Light Field Displays: From Current Developments to the Next Generation

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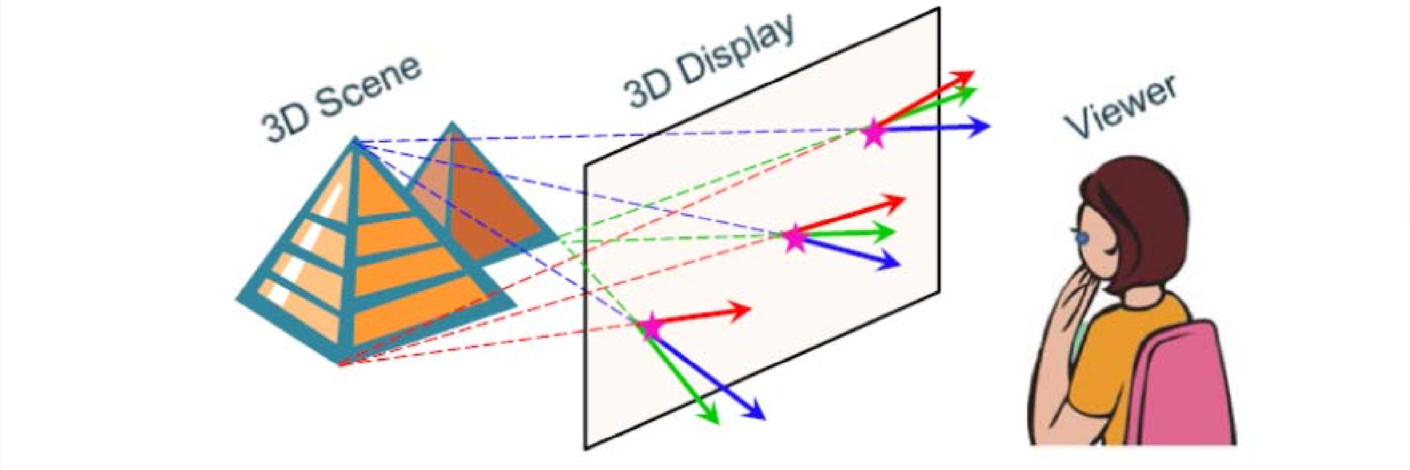
SMFoLD Workshop, October 2017

What is a Light Field Display?

- Essentially, the best reproduction of the radiance eyes encounter normally



Geng, J. (2013). Three-Dimensional display technologies. Advances in Optics and Photonics, 5(2), 131.

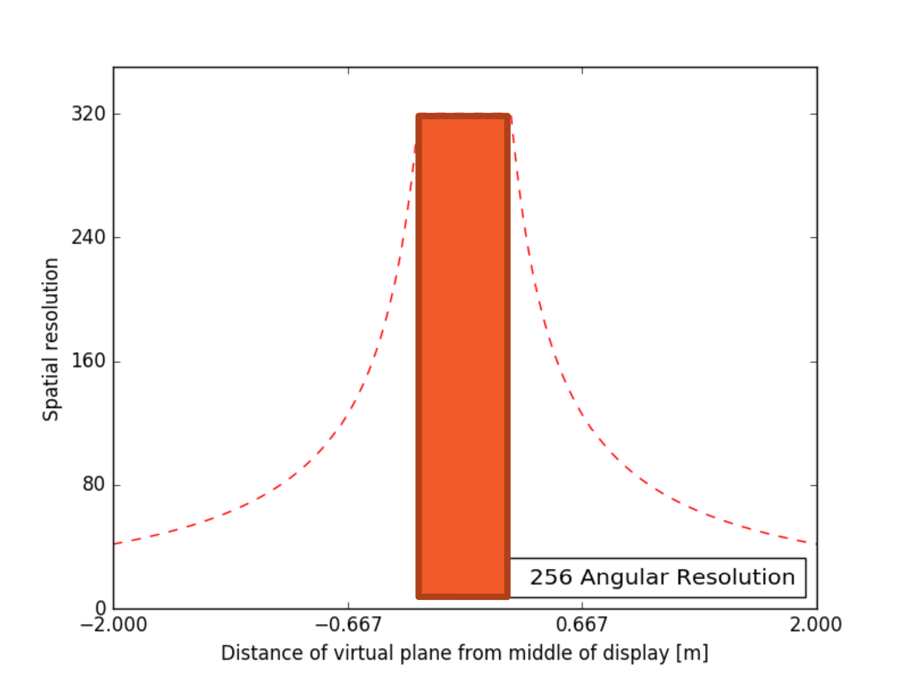
What is a Light Field Display?

- Perceptual cues provided by light field vs. 2D display
  - Accommodation
  - Convergence
  - Motion Parallax
  - Binocular disparity

Key Concept: Resolution at Depth

- Depth of field of display – range of depths that can be reproduced at maximum resolution

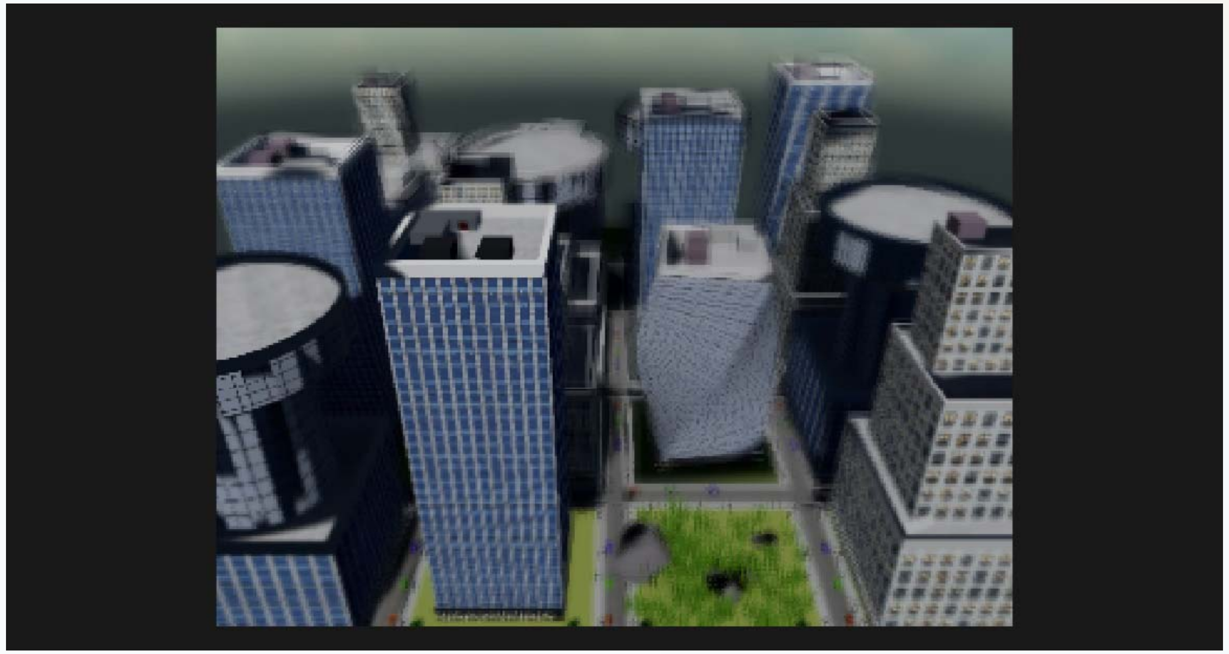
320x240 3D display, 90° field of view



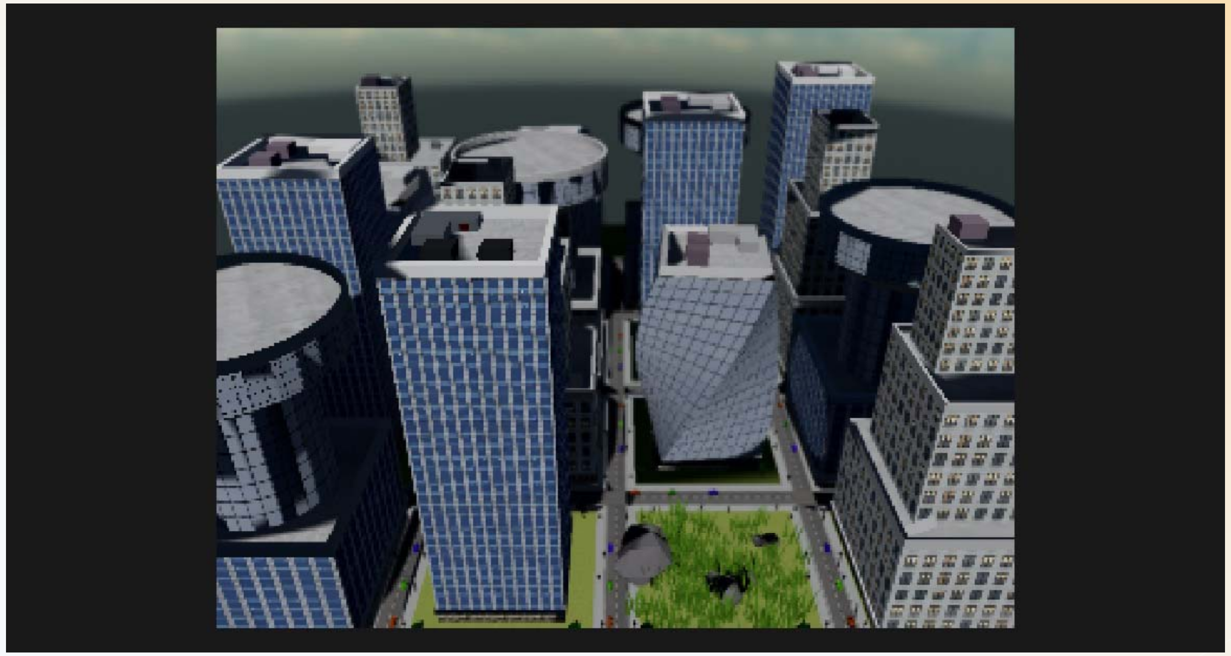
Matthias Zwicker, Wojciech Matusik, Fredo Durand, and Hanspeter Pfister. Antialiasing for Automultiscopic 3D Displays. Eurographics Symposium on Rendering 2006.

Key Concept: Resolution at Depth

- Good effective depth resolution requires high angular resolution
  - Number of views in current displays give very small DoF
  - Worse in practice due to optical imperfections, etc.



128x128 views

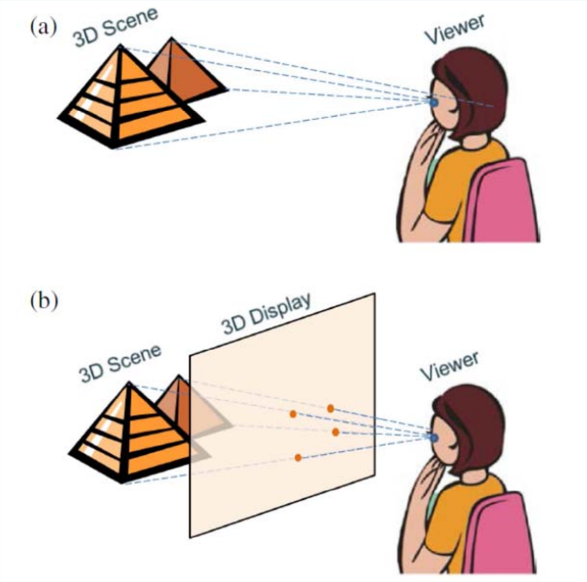


512x512 views

(simulated 320x240 3D display, 90° field of view, observer @ 0.6m)

Ideal 3D Display

- Banks *et al.* concept of Turing Test for 3D Displays:
  - "A person views input that comes either from a direct view of the real world or from a simulated view of that world presented on a display. He or she has to decide: real or display?"
- Geng: Perfect display should function as "window to the world"



Banks, M. S., Hoffman, D. M., Kim, J., & Wetzstein, G. (2016). 3D Displays. Annual Review of Vision Science, 2(1), 397–435.

Geng, J. (2013). Three-Dimensional display technologies. Advances in Optics and Photonics, 5(2), 131.

Ideal 3D Display

- No displays meet the ideal criteria… YET
- Main shortcomings:
  - Objects become blurred at distance
  - Lack of correct focus cues
  - Small Field of View (FOV)
  - Spatial resolution not “retina”
  - Various artifacts… lots to optimize

Review of Light Field Displays

AVALON HOLOGRAPHICS

Overview

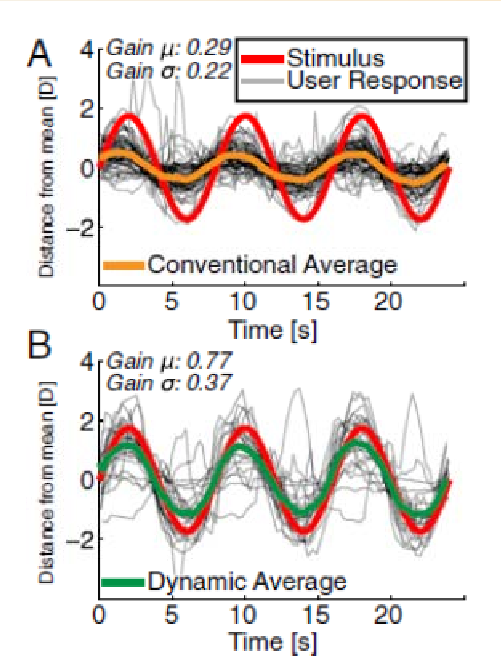
- Group Display vs. Personal Head-Mounted
- Refractive (Integral Imaging)
- Diffractive
- Temporally-multiplexed
- Stacked Displays
- Projection based

Head-Mounted vs. Stand-Alone

- Perceptual cues provided by current VR HMD (similar to FoLD):
  - ~~Accommodation~~
  - Convergence
  - Motion Parallax
  - Binocular disparity
- Accommodation-convergence conflict
  - Are light fields truly needed for HMD?
  - Maybe, maybe not…

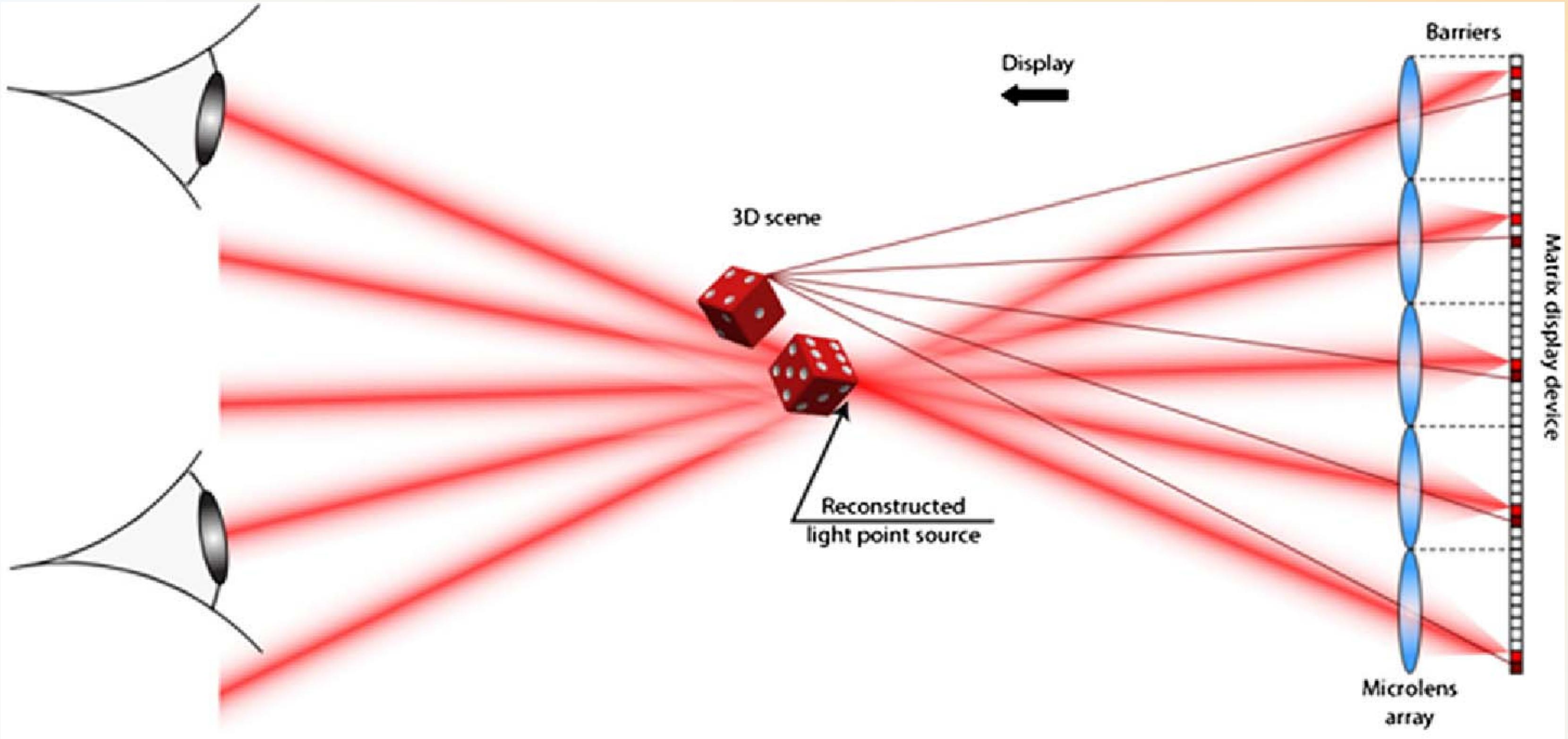
Head-Mounted vs. Stand-Alone

- Recently shown: Accommodation can be driven by adaptive focus displays
- AC-conflict can be eliminated, shown experimentally
- Still may not provide focus cues correctly



(2017) Optimizing virtual reality for all users through gaze-contingent and adaptive focus displays
Nitish Padmanaban, Robert Konrad, Tal Stramer, Emily A. Cooper, and Gordon Wetzstein

Integral Imaging (Refractive)



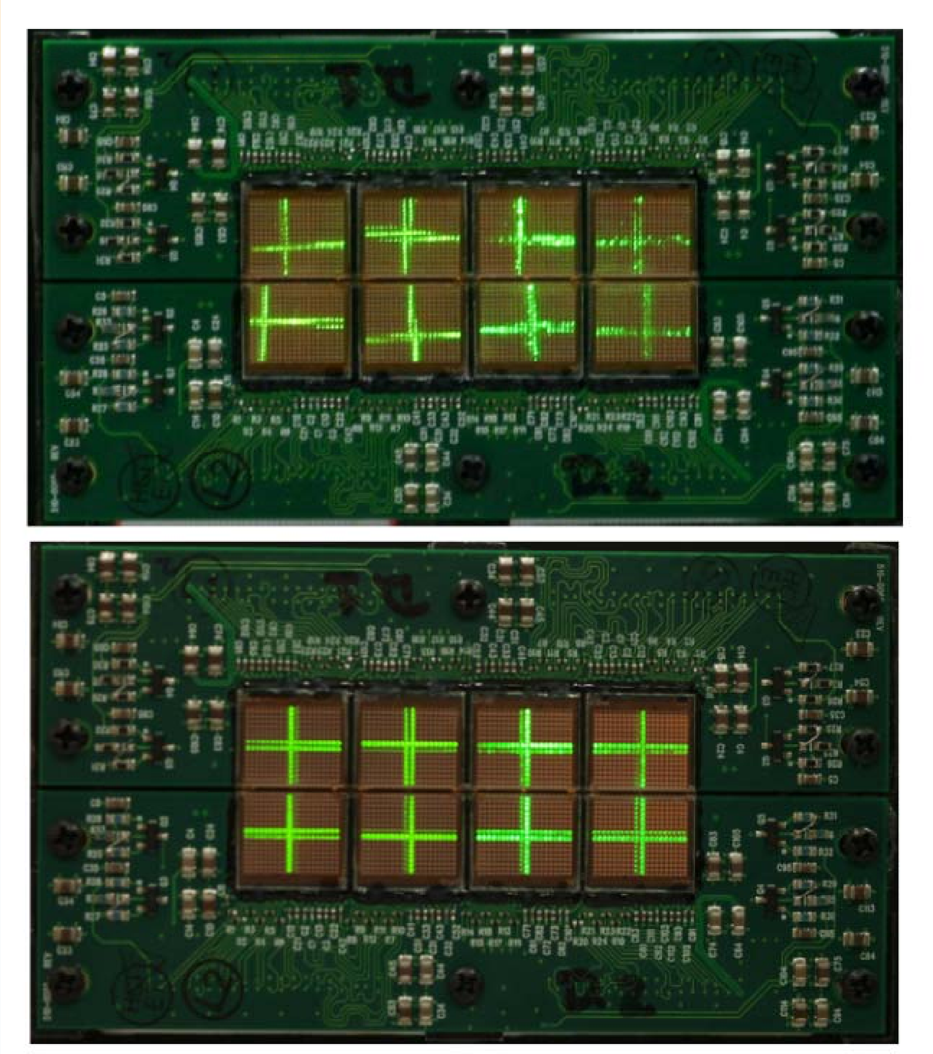
Advances in three-dimensional integral imaging: sensing, display, and applications [Invited]Xiao Xiao, Bahram Javidi, Manuel Martinez-Corral, and Adrian Stern Applied Optics Vol. 52, Issue 4, pp. 546-560 (2013)

Integral Imaging (Refractive)

- Inherent spatial-angular resolution trade-off
  - Larger lens -> more pixels underneath
- Limited field of view (limits of lenses)
  - Multiple lenses can increase to ~90°
- Difficult to achieve large depth of field;
  - Quickly hit pixel size limit
- Collimation can effect resolution at depth

Integral Imaging (Refractive)

- Angular calibration challenge:
  - Difficult to make ideal lens
  - Imperfections further degrade effective depth resolution of display
  - Calibration can correct, but can this scale to larger and larger direction pixel numbers?



Zahir Y. Alpaslan, Hussein S. El-Ghoroury, "Small form factor full parallax tiled light field display", Proc. SPIE 9391, Stereoscopic Displays and Applications XXVI, 93910E (17 March 2015)

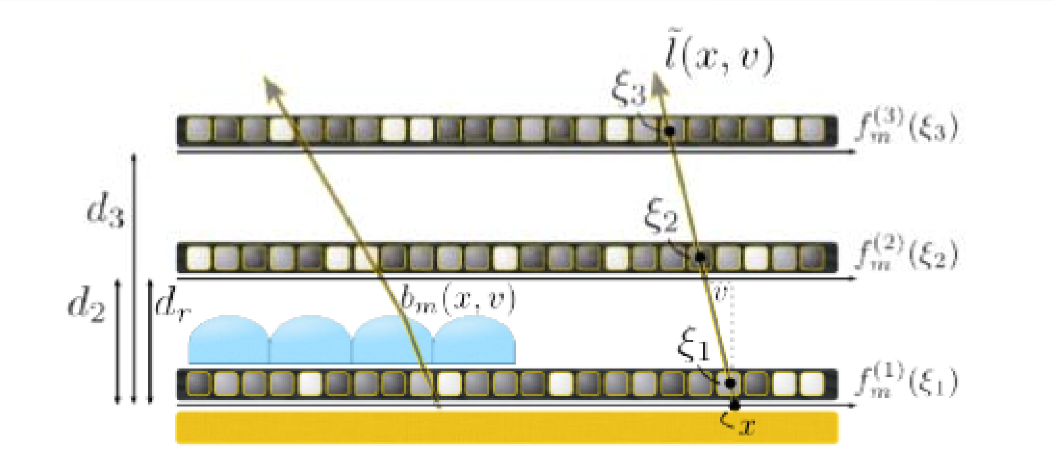
Integral Imaging (Near-Eye Display)

- Angular-space trade-off flips
- Limited FOV, due to screen size (micro display)
  - Require larger displays with greater pixel density to compare with current VR resolution
- Some blur cues, reduces AC-conflict
- Does not require optics of conventional VR

Near-Eye Light Field Displays. Douglas Lanman, David Luebke. ACM Transactions on Graphics (SIGGRAPH Asia 2013 Proceedings), Hong Kong (November 2013).

Multi-Layered Approach

- Stacked high speed, LCD attenuation layers with direction backlight (integral imaging based)
  - Based on superposition of light, rather than direct representation of each ray (more rays per pixel, thus compressive)
  - Temporal modulation and attenutation used



G. Wetzstein, D. Lanman, M. Hirsch, R. Raskar. Tensor Displays: Compressive Light Field Synthesis using Multilayer Displays with Directional Backlighting. Proc. of SIGGRAPH 2012 (ACM Transactions on Graphics 31, 4), 2012

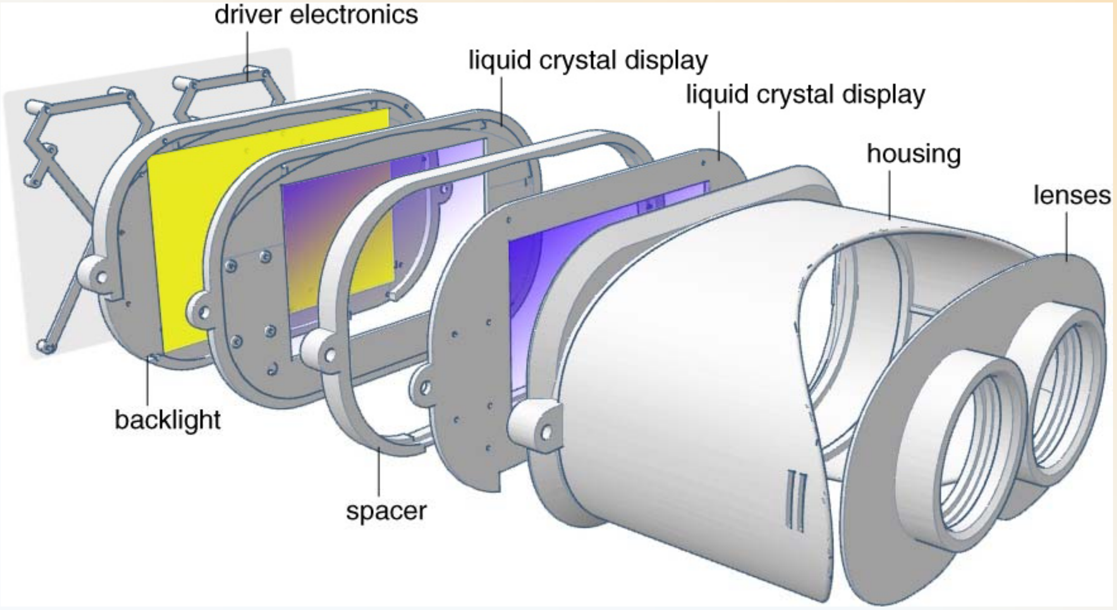
Multi-Layered Approach

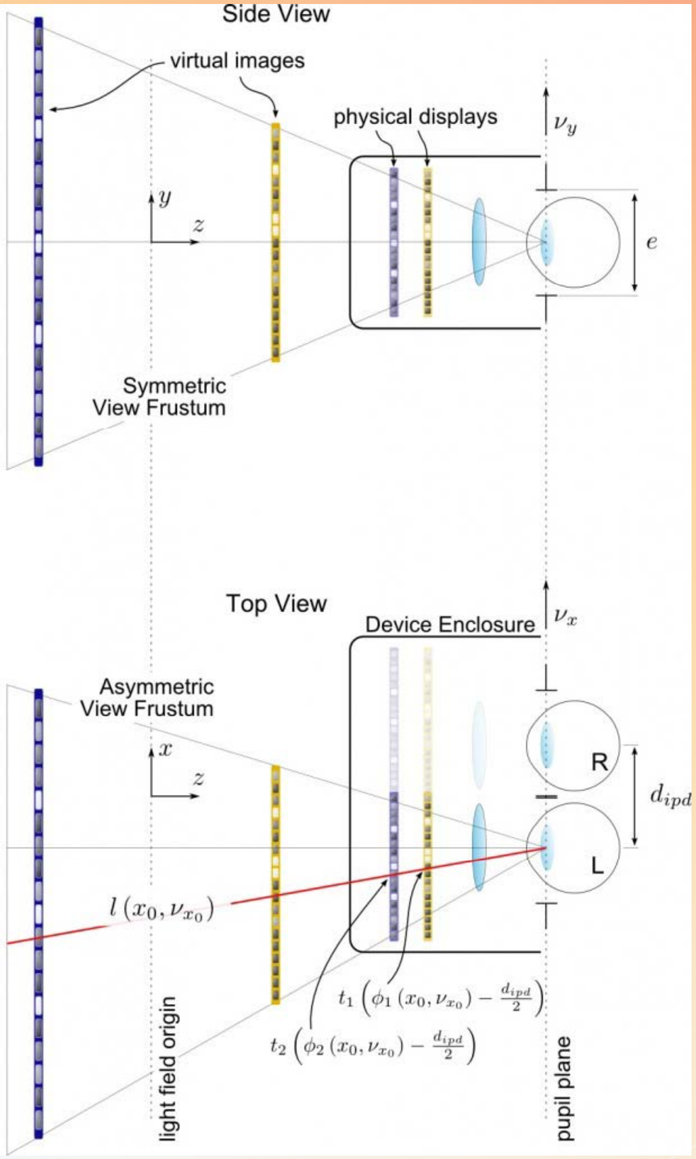
- Can overcome spatial-angular trade-off
  - Scaling not limited by pixel size
  - Additional layers provide
- FOV still limited by directional backlight layer
- Require complex optimization to produce image
  - Not suitable for interactive content.
  - May be OK for static content

G. Wetzstein, D. Lanman, M. Hirsch, R. Raskar. Tensor Displays: Compressive Light Field Synthesis using Multilayer Displays with Directional Backlighting. Proc. of SIGGRAPH 2012 (ACM Transactions on Graphics 31, 4), 2012

Multi-Layered Approach

- Near-eye Display based on this approach
- Blur cues provided
- Requires less expensive optimization computation
  - Still has latency issues

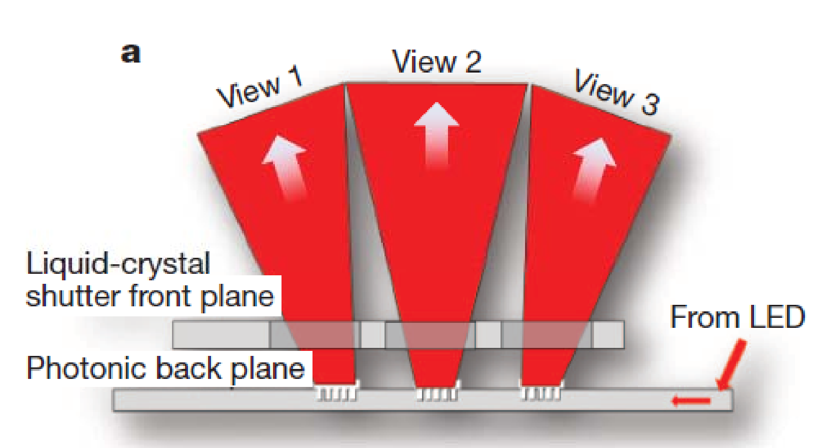


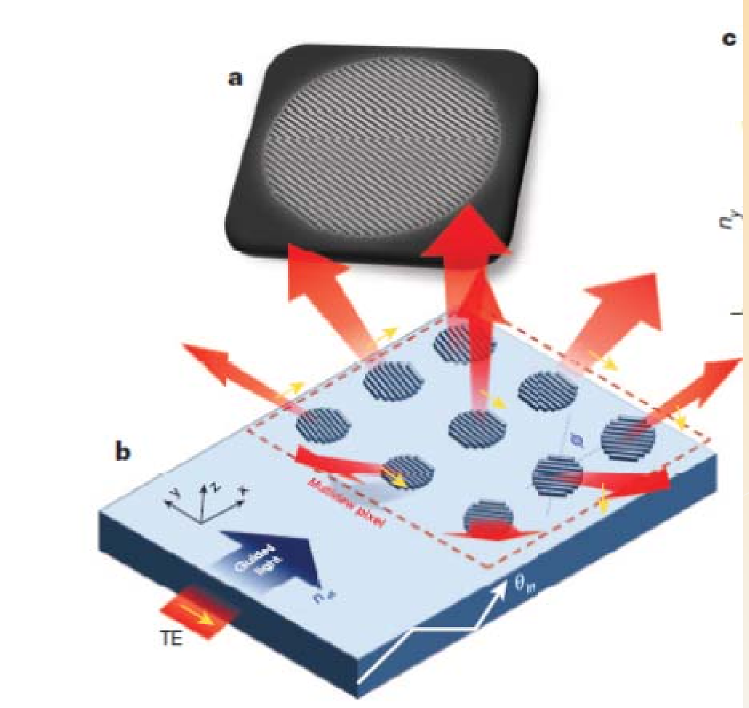


F. Huang, K. Chen, G. Wetzstein. "The Light Field Stereoscope: Immersive Computer Graphics via Factored Near-Eye Light Field Displays with Focus Cues", SIGGRAPH (Transactions on Graphics 33, 5), 2015.

Diffractive Approach

- Wavelength-scale diffraction gratings
- Advantage: Can direct light at each pixel at any direction
  - Design for large FOV or small eyebox, arbitrary light distribution
- Advantage: Diffractive backlight allows switch
  - 2D-3D mode possible
- Limitation:
  - Size (diffractive slits must be on order of wavelength of light), how to scale to smaller pixels?
  - Large FWHM would not work well with higher view density





Fattal, D., Peng, Z., Tran, T., Vo, S., Fiorentino, M., Brug, J., & Beausoleil, R. G. (2013). A multi-directional backlight for a wide-angle, glasses-free 3D display. Nature ***495,*** *348-351 (March 2013).*

Volumetric Display Approach

- Additive layers (vs. multiplicative layers)
- Interesting, useful effect
  - Appear quite useful in medical visualization use case or other 3D field visualizations
- Will fail Turing Test in many cases
  - Cannot support occlusion, specular highlights, other effects

Temporal Multiplexing Approach

- Avoid spatial-angular trade-off
- One approach:
  - Dynamic system of multiple lenses
  - Horizontal-only parallax;
  - 40-90 views, ~50° field of view

- Mechanical movement would likely present calibration and longevity issues…

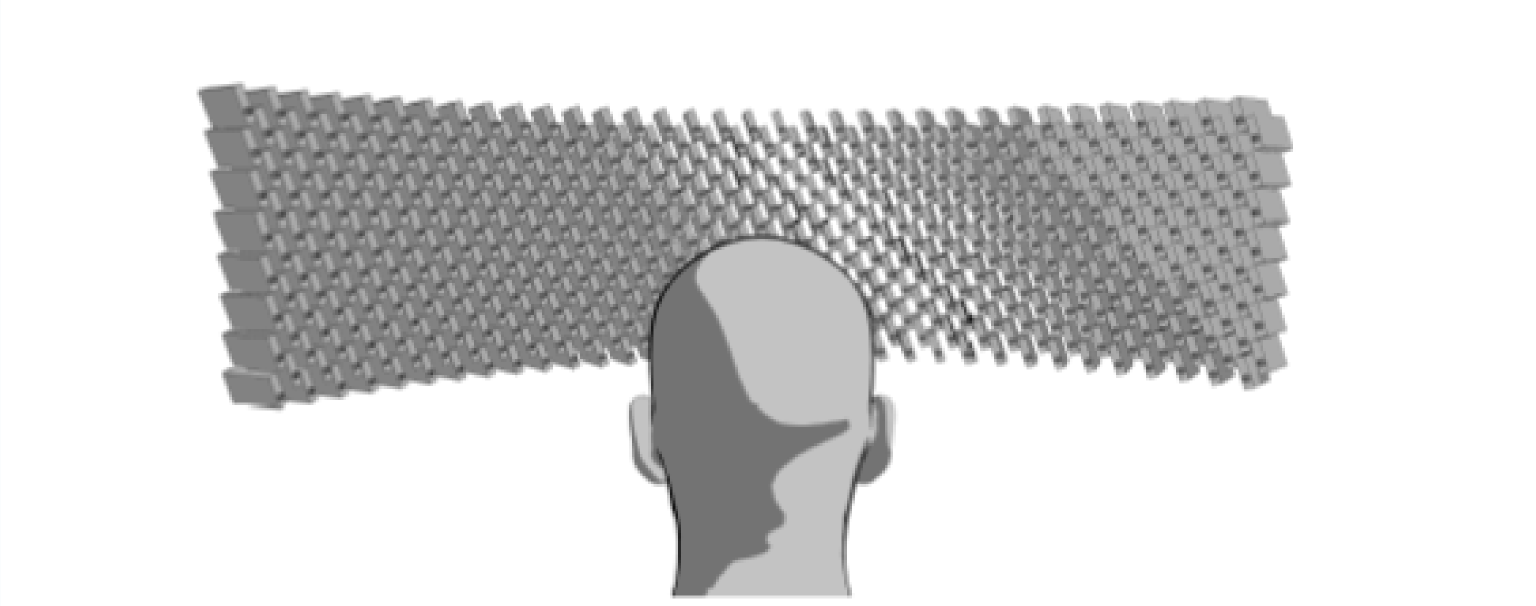
“The solution to glasses-free high-resolution 3D Displays” White Paper, Zeckotek 3D Display.

Projection-based Approach

- Large FOV can be achieved (up to 180°)
- Light distribution manipulated easily by altering projector positioning
  - Flexibility to design group view type display (Holografika) or fixed observer position display (Third Dimension Technology)
- Existing seem to be limited to horizontal-only parallax
  - Can achieve >80 views
  - Still requires large data to drive display

Projection-based Approach

- Could scale to full parallax, bandwidth an issue
- Quality scaling limited by projector size



Jurik, J., Jones, A., Bolas, M., & Debevec, P. (2011). Prototyping a light field display involving direct observation of a video projector array. IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops.

Summary of Existing Displays

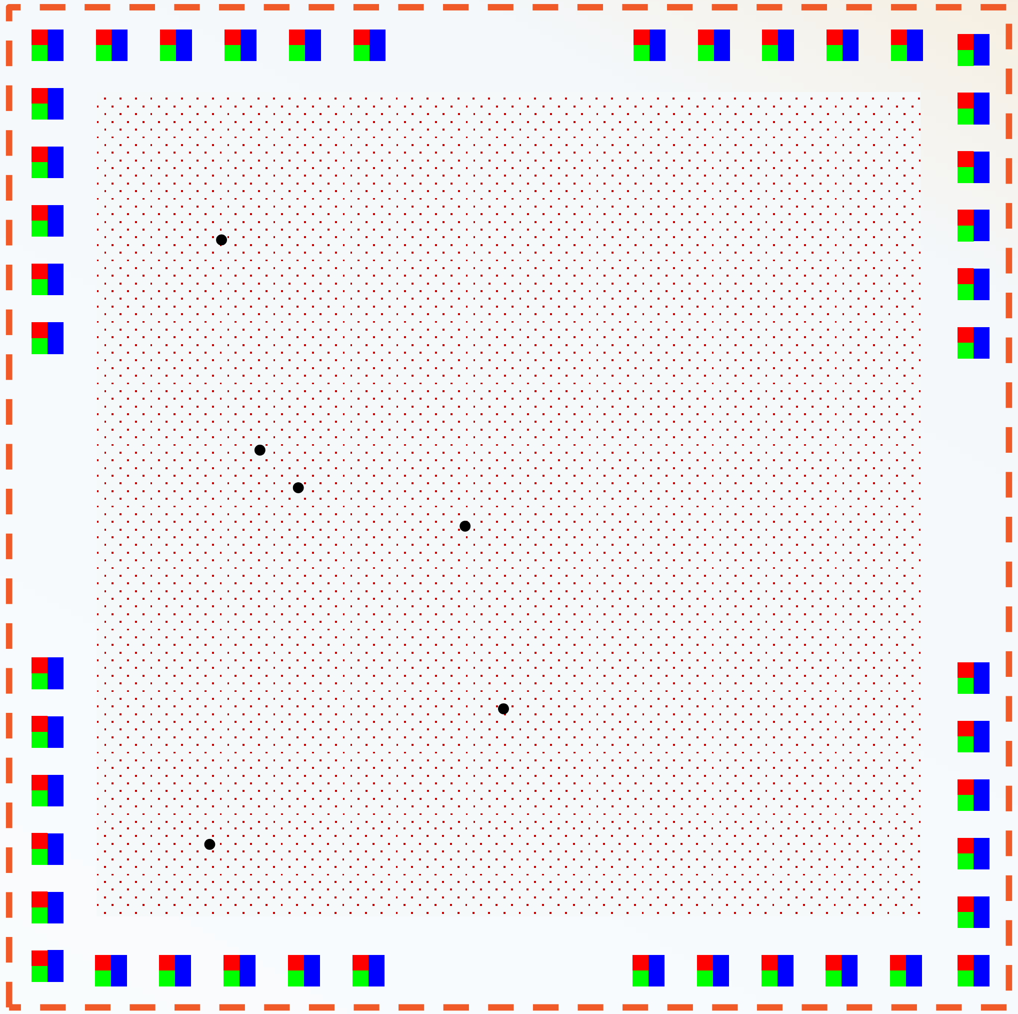
- Spatial vs. angular resolution trade-off a problem
- Still too low angular resolution.
- Fail 3D Display Turing Test on simple grounds:
  - Lack of focus cues
  - Lack of effective depth of field

Next Generation Displays

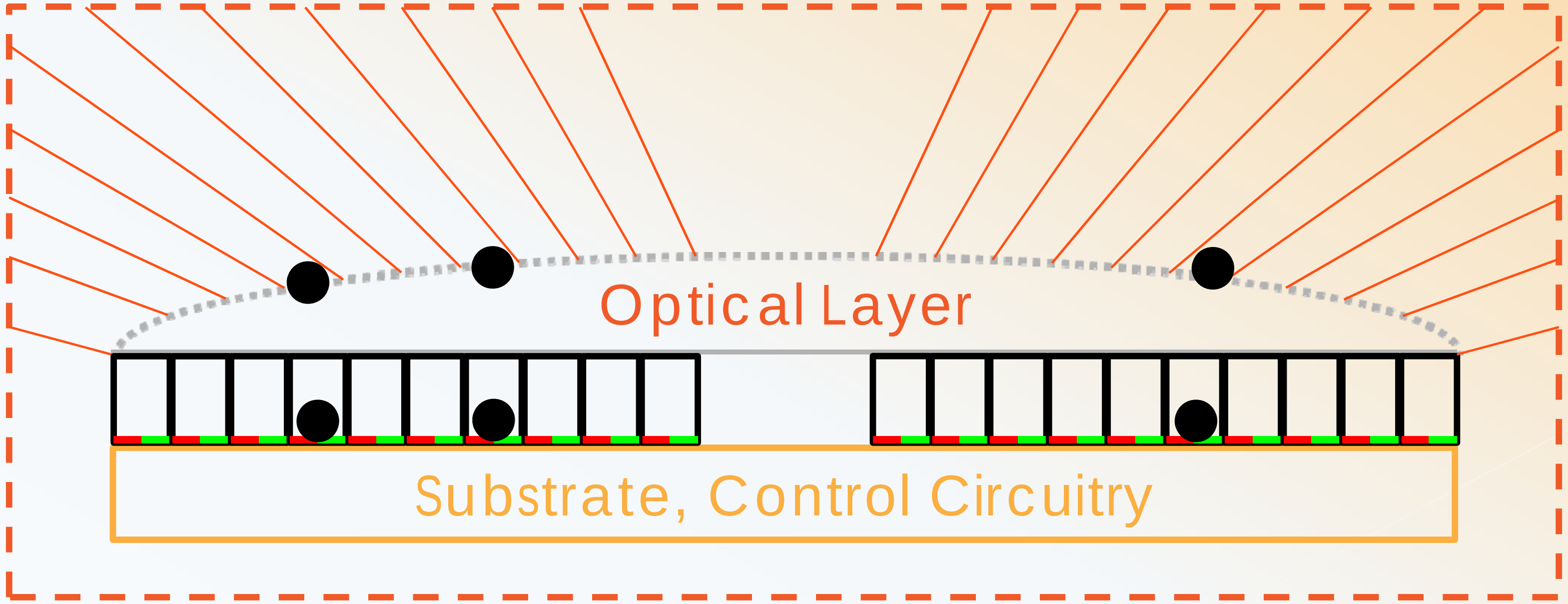
Core Display Design: Targets for Future

- Denser pixels on larger control substrates (< 5 micron, scale to > 24 inch panels)
- Microdisplays already close (single digit microns), need to scale to larger substrates
- Larger field of view (~150 degrees)

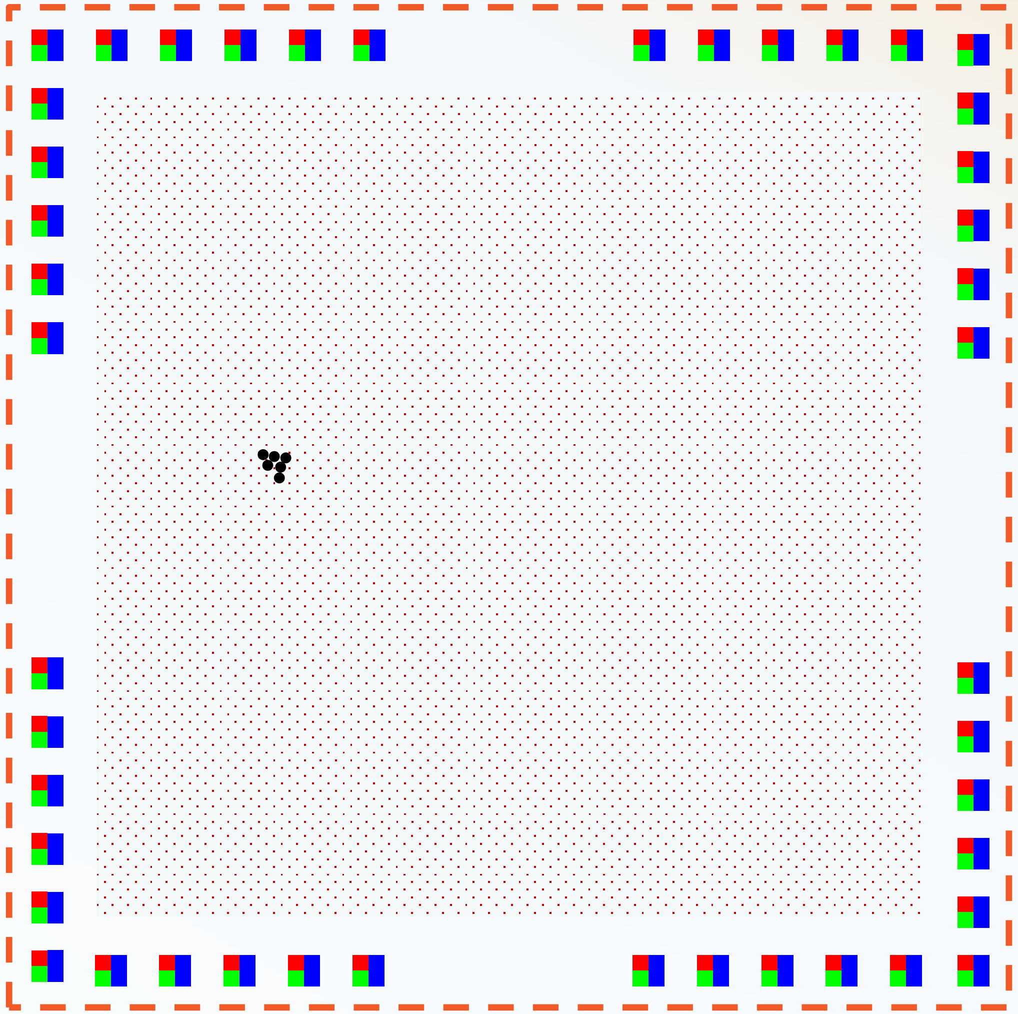
Yield and Fault Tolerance



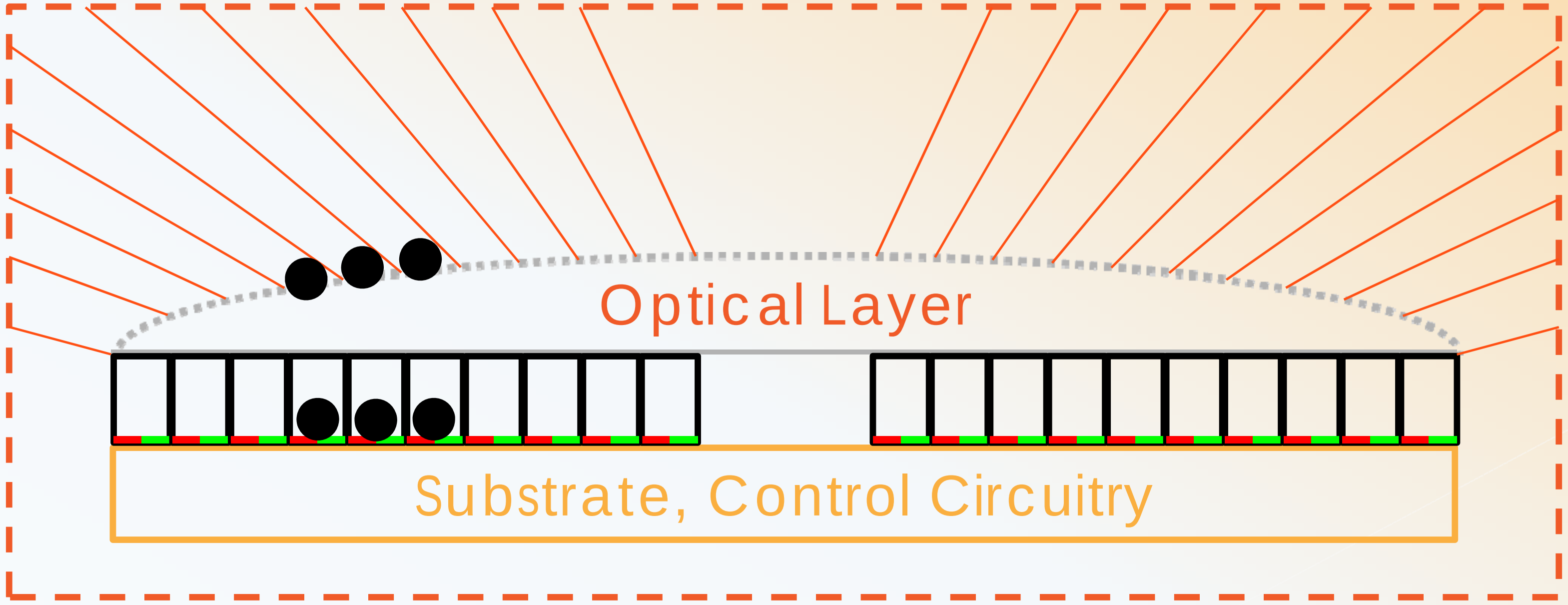
- Dead pixels only visible in small range of views
  - Multiple Views per eye
  - Multiple eyes per observer
  - Almost impossible to see single dead pixel
- Individual faults do not hurt yield



Yield and Fault Tolerance

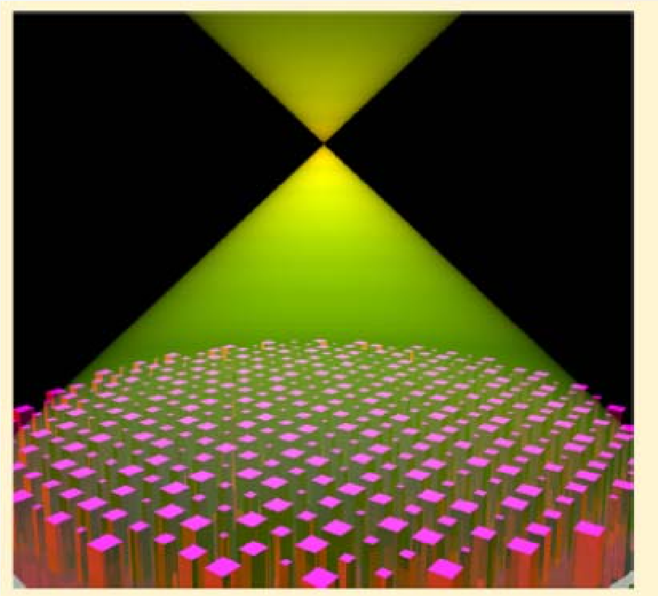


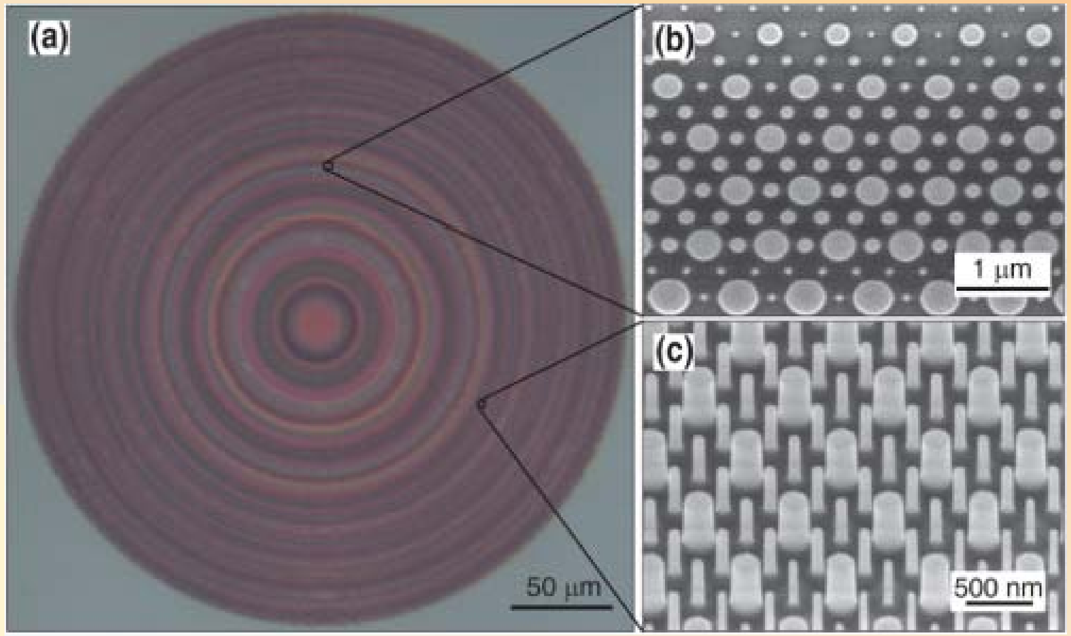
- Only fault clusters hurt yield
  - Lose 3 adjacent pixels, becomes visible



Optics: Challenges for the Next Generation

- High-performing optics (sub-degree widths)
- Smaller sizes for denser control of light
  - Tolerances important wrt calibration issues
- Promising work in nanoscale optics:
  - Cappasso group @ Harvard
  - Faraon group @ Caltech





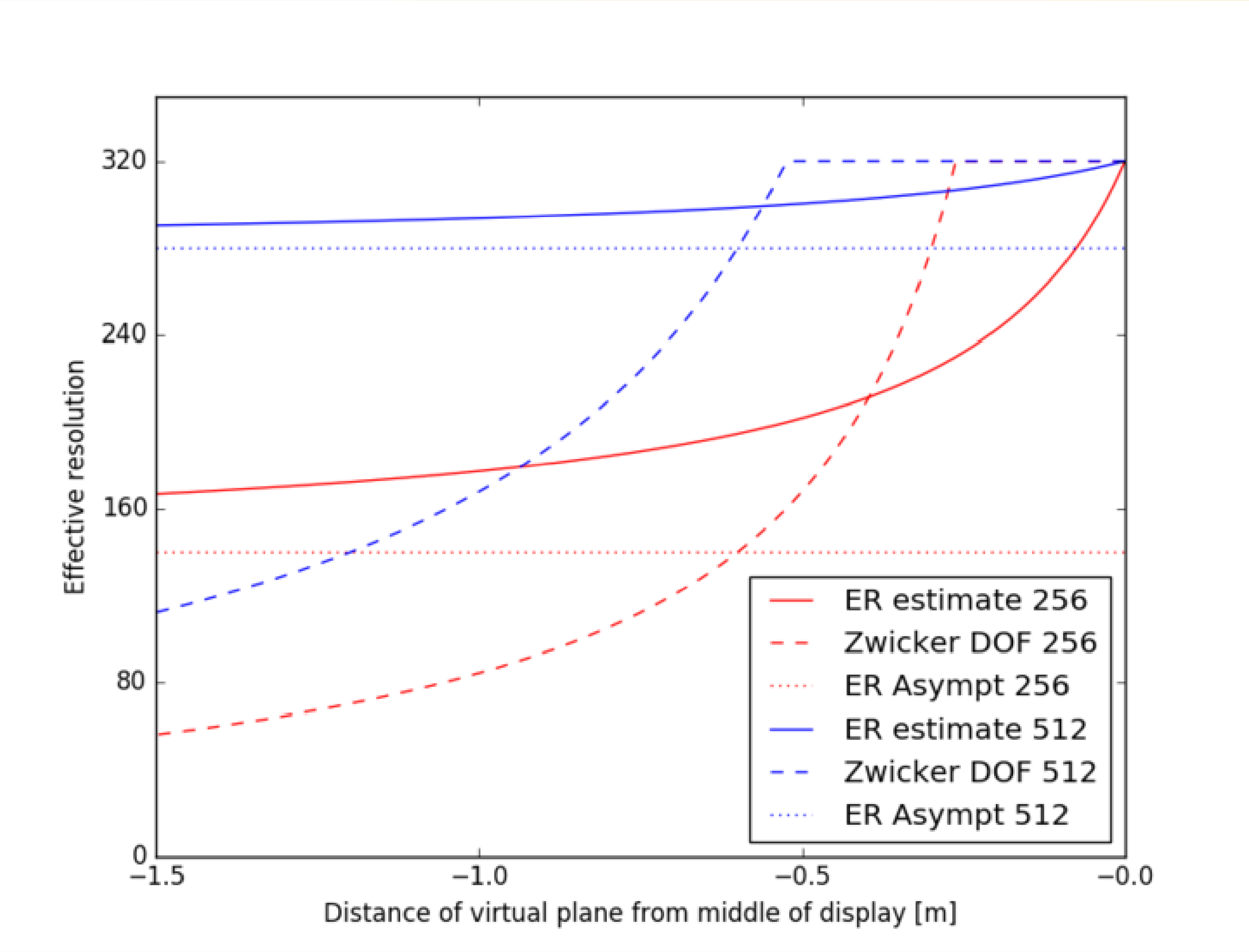
Theory of Asymptotic Effective Resolution at Depth

- DoF concept is observer-independent
  - Focus: light field representation, not what a particular observer may see
- Developed observer-based method to estimate resolution at depth
- Can calculate lower bound asymptotic resolution (AR):
- $AR = \dfrac{wN}{z_O 2 \tan(\frac{\theta}{2})}$

w – display width
N – views in one direction
Zo – observer distance from display
ϴ – field of view

Theory of Asymptotic Effective Resolution at Depth

3D Display: 60cmx48 cm, 320x240, 90 degree FOV, Observer @ 60cm.



Theory of Asymptotic Effective Resolution at Depth

- Implies there might be "enough" angular resolution given a target spatial resolution and FOV and an observer position:
  - $N = \frac{M\ Z_O \tan(\frac{\theta}{2})}{w}$
  - Gives straight line plot of resolution with depth
  - Effective bound will degrade if observer is further
- Must be verified in practice, on real displays

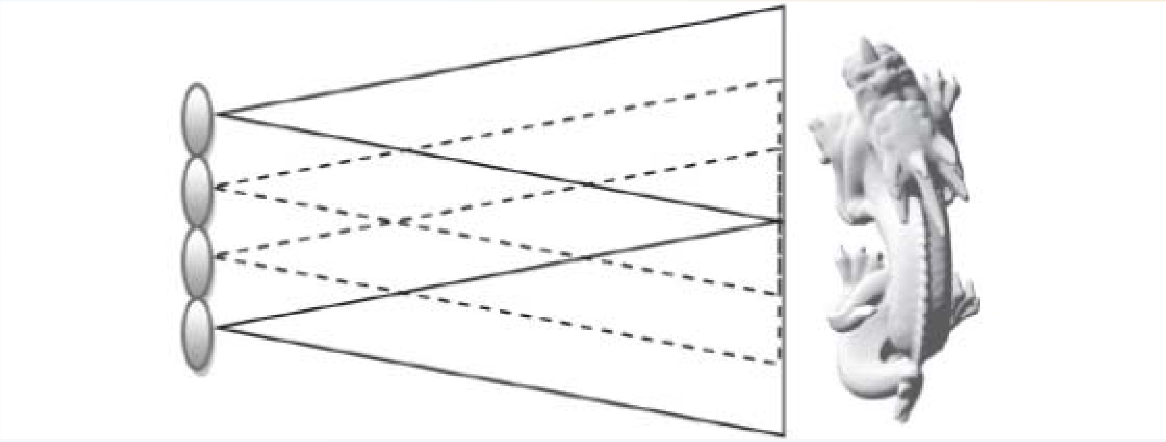
Bandwidth: Challenges for the Next Generation

- Massive bandwidth required. How to drive to display for both interactive (rendering) live (video) and static content (videos)?
- Transform-based approaches trouble for interactive applications
- Entire light field (Tb) must exist a priori, truly only need the light field at the display itself, before pixels

Graziosi, D. B., Alpaslan, Z. Y., & El-Ghoroury, H. S. (2015). Depth Assisted Compression of Full Parallax Light Fields. Proc. SPIE 9391, Stereoscopic Displays and Applications XXVI, (FEBRUARY), 93910Y–93910Y–15.

Bandwidth: Challenges for the Next Generation

- Graziosi *et al.* approach to sub-sampling light field
- Does not yield guaranteed compression rate – Still must resort to transform method for some cases
- Future: fully general, completely sub-sampling approach possible, can have bounded compression rates



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Conclusion

- Many existing approaches, many clever ideas as starting points
- Still suffer from quality issues
  - Likely why widespread adoption is limited
- Does appear to be “enough” resolution to have high quality display
- Challenges must be overcome to meet consumer expectations for a natural experience without noticeable/relevant limitations or physiological issues

Questions?