz refresh refers to binary frame throughput. Final framerate depends on how many subframes are needed per image. For example, 24-bit RGB color yields 240 fps. Lower color depth and smaller FoV modes allow much higher rates —up to 8’000 fps. These tradeoffs are fully programmable on-the-fly.

depth for speed or brightness depending on content. Binary monochrome scenes can be updated at 8’000 fps. Full 24-bit color frames at 240 fps.

- **Efficient Light Use**: While not emissive, FLCoS can be highly efficient in AR by precisely controlling etendue and selectively illuminating only active sections of the FoV. In moderate scene fills (>5%), overall system efficiency exceeds emissive displays even with LED illumination [2,3,4].Laser illumination delivers an additional 5–10x efficiency gain by combining higher directionality (for improved etendue matching) with polarization and precise diffraction behavior.

Key Takeaway: FLCoS bridges critical gaps in AR displays, combining unmatched speed, compact pixels, and dynamic performance flexibility that emissive and conventional reflective technologies cannot achieve.

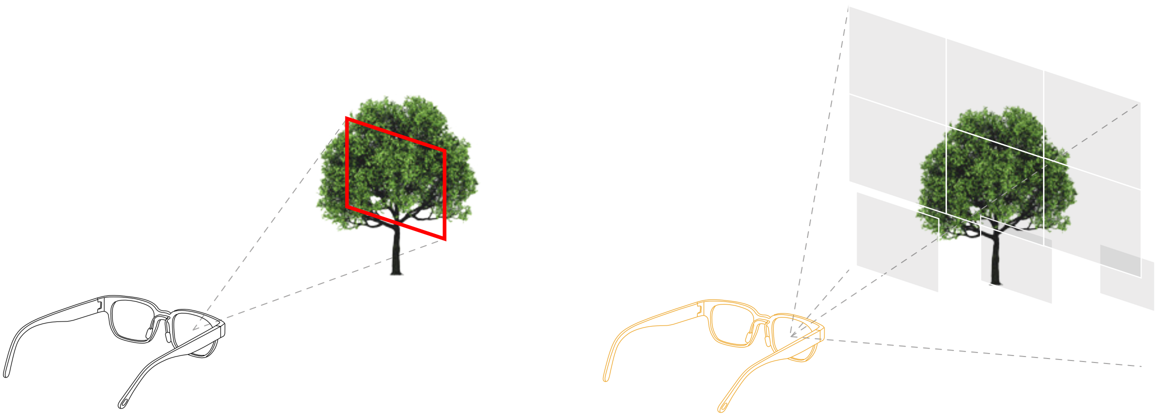
FLCoS’s Breakthrough Capabilities

A Step-Change in Pixel Efficiency and Display Miniaturization

FLCoS leverages its ultra-high binary switching speeds (above 8 kHz) to enable a fundamentally new foveated projection paradigm: **Time-Sequential Pixel Replication**. Unlike traditional raster displays that project pixel and color information uniformly, FLCoS dynamically allocates image information according to human visual acuity, maximizing perceptual effectiveness.

Sequential Pixel Replication: Higher Effective Resolution from Smaller Engines

By rapidly sequencing binary frames, the pixel replication system “tiles” the FLCoS panel in time to create effectively a larger panel in a wider total FoV, while precisely allocating resolution and color depth where perceptually critical - high detail in the center, less detail at the periphery. No pixels and no light if there is no content. This significantly reduces the total image information required to achieve a wide FoV (>70°) and high perceived resolution (>40 ppd), enabling ultra-compact display engines (<1 cc).



(a) (b)

Figure 4: Brute force display approach spreads a uniform pixel grid across a limited Field of View, (a). FLCoS enables efficient Field of View Expansion by time-sequential tiling of lower color-resolution frames, (b). Alternatively, dual FoV expansion architecture (not show in the picture) with lower color- and spatial-resolution at the periphery is also possible and demonstrated by CREAL.

Pixel Replication Pays Off

Pixel replication optics adds certain volume to the display engine, but, like in the case of LCoS vs. µLED systems [4], the benefits outweigh the cost beyond a certain FoV. The ability to use smaller pixels and deliver light more efficiently enables a wide FoV from compact engines. As shown in Fig. 5, only sequential pixel replication enables >70° FoV at >40 ppd from a sub-1 cc engine.

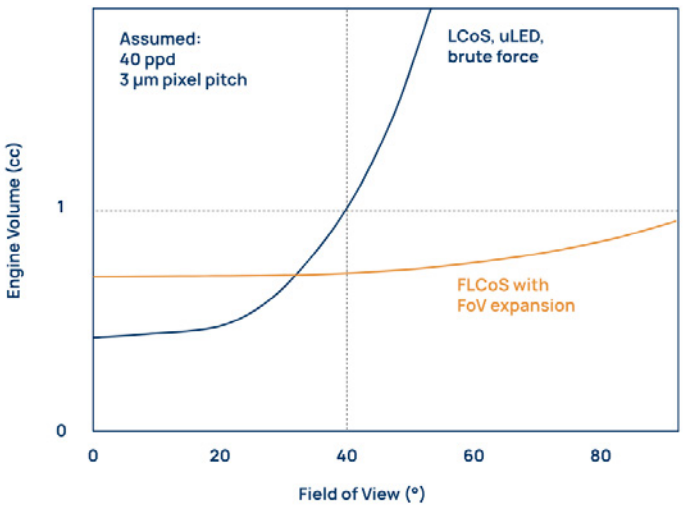


Figure 5: Display engine volume scaling with Field of View at constant resolution (40 ppd), assuming an identical pixel pitch of 3 µm. For LCoS and µLED, engine volume grows with the cube of Field of View, reaching 1 cc near 40°, and becoming impractical beyond that. FLCoS, even with the same base pixel pitch, benefits from sequential pixel replication, enabling significantly lower engine volumes at a wider Field of View. Moreover, FLCoS supports even smaller physical pixels (down to 2.8 µm with reliable processes, <1.5 µm demonstrated), allowing further miniaturization beyond what's practical for emissive or nematic LC-based displays. (Illustrative)

Key Advantages:

- **Optimized Resolution**: Efficiently matches pixel density and color detail to visual acuity, substantially reducing unnecessary information, pixels, and power without perceptual loss.
- **Selective Brightness**: Segmented illumination delivers light only to FoV segments with some content, greatly enhancing brightness-per-watt compared to emissive technologies, particularly at moderate scene fills (>5%). Laser illumination increases optical efficiency by an extra factor of 5-10x compared to LED systems.
- **Dynamic Adaptability**: Supports dynamic adjustments in frame timing, resolution distribution, and color depth, enabling rapid monochrome overlays (up to 8'000 fps) and rich, full-color imagery at 240 fps within the same device.
- **Waveguide Compatibility**: CREAL's FoV-expanded FLCoS architecture is fully compatible with industry-standard waveguides. Note: FoV is limited by the waveguide.

Key Takeaway: FLCoS's Time-Sequential Pixel Replication breaks through traditional limitations, enabling compact, high-performance foveated AR displays that deliver a wide Field of View, high perceptual resolution, and exceptional power efficiency.

Performance Advantages of FLCoS Over Emissive and LCoS Displays

FLCoS offers fundamental improvements compared to mainstream AR micro-display technologies —emissive (µLED) and reflective (LCoS)— particularly in addressing key AR requirements: FoV, resolution, speed, miniaturization, and power efficiency.

Metric	Color µLED	LCoS	Laser-FLCoS with Sequential Pixel Replication
Max Field of View @ 40 pp, & 1cc	<40°	<40°	>75°
Pixel Pitch	>4.5 µm (RGB)	>3.3 µm	2.8 µm (1.5 µm demonstrated, < 0.7 µm effective with pixel replication)
Framerate	~120 fps	~120 fps	>8'000 fps binary, (240 fps @ 24 bit)
Display Latency	>5 ms	>5 ms	0.2 ms
Brightness/power (@ 70° FoV)	200 nits/400 mW (@ 28 ppd, > >1 cc)	Exceeds µLED above 5% scene fill (with seg. illum.)	5-10x brighter/W than µLED at 5% scene fill and more above
Contrast Performance	1'000'000:1 (local pixel crosstalk)	1'000:1	2'000:1
Display Engine Size (@ 75° FoV & 40 ppd)	6–8 cc (extrapolated; FoV³ scaling)	5–7 cc (extrapolated; FoV³ scaling)	0.8–1.3 cc (design concept)
Integration Complexity	Low	Medium	Medium
Cost (RGB engine)	>$100	$10s	$10s
Manufacturing Maturity	Early	Mature	Mature

Key Comparative Insights:

- **Field of View and Pixel Efficiency - Foveation**: FLCoS uniquely enables expanded FoV with fewer physical pixels through sequential pixel replication, fundamentally enhancing pixel efficiency.

- **Brightness and Power Efficiency**: While emissive technologies excel at very low scene fills, LCoS and FLCoS become superior at moderate scene fills due to directional illumination and efficient light coupling. Laser illumination systems add 5-10x efficiency boost compared to LED ones.

- **Integration & Size**: Despite needing illumination and FoV expansion elements, FLCoS achieves compact integration at a wide FoV due to smaller pixel size, reduced thermal demands, and pixel replication.

Key Takeaway: FLCoS uniquely addresses the critical constraints of AR displays, providing fundamental, qualitative improvements in FoV, resolution scalability, brightness efficiency, and compact integration. These advantages establish FLCoS as a highly practical and effective platform for next-generation AR systems.

Technology & Manufacturing Maturity

FLCoS leverages decades of proven high-volume production, matching LCoS in maturity while offering greater miniaturization potential, and far ahead of emissive microdisplays (µLED) in readiness. Built on established silicon CMOS processes, it delivers high reliability, high yields, and predictable production costs.

- **µLED**: Early-stage, with significant challenges in RGB integration, low manufacturing yields, and no HVM infrastructure.

- **LCoS**: Fully mature and commercially proven, but inherently constrained in miniaturization at small pixel sizes without major breakthrough.

- **FLCoS**: Fully mature, robust, and manufacturable in volume at smaller pixel sizes, with high yields and reliability.

Key Takeaway: FLCoS stands out as the most production-ready path to high-performance AR displays, combining proven scalability with a clear roadmap for further miniaturization.

FLCoS Roadmap

FLCoS offers immediate compatibility with today's AR ecosystems and a path toward digital light field displays - the ultimate immersive format.

Current State: Proven Performance and Maturity

FLCoS has a decades-long manufacturing track record, with past high-volume production at ~4.3 µm pixel pitch confirming scalability and reliability. CREAL's current platform sets new benchmarks:

- **7 µm Pixel Pitch**: The fastest available FLCoS display, operating at over 8 kHz with 1000 × 1000 pixels and exceeding 2000:1 contrast. It uniquely provides per-frame contrast optimization and unparalleled data manipulation flexibility, making it fully suitable for AR today.

- **2.3 µm pixel pitch effectively**: Sequential pixel replication (9x) makes it effectively a 2.3 µm pixel pitch display with **3K resolution** in a **< 3 cc** engine volume today.

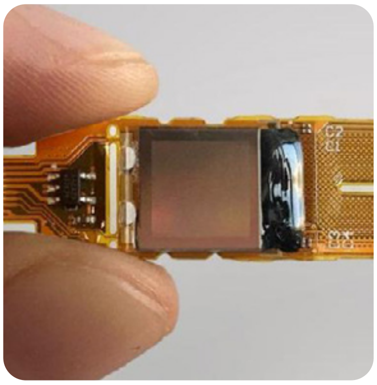
Immediate Miniaturization Pathways

- **2.8 µm Pixel Pitch (180 nm CMOS)**: A pragmatic near-term solution using mature, low-cost processes. Enables 1000 × 1000 pixel displays with an active area of ~2.8 × 2.8 mm^2 and package size around 5.4 × 8.6 mm^2, suitable for integration into **sub-1 cc display engines**, including illumination and optics. This resolution level also ensures high manufacturing yield and reliability, avoiding the cost and risk penalties of extreme scaling. Pixel replication (9x) results in an **effectively < 1 µm pixel pitch 3K** display.

→ **Sub-2 µm Pixel Pitch**: Experimentally demonstrated pixel pitches below 1.5 µm [7] show the feasibility of further miniaturization. While smaller pixels do not scale linearly in package size due to fixed optical/mechanical components, they allow tighter integration and expanded functionality. Pixel replication (9x) results in an **effectively < 0.7 µm pixel pitch 3K** display.

Today

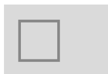
10 × 10 mm^2
7 µm pixel pitch
1000 × 1000 pixels
2.5 cc engine



(a)

2027

5.4 × 8.6 mm^2
2.8 µm pixel pitch
1000 × 1000 pixels
~0.3 cc engine



(b)

Feasible

4 × 6 mm^2
1.8 µm pixel pitch
1000 × 1000 pixels
< 0.3 cc engine

(c)

Figure 6: Size comparison of FLCoS display modules with 1000 × 1000 physical pixels: (a) Current 7 µm pixel pitch (2.5 cc engine), (b) Near-term 2.8 µm pixel pitch (~0.3 cc engine), (c) Feasible 1.8 µm pixel pitch (< 0.3 cc engine). Combined with time-sequential pixel replication, these compact chips enable perceived resolutions exceeding 3K × 3K per eye within sub-1 cc display engines, breaking the brute-force scaling barrier and unlocking wide Field of View AR.

Time-Sequential Pixel Replication Systems

FLCoS inherently supports advanced sequential projection methods to expand achievable FoV without substantially enlarging the engine:

- **FoV Expansion Demonstration**: Two architectures successfully built and tested - **FoV tiling** and **dual FoV** (details will be provided in private conversation). These techniques deliver up to 9x pixel replication, resulting essentially in **~27x wider FoV per engine volume** compared to brute force approaches.

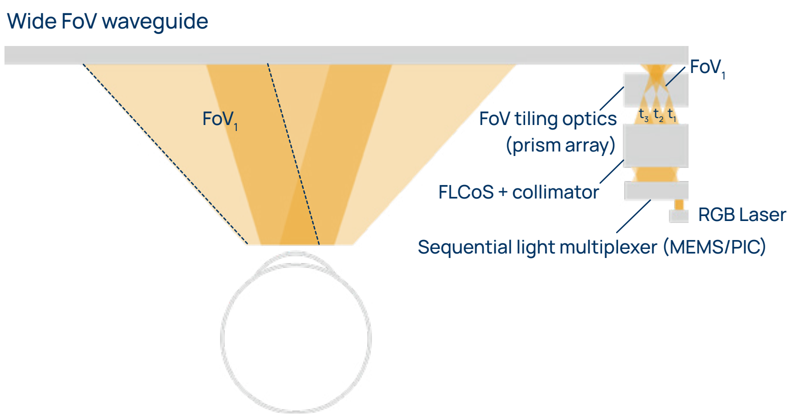


Figure 7: Schematic example of a sequential FoV expansion architecture using FLCoS. One of several possible system designs combining time-multiplexed modulation, optical tiling, and compact projection optics.

- **Engine volumes**

Figure 8: Visualization of foveated 3K × 3K laser-FLCoS engine volumes alongside a glasses frame. (a) Current 7 µm pixel-pitch implementation. (b) Future 2.8 µm pixel-pitch concept. Note, only active optical volumes are shown; mechanical structures are excluded.

Ultimate AR – Digital Light Field Display with Prescription Lens

CREAL's FLCoS architecture was originally developed for full-featured digital light field displays [8], delivering realistic depth cues and natural visual experiences with conventional ophthalmic lenses. The core technology is validated, and we expect alignment with the broader AR ecosystem within the coming years.

Strategic Roadmap Overview

- **Current Phase**: Proven FLCoS display (7 µm pitch, 8 kHz, 2000:1 contrast, unmatched flexibility). Perceived 3K resolution via FoV expansion to 75° from 3 cc engine.
- **Intermediate Phase (2027)**: Miniaturization to 2.8 µm pixel pitch, full integration of time sequential pixel replication. Perceived 3K resolution from sub-1 cc engine.
- **Ultimate Phase (2028+)**: Sub-2 µm displays, FoV expansion, and foveated light field.

Key Takeaway: FLCoS offers a rare combination of mature, manufacturable technology that solves critical problems in today's waveguide ecosystem and, simultaneously, has a clear roadmap toward AR's most demanding goal - digital light field with native prescription lens. It delivers what AR needs now, and what immersive computing will require next.

About CREAL

CREAL is a deep-tech company based in Lausanne, Switzerland, developing the most advanced display engines for augmented reality. Our technology stems from years of innovation in high-speed spatial light modulation and pixel-efficient rendering. Our team includes former leads from **Intel Vaunt**, **Magic Leap**, and **Meta's Orion project**, blending expertise across optics, displays, and AR systems.

CREAL is also partnering with **Zeiss** to apply light field displays in vision care, bringing medical-grade simulation and patient demonstration tools into real-world clinical environments.

Let's Collaborate

We offer:

- **FLCoS display modules** for immediate integration and evaluation
- **Development partnerships** on custom projection engines
- **Licensing opportunities** for AR, HUD, vision care, and light field applications

We're currently particularly interested in:

- **Waveguide-integrated FLCoS** for wide-FoV situational awareness AR
- **Light field visualization** in medical and industrial applications

Contact us to explore how FLCoS can accelerate your product roadmap:

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