高解析實境顯示基礎原理

Basic principles of high-resolution reality displays

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Chapter 9:近眼顯示技術介紹

Outline

1. 為什麼我們需要近眼顯示器？
2. 眼睛與近眼顯示器的關係
3. VR：瓶頸與解決方案
4. AR：瓶頸與解決方案
5. 我們在 AR/VR 方面的研究
6. 結論與展望

為什麼我們需要近眼顯示器？

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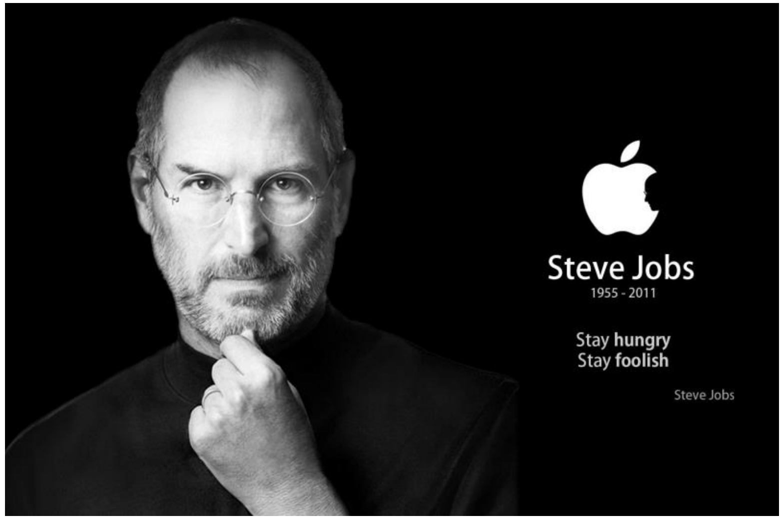
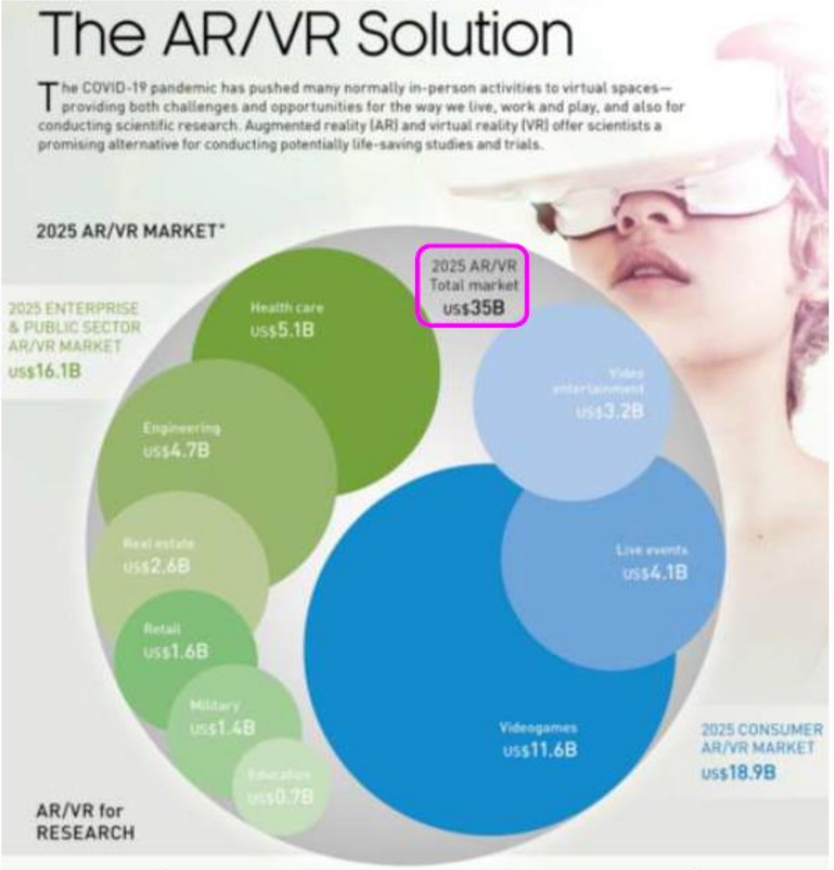


AR/VR市場概況

1. Head-Mounted VR (~$300)
   Oculus, HTC, Sony, etc.

2. See-through AR/MR (>$2000)

3. AR/VR market $35B by 2025



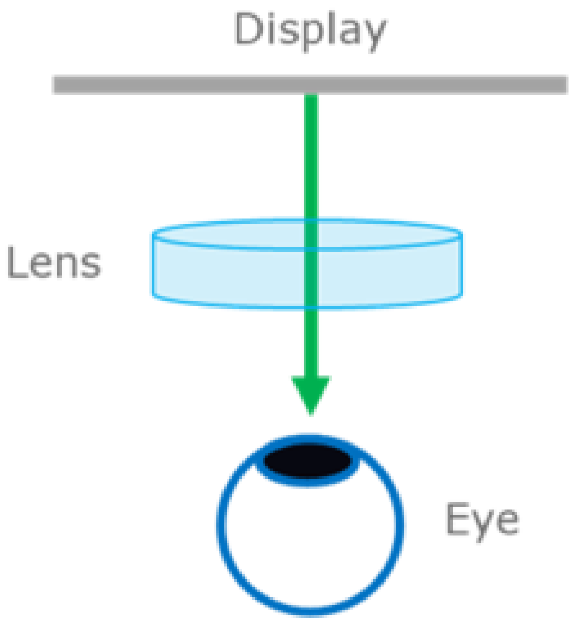
Alessia Kirkland, **OPN, April 2021**

215.9 公厘

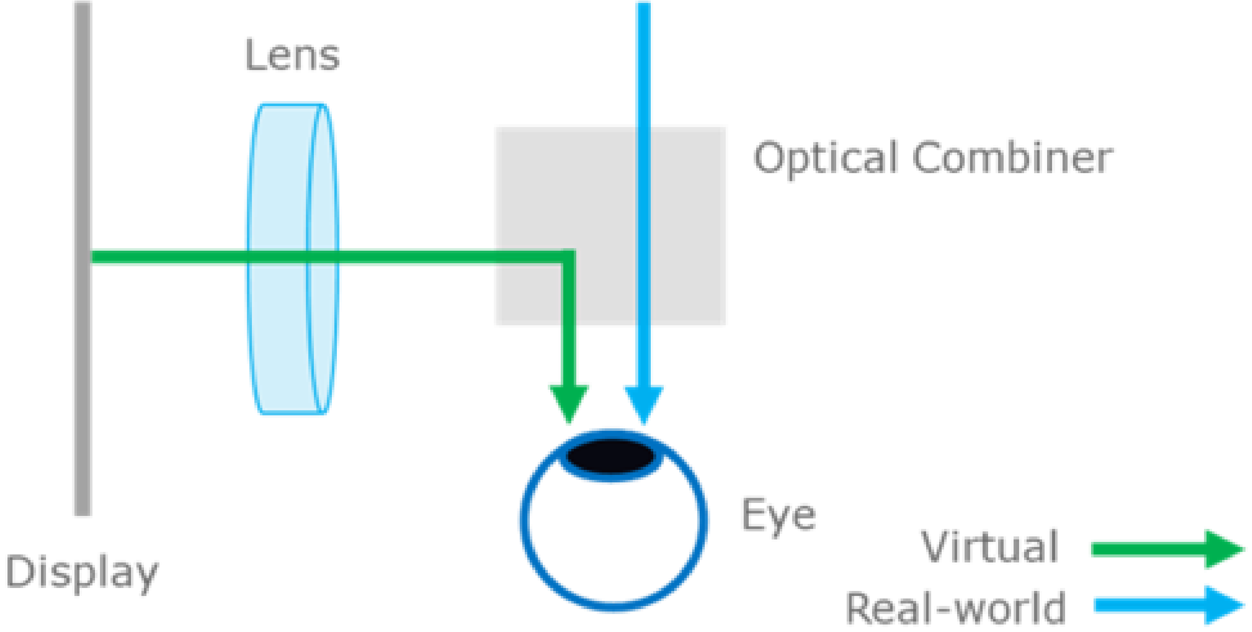
AR/VR應用

VR和AR的光學系統

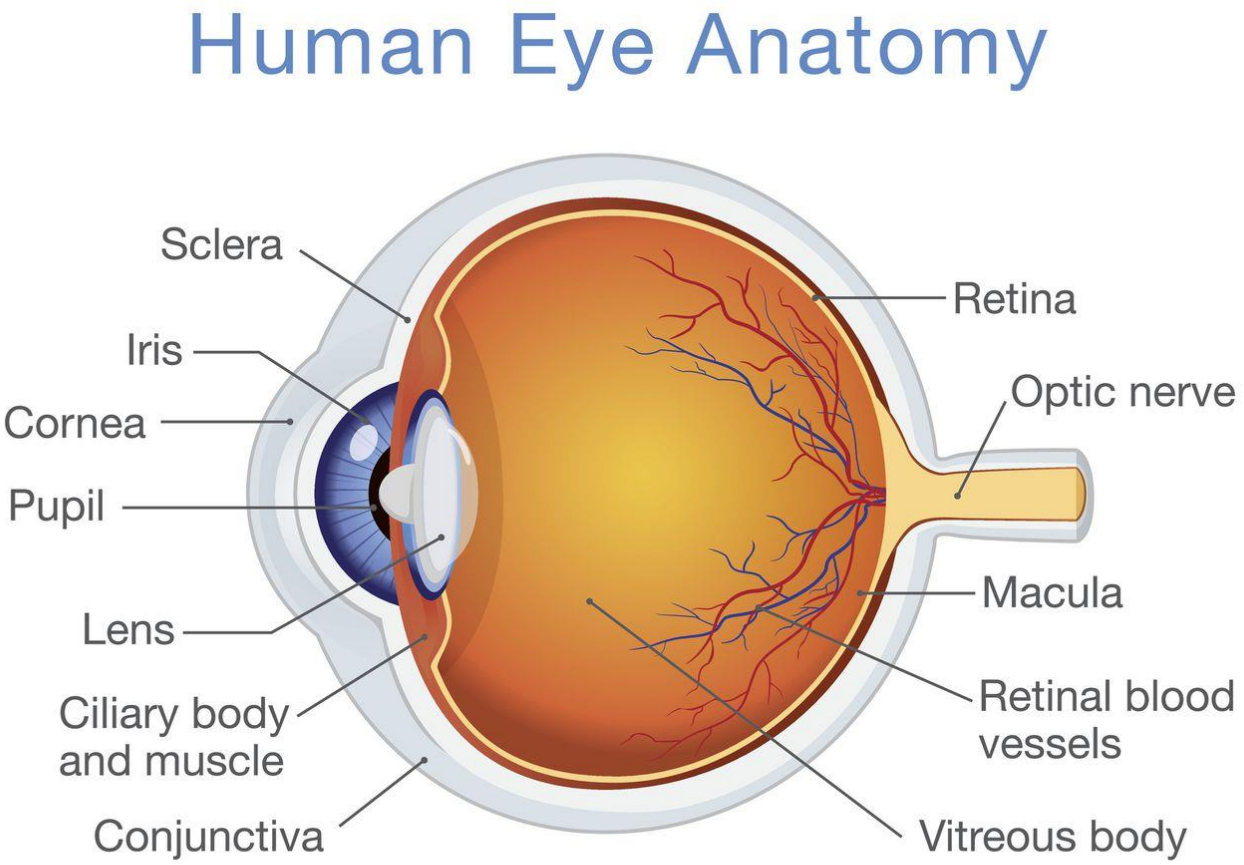
VR



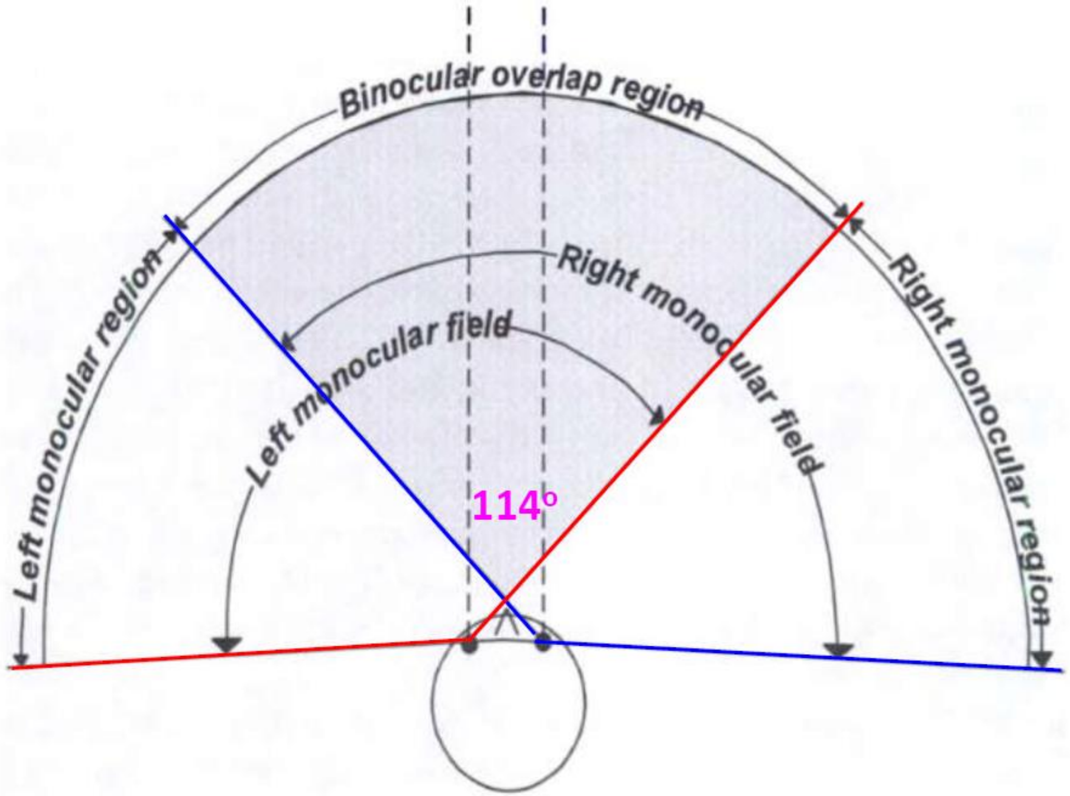
AR



眼球： Field-of-View (FOV)



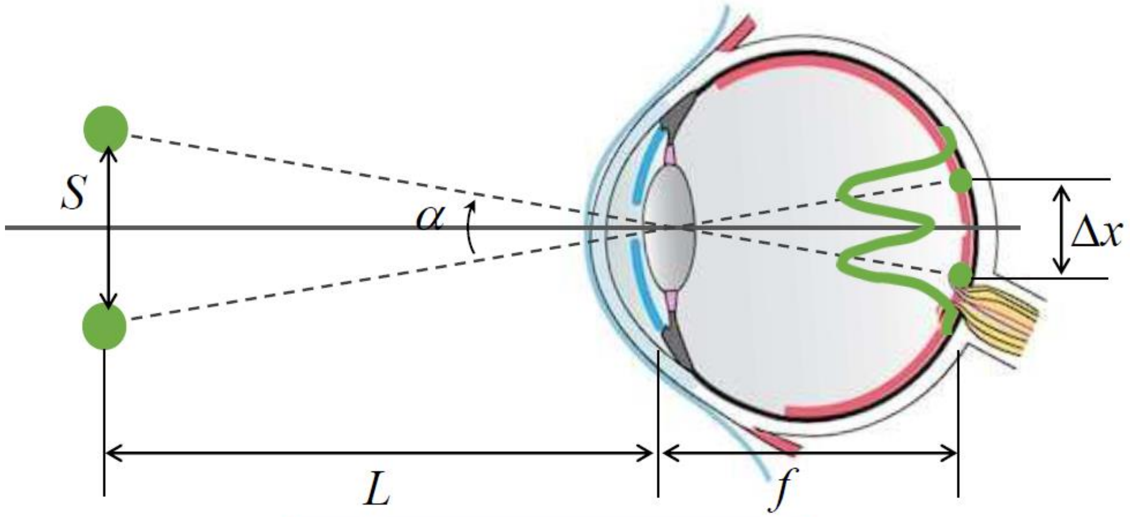
眼球： Field-of-View (FOV)



1. Instantaneous monocular FOV: H ≈ 150°; V≈120°
2. Binocular FOV: H ≈ 200°; V ≈ 120°
3. FOV ≈ 114° when two eyes converge symmetrically
4. Current VR: Diagonal FOV ≈ 100°

角分辨率與FOV

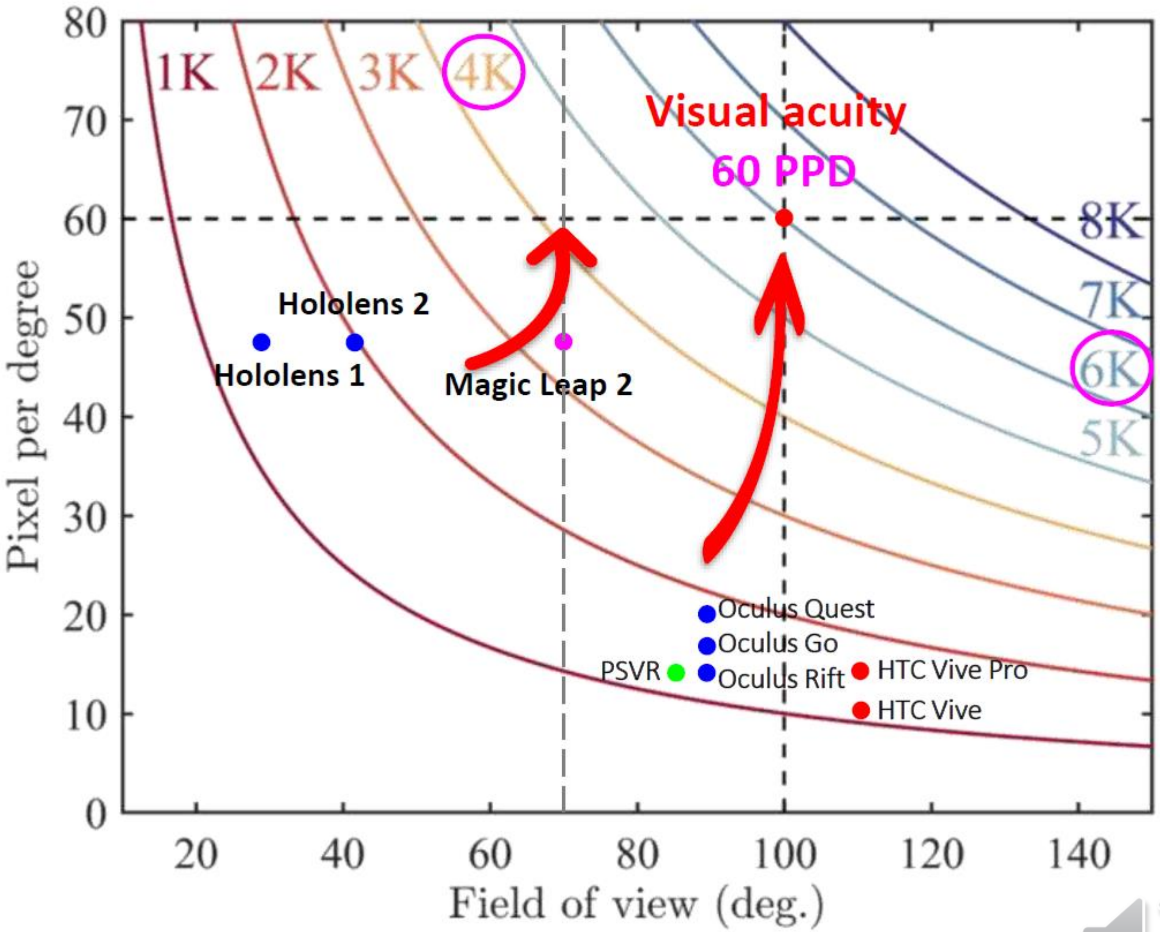
Human visual acuity



$$\tan\frac{\alpha}{2} = \frac{S}{2L} = \frac{\Delta x}{2f}$$

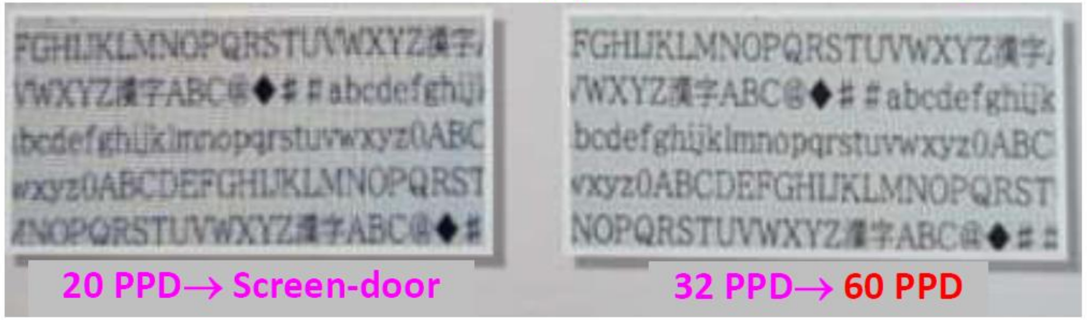
Human eye: f=17.1 mm and cone cells Δx=2.5 μm
→ $\alpha \approx (1/60)^{\circ}$ → visual acuity = 60 PPD

Angular resolution vs. FOV

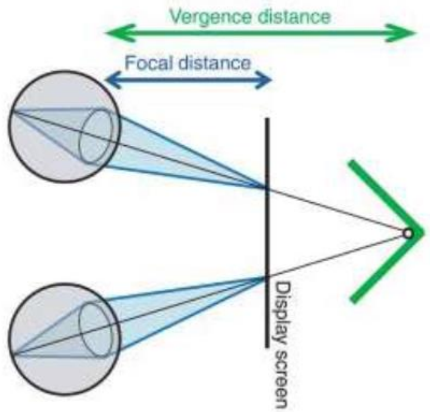


2. VR顯示的挑戰

1. Resolution density (2022 JDI: 2016 PPI)



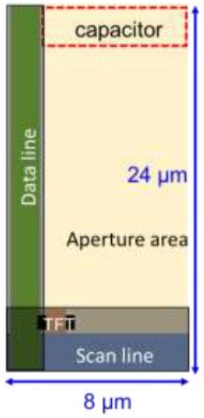
2. Vergence-Accommodation Conflict (VAC)

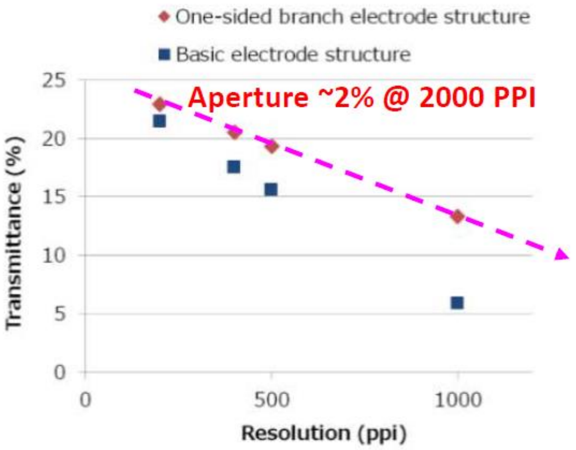


3. Compact, Lightweight, Center of Gravity

No head strap,
Glasses-like &
Lightweight

4. Power consumption (Heat/Battery)



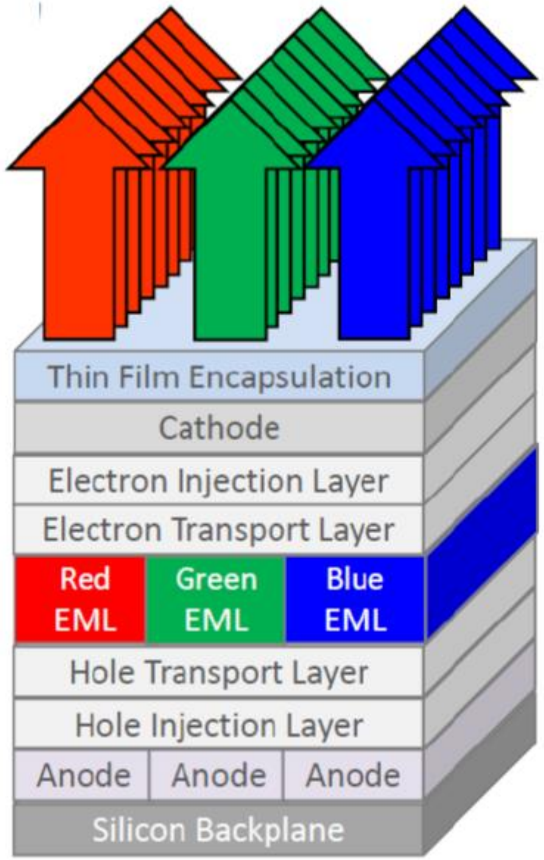


T. Matsushima, et al. JSID 29, 221 (2021)

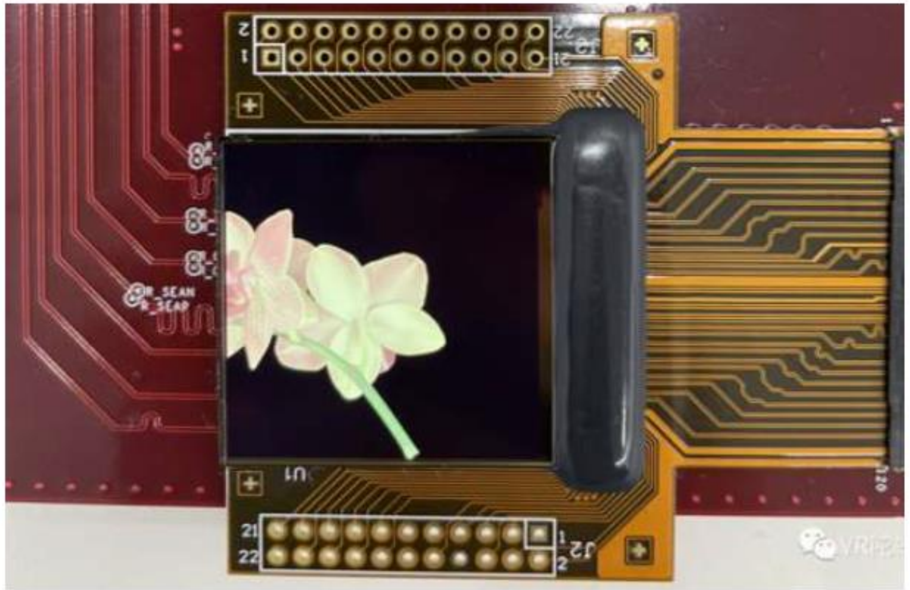
OLED-on-Silicon

eMagin 2.1" 2645-PPI 4K OLED-on-Si

LUMICore 1.3" 2K OLED-on-Si

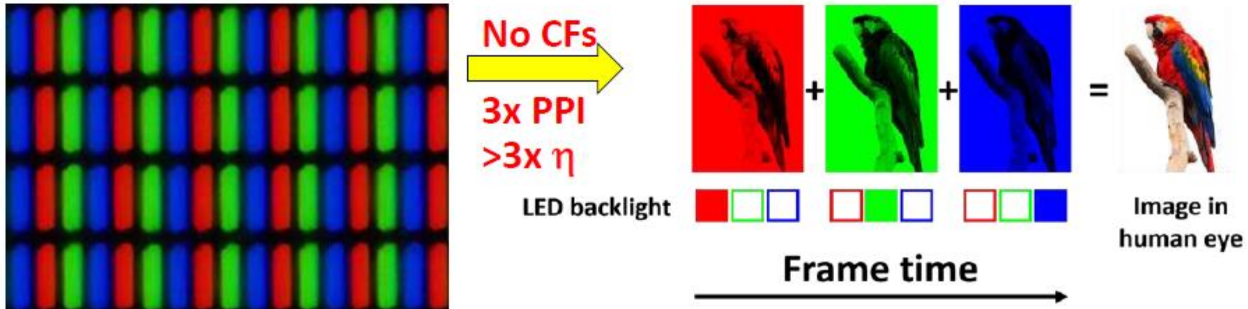


Pixel pitch ~23.2 μm
Resolution: 3600x4000
PPD: 42
Luminance: 10,000 nits
Frame rate: 120 Hz
Lifetime ?
8" wafer <26 2.1" μOLED

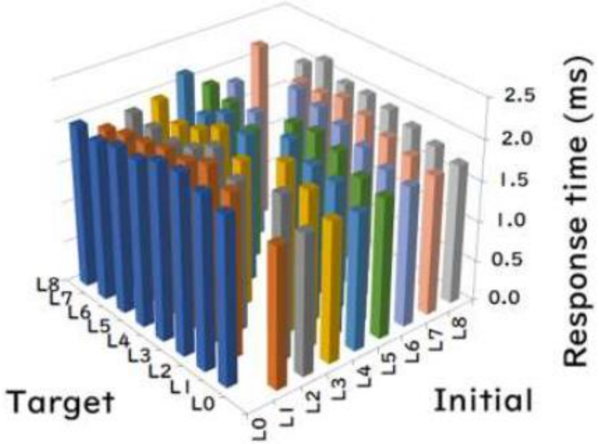


1. Resolution: 2048x2048
2. Luminance: 3000 nits
3. 120 Hz
4. FoV < 70° (Étendue)

AMLCDs: Field Sequential Color



FSC→ 3780/3=1260 PPI→ Aperture>20%



Short-Range Lurch
IPS: GTG≤ 2.2 ms
Dead zones: T≈50%

T. Matsushima, et al. JSID 29, 221 (2021)

Eye saccade
Color breakup

(a) Target image (b) CBU image

F. C. Lin, Y.P. Huang, et al. J. Disp. Technol. **6**, 98 (2010)

	1	2	3	4	5	6	7	8
1		0.75	0.88	1.00	1.12	1.27	1.47	1.83
2	1.53		0.27	0.48	0.66	0.86	1.10	1.53
3	1.63	0.45		0.21	0.41	0.61	0.87	1.35
4	1.72	0.75	0.31		0.20	0.41	0.68	1.23
5	1.83	0.98	0.57	0.26		0.22	0.50	1.14
6	1.95	1.21	0.81	0.51	0.25		0.30	1.09
7	2.11	1.44	1.06	0.77	0.52	0.27		1.11
8	2.32	1.72	1.37	1.10	0.86	0.64	0.40	

VA⊕FFS d=2.6 μm; OD, <GTG>= 0.94 ms

F. Gou, et al. Opt. Express **25**, 7984 (2017)

VR高解析度的問題

Fabrication difficulty

Commercial 80” 8K4K TV ≈ 100 PPI; For VR 6K×6K in 3” ≈ 2000 PPI. Recently, the VR display resolution has been pushed to ~4K×4K.

Driving electronics

To drive a 6K×6K display at 120 Hz refresh rate, the addressing time for each line is only 1.4 μs.

Data transport

For a 120-Hz 6K×6K display panel, we need to deliver >93 Gbit/s to the display panel, not even to mention light field displays with space-, time- or polarization-multiplexing.

Image rendering

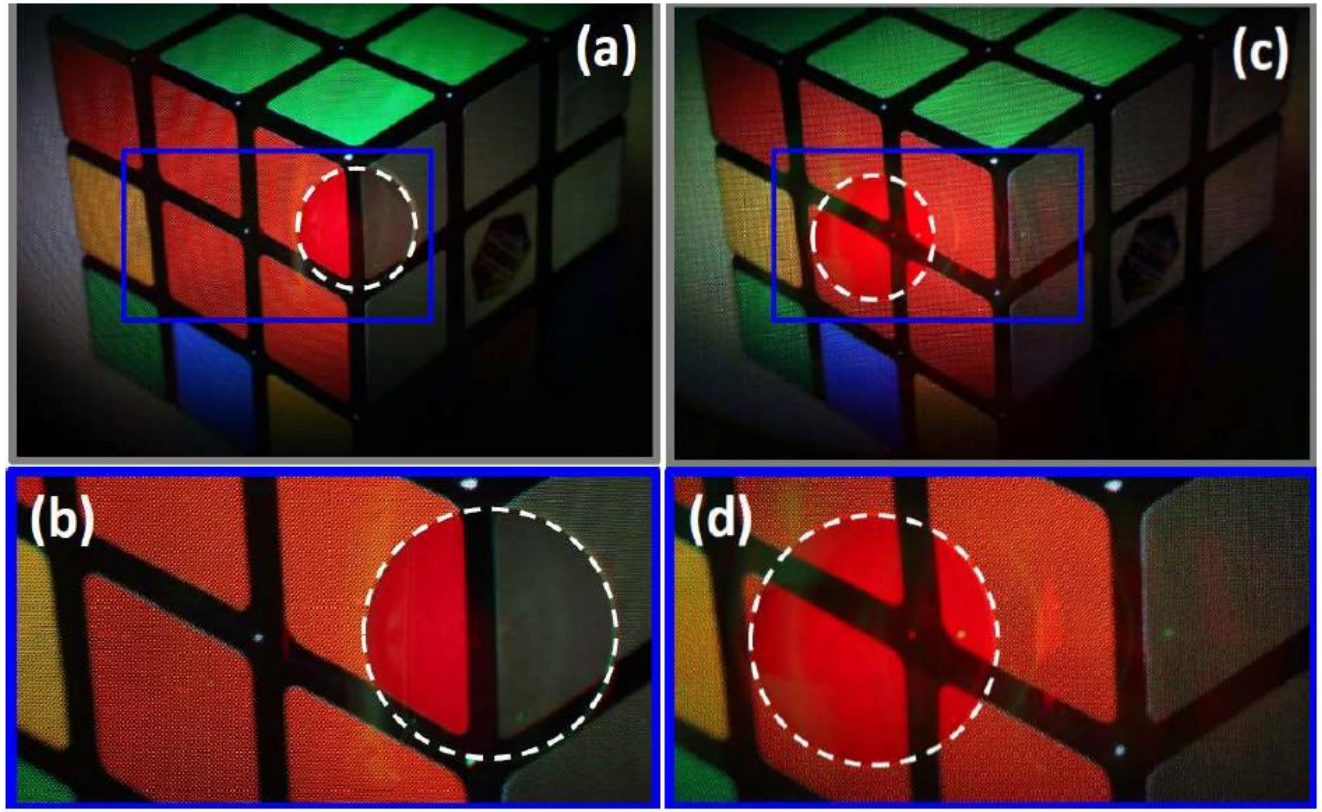
It would be extremely challenging to render high-resolution images and videos in real-time, due to the limitation from the computing power.

Is there other way to improve resolution?

眼球追踪

5X↑ resolution Low resolution

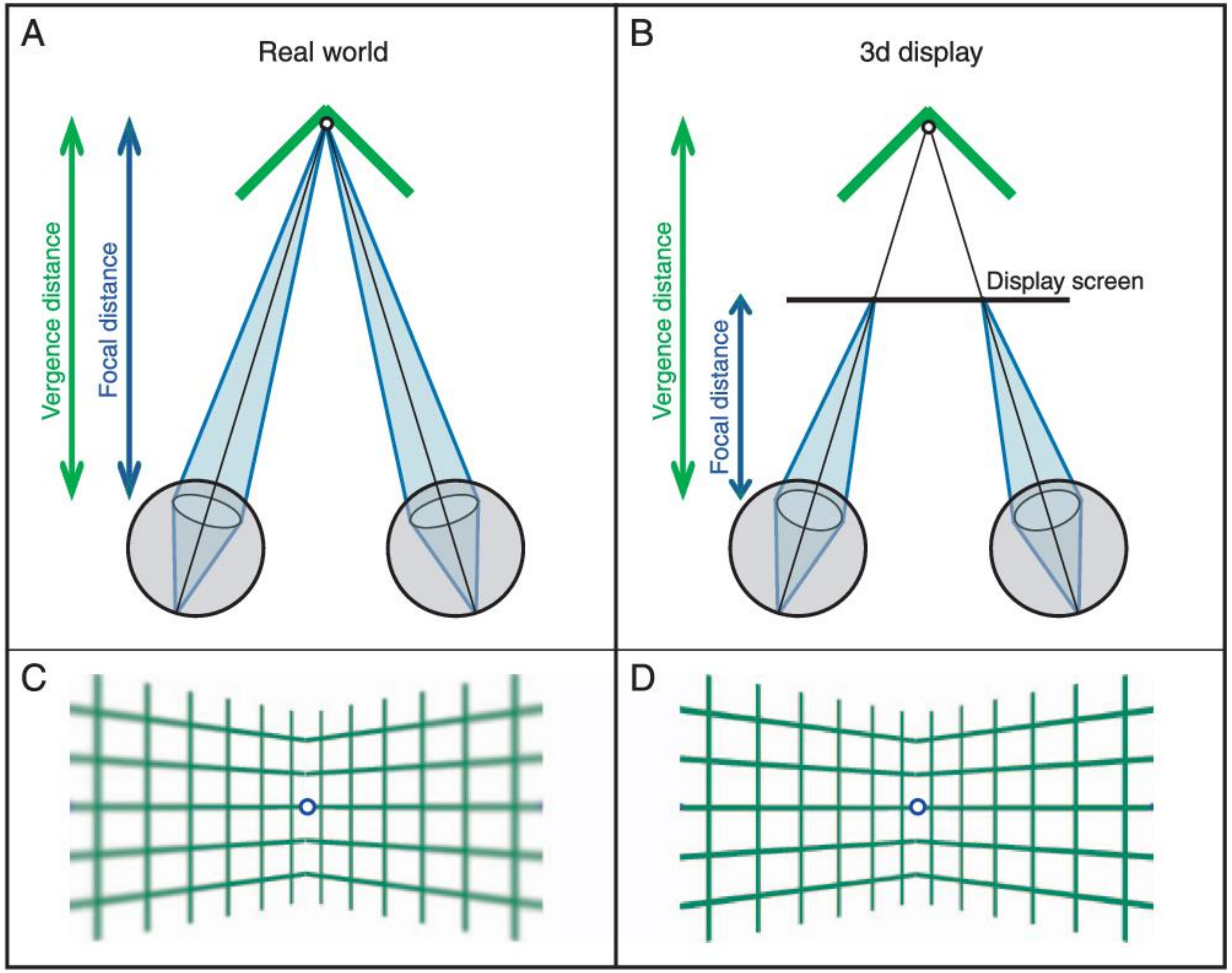
Original V=0 Shifted V=8V



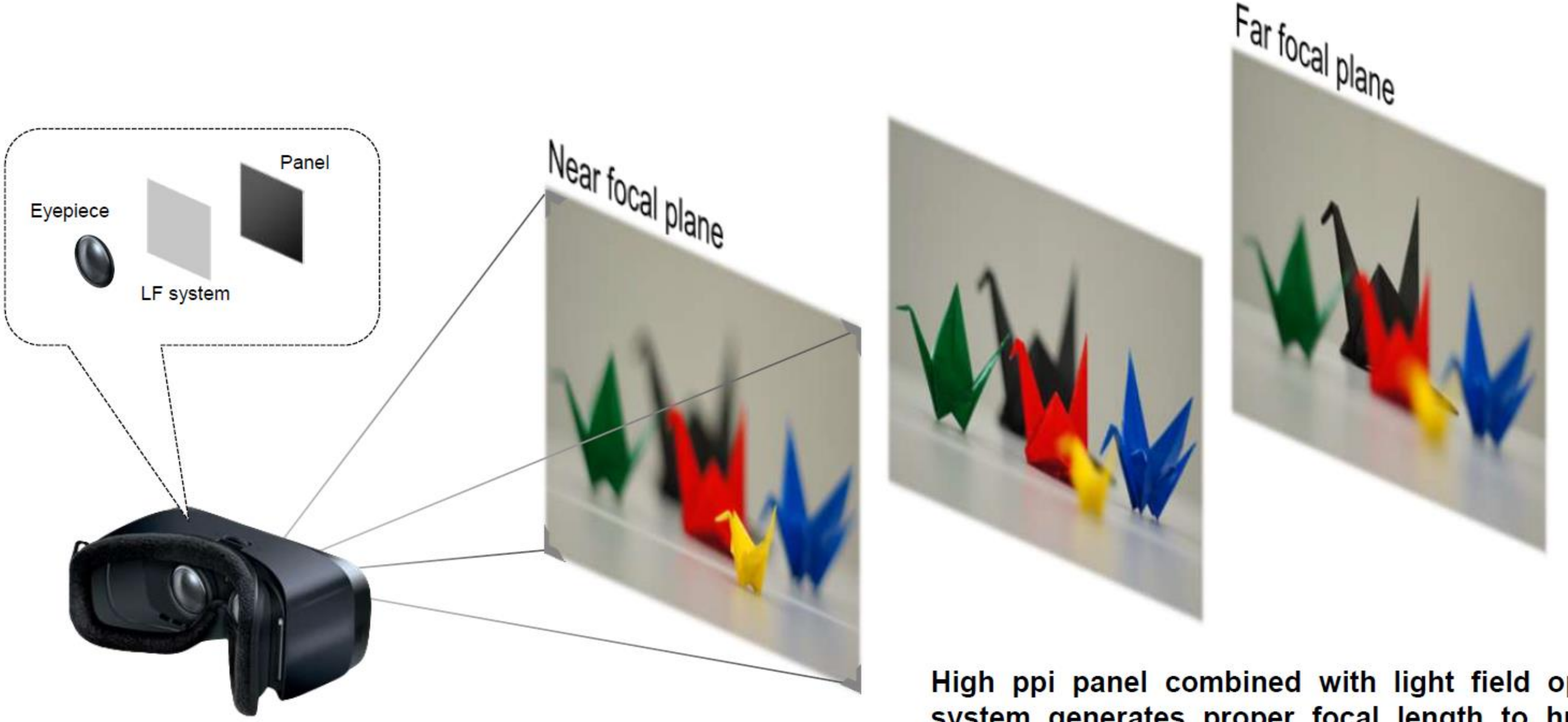
1. High efficiency ~100%→ No ghost image
2. Low voltage: 7-8V; Switching time~1 ms

G. Tan, et al. Opt. Express 26, 25076 (2018)

Vergence-Accommodation Conflict (VAC)

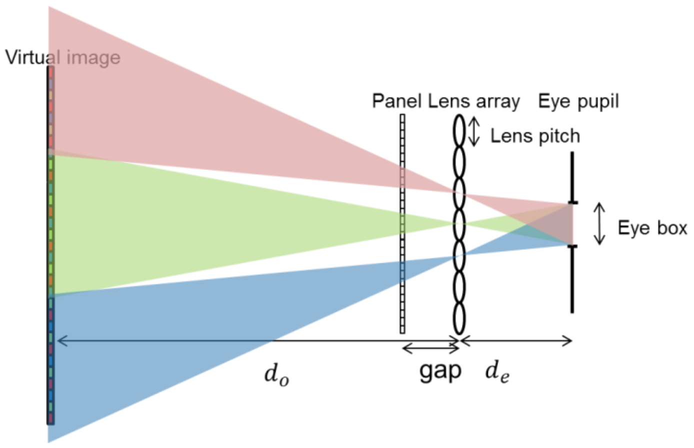


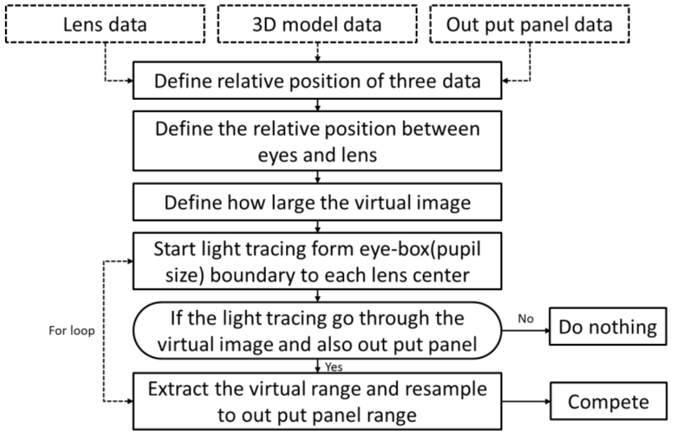
VR Challenge 2: VAC-free (Innolux & CoreTronic)

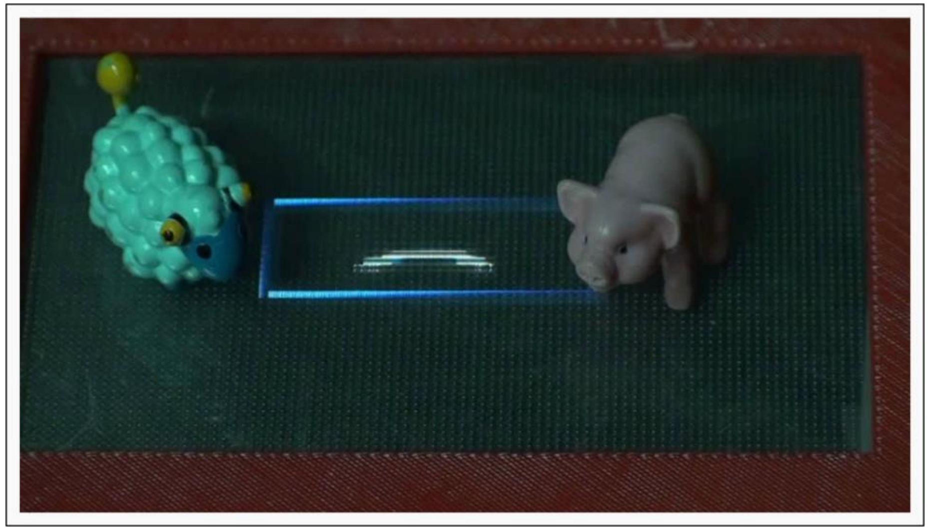


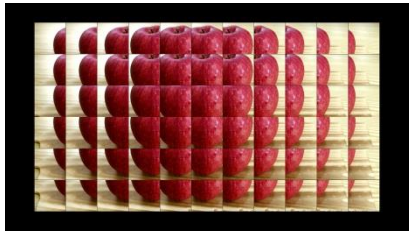
High ppi panel combined with light field optical system generates proper focal length to human eyes without VAC.

VR Challenge 2: VAC-free (Innolux & CoreTronic)

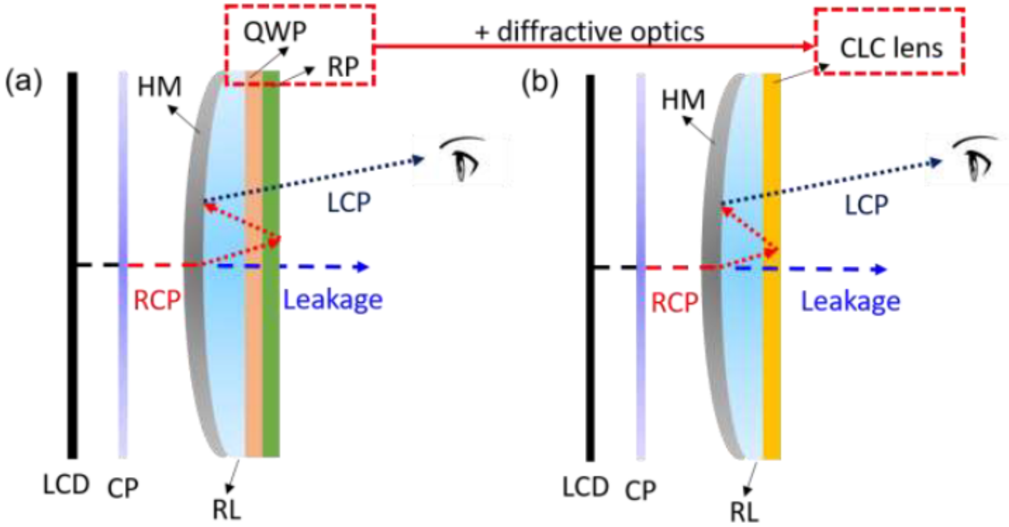






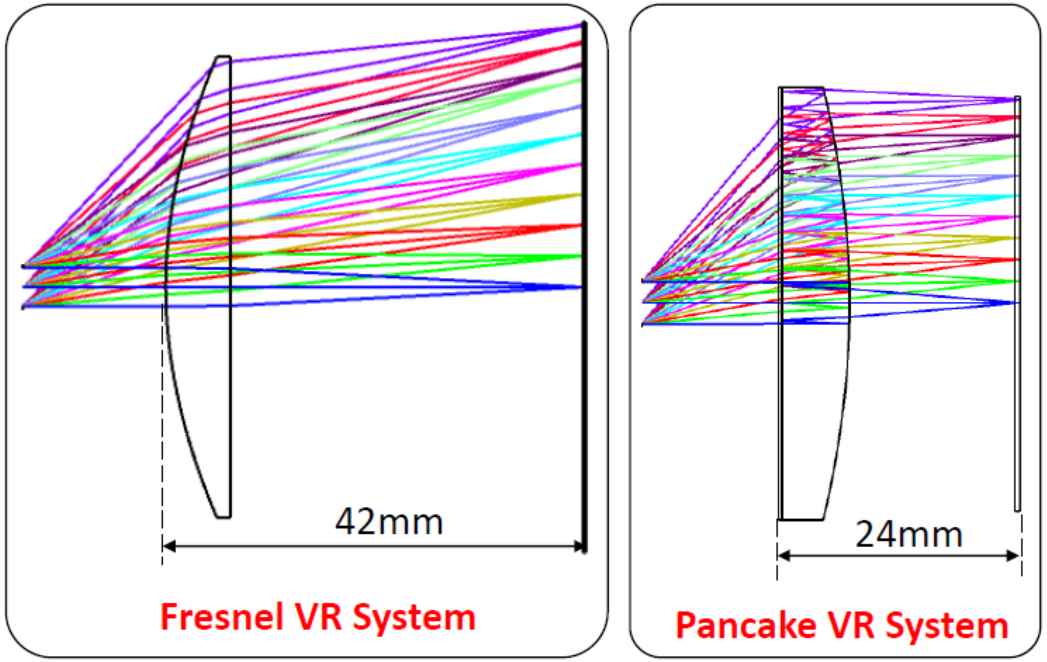


VR Challenge 3: Compact Size (Pancake Lens)



A. Maimone & J. Wang, ACM Trans. Graph. 39, 67 (2020)

Y. Li, et al. Opt. Express 29, 6011 (2021)



(a) Pancake Lens: a half mirror/holographic lens (T=R=50%), refractive lens, & reflective polarizer ⊕ QWP→ Max efficiency ≈25%.

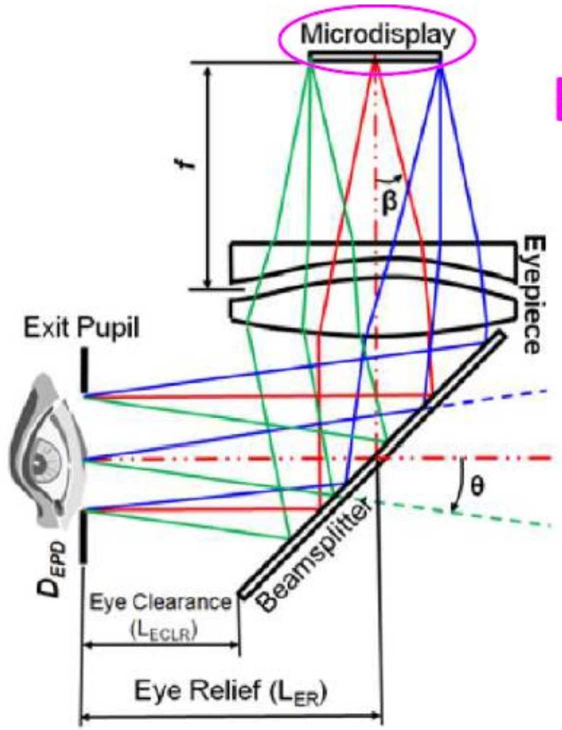
(b) Replacing the reflective polarizer ⊕ QWP by a flat CLC lens.

1. **Size reduced by ~40%, but**
2. **Light efficiency is reduced by 400%!**
3. **How to improve optical efficiency?**

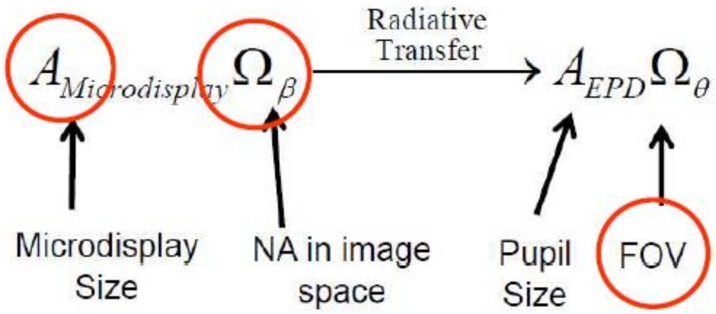
VR Challenge 4: Power Consumption

1. Oculus Quest 2 (807 PPI): 3.5W (3 Hours)
2. LCD panel T>60°C: no fan; overheat ☹
3. Pancake lens: 4x lower efficiency
4. 2000 PPI (SPR): Aperture <20%
5. 4000 PPI: Aperture → 0%
6. Target < 0.5W (7x improvement!)
7. Field Sequential Color: 3x PPI (larger aperture, but need 360 Hz frame rate) and >3x optical efficiency (no CFs)

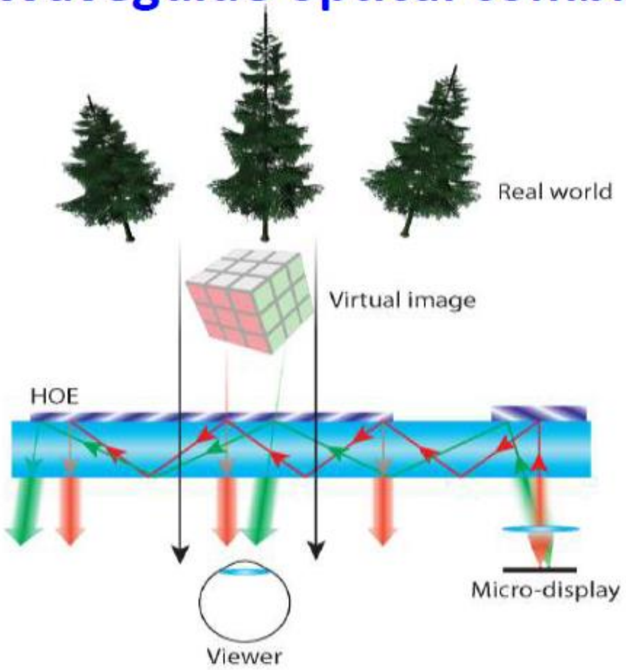
3. AR Bottlenecks



Etendue conservation



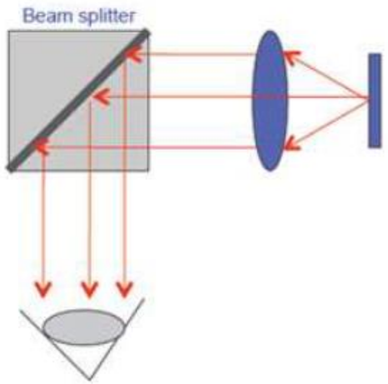
AR: Waveguide optical combiner



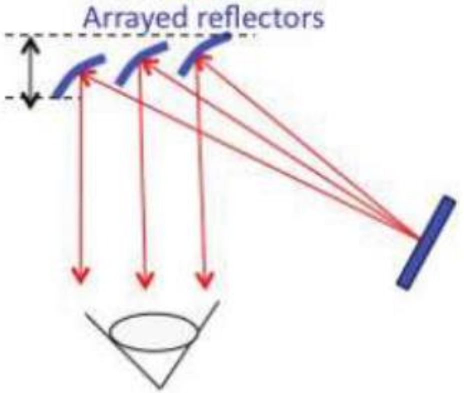
1. Display < 0.5" 2. FOV < 78° limited by TIR
3. Exit Pupil Expander → Waveguide efficiency <10%
4. Compact/lightweight 5. VAC
6. ACR>5:1 (Power) 7. Cost, cost, cost! (>$2000)

Optical Combiners: Partial List

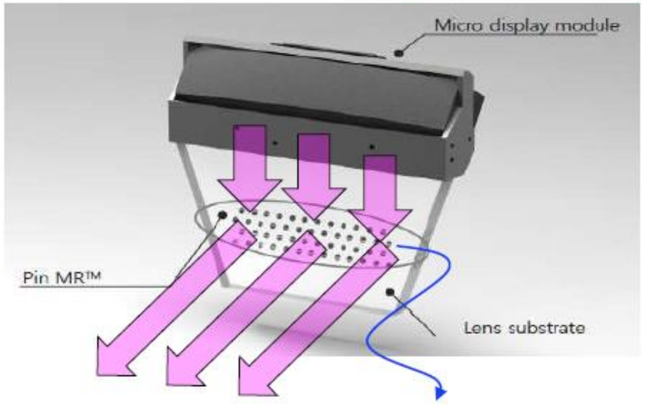
1. Flat on-axis combiner



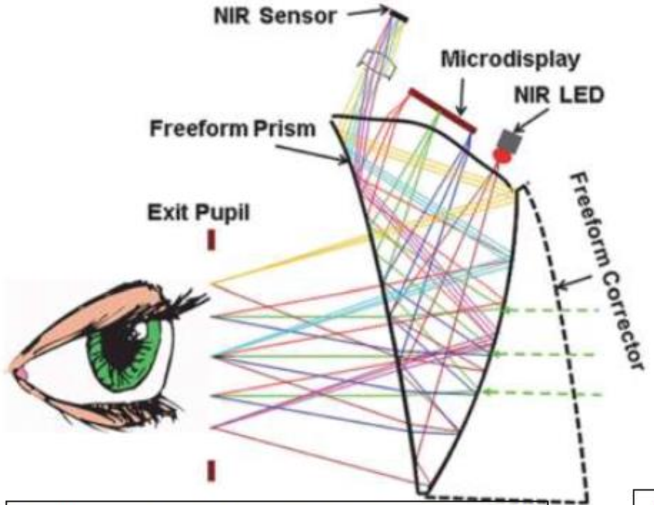
2. Off-axis arrayed combiner



3. Pin Mirrors (Letin AR)

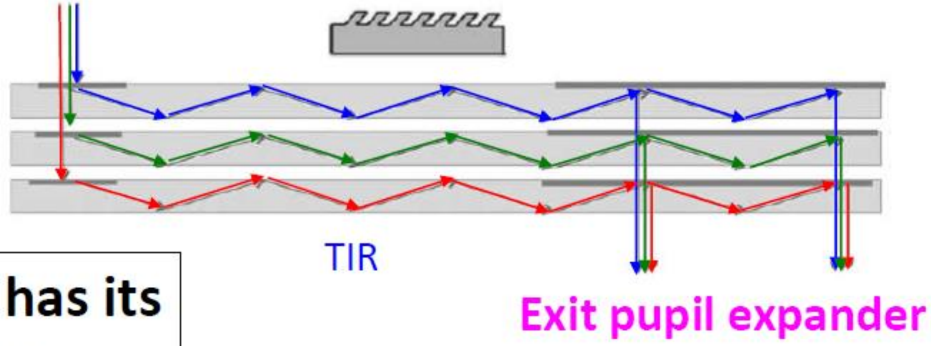


3. Freeform TIR prism combiner



D. Cheng, et al. Appl. Opt. 48, 2656 (2009)

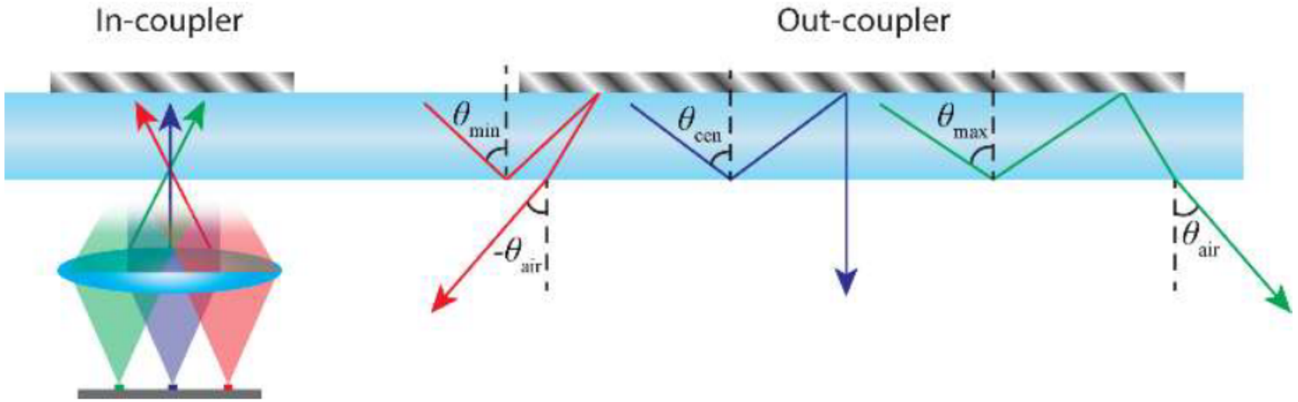
4. Waveguide combiner



Each approach has its own pros & cons

B. Kress & T. Starner, Proc. SPIE 8720, 87200A-1 (2013)

Fundamental FOV Limit for Waveguide AR



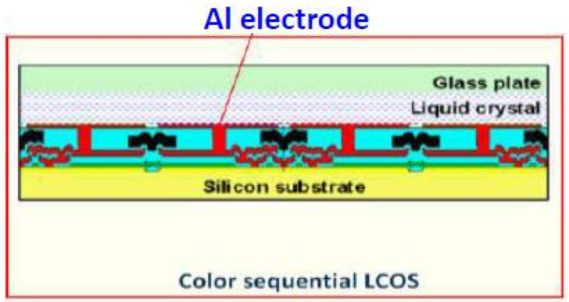
$$FOV = 2\arcsin\left[\frac{1}{2}\left(n_g \sin\theta_{max} - 1\right)\right]$$

1. Let us assume n_g = 2 and θ_{max} = 90° as two extreme cases, then FOV is 60° for one dimension, and 78° for the diagonal.
2. Magic Leap 2: 70°!

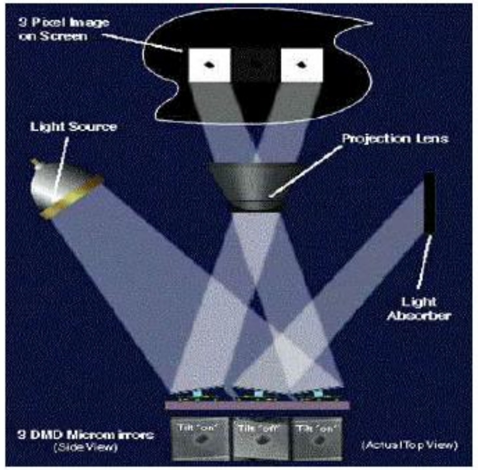
1. J. Xiong, et al. OSA Continuum 3, 2730 (2020);
2. J. Xiong et al. Adv. Photonics Res. 2, 2000049 (2021).

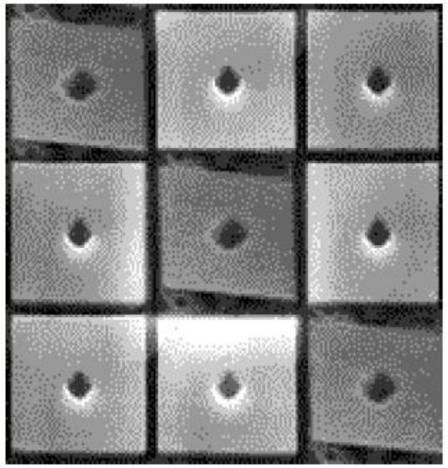
AR Light Engines: High Brightness

1. Liquid-Crystal-on-Silicon (LCOS)

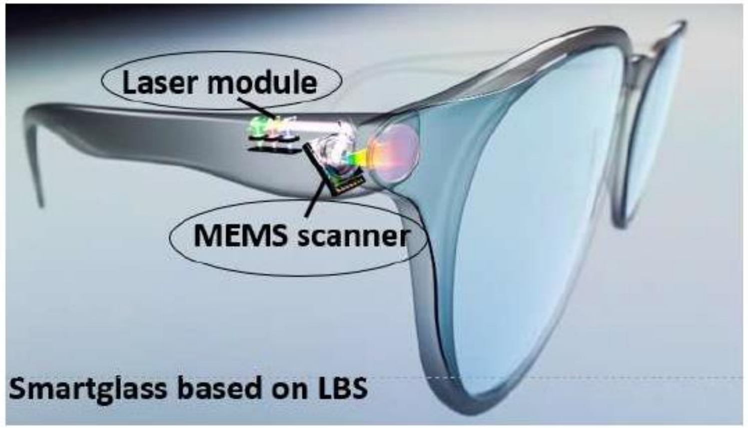


2. Digital Micromirrors



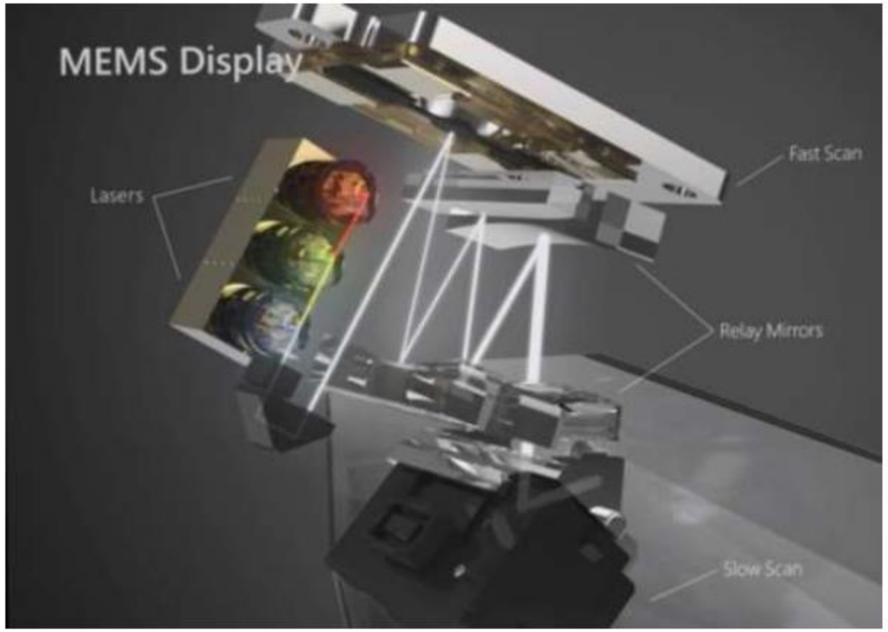


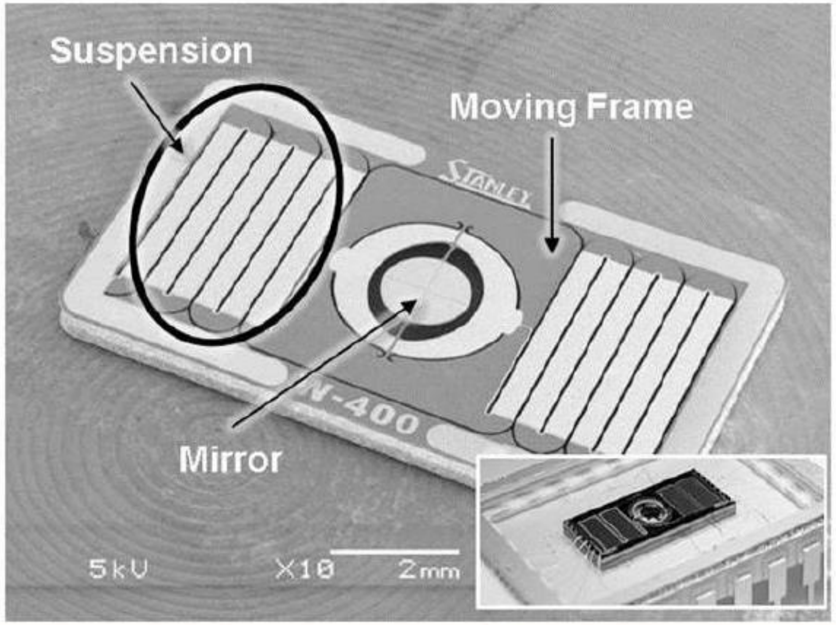
3. Laser beam scan (LBS)



4. μLED/μOLED

Microsoft HoloLens 2: Laser Beam Scan





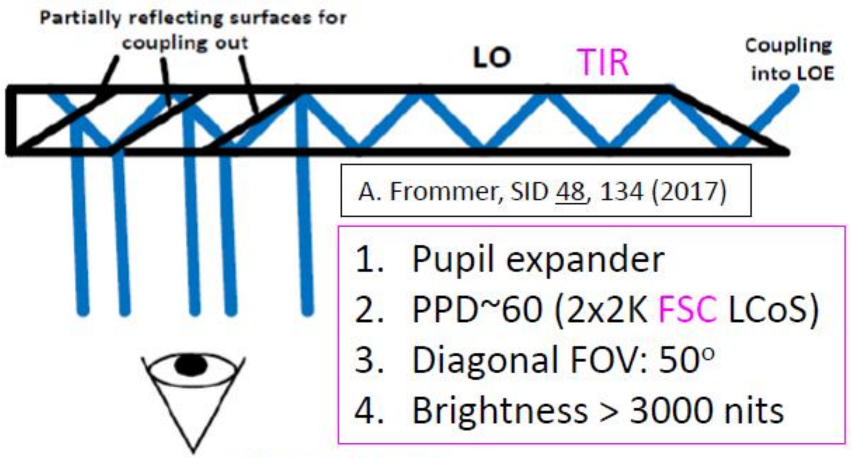
1. Microvision piezoelectric actuator (PZT)
2. Mirror: 1.4 mm; Scan angle= 38.5°
3. Dual 1D MEMS scanner (Raster scan)
4. Frame rate: 60 Hz RGB colors
5. Diagonal FOV: **52°** (H43°; V29°)

Pros	Cons
1. Small formfactor	1. Low frame rate (60 Hz)
2. High brightness	2. Low resolution
3. High contrast ratio	3. Laser speckles
4. Low power consumption	4. Uniformity

O. Petrak, et al. Laser beam scanning-based AR-display applying resonant 2D MEMS mirrors. Proc. SPIE 11765, 1176503 (2021).

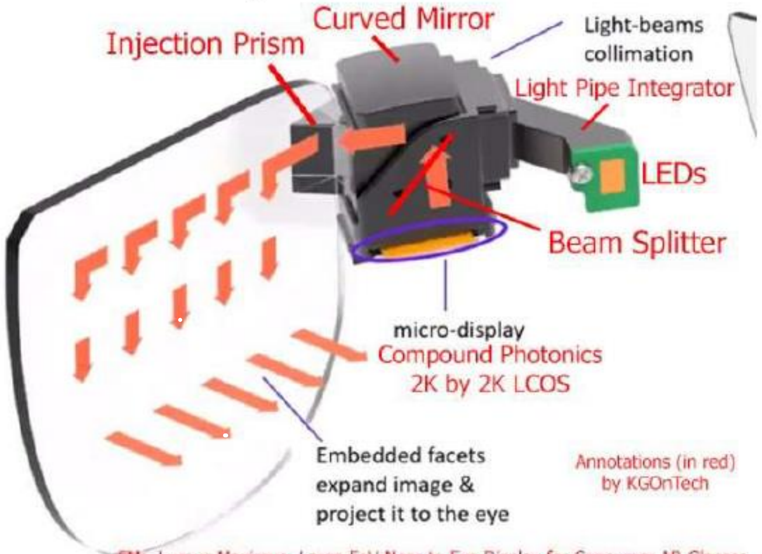
J.B. Tauscher, et al. US Patent 9,946,062 B1 (4/17/2018).

LCoS for AR: Lumus Partial Reflectors



A. Frommer, SID 48, 134 (2017)

1. Pupil expander
2. PPD~60 (2x2K FSC LCoS)
3. Diagonal FOV: 50°
4. Brightness > 3000 nits

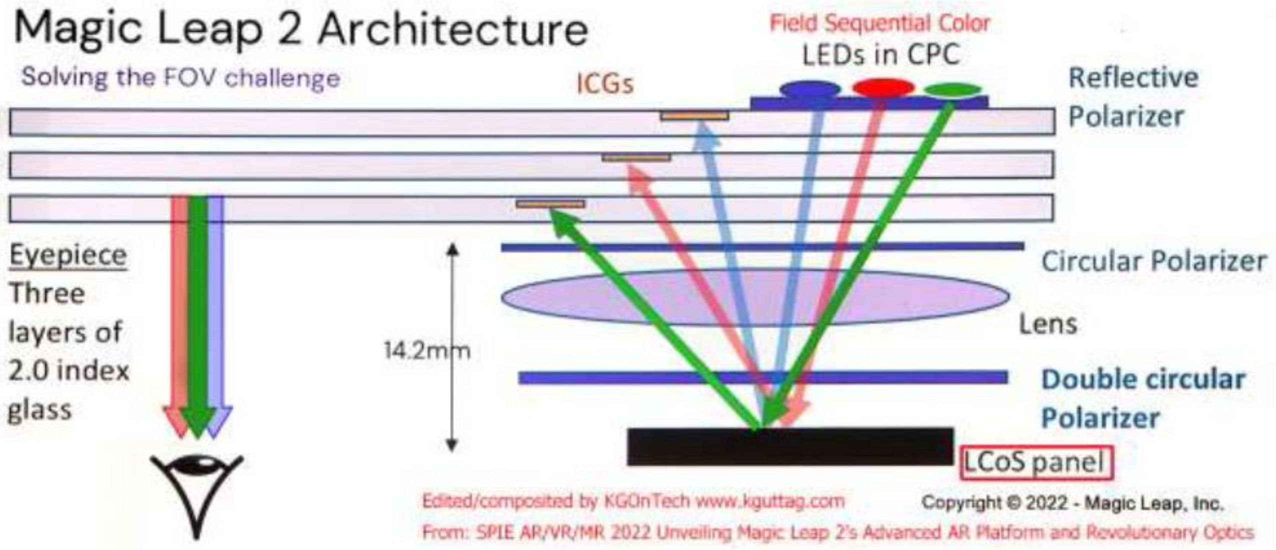


FM: Lumus Maximus: Large FoV Near to Eye Display for Consumer AR Glasses https://doi.org/10.1117/12.2597431 Event: SPIE AR VR MR, 2021

Higher transmittance, sharper resolution, & better uniformity than HoloLens 2

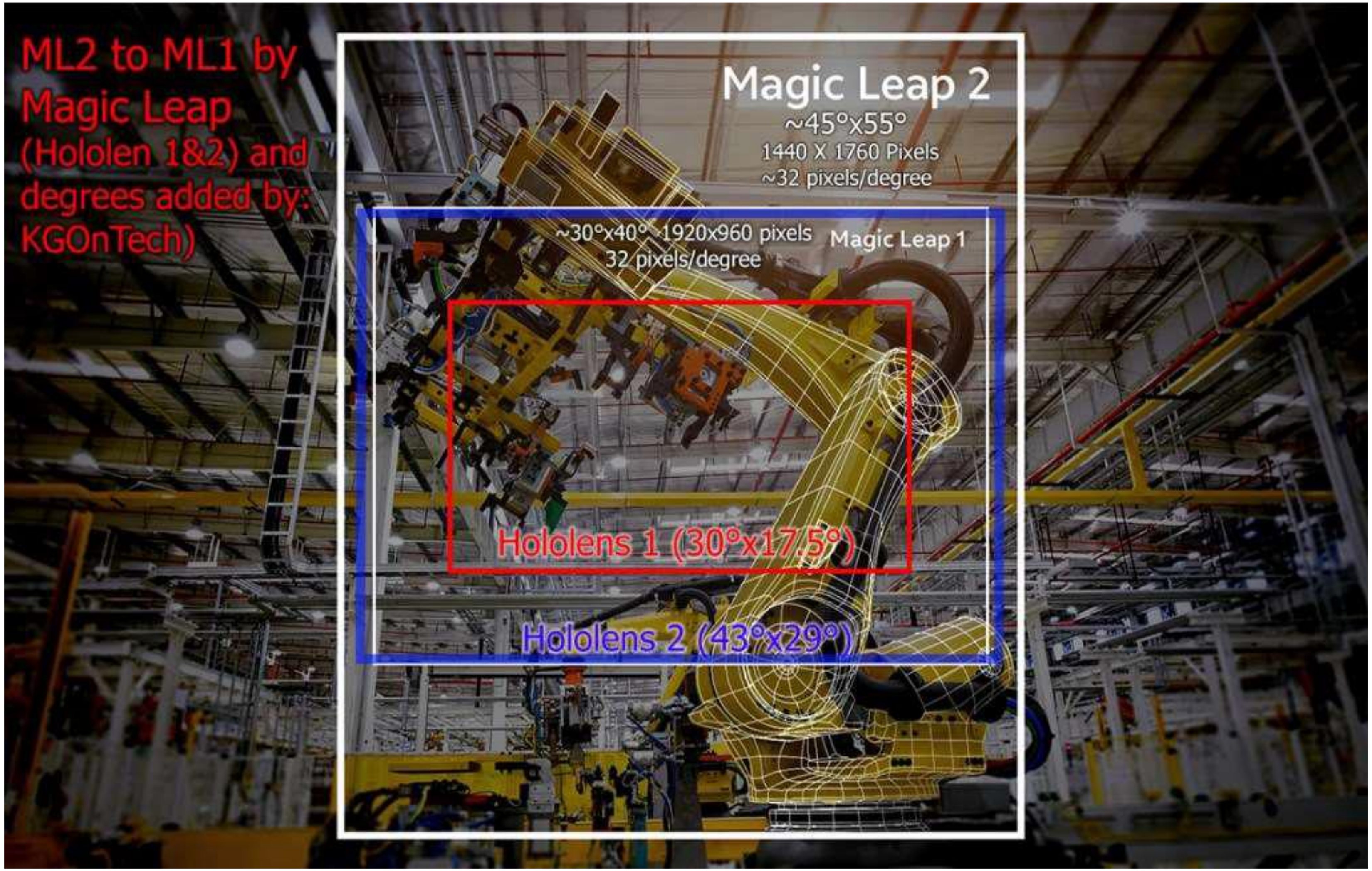
https://kguttag.com/2021/05/24/exclusive-lumus-maximus-2k-x-2k-per-eye-3000-nits-50-fov-with-though-the-optics-pictures/

Magic Leap 2: Architecture



Raontech developed LCoS panels for VR/AR. The viewing angle corresponding to a 100” large screen in VR display is 47°, limited by the panel size and imaging system.

Magic Leap 2: 70度 FOV



Ambient Contrast Ratio (ACR)

Ambient illuminance (lux)		Display peak luminance (cd/m^2) 625	1000	2500
Indoor lighting	200	250:1	400:1	1000:1
Cloudy day	2000 ≀	25:1	40:1	100:1
Full daylight	20,000	3.5:1	4.9:1	10.8:1
Direct sunlight	100,000	1.5:1	1.8:1	3.0:1

ACR < 5:1
→ Safety alert

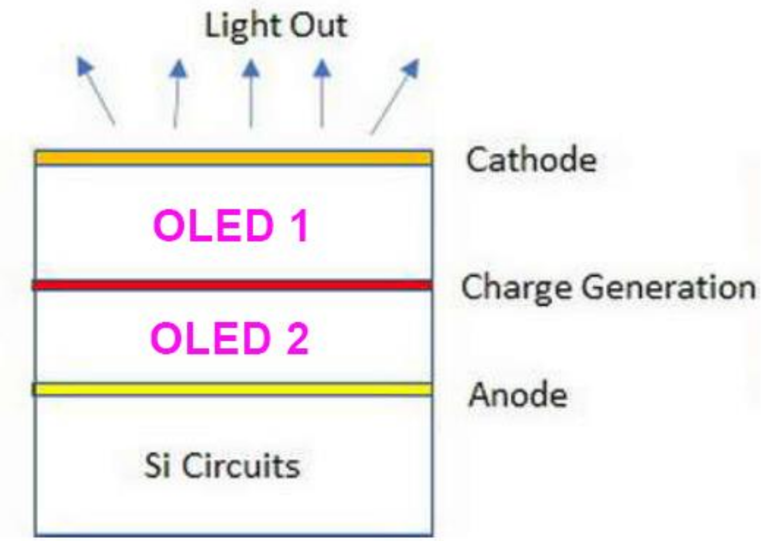
AR Challenge: Power Consumption

For a waveguide-based AR display using μLED as display source. Let us assume the waveguiding efficiency is 10%, transmittance to the ambient light is 50%, and the exit pupil expander has 4X extension in eye-box along both directions. If we want to get ACR=5:1 at outdoor ambient whose luminance=3000 nits. What is the required output brightness at the μLED microdisplay?

$$\boxed{ACR = \frac{L_{\text{on}} + L_{\text{ambient}} \cdot T}{L_{\text{off}} + L_{\text{ambient}} \cdot T}}$$

1. The waveguide has a transmittance η=50%
2. Outdoor ambient: 3000 nits → ACR= (x+3000x0.5)/(3000x0.5)= 5
   → x=6000 nits
3. The luminance at eye-box is 6,000 nits
4. Lightguide efficiency is 10% and eye pupil expansion is 16x
5. The luminance at microdisplay= (6000 nits x 16) ÷10% = 0.96M nits
6. Power consumption?

Kopin 1.3” 2.6Kx2.6K Duo-Stack μOLED



Green OLED:
Pixel pitch ~15.5 μm
Luminance: >35K nits
CR: 10,000:1
FoV: 90
Lifetime ↑ 3X

Panasonic HMD

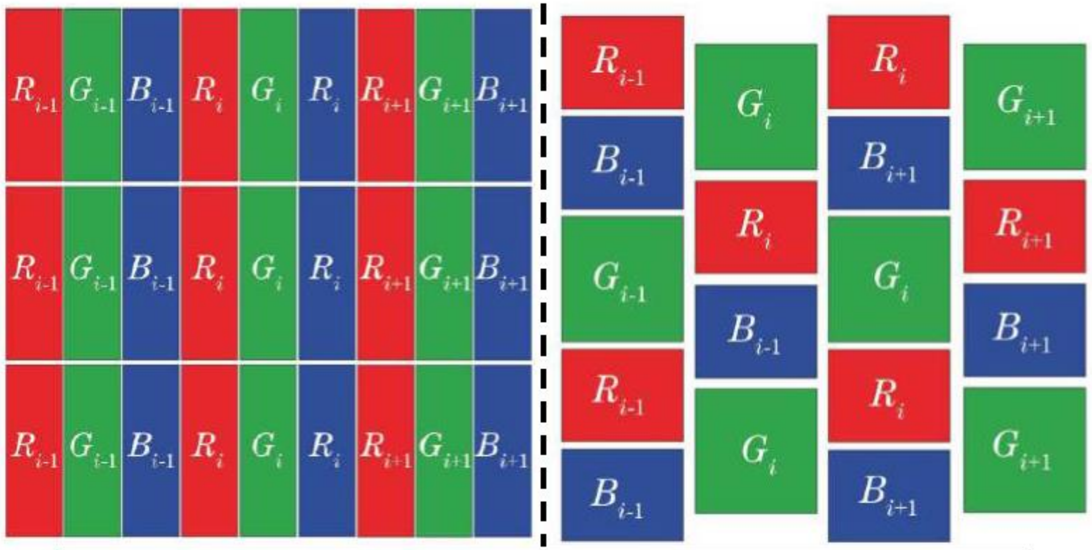
Micro-LED for AR: Single Color

JBD 0.13” VGA: Green color

1. Monochrome→ 4 μm pitch, 2M nits, but need 3 panels & pixel registration
2. Single RGB micro-LED panel preferred

PlayNitride 4536-PPI RGB μLED Panel

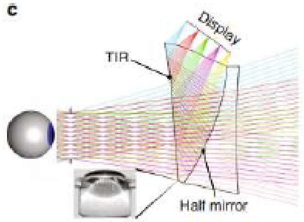
Regular stripe pixels | Sub-Pixel Rendering

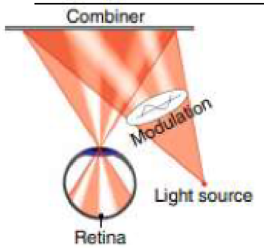


0.49" panel: 1920x1080 → 4536 PPI
Pixel pitch 5.6 μm; Pixel size: 2.5 μm
Quantum-dot color conversion
Sub-Pixel Rendering
@ 2022 Touch Taiwan & Display Week

Credit: Dr. Lynch Wu (PlayNitride)

AR Optics: Overview





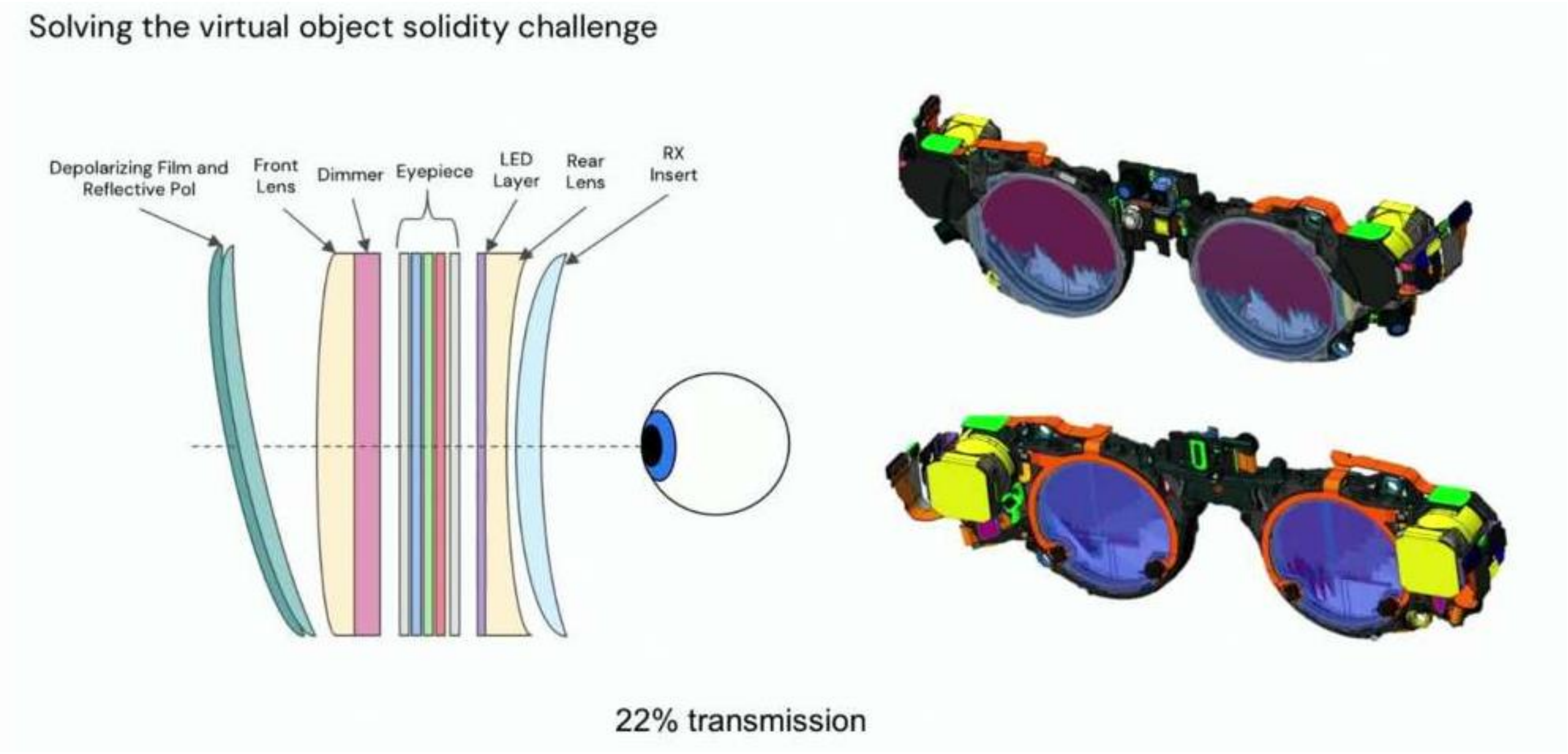
	Combiner efficiency	FoV (diagonal)	Eyebox	Form factor
Geometric optics (Freeform optics)	~4000 nit/lm	50°–120°	~8 mm	Large
Maxwellian-type (Maxwellian, Holographic)	Pupil st. ~50K nit/lm Pupil dup. ~3K nit/lm	~100°	2–4 mm (single view) ~8 mm (pupil st./dup.)	Small
Diffractive waveguide	50–200 nit/lm	~50°	~15 mm	Medium (multilayer)
Achromatic waveguide (Partial mirrors)	650–1000 nit/lm (2D EPE) 1500–3000 nit/lm (1D EPE)	~60°	~15 mm	Small

10X

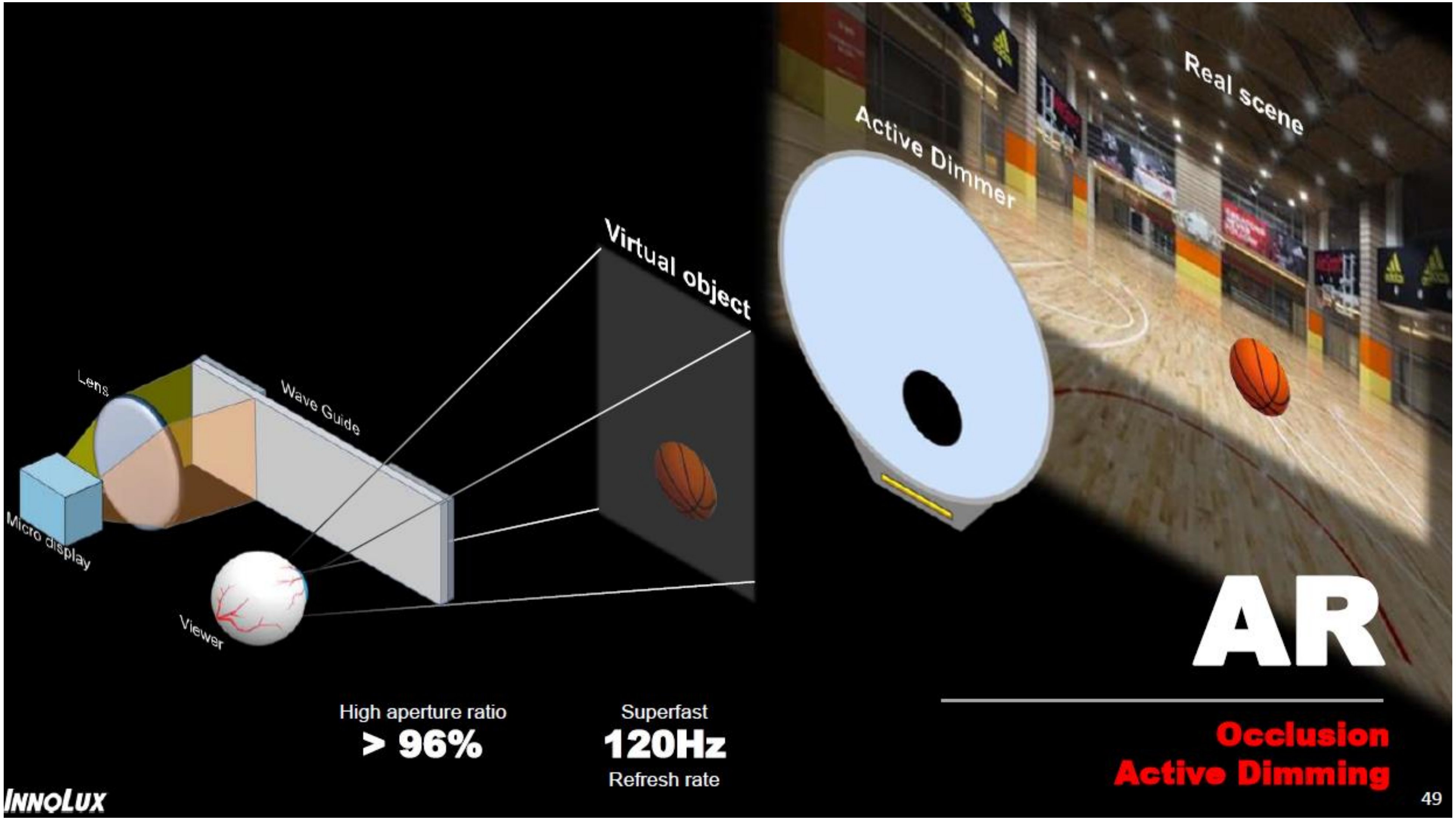
50X

Geometric: balanced performance, but **form factor** needs improvement
Waveguide: Large eyebox, but **efficiency**, **FoV** and **uniformity** need improvement
Maxwellian-type: **ALL** great except tiny **eyebox**→ ***Pupil steering!***

Magic Leap 2: Segmented Dimmer



AR Occlusion Active Dimming



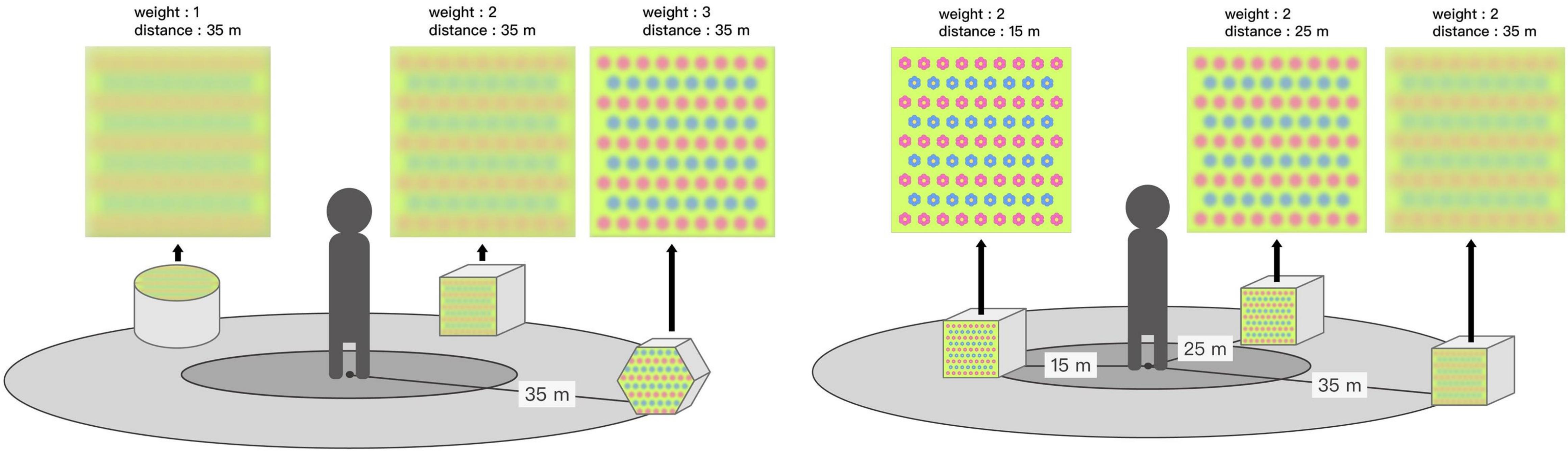
4.Our research in AR/VR

Cybersickness

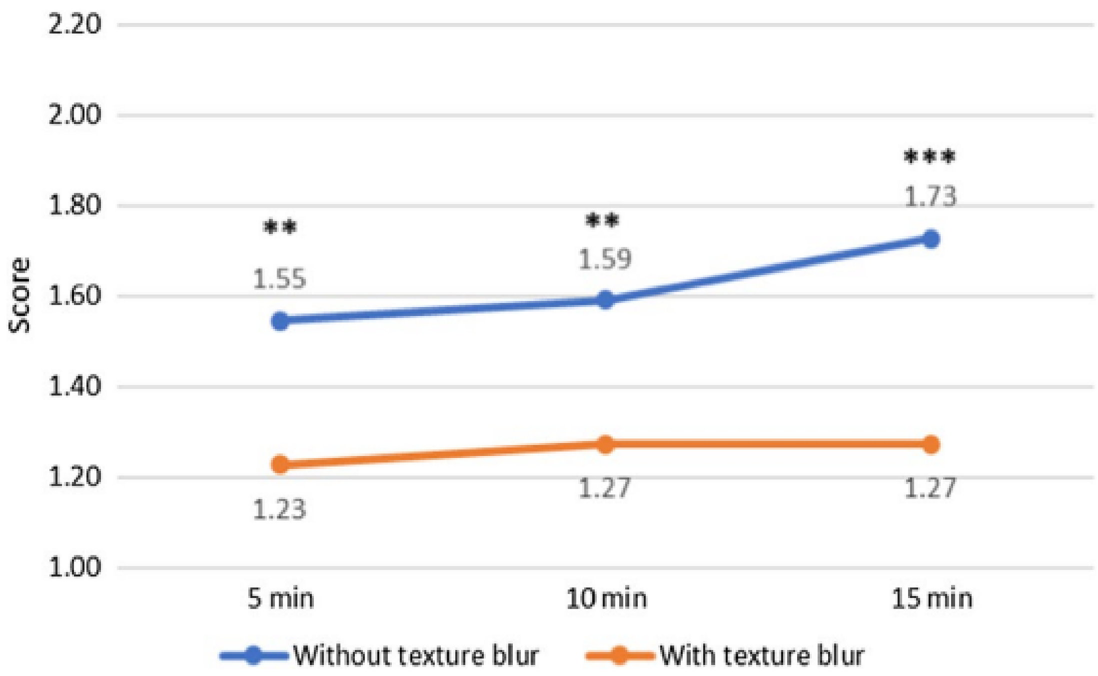
Nausea	Oculomotor	Disorientation
General Discomfort	General Discomfort	Difficulty focusing
Increased Salivation,	fatigue	Nausea
Sweating,	headache	Fullness of Head
Nausea,	eye strain	Blurred Vision
Difficulty Concentrating,	Difficulty focusing	Dizzy (eyes open)
Stomach Awareness	Difficulty concentrating,	Dizzy (eyes closed)
Burping	Blurred Vision	Vertigo

Texture blur in the virtual reality content

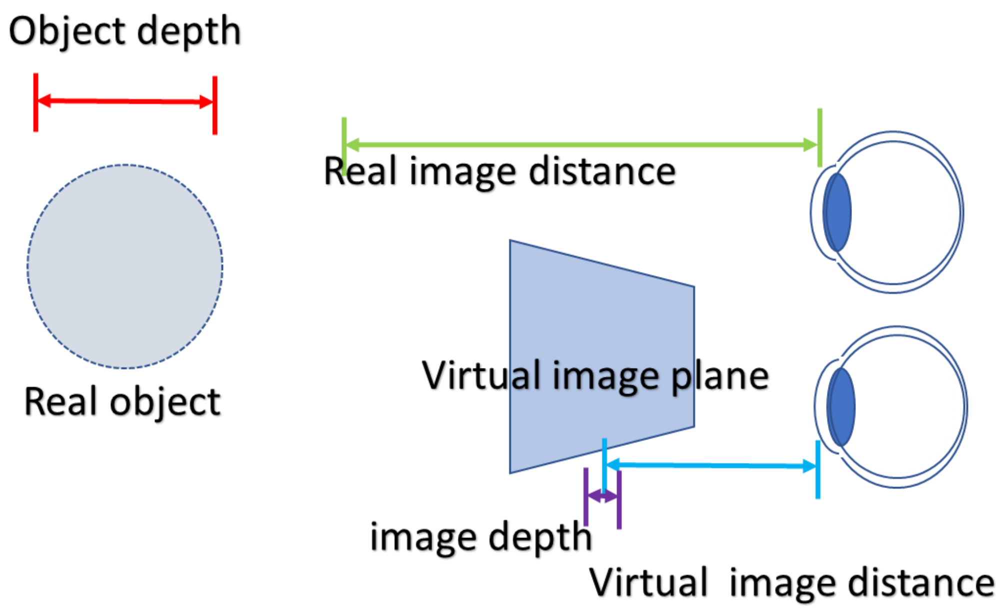
Texture Blur



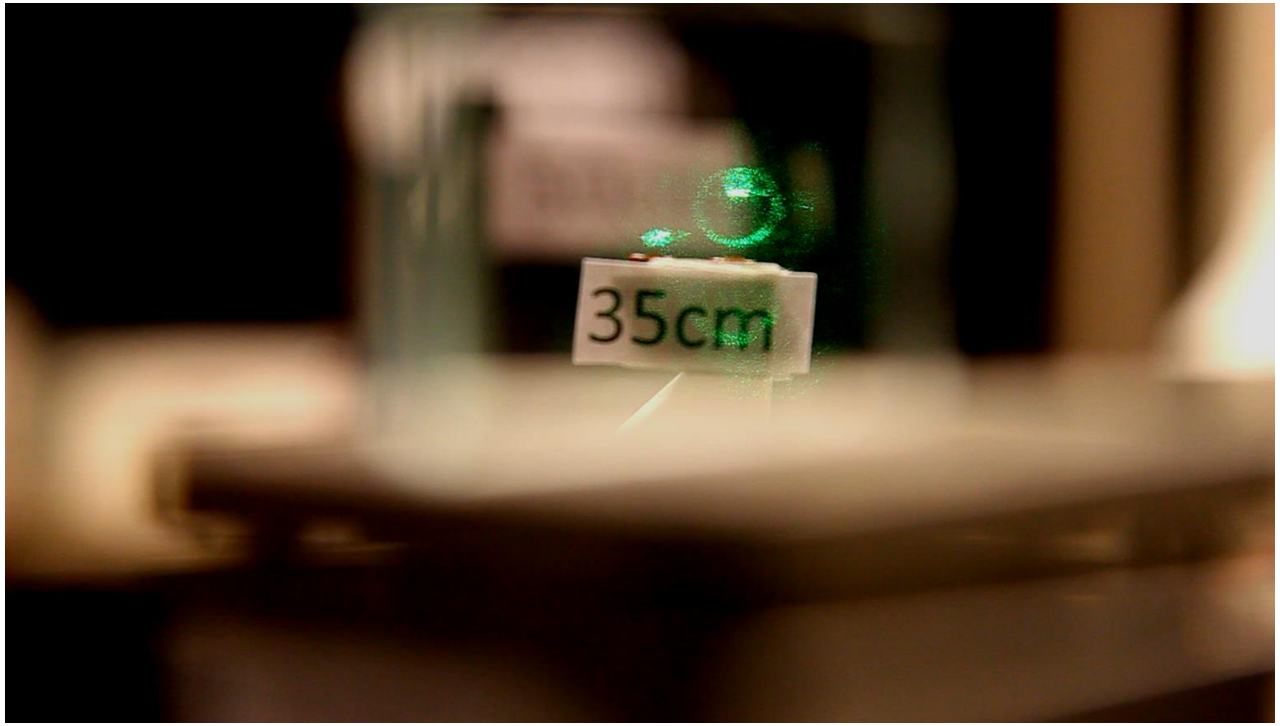
Texture blur in the virtual reality content



Holographic display for AR



Hyper reality AR issue



Conclusions & outlooks

1. VR
   - Compact, lightweight, & low power are new trends
   - Pancake lens: Reduce depth by 40% but decrease optical efficiency by 4x! Beam shaping & mini-LED can help.
   - FSC opens a new door for 60 PPD & high aperture ratio
   - Shifting from AMOLED to HDR AMLCD
2. AR
   - Display engines: LCOS/MEMS/ μOLED/μLED: who wins?
   - Waveguide: larger eyebox, but FOV is limited to 78°
   - Compact & lightweight: glasses-like formfactor
   - Smart dimmer: ↓power consumption & occlusion!
   - Cost, cost, cost!

Thank you for your attention