High Speed MEMS Beamforming for FSO and LiFi

SILICON LIGHT MACHINES

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Silicon Light Machines

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SCREEN & Silicon Light Machines

SCREEN

SILICON LIGHT MACHINES

Precision Equipment Supplier

- Founded 1943 (roots in Kyoto from1868)
- >5000 employees, >$2.5B annual revenue
- Semiconductor fabrication equipment
- Printed circuit board tools
- Flat panel display tools
- Graphic arts systems

Optical MEMS Specialists

- Unique diffractive MEMS technology
- Building optical MEMS for >20 years
- Semiconductor, electronics & optics
- Demanding industrial applications
- Began working with SCREEN 1997
- SCREEN subsidiary since 2008

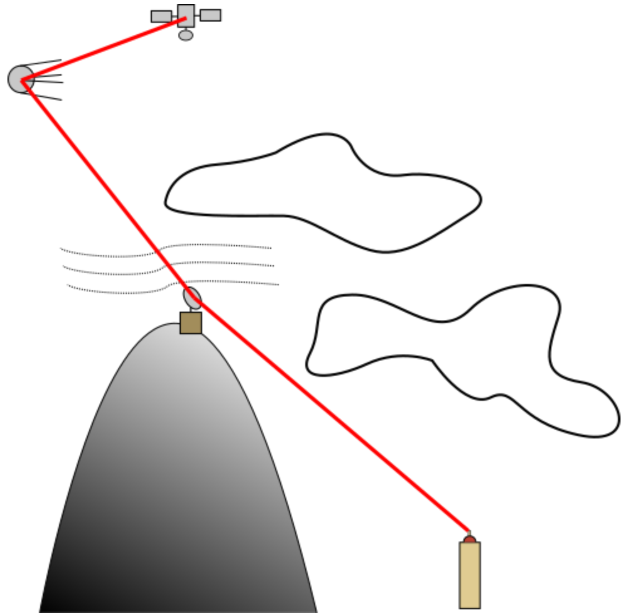
Siliconlight.com

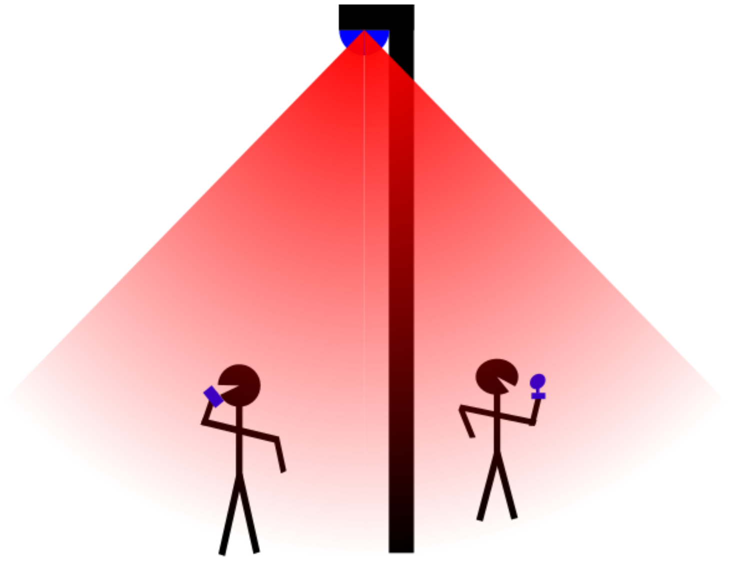
Summary

- Beamforming for LiFi and FSO
- Beamforming In The Fraunhofer Regime And Effects of Array Elements
- Technology example: The GLV (and the PLV)
- Technology available today

What is FSO? What is LiFi?

- **FSO = free space optical communications**
- **LiFi = Light Fidelity**
  - WiFi, but light





Why light?

- Short wavelengths, narrower beams:
  - $Beam\ divergence\ \theta \sim \frac{\lambda}{D}$
    - Short wavelengths, smaller divergence; direct light where you want to go
    - Harder to intercept narrower beams, stronger security and privacy
- Increased Modulation Bandwidth:
  - Optical carrier frequencies 100s THz, (often use 1% of bandwidth)
    - Compared to the MHz frequencies often used in RF communication, (often use 20% of bandwidth)
    - Practical *data bandwidth* increase of ~100X [1]
- Unlicensed Bandwidth:
  - High congestion in RF requires licensing, significant costs to expanding networks
- Available technology
  - Fiber optics communication gives NIR framework, or there are countless VIS sources
  - Research in holography, AO, microscopy, LIDAR all also benefit LiFi
- Compact size, less power than RF [1]
  - Save weight and power where critical, such as on satellites, airplanes
- Does not cause electronic interference
  - Wifi in hospitals can interfere with medical [2]

Use Cases

- **Military – Security (~5-30m)**
  - Kitefin by Purelifi - $4.2 million order from US Army

- **Aviation / Aerospace – Lighter weight (~1-3m)**
  - One ton of wiring, or ~10 (American) passengers + carry-on worth for on-board WiFi

- **Factory and hospitals – No EM interference (~5-30m)**
  - RF interference from equipment disrupts connection, or from WiFi disrupting devices
- **Disaster relief – High bandwidth, channel count (~10-50m)**
  - Stadiums, airports, places where connection effected due to number of users

- **Consumer – Supplemental to WiFi, 5G, smart housing (~1-3m)**
  - Phone dongles and usb based transceivers available now
  - Generally will be short range wireless high bandwidth bridges

LiFi for Industry 4.0

- **Industry 4.0 = “smart factory”**
  - Machinery tied to IoT; allows remote monitoring and AI control
  - Industry 1.0 = steam and water, Industry 2.0 = assembly line, Industry 3.0 = computers + automation
- **LiFi good fit for smart factory wireless communication**
  - EM interference makes WiFi unusable
  - Hard wiring is inflexible and complicated
  - LiFi flexible enough, while positioning of recievers can be planned for line of sight (LoS)
- **Beamforming is necessary for the data rates and distances of large factory floorplans with many devices**
  - LIDAR type beam steering, UV-NIR
  - Transceiver modules on bases and large items can have more complicated optics than consumer devices, less power and cost sensitive

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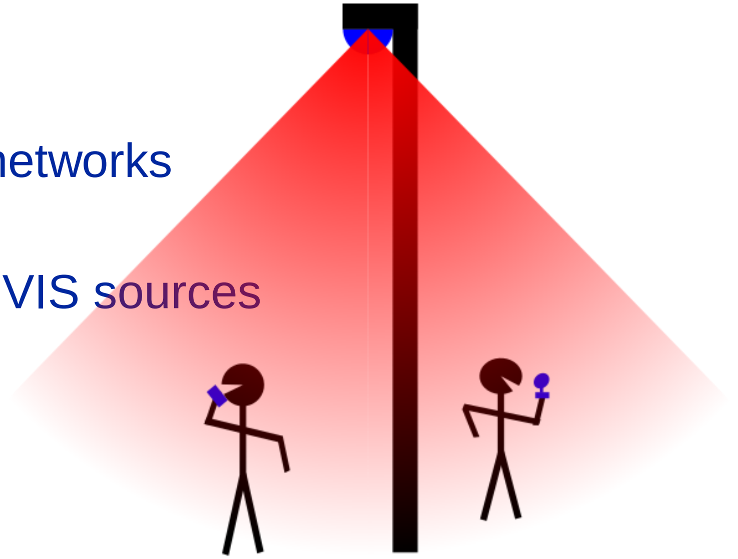
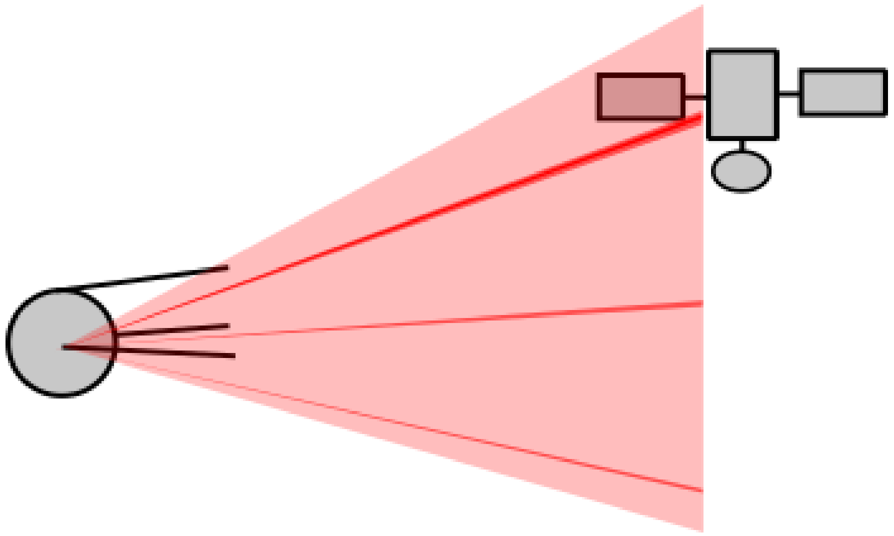


Beamforming for Lifi

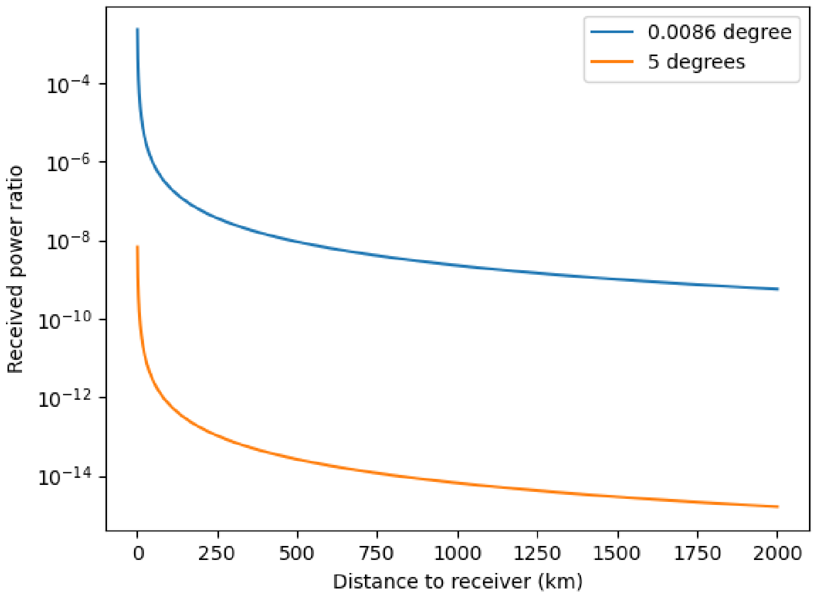
Beamforming is necessary for FSO …

- … for longer range. Scanning gives orders of magnitude higher signal over equivalent FOV.
  - Received power ~ $(\theta L)^{-2}$



Fine angle steering over 5 degree FOV
(20um PLV pitch with 1.55um light)

7-8-21



Beamforming for Lifi

- **Beamforming is necessary for LiFi …**
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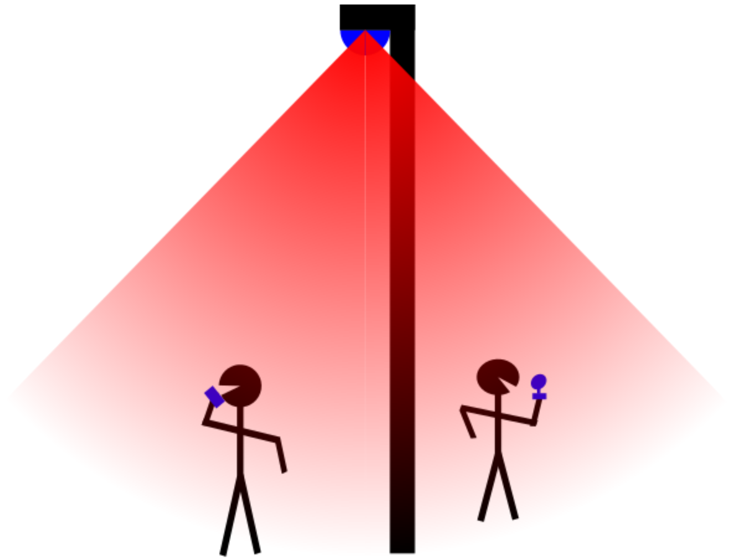
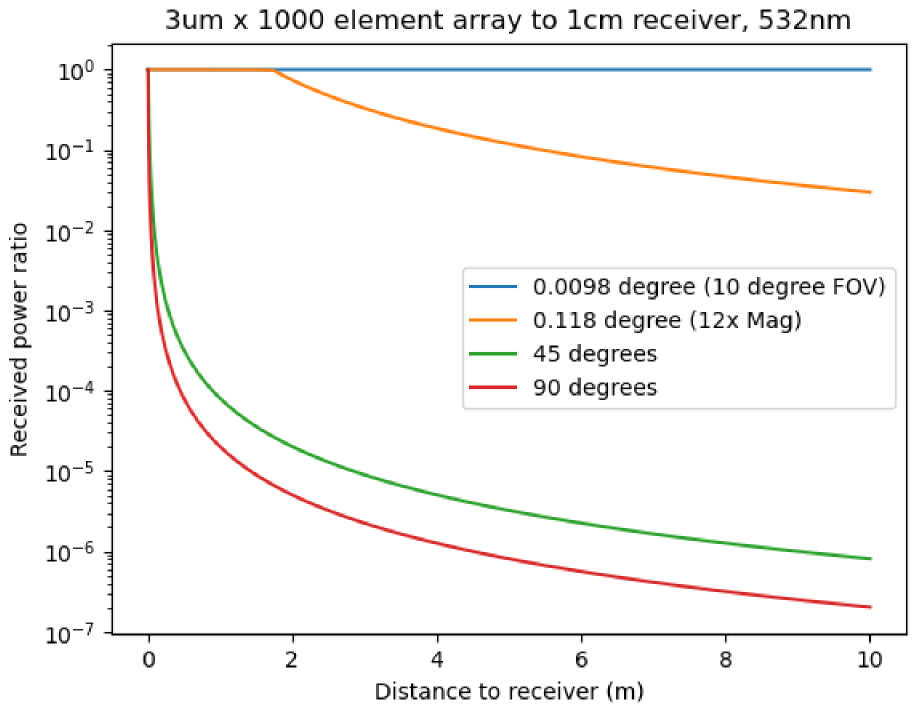
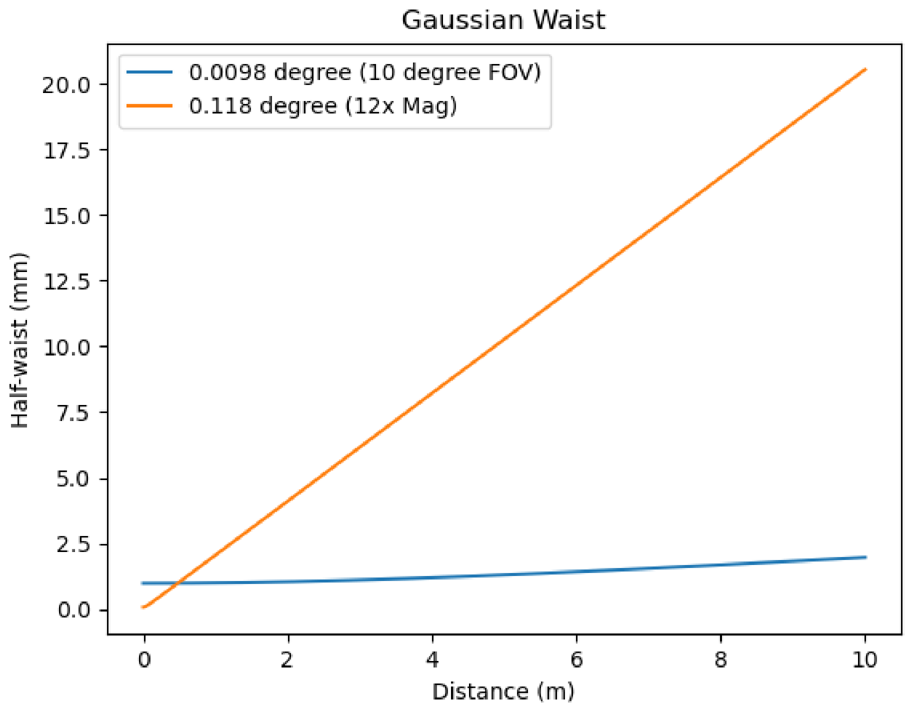
    - Sung-man Kim: 3x noise-limited range and 1000x lossless transmission speeds at 4m [2]







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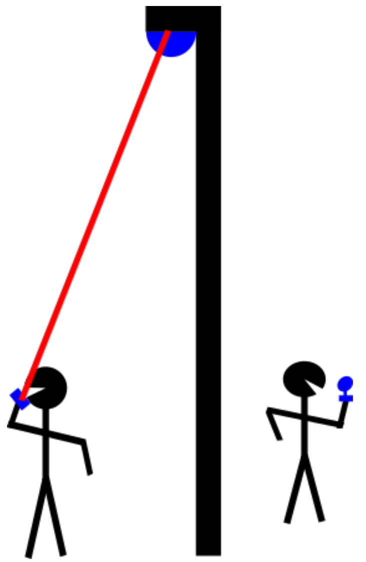
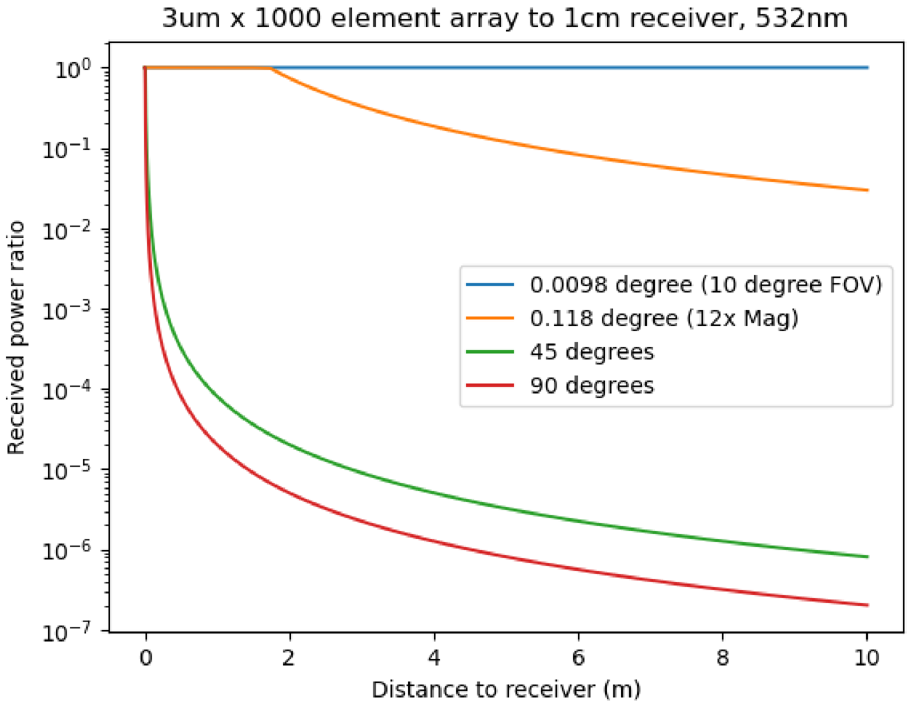
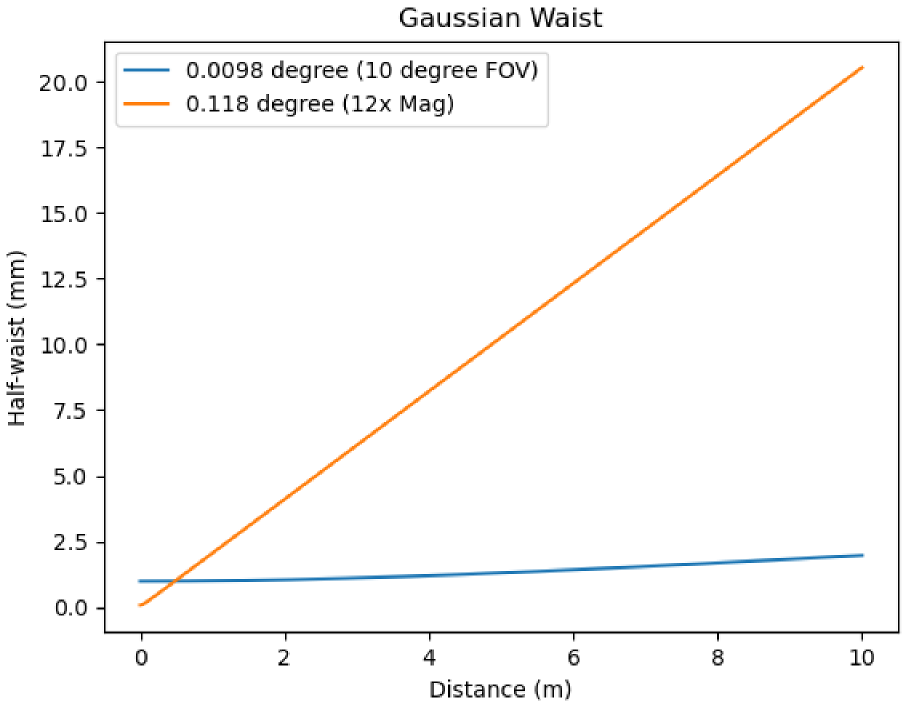
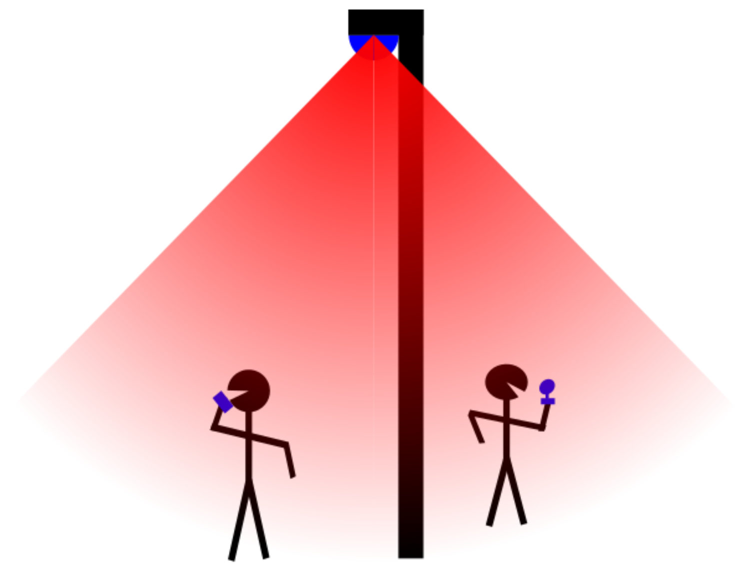






Beamforming for Lifi

- **Beamforming is necessary for LiFi …**
  - … for longer range. Scanning gives orders of magnitude higher signal over equivalent FOV.
  - … for privacy.

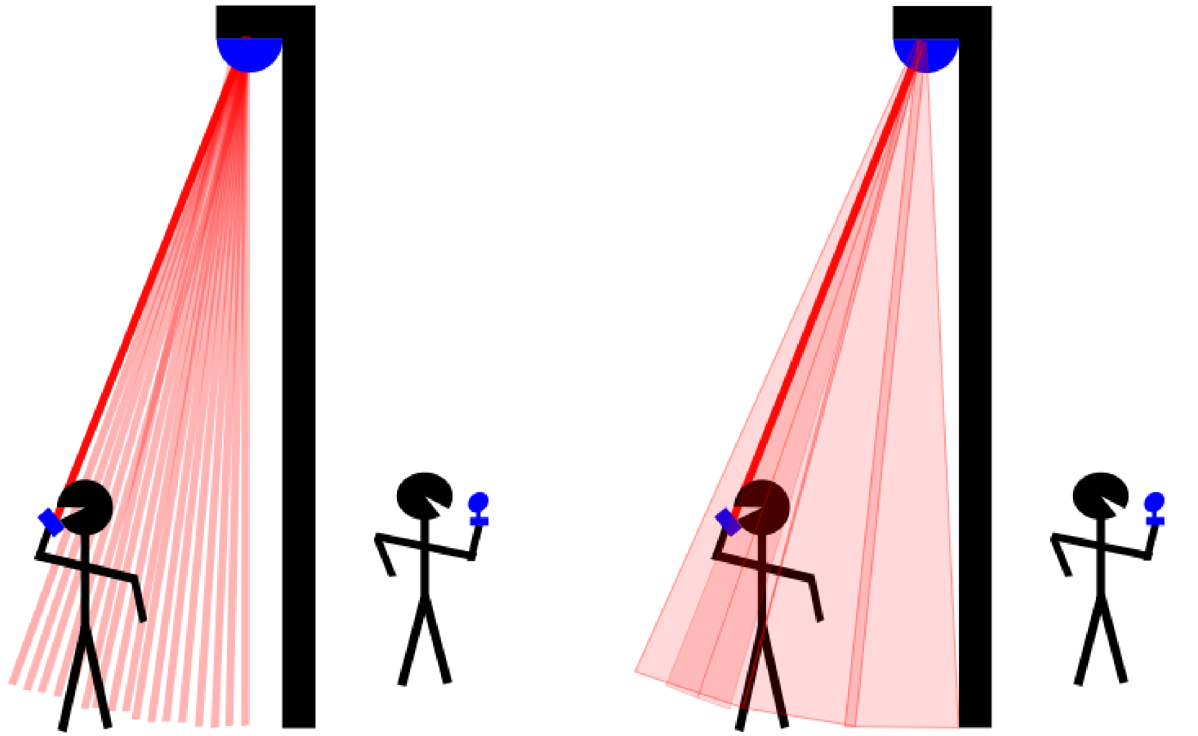


Beamforming Performance Evaluation

- **Speed:**
  - Fast enough to track? To multiplex? Both?
  - Point to point or continuous
  - Magnitudes different speeds between technologies
- **Power:**
  - Mobile devices
  - Benefits outweigh power cost
- **Wavelength:**
  - VIS for lighting conditions
  - NIR for invisible uplink [1] and long distance
  - Coherent/incoherent
- **Signal:**
  - Efficiency and beam quality
    - Determined by pixel size, count and fill factor
  - Sidelobes, grating lobes
    - Determined by pixel size and fill factor
- **Coverage:**
  - Field of view
    - Determined by pixel size and wavelength
  - Resolution, resolvable spots
    - Determined by pixel size, count, wavelength, fill factor and input illumination shape
- **Range:**
  - Beam divergence
  - Lensing power
    - Determined by pixel size and count
    - With fixed optics or not

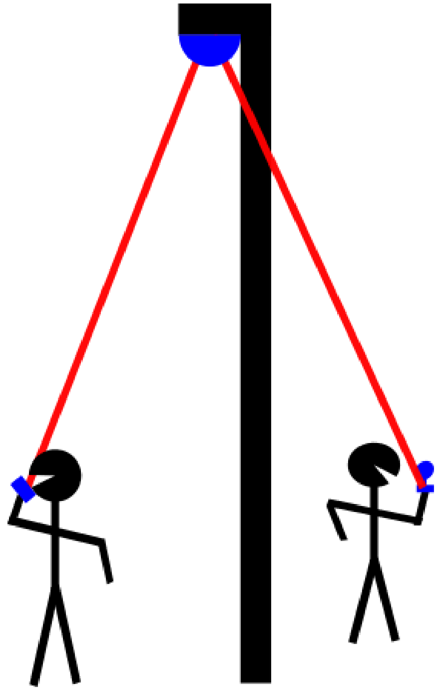
High Speed Random Access

- **High speed necessary for receiver acquisition and tracking**
  - .2º beam, 90º FOV, 3 us point to point -> ~150 ms max time to find stationary target
  - Random access beamforming for smarter, faster acquisition [2]



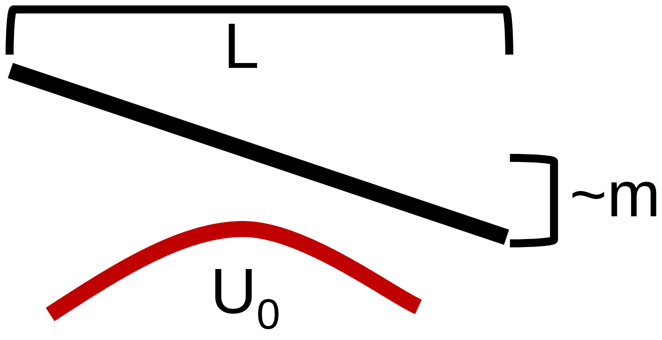
High Speed Random Access

- **Very high speed technologies enable time based multiplexing**
  - Give each time slot equally or according to need
    - Kim et. Al. demonstrated SNR improvement with TDMA [3]
  - Random access essential
  - Signal splitting, wavelength multiplexing, multiple spot may be used alternatively or concurrently



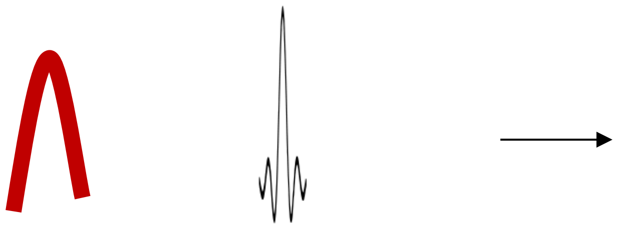
Mirror versus MEMS Phased Array

- **Phased arrays = wave optics, tilted mirrors = geometric optics?**
  - Wavefronts of reflected flat pixels interfere in far field to create main lobe



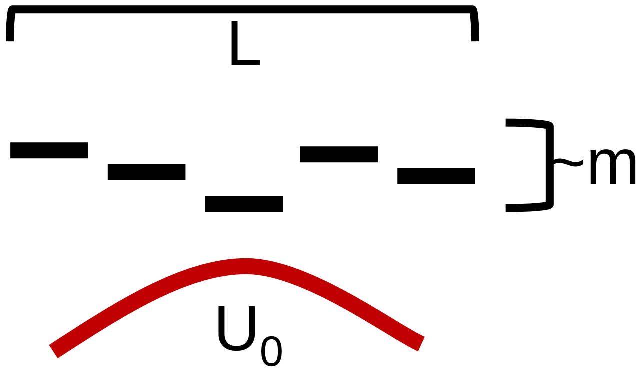
Illumination profile | Scan mirror aperture | Scan mirror as phase ramp

$$U_0(x) \times rect\left(\frac{x}{L}\right) \times e^{-jmx}$$



Fraunhofer of illumination profile | Sidelobes | Steering

$$\mathcal{F}\big(U_0(x)\big) * sinc(Lx') * \partial(x' - m\lambda d)$$



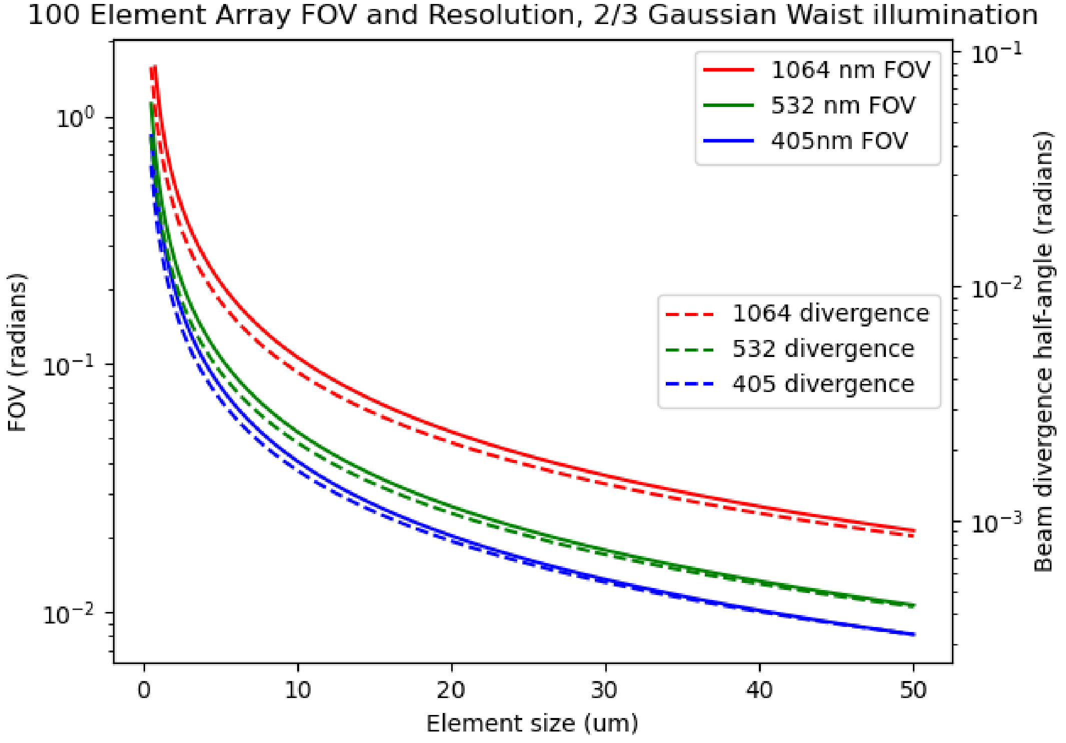
Illumination profile | Phased array aperture | Element width | Sampling | Ramp

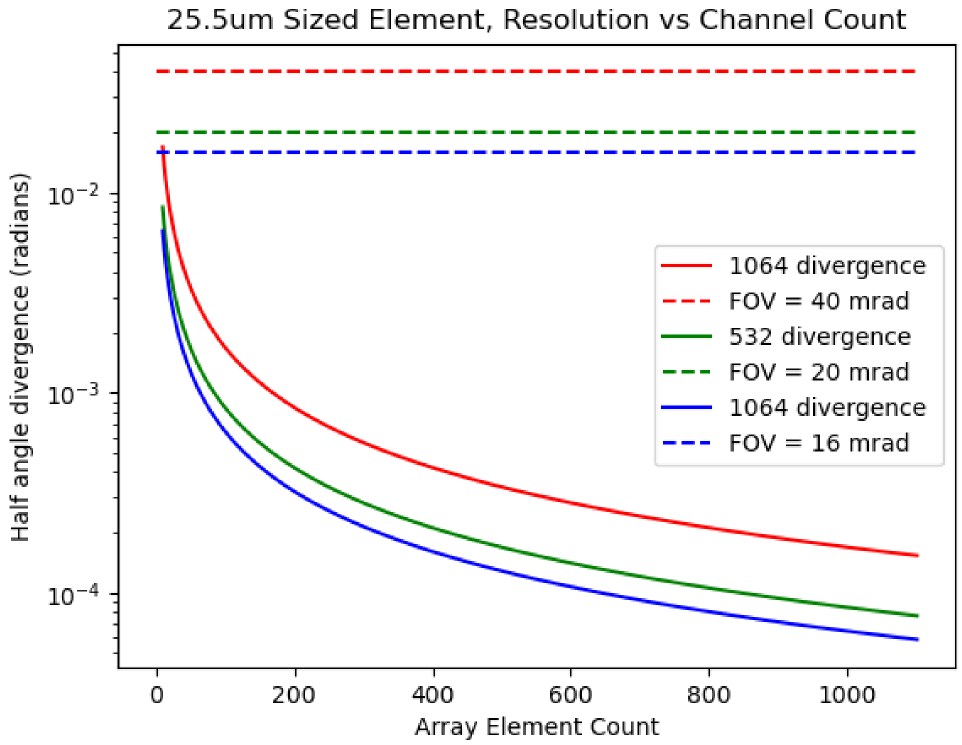
$$U_0(x) \times rect\left(\frac{x}{L}\right) \times \left(rect\left(\frac{x}{w}\right) * comb\left(\frac{x}{p}\right) e^{-jkmx\%2\pi}\right)$$

Fraunhofer of illumination profile | Sidelobes | Envelope | Grating Orders | Steering

$$\mathcal{F}\big(U_0(x)\big) * sinc(Lx') * \big(sinc(wx') \times comb(px')\big) * \partial(x' - m\lambda d)$$

Array Dimension Effects on Steering

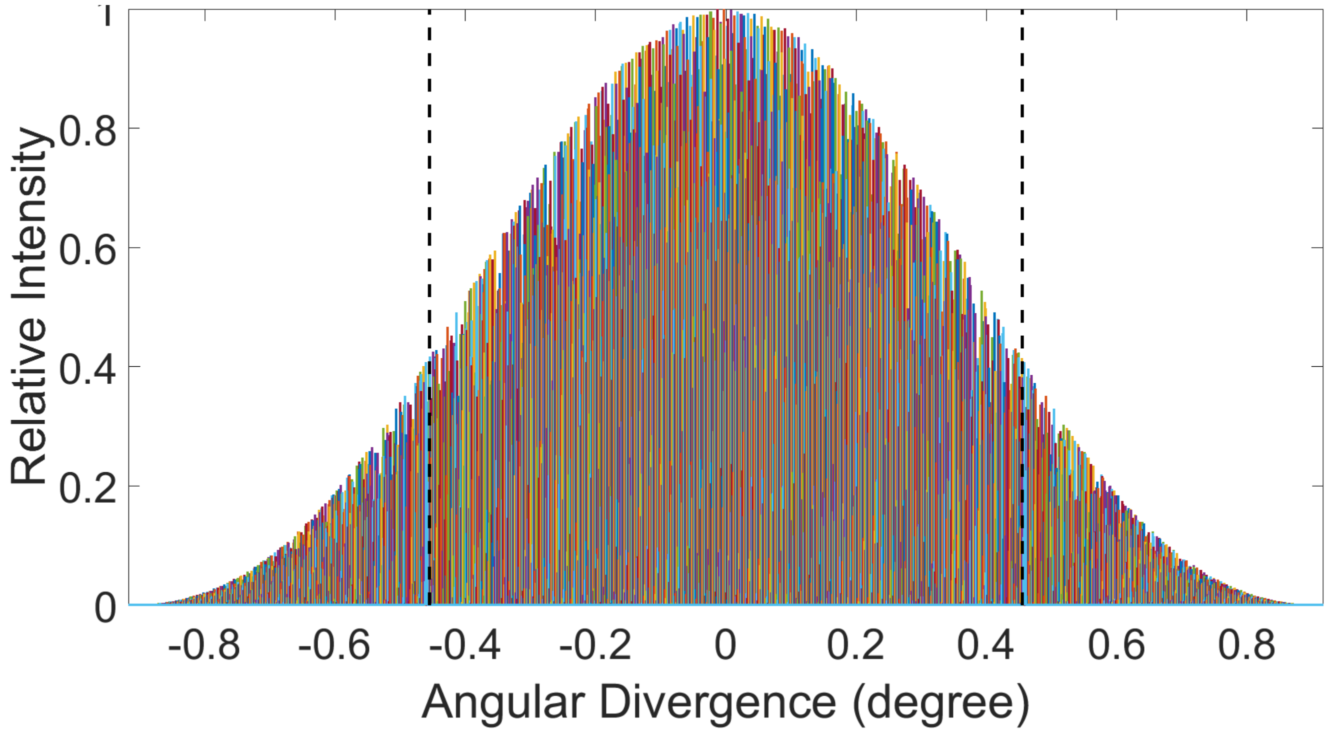




- **Field of view determined by pixel size**
  - $FOV = 2\sin^{-1}\frac{\lambda}{2a}$
- **Resolution determined by aperture size and illumination/apodization**
  - Gaussian divergence of $\theta = \frac{.85\pi\lambda}{w}$
- **Number of spots determined by pixel channel count**
  - Repeating array creates phasing effects
- **Magnification optics increases FOV, decreases resolution**

Array Dimension Effects on Efficiency

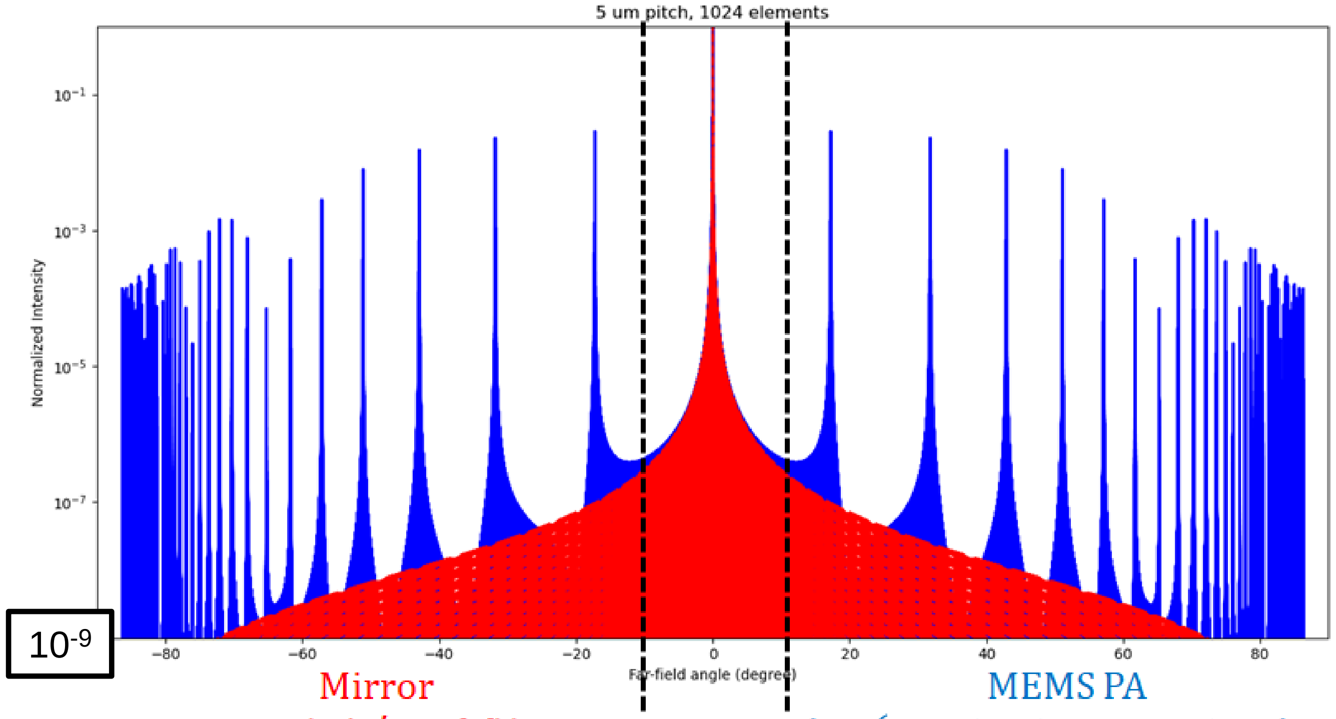
- **Beam efficiency and grating lobes depends on technology**
  - Diffraction efficiency, grating order location, FOV ~ *channel spacing* for emitters [7]
  - Zero order efficiency ~ *fill factor* for SLMs
    - Zero order efficiency ~ $ff^2 * R_{mirror}$
  - Grating orders, FOV ~ *pixel size* for SLMs
    - Grating order location = $\sin^{-1}\frac{\lambda}{a}$
- **Grating orders can be filtered**
  - 2 lens with low-pass
- **Steering response has non-uniform power**
  - First orders defines max FOV, power split equally
  - Restrict FOV further to increase system efficiency



Fourier simulation of 25.5um element, 85% fill factor, see [5]

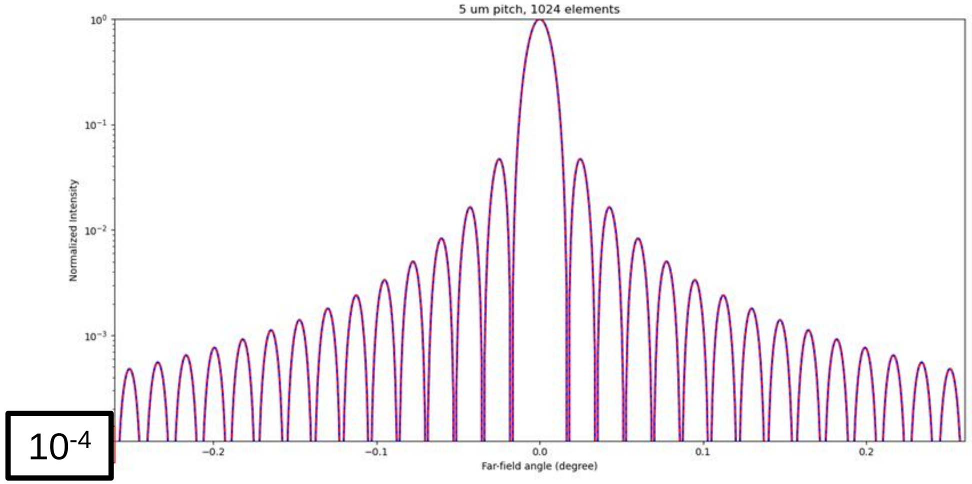
Uniform (Top-hat) Illumination

- **Uniform illumination generally gives "highest" resolution but with significant side lobes**

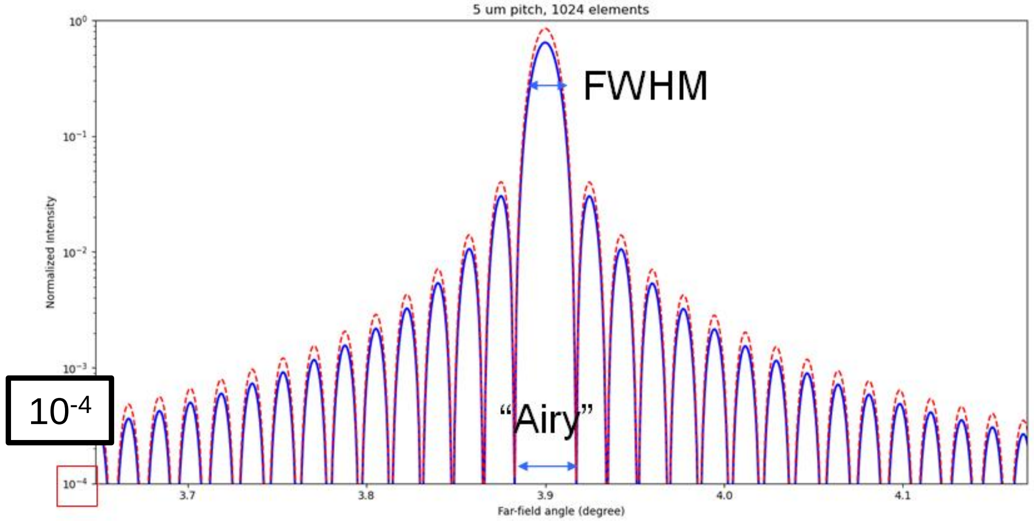


Mirror
$sinc(L(x'-m\lambda d))$

MEMS PA
$sinc(Lx') * (sinc(wx') \times comb(p(x'-m\lambda d)))$



Mirror Norm. to itself MEMS PA



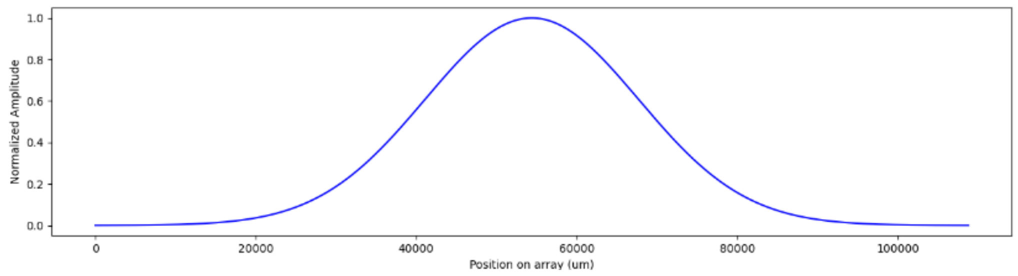
Mirror Norm. to mirror MEMS PA

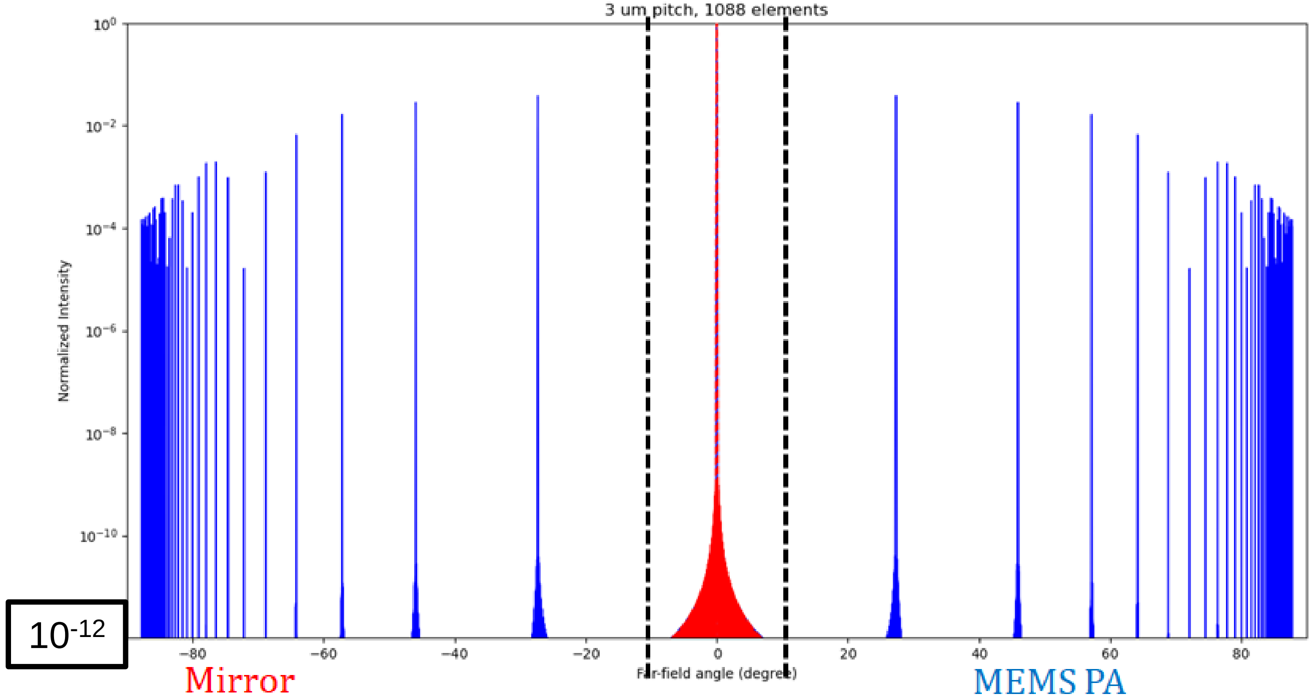
Gaussian Illumination

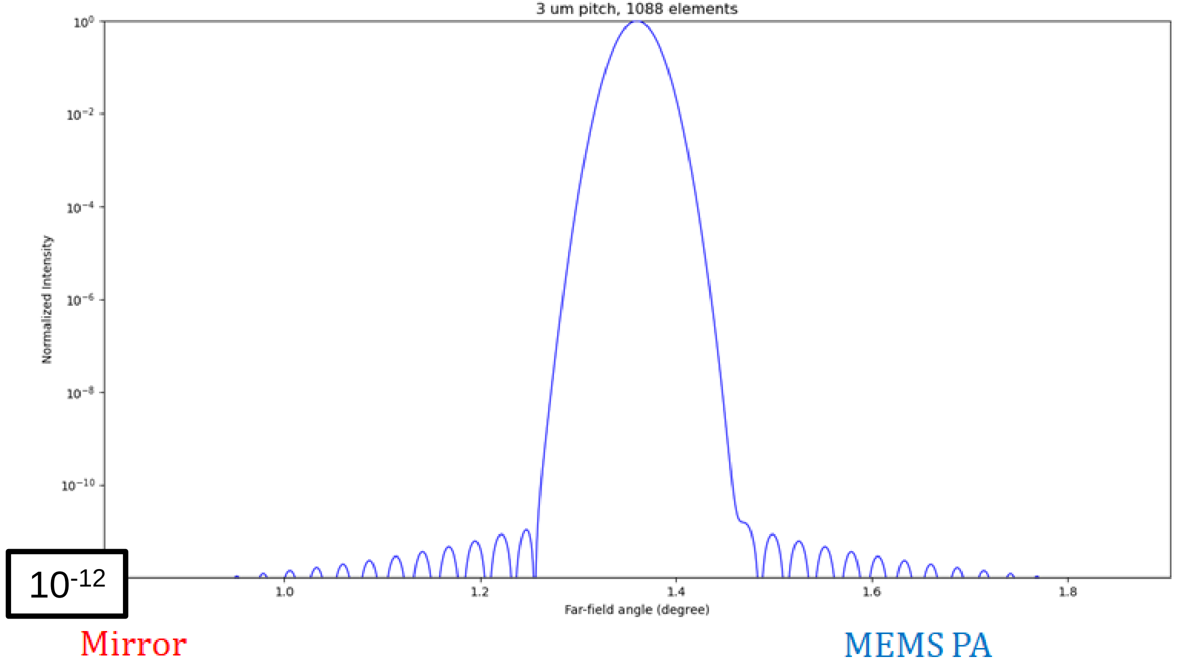
- **We can engineer a better illumination to suppress sidelobes**
  - Gaussian illumination on the phased array will give a Gaussian response in far field
  - Gaussian apodization also possible for any phased array [7]

Illumination profile

$$e^{-2\left(\frac{x}{w}\right)^2}$$





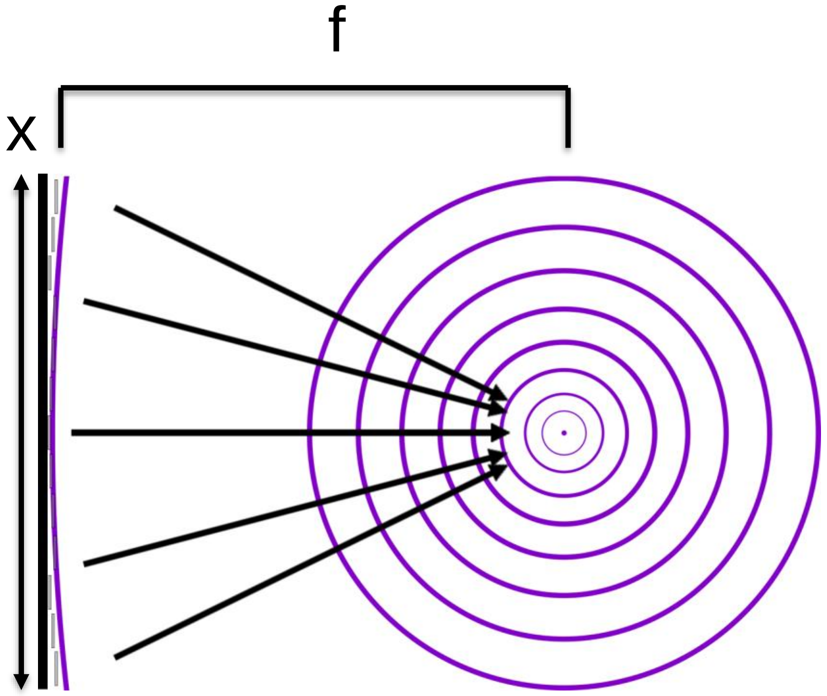


$$e^{-2\left(\frac{w\pi x'}{d\lambda}\right)^2} * sinc(L(x'-m\lambda d)) \qquad e^{-2\left(\frac{w\pi x'}{d\lambda}\right)^2} * sinc(Lx') * \left(sinc(wx') \times comb(p(x'-m\lambda d))\right)$$

Phased Lensing

- **Spherical (cylindrical) lens**
  - Phase ~ $\frac{2\pi}{\lambda}\left(f \pm \sqrt{f^2 - x^2}\right)$
  - Describing hologram of a point source
  - + for converging
  - - for diverging
- **Parabolic works well too**
  - Phase ~$\frac{x^2}{4f}$ (Fresnel lens)
- **Gaussian waist - change divergence angle by 40%**
  - Maximum focus: $f = z_R$
  - $w_{02} = \frac{1}{\sqrt{2}} w_{01}$
  - $\theta_2 = \sqrt{2}\,\theta_1$

$$U_0(x) \times rect\left(\frac{x}{L}\right) \times \left(rect\left(\frac{x}{w}\right) * comb\left(\frac{x}{p}\right) e^{-jk\left(mx+f-\sqrt{f^2-x^2}\right)}\right)$$

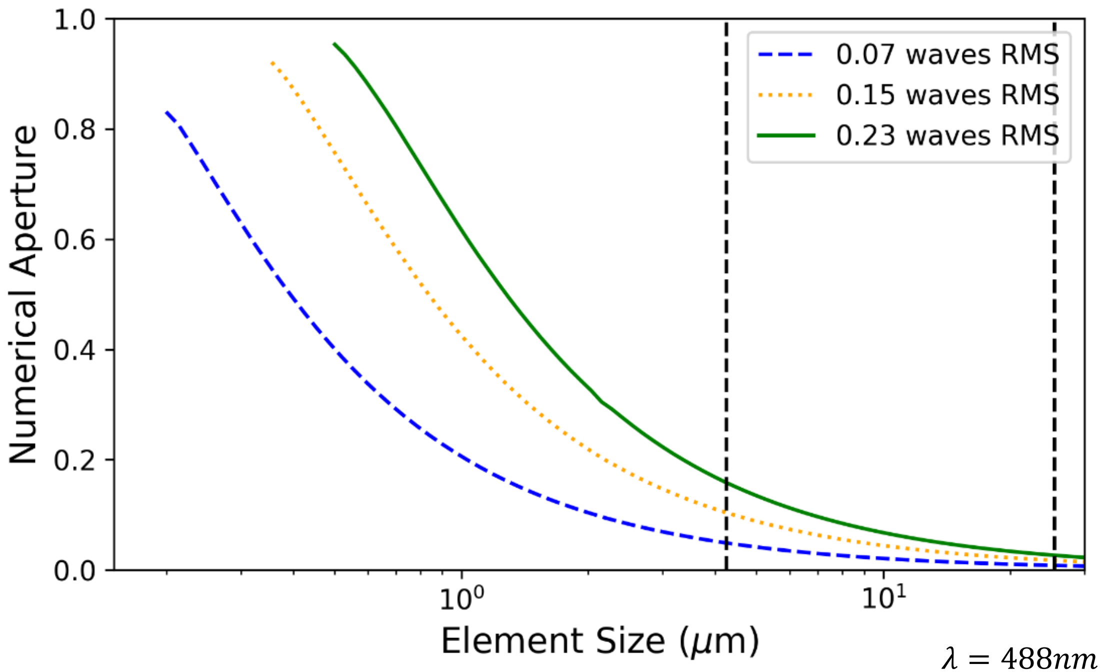


$$\mathcal{F}\big(U_0(x)\big) * sinc(Lx') * \big(sinc(wx') \times comb(px')\big) * \mathcal{F}\left(e^{-jk\left(f-\sqrt{f^2-x^2}\right)}\right) * \partial(x' - m\lambda d)$$

Array Dimension Effects on Lensing

Element size determines NA

- Scales linearly with wavelength
- Maximum lens power determined by aperture
- Minimum lens power determined by phase control depth, number of elements

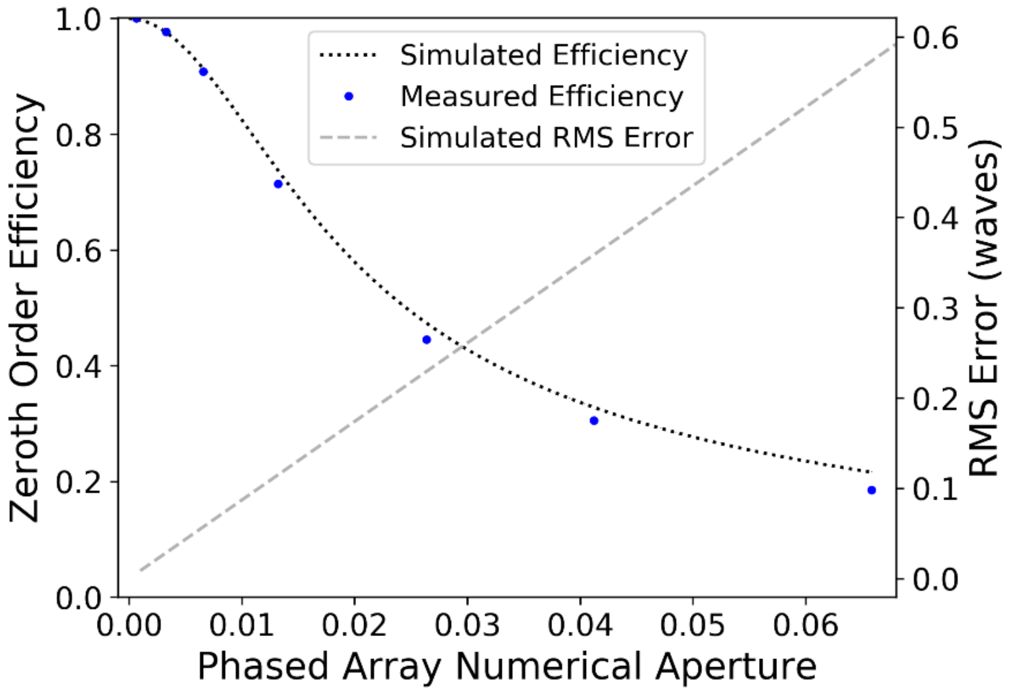


$\lambda = 488nm$

[6]

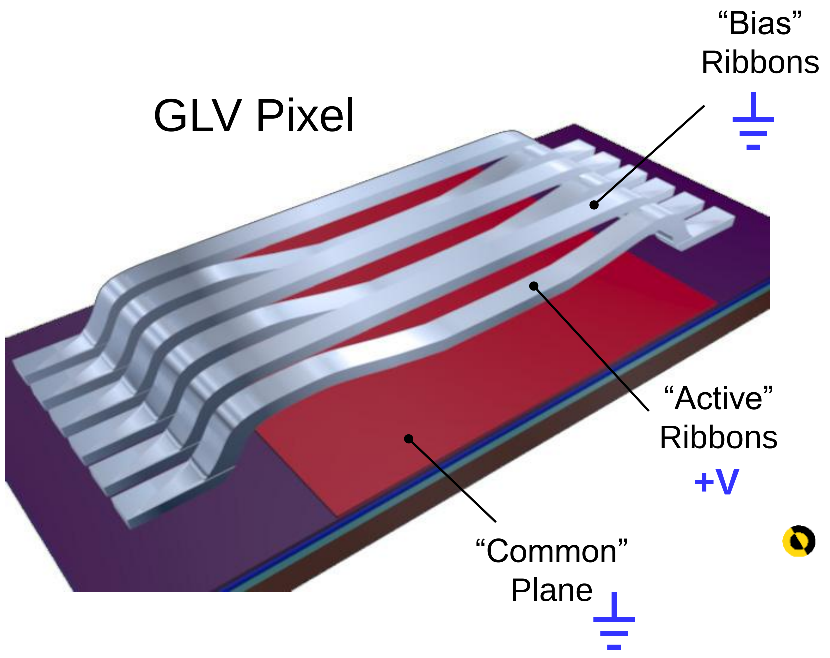
Acceptable NA depends on use case

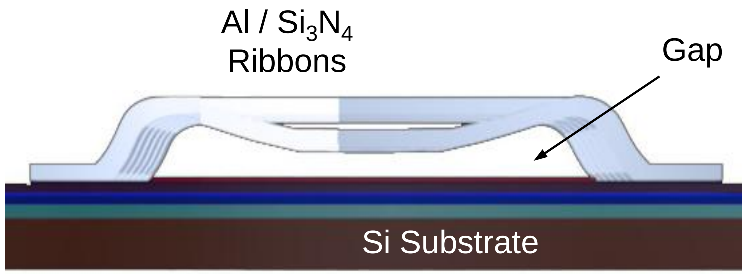
- Imaging aberrations as RMS wavefront error
  - "Perfect Imaging", RMS error = .07 waves
  - LiFi is not imaging, higher RMS error okay
- Zero order efficiency decreases with NA
  - .07 waves ~ 90% efficiency

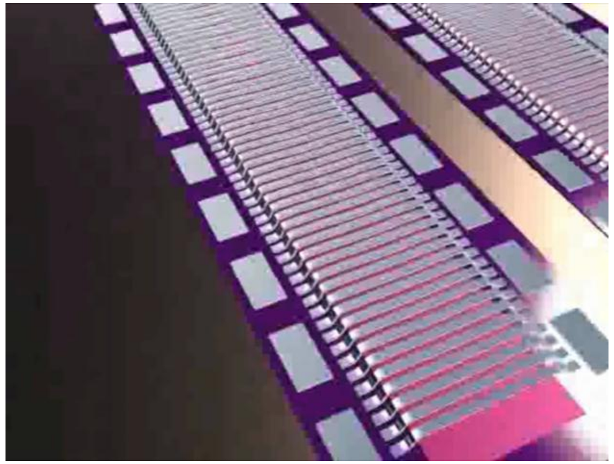


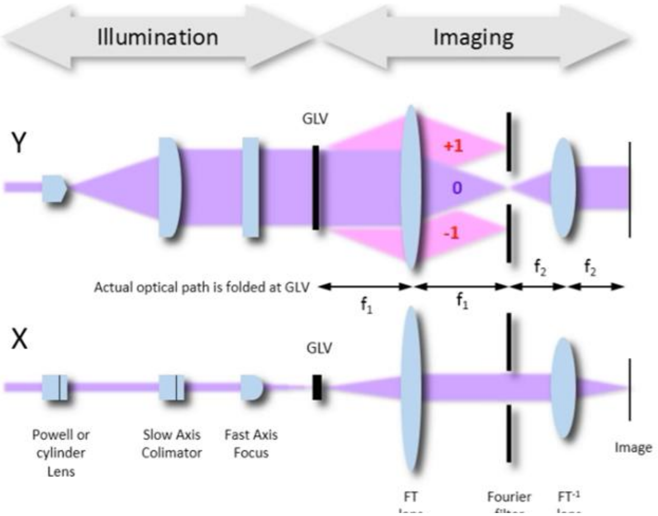
[6]

Grating Light Valve ® – High Speed Amplitude

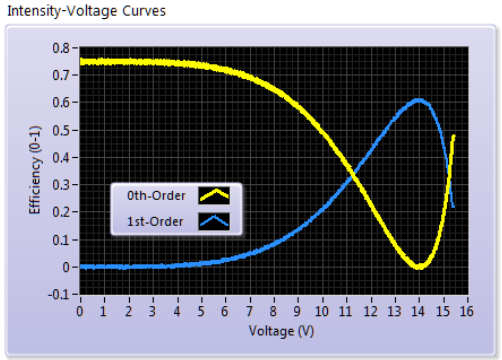


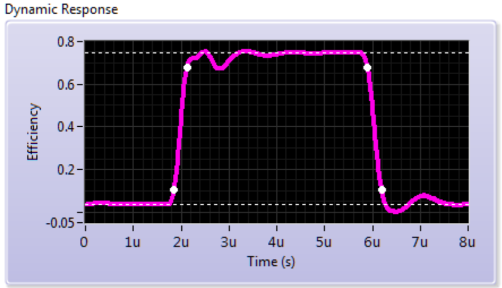






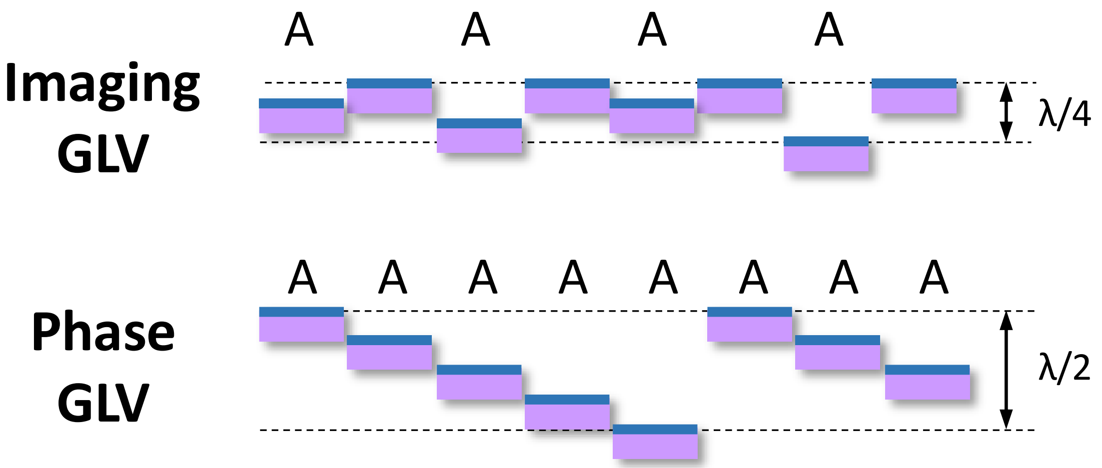
- **The GLV ® is a high-speed diffractive MEMS light modulator fabricated from aluminum & silicon-nitride**
- **The GLV ® uses phase interference to modulate light intensity reflected into fixed diffraction angles at high speeds**
- **Originally developed for displays, now used in printing, lithography, and many other applications**

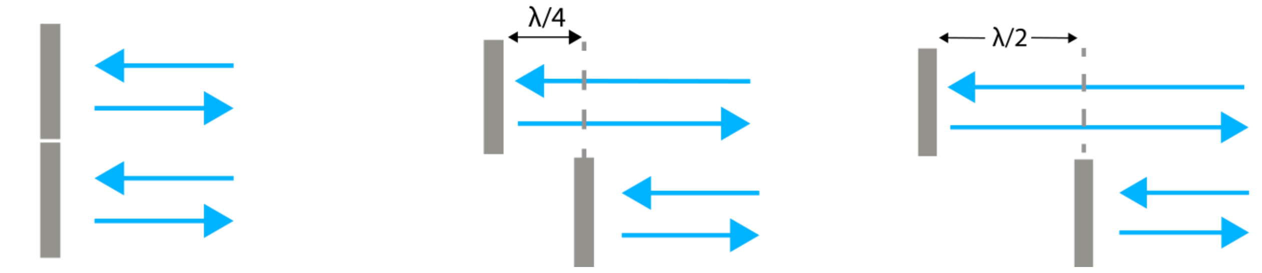




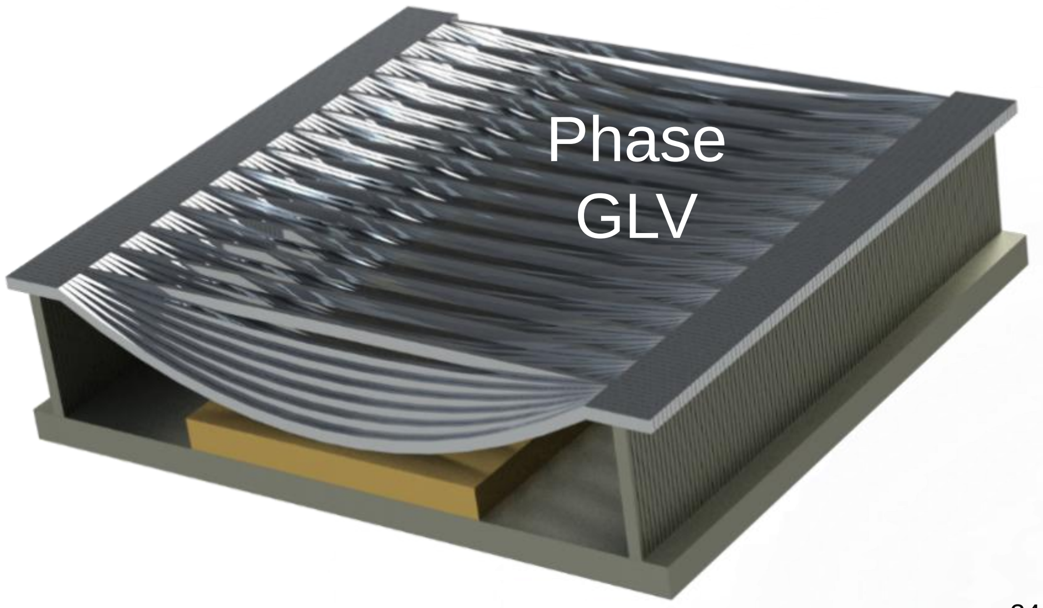
Phase GLV® – High Speed Linear Phase

- **The conventional GLV® for imaging employs interleaved static and active ribbons to create localized image contrast**
  - Maximum deflection is $\lambda/4$ for 1π phase shift
- **In the phase GLV®, every ribbon is active, allowing arbitrary phase modulation of the reflected beam**
  - Maximum deflection is $\lambda/2$ for 2π phase shift





φ = 0 waves φ = 0.5 waves φ = 1.0 waves



High Speed Buddy Phase Modulator

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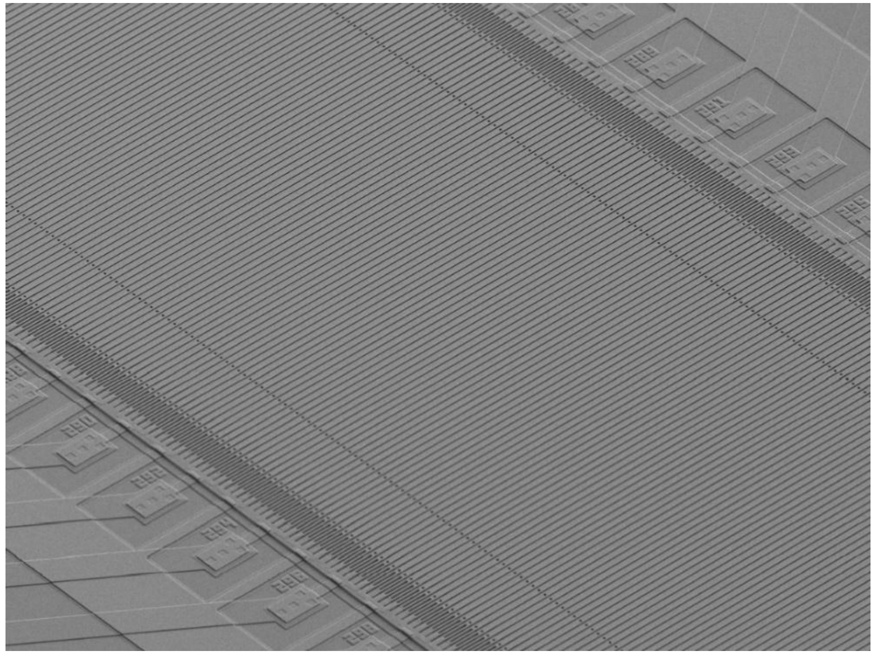
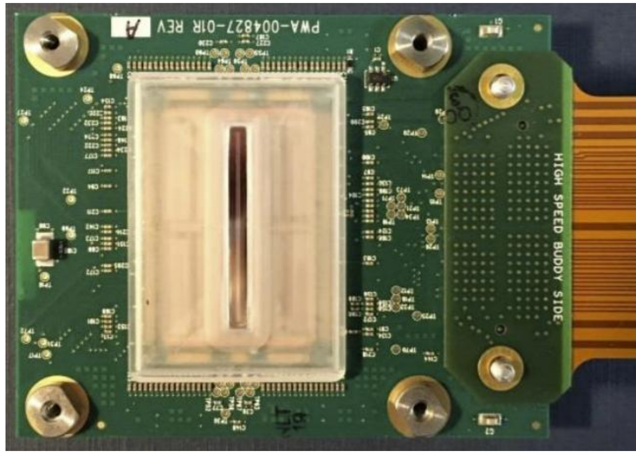
- **Specs of UV-VIS demo device**
  - 350 kHz Maximum rate
    - Signal limited
  - 1088, 25.5 um pixels
    - 1 pixel = 6 ribbons
  - 2π phase modulation up to 488nm
  - 10 bit modulation
    - Voltage – deflection response nonlinear

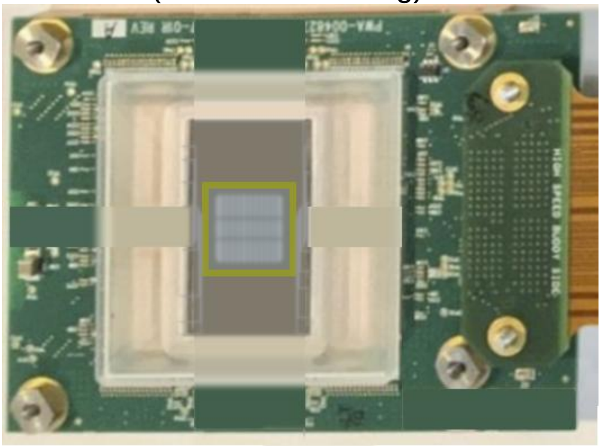


F1088-HS Module



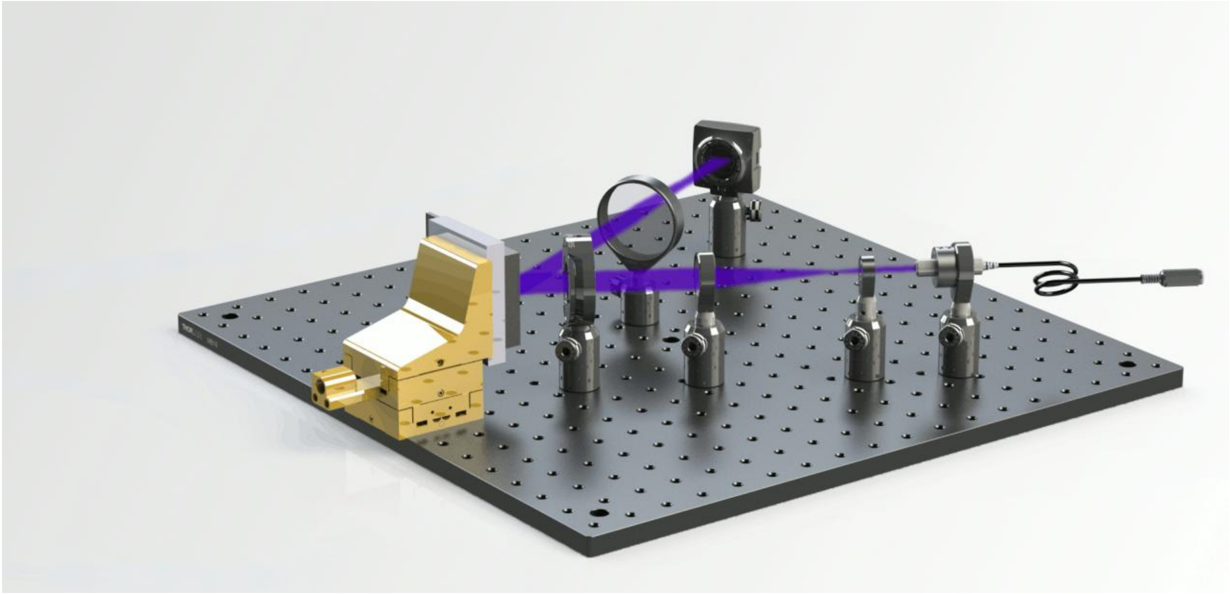
- **Single ribbon pixels, larger aperture in development**
  - NIR operation
    - 2π phase modulation >1550nm
  - Small element (~28^{o} FOV @ 1550nm)
  - Multiple array for spot multiplexing
  - Demo expected in the fall

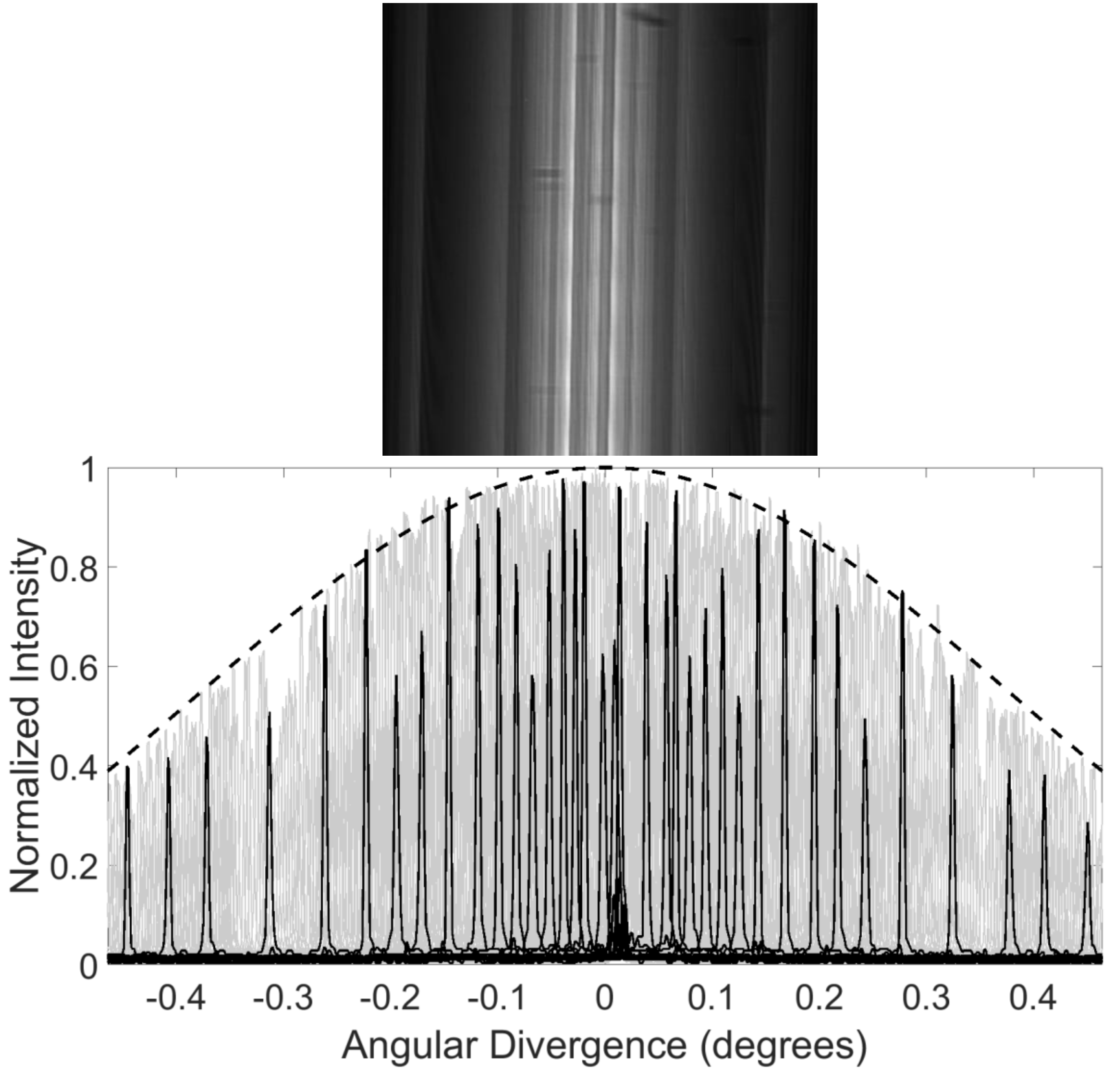
(Artistic Rendering)



Lateral Scan Profile

- **Results from Hamann et. al. [5]**
  - 940 scan lines shown over 1° FOV
  - Variation in amplitude from multiple sources
    - Convolved sinc pattern from theory
    - Lines straddling pixels

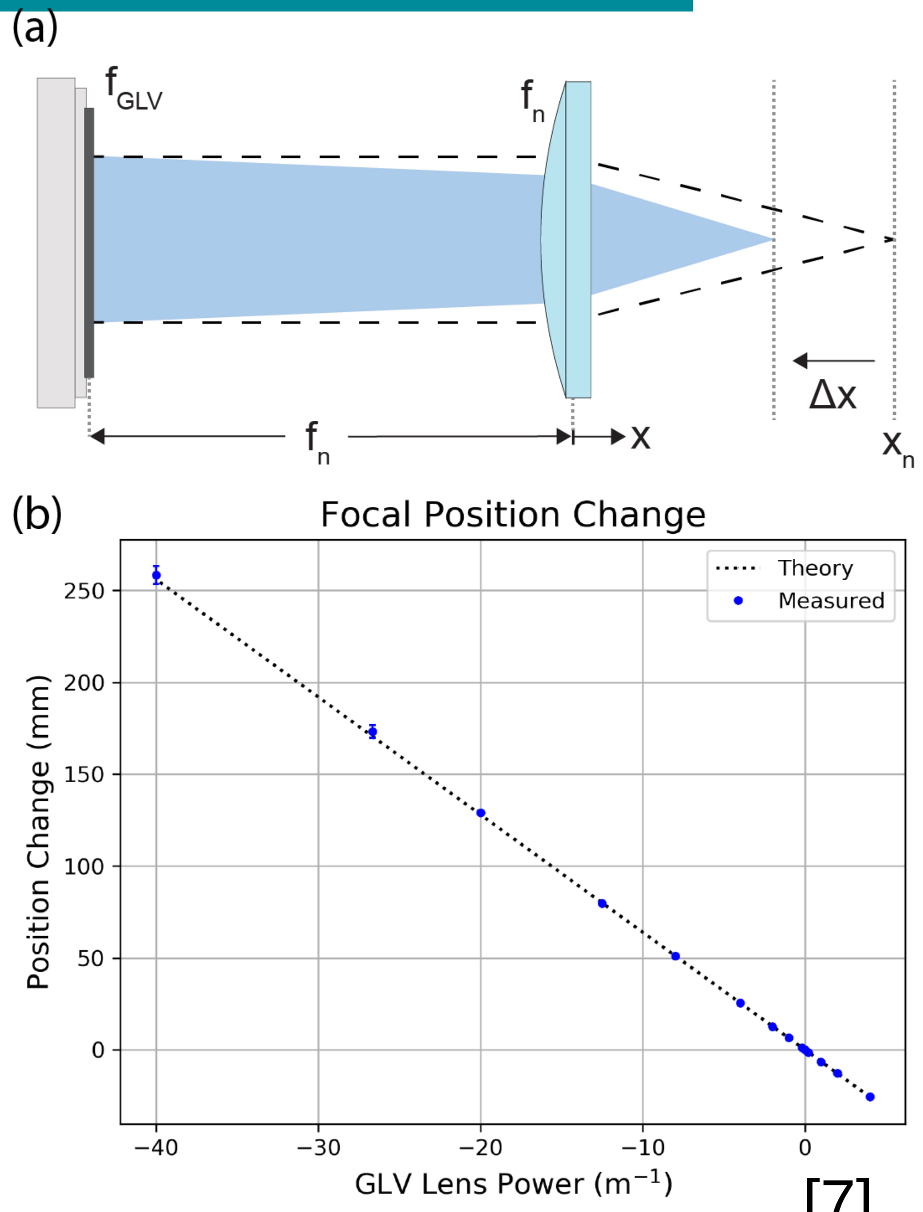




[5]

Phased Array with Fixed Optics

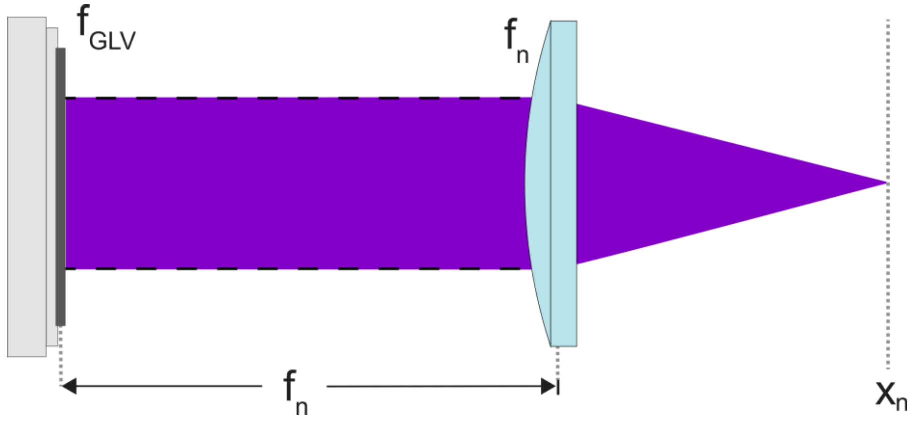
- **Beam Characterization Done with Lens**
- **Changing Lens Power of System**
  - $x = x_n - \Delta x$
    - x = distance to new focal plane
    - Δx = shift in focal plane
    - x_n = nominal focus of system
  - $\Delta x = \frac{f_n^2}{f_{PA}}$
    - f_n=focus of lens
    - f_{PA}=focus of phased array
- **Maximum focal shift limited by pixel effects**
  - Not Rayleigh range of Gaussian waist at the array

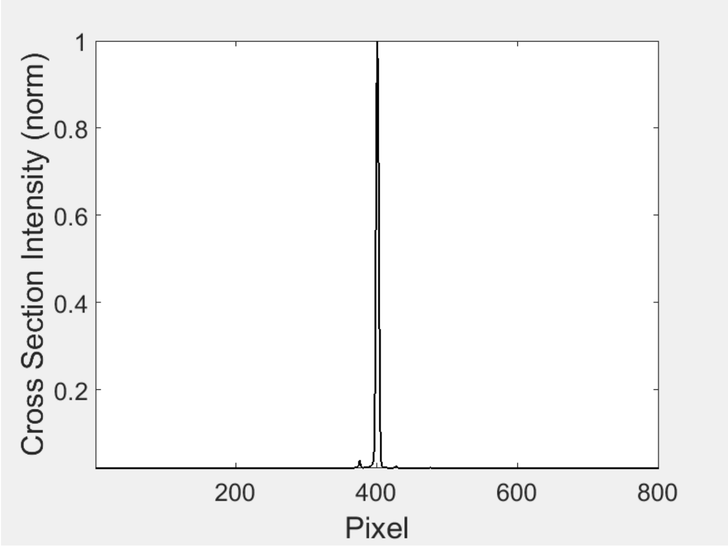


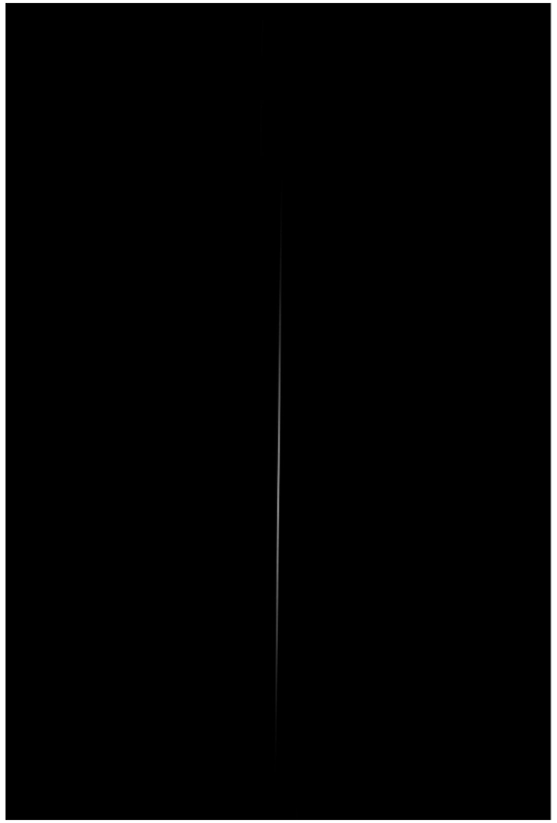
[7]

Passive State (Mirror)

- **Line is focused at nominal focus**
  - Focal length is 150mm
- **Set full width half maximum (FWHM) of nominal plane as reference**
  - w_o = 3.3 um (~256 pixels covered)
    - Note cleaner Gaussian response, limiting aperture is not GLV

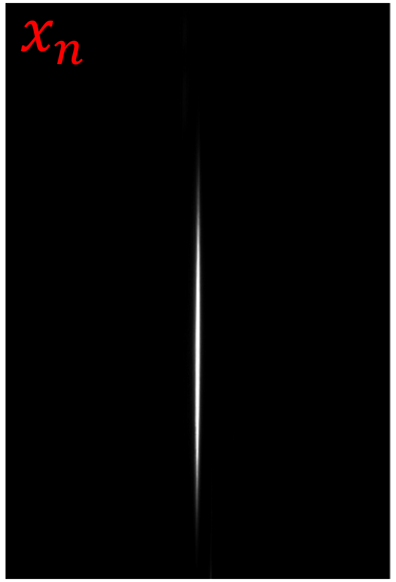


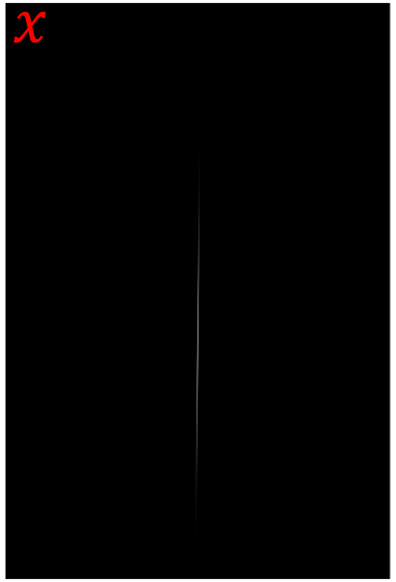


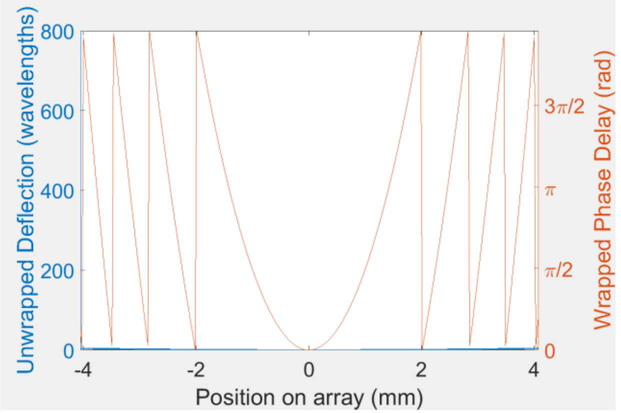


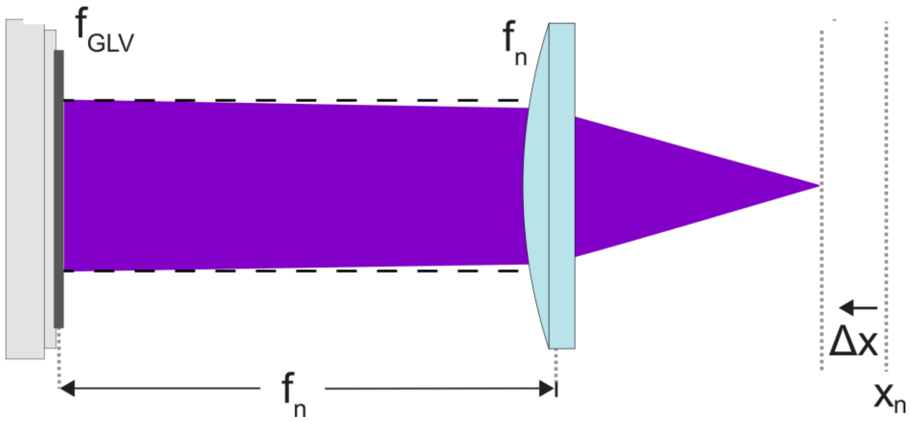
Focus = +5000 mm

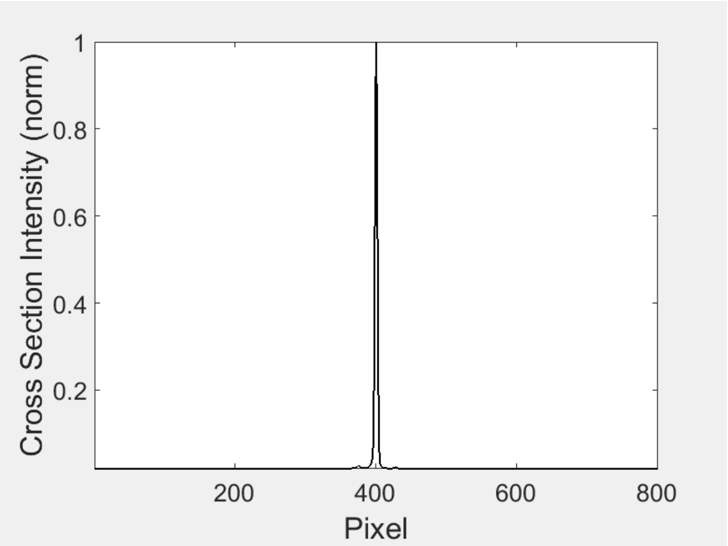
- **FWHM/nom = 0.95**
- **Acts as a converging lens**
  - $\Delta x = -4.5mm$





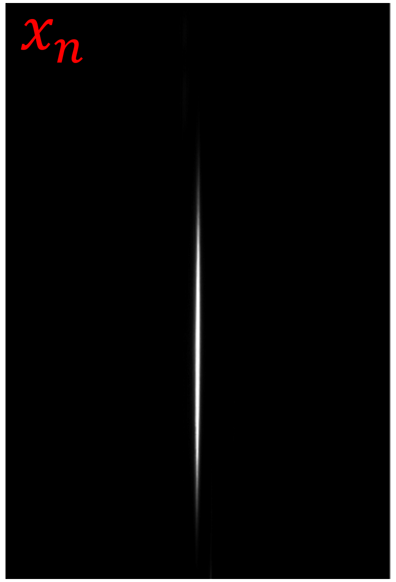


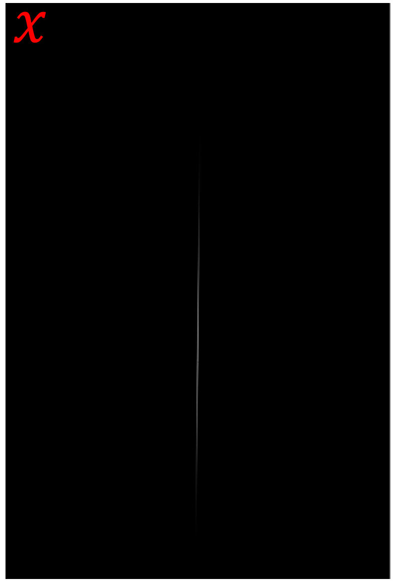


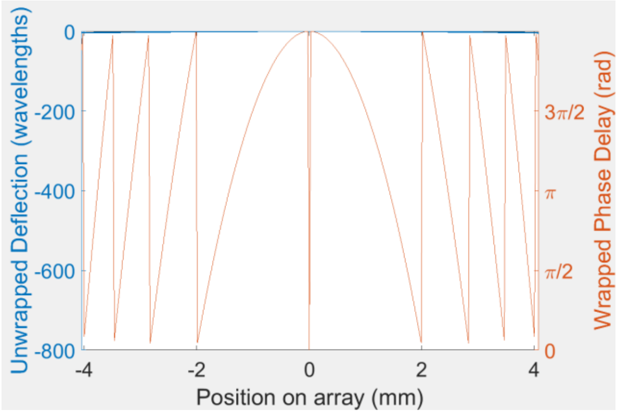


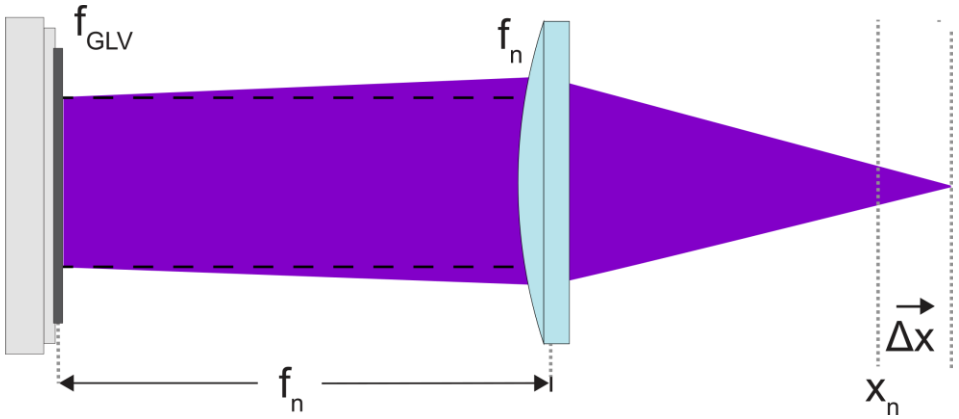
Focus = -5000 mm

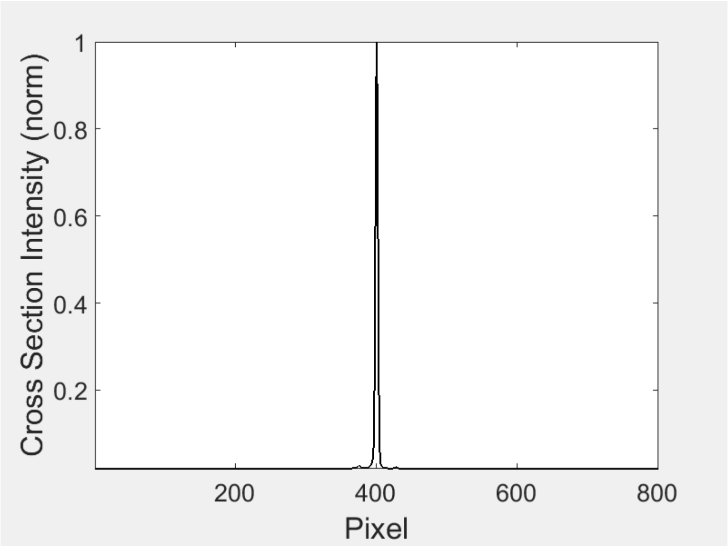
- **FWHM/nom = 1.05**
- **Acts as a diverging lens**
  - $\Delta x = +4.5mm$





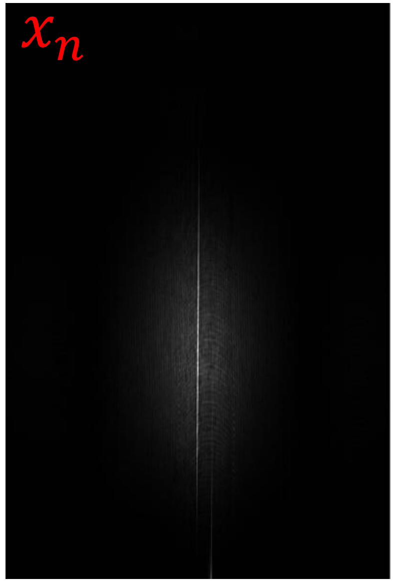


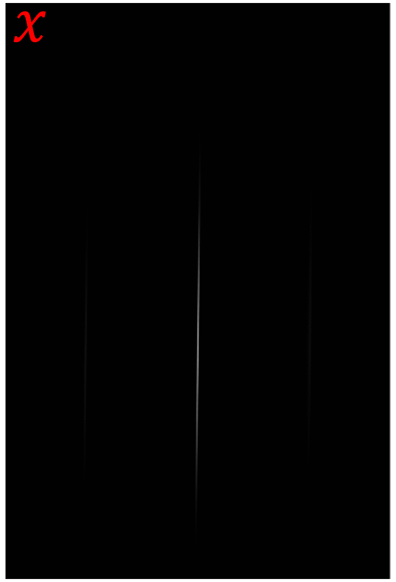


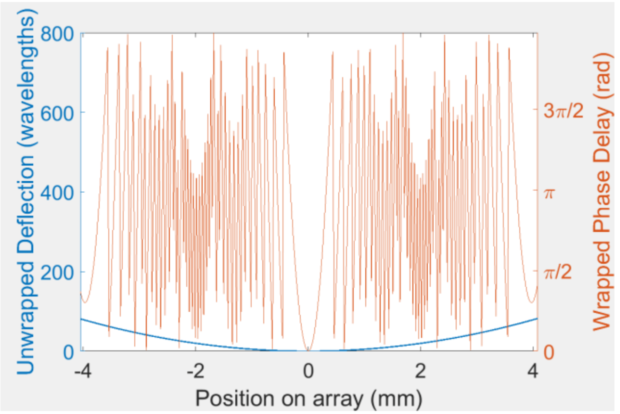


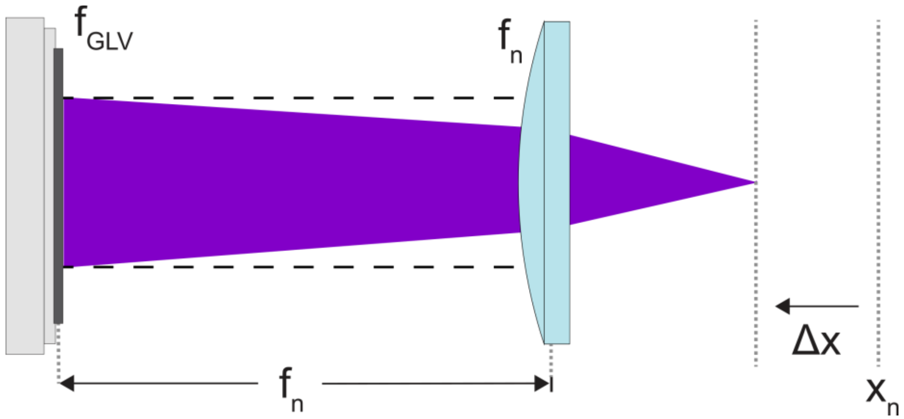
Focus = +250 mm

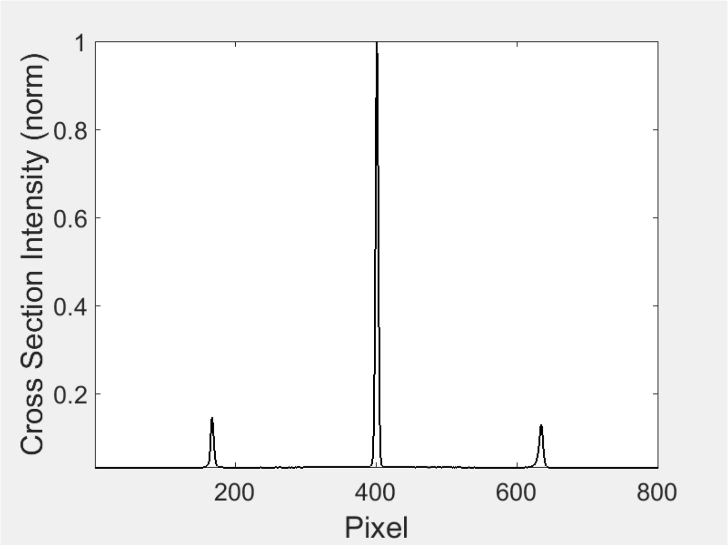
- **FWHM/nom = 1.04**
- **Acts as a converging lens**
  - $\Delta x = -90mm$
- **Phase wrap effects**
  - Higher orders start to appear
    - 25um grating response
  - Nominal plane sharpness





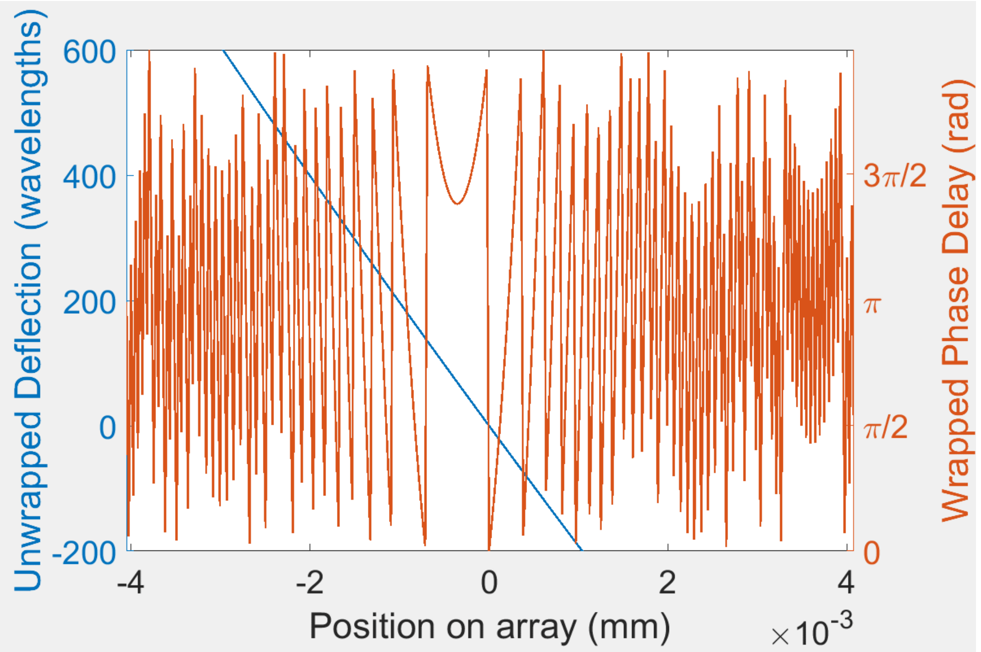


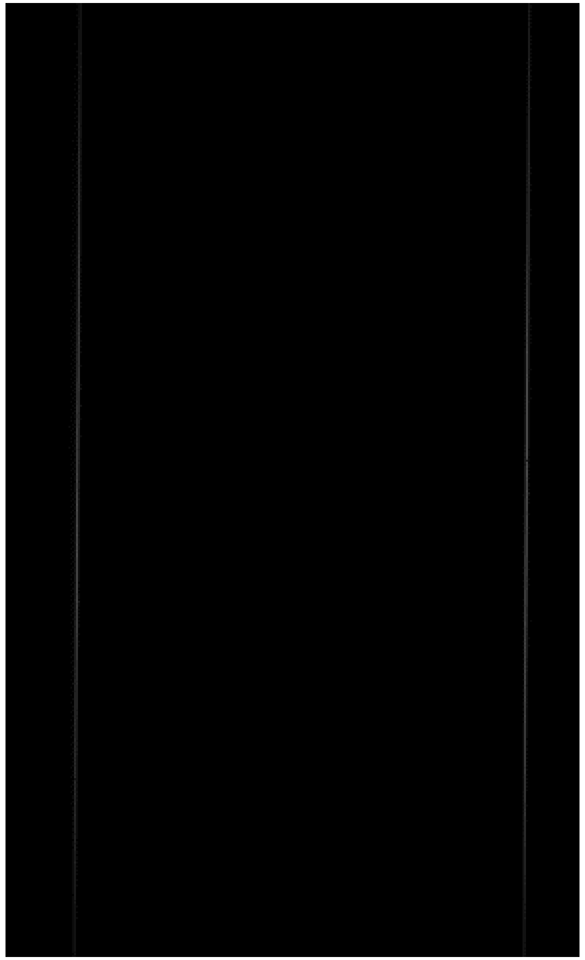


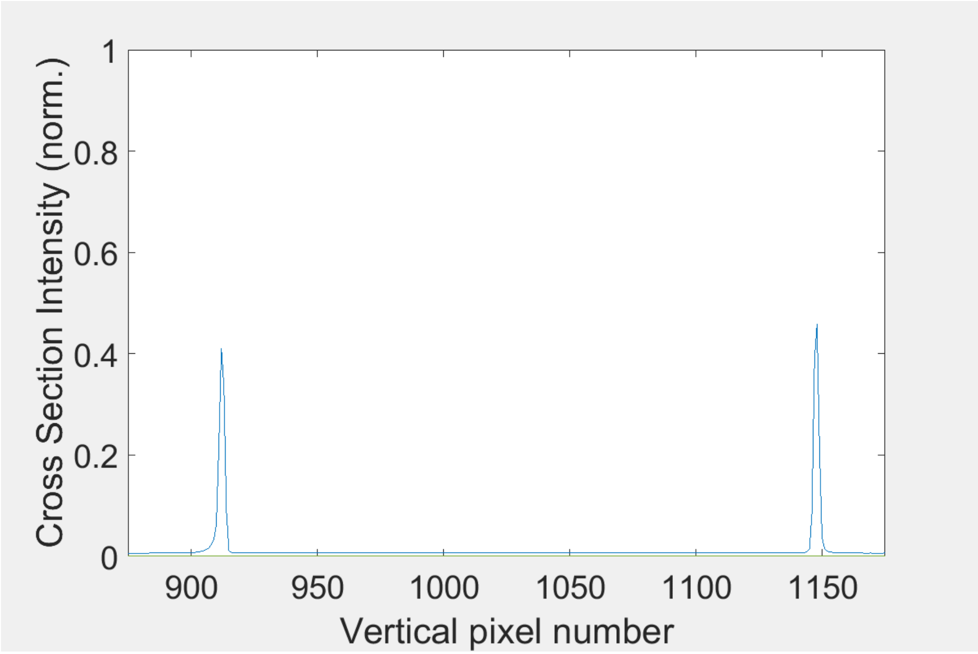


Full Beamforming Demonstratoin

- **Scan performed by adding linear and cylindrical phases (modulo 2π)**
  - f=500mm, x=115 mm
  - Note FWHM widening at edges





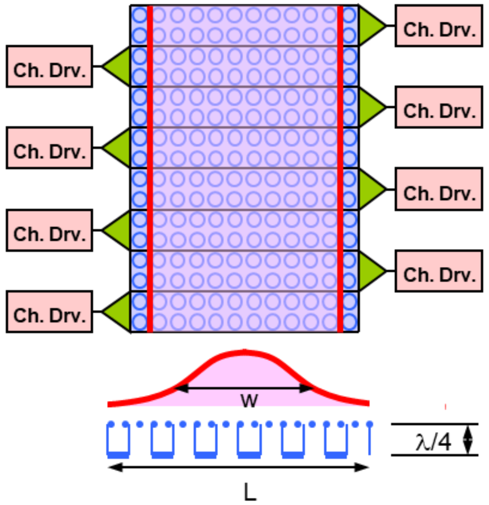


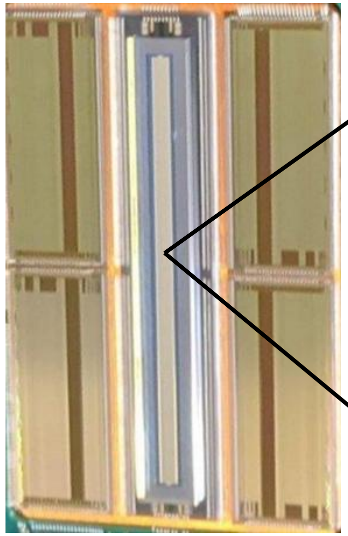
Far field Scanning Demonstration

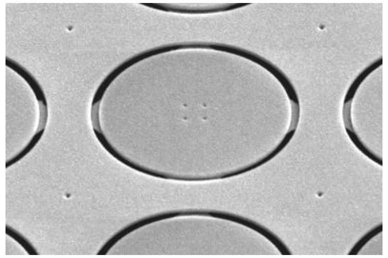
- **20x Magnification for ~20^{o} FOV at 405nm**
  - 2 lens mag w/o filter
  - Orthogonal divergence also magnified

2D High Speed Phase Modular – the PLV

- **Phase action through pistons**
  - 2D faceplate allows for high power, larger etendue, 2D control
- **Currently available, the Linear Planar Light Valve**
  - 2D aperture with 1D control
  - LPLV used for high power processing
  - Change of face plate possible for phase control



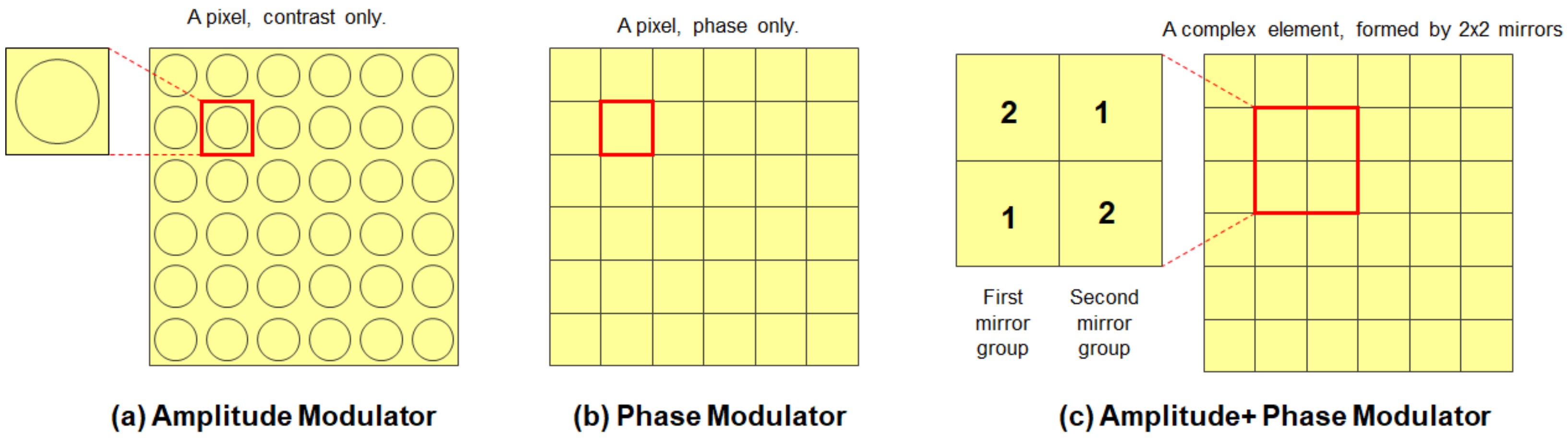




LPLV Piston design top view

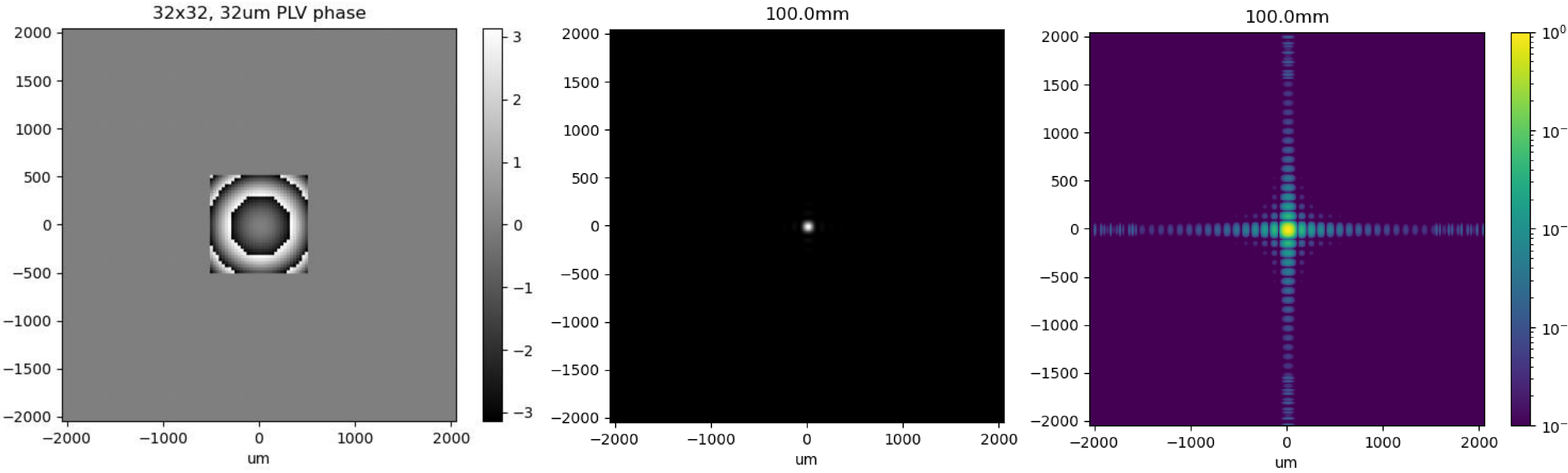
2D Modulation Coming Soon

- **2D Control**
  - Grayscale amplitude with contrast
  - Phase only
  - Complex modulation
    - 4 element, double phase method creates grayscale amplitude with averaged phase change

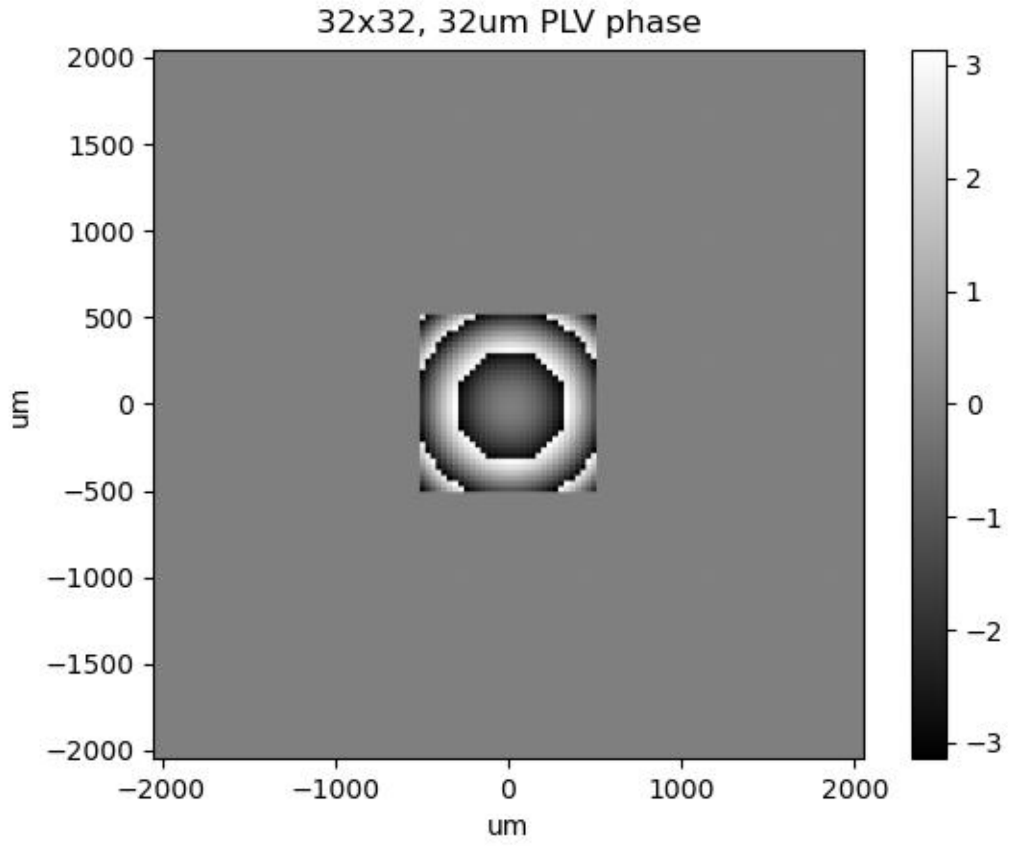


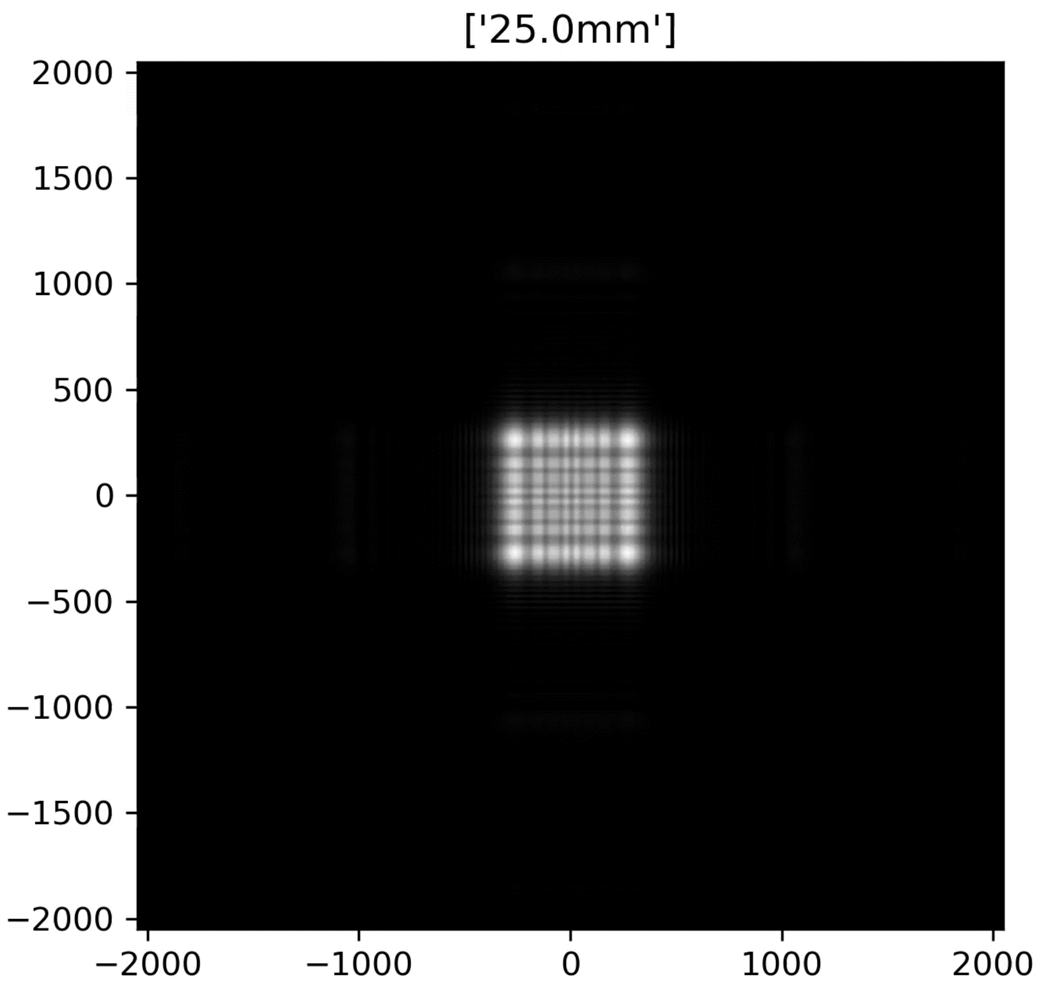
- **Demo module in development, expected end of year**
  - 100 kHz operation, 32 x 256 pixel count (8000 channels)
  - ~10 um pitch possible

Fresnel Simulation – 100mm lensing

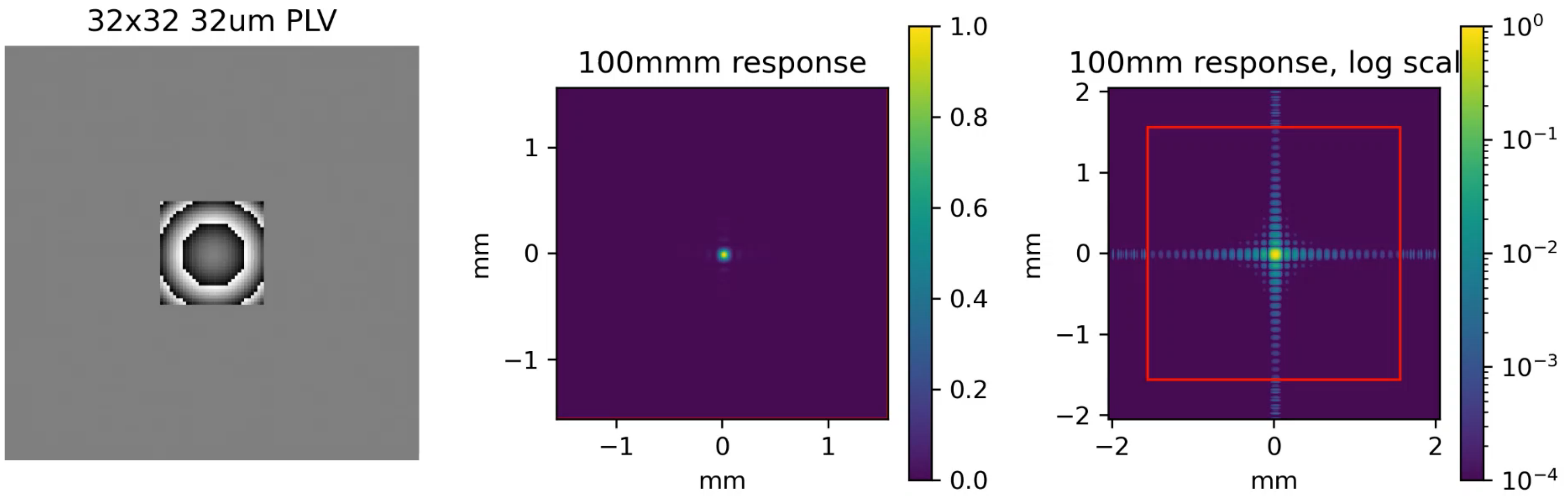


Fresnel Simulation – Through Focus

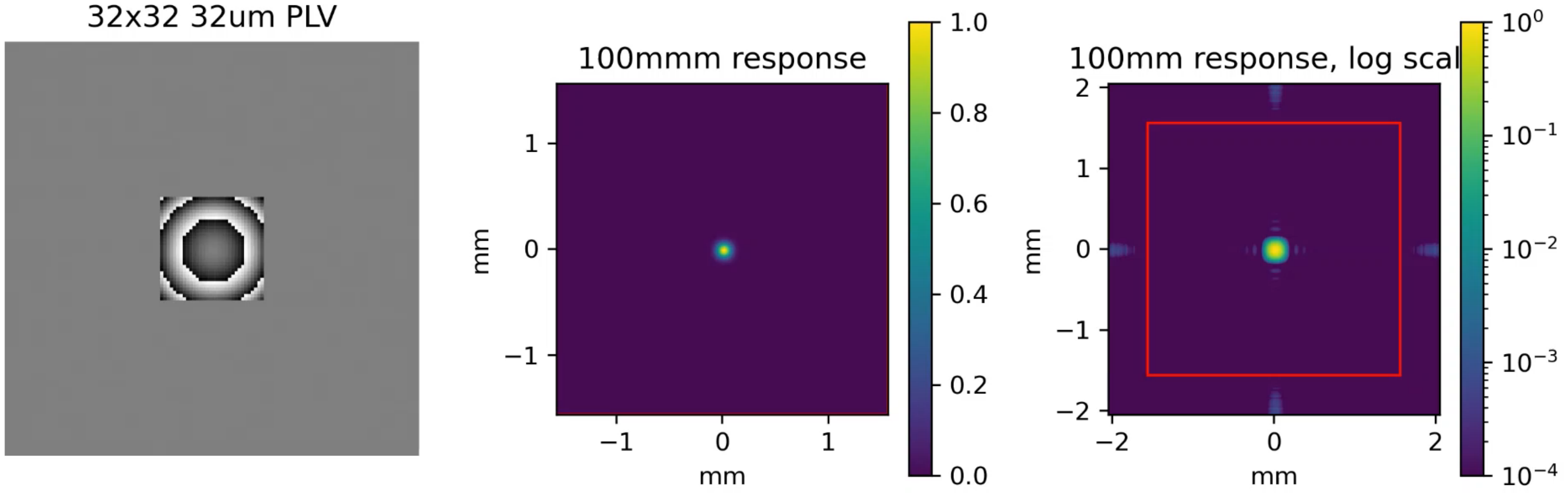




Fresnel Simulation – Steering at 100mm



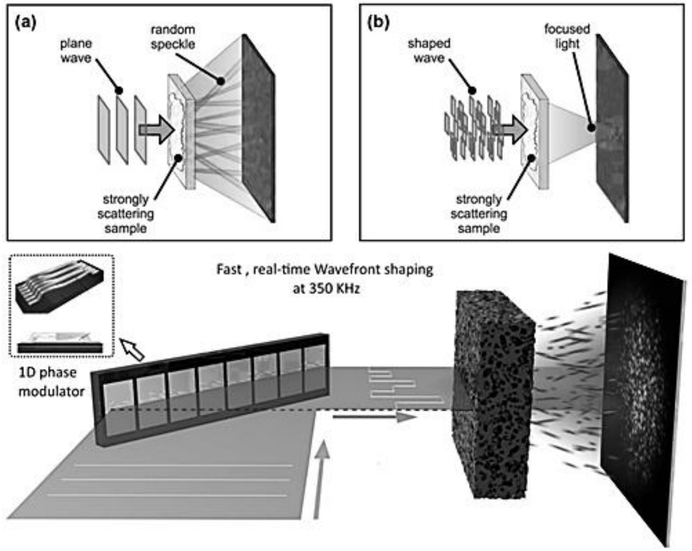
Fresnel Simulation – Gaussian apodization

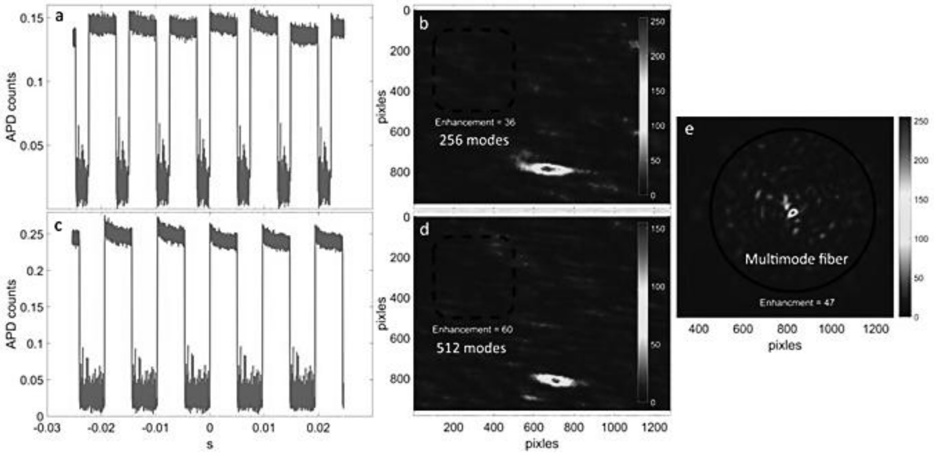


Line of sight?

- **No, beamforming does not require line of sight anymore than non-beamforming LiFi**
  - Concentrate light at a location for best bounce angle
  - Wavefront shaping to optimize transceiver-receiver link (demonstrated by Cao. Et. Al. [9])

- **Team at CU, Boulder demonstrated 1D phase GLV for focusing through scattering media [8]**
  - F1088-HS phase modulator is used in real time to shape wavefront; high speed with feedback absolutely necessary
  - Such techniques can be used for:
    - Turbulent media (clouds, fog, etc.) for long distance FSO
    - Indirect relay off of scattering surface (a wall) for LiFi, as with [9]





[8]

Scanning Mirrors and Lenses

- **Mechanical scanners too slow**
  - Steppers, etc.
  - Generally high power requirements
- **Tunable Lenses, only lens**
  - ~10 Hz switch speed
  - May be useful in larger systems, with other technologies
- **MEMS Mirrors and Galvos steer quickly on resonance**
  - Galvos ~10 kpps (ILDA test), resonant mode; MEMS – 10s kHz, resonant mode
  - Galvo – Thorlabs Digicube – “1000 impressions per second”, 45^{o} FOV, 24V 4A power supply [10]
  - MEMS Mirror – Hamamatsu – $10^{2}(-10^{4})$ Hz, ~$20\text{-}40^{o}$ FOV, USB powered (<2W) [11]

Other Established Technologies

- **Acousto-optic, Electro optics Deflectors**
  - Steering only, generally not used for point scans
  - Acousto-optic: Speed ~10^7 Hz range, ~10-100 mrad FOV [12]
  - Electro optics ~10^5 (steering) – 10^9 Hz (modulation), efficient
- **Deformable mirrors (Adaptive Optics)**
  - Piston actuators connected by deformable membrane
  - Not made for beamforming, generally low pixel count with large pixels
  - Boston Micromachines – 137 (100 kHz) to 4092 (15 kHz) [13]
- **Liquid Crystal On Silicon (Beamforming)**
  - High pixel counts, 10^2-low 10^3 Hz range [14],
  - Meadowlark - 1920x1152 pixels, 9.2um with 95.7% FF, up to 422.4 Hz [15]
  - Lumotive – Liquid crystal “metasurface” mobile LIDAR [16]

MEMS Phased Array Technologies

Silicon Light Machines

- GLV – 350 kHz, VIS-NIR, 1D 1000-8000 channels, 100 uW-1 mW / channel, 10-bit phase control
  - PLV – 100 kHz, VIS – NIR, 2D 8000 channels, available soon
- High speed, repeatable aperture, high quality beams

Tip-tilt phased arrays

- One or multiple actuators with both piston action and a tiltable faceplate
- Like deformable mirrors, generally low pixel counts
- Boston Micromirrors – 111 actuator, 37 segment 100 kHz -> 3063 actuator, 1021 segment, 15kHz [17]

More MEMS technology coming out

- Tip tilt and others often in academic journals
- Prof. Wu lab at Berkeley – Lateral moving gratings to produce phase shift
  - 160 x 160 phased array, 19.1x20um, 175 kHz, 85% FF [18]

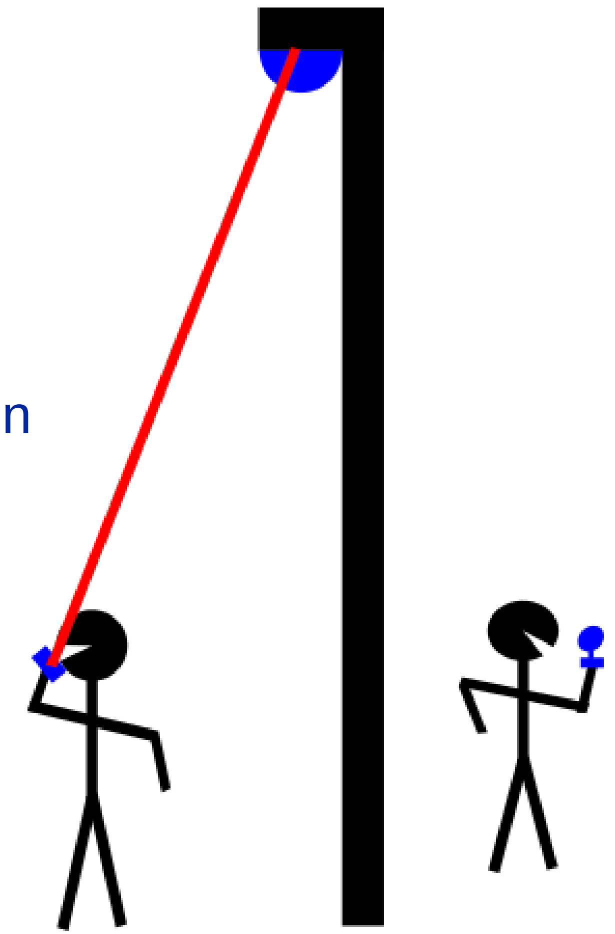
On-chip photonic Technologies

- **Waveguide based emitter phased arrays**
  - Integrated for possibly low power, high channel counts, high speed, low cost
    - Channel counts ~10^2-10^3, speeds (10^2-) *10^5* (-10^6) Hz
    - VIS (SiN) – NIR (Si)
  - Multiple tuning techniques for 1D or 2D control: thermal, wavelength, resonator…
- **Impressive in lab results**
  - Analog Photonics, Poulton et. Al.
    - 46^o x 36^o FOV, $.85^o$ x $.18^o$, thermal (1.2W) and wavelength, 1.2 x .5mm footprint, [19]
  - Higher grating and sidelobes than theoretical due to phase control
    - Have not started to thoroughly explore wavefront shaping
  - " Working to bring down power"
- **Stealth mode technologies**
  - Analog Photonics (Dr. Watts) – Exciting product list [20]
  - Expect to see more and more OPA tech with more LIDAR startups

Technology Depends on Use

SILICON LIGHT MACHINES

- **Base needs to cover wide area, multiple devices**
  - High speed for tracking and multiplexing
  - Higher beam quality needed for small receivers
  - May have space for more complex optics, multiple transcievers
  - MEMS phased arrays, galvo/MEMS scanner, OPAs
- **Mobile devices have different needs**
  - Power and space more critical
  - Communicate with single device, only need high speed for aquisition
  - Base may have larger receiver -> mobile larger divergence
  - On-chip OPAs, MEMS mirror, MEMS phased arrays



Conclusion

- **Beamforming is needed for LiFi 2.0**
  - Steering gives at least ~40 dB higher signal than non-directed
  - High speed random access needed for receiver finding, tracking and multiplexing
  - Consumer use cases will still need non-line of sight devices
- **Technology for beamforming exists now**
  - Scanners too slow, not random access
  - Older technologies ready for demonstration, but may still be too slow
  - High speed photonic technology gives random access and flexibility
  - Silicon Light Machines technology
    - Demonstrated visible MEMS 1D beamforming, NIR and 2D demonstrations later this year
    - 100s kHz range, small elements, large apertures, high power capabilities
    - Long range transmission with narrow, high-quality beams with flexibility of full phase modulation

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