MEMS Displacement Phase Modulator for Quantum Computing

SILICON LIGHT MACHINES

With support from Infleqtion

Contents

Introduction

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Inflection

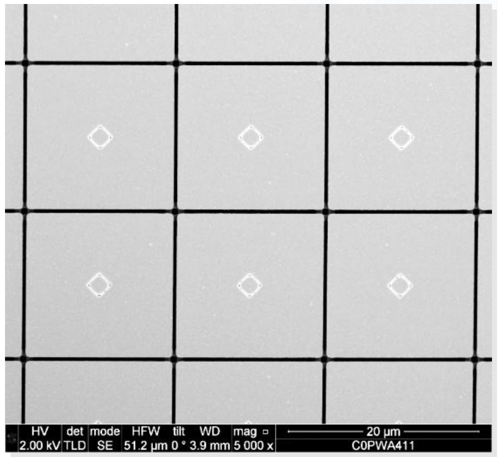
Introduction

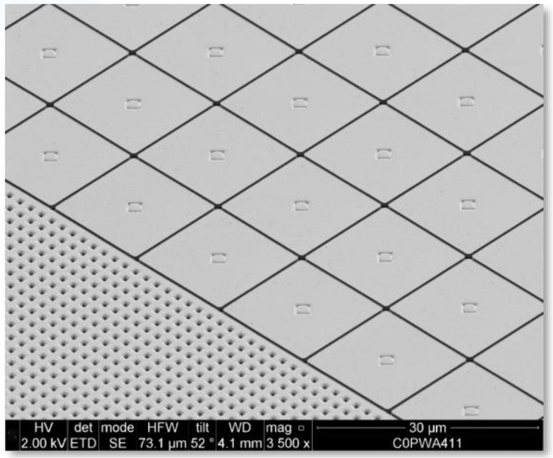
- **Quantum Computing is an exciting technology that has many important applications including**
  - Material science
  - Chemical and pharmaceutical simulations
  - National defense (e.g. combinatorial optimization, cryptography)
- **Silicon Light Machines new MEMS Displacement Phase Modulator (DPM^{TM}) technology offers unprecedented speeds that will enable new and improve existing approaches in quantum computing**
  - SLM’s SiGe MEMS technology integrates non-contact piston modulators monolithically onto CMOS drivers for unparalleled speed and reliability
  - This high-speed phase modulation has exciting applications for quantum computing including cold/neutral atom and ion trapping qubit addressing, free space and fiber multiplexing, and laser processing for waveguides
- **Infleqtion’s unique optical architecture for neutral atom enables large qubit arrays and high-fidelity gate operations at high speed**
  - Fidelity: Alkali hyperfine qubits are highly coherent, naturally-pristine qubits; Rydberg interactions enable precision qubit interactions
  - Scale: Optical tweezer arrays have demonstrated scaling to several thousand qubits with the potential to scale much further
  - Speed: Individual atom addressing reduces reliance on slow mid-circuit atom reconfiguration; Dual species arrays enables in-place, low-overhead mid-circuit quantum state readout

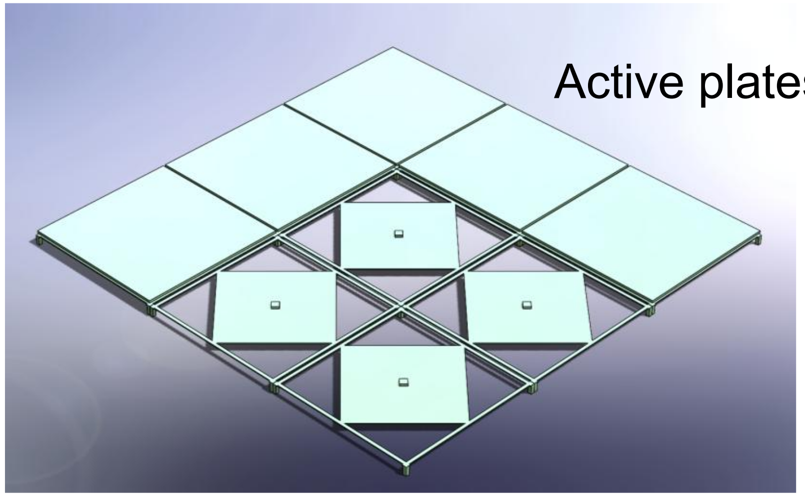
DPM^{TM} Technology

Displacement Phase Modulator™ – 2D Phase

Phase Modulator

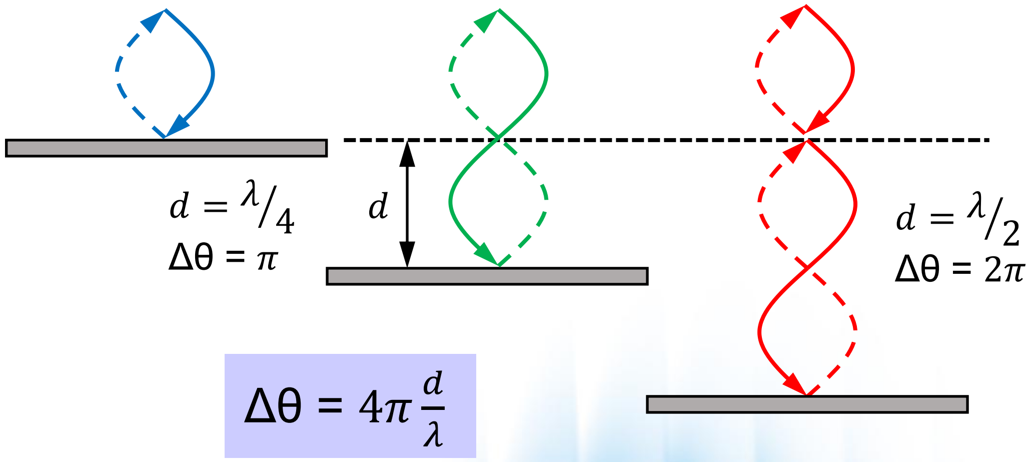




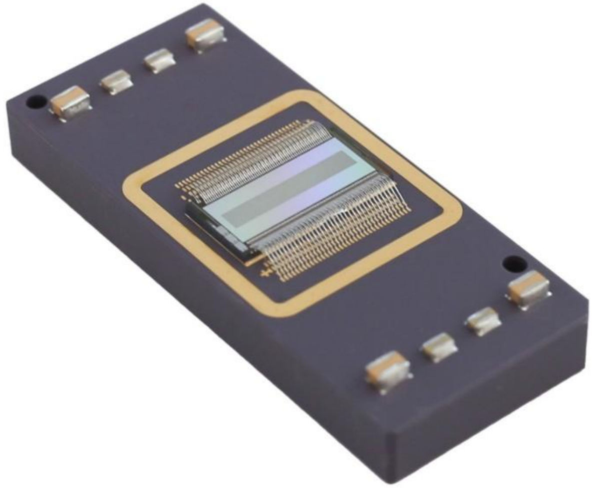


Top left – released 16um pitch elements
Top right – Cartoon of two layer design
Bottom right – displacement phase modulation

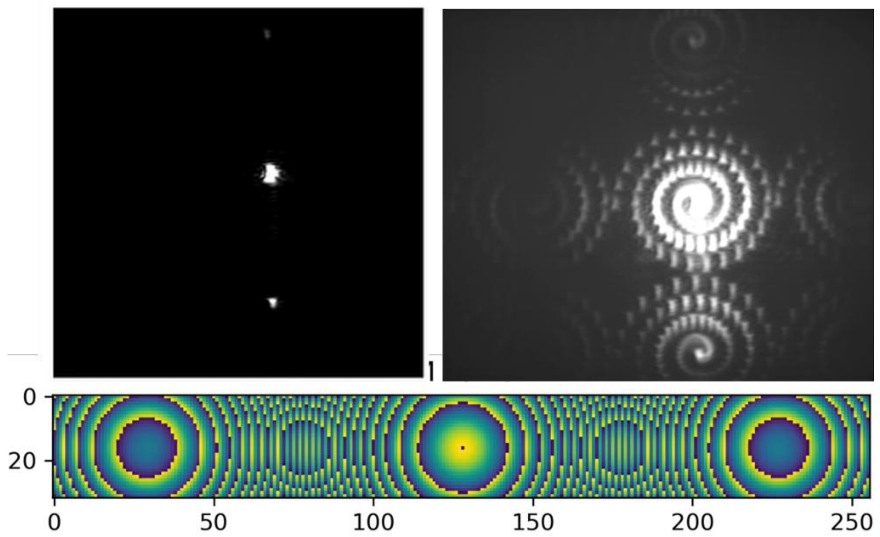
- **Pure piston motion for high speed phase modulation**
  - Non-contact piston motion for speed and reliability
  - Square faceplate with high fill factor
  - Broad wavelength control



DPM^{TM} – Available Now 32x256 UV-VIS

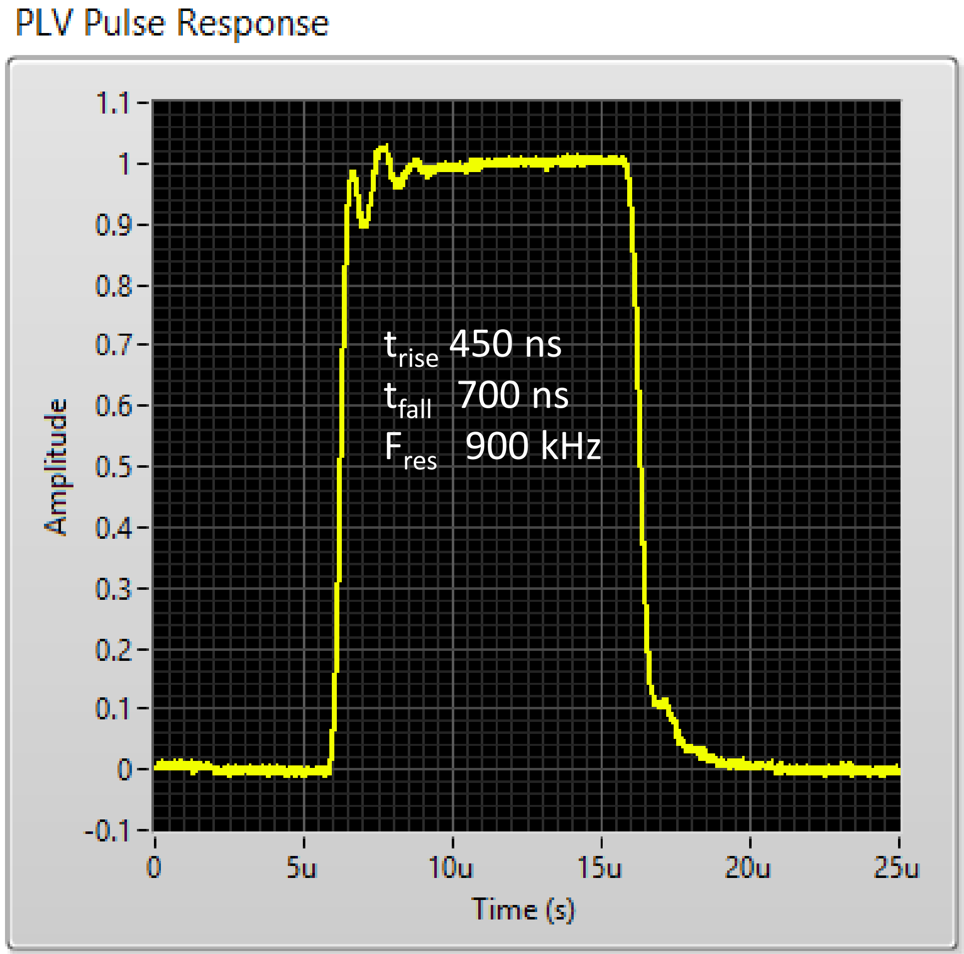


- **Available now - 32x256 UV-VIS(Green) DPM**
  - 250 kHz, 7-bit linearized DAC
  - ~343 - 532nm (at 15^{o} AOI)
  - 32x256 pixels, ~1x8.2 mm active aperture
- **Coming soon - 128x128 UV to NIR DPM**
  - First devices coming Summer 2026
- **Future – More pixels, higher speeds**



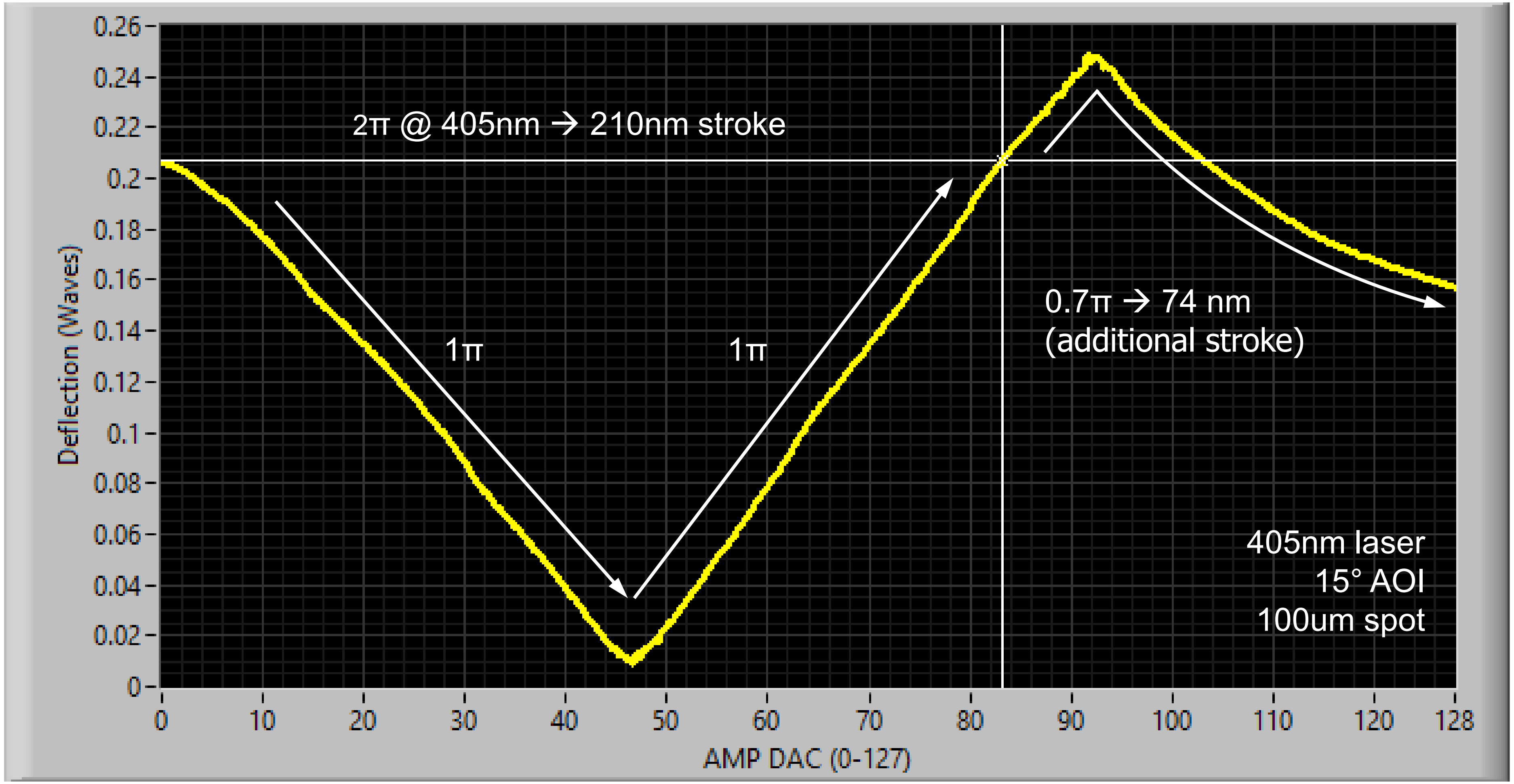
High Speed Modulation

- **The 32x256 DPM is capable of 250kHz modulation**
  - Full frame refresh - 4µs period
  - Preloaded controller full speed
  - Streaming controller depends on system
- **Right shows a typical pulse response of the PLV**
  - Shared platform – same speed



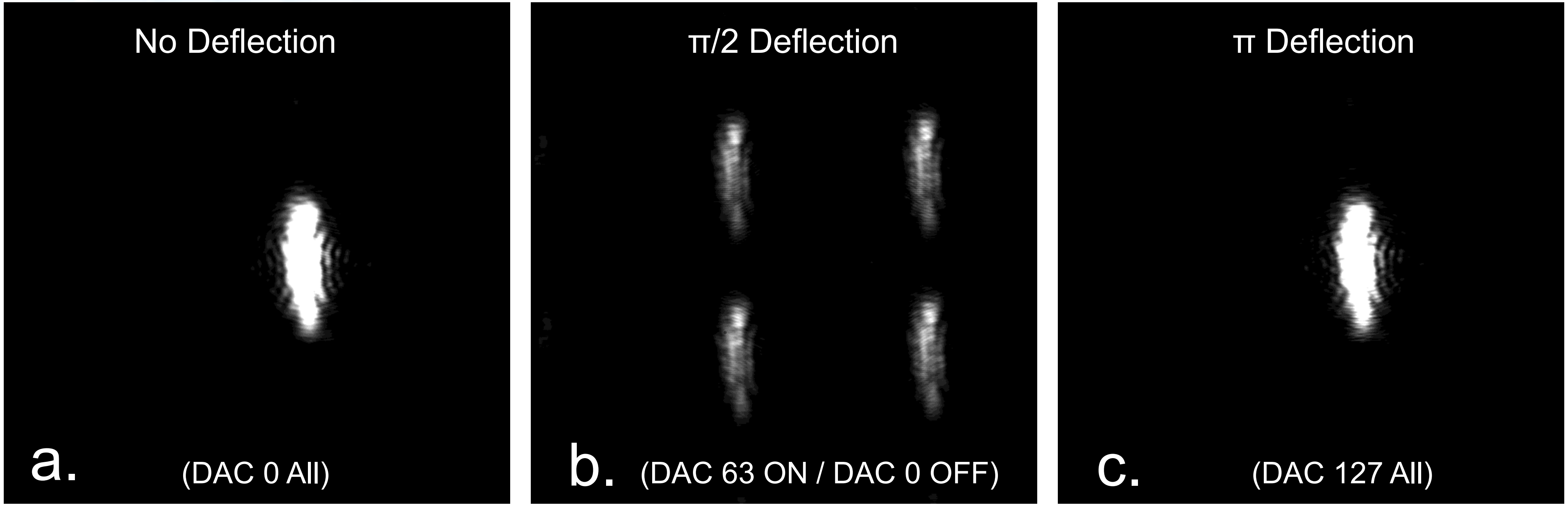
Phase Linearized DAC

6364-09 Peregrine Phase Modulator 405nm (REFG 170 VHV 970, VSSC 170)

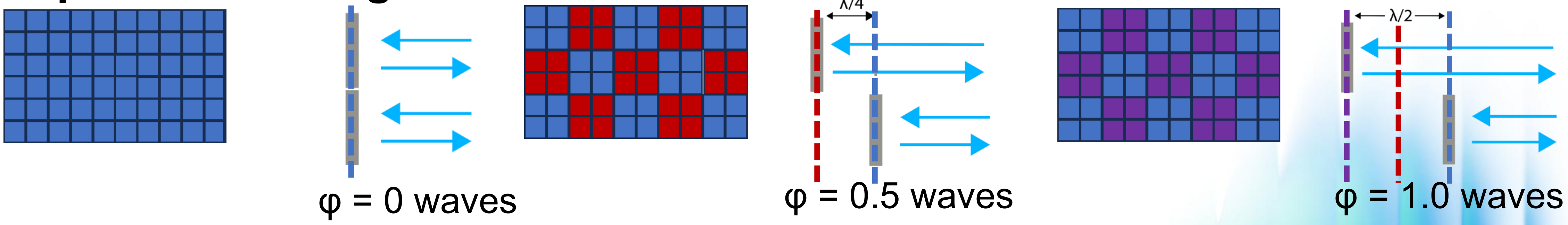


- **With 284nm stroke, phase modulation at 560 nm (green) phase modulation possible**

Phase Modulator Testing



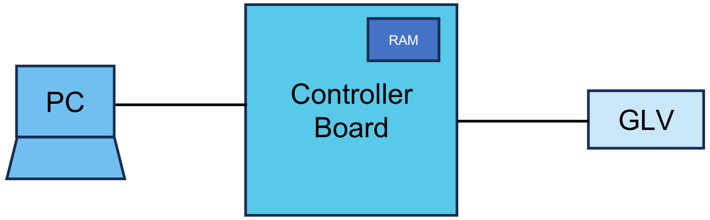
- **Far field response of on/off checkerboard pattern further demonstrates linearity and potential for high zero order contrast**

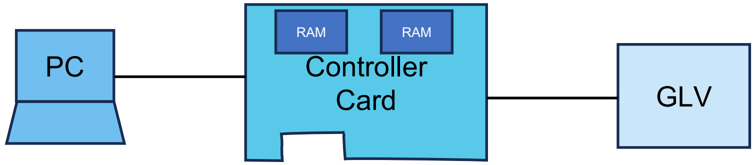


Controlling the DPM at High Speed

Predetermined Controller

- Enables evaluation of various devices using a single controller board.
- Supports single pre-determined data uploading of 50k+ columns/frames with actual upload size depending on the device.



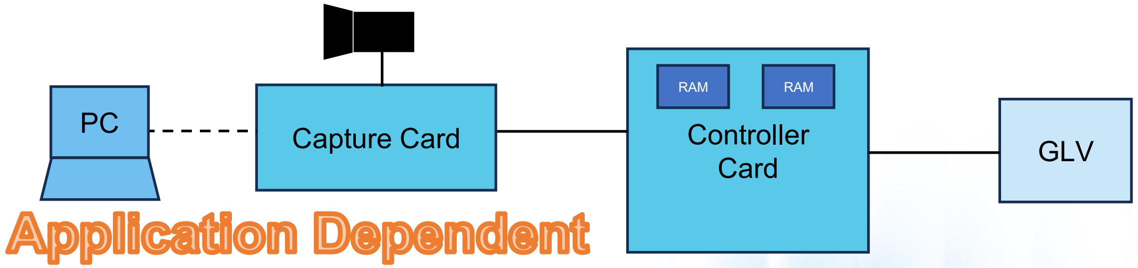


Streaming Controllers

- Features dual bank memory for streaming nonstop continuous data.

Real Time Controllers

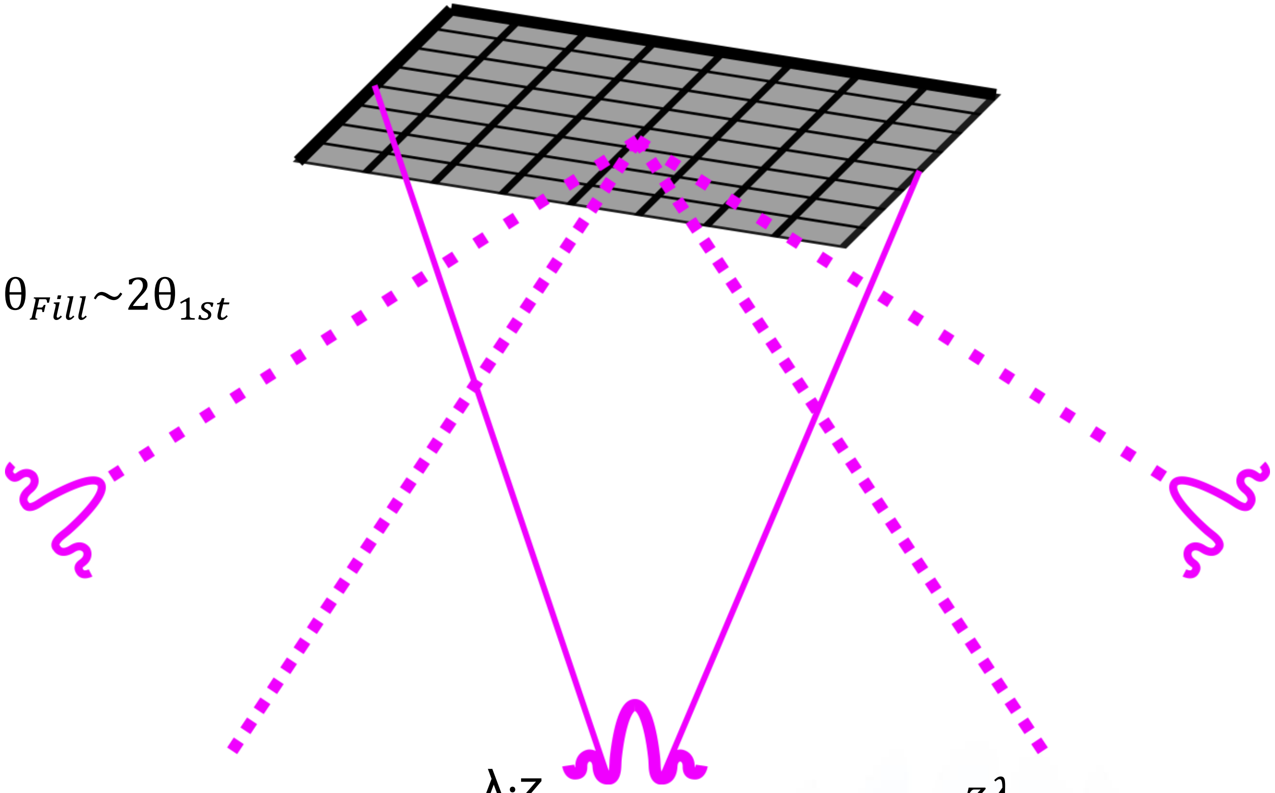
- Designed to achieve a single column continuous data stream.
- Requires an additional capture board to send data directly to the streaming controller.



DPM Holography

DPM™ Phase Only Holography

- **The DPM is a phase modulating device and may use any phase-only CGH technique**
  - The following examples use an IFTA based approach
  - Fraunhofer holograms are formed in the far field or in the "Fourier plane" or focus of a lens
  - Fresnel holograms may be formed at an arbitrary distance, including at a lens focus
- **Certain aspects of a hologram are determined by the modulator specs**
  - The field of view of a hologram is constrained by the first order diffraction angles, dependent on wavelength and pixel pitch
  - The minimum resolvable spot is dependent on the device aperture
  - The fidelity and "addressable grid" of a hologram is dependent on the modulator resolution, both spatial (number of pixels) and angular (DAC levels)
  - The zero-order efficiency goes as the square of the pixel fill factor.



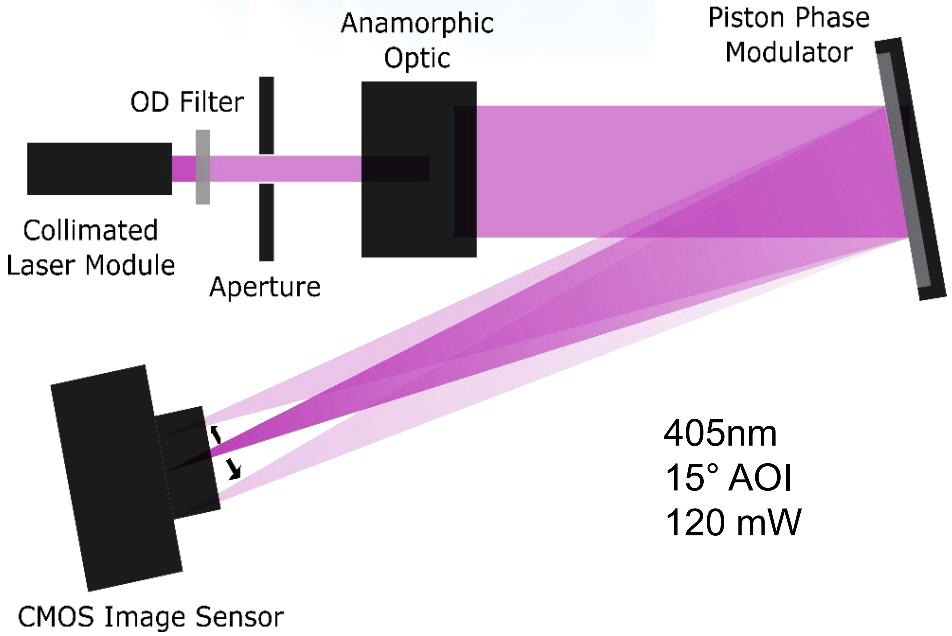
$\theta_{Fill} \sim 2\theta_{1st}$

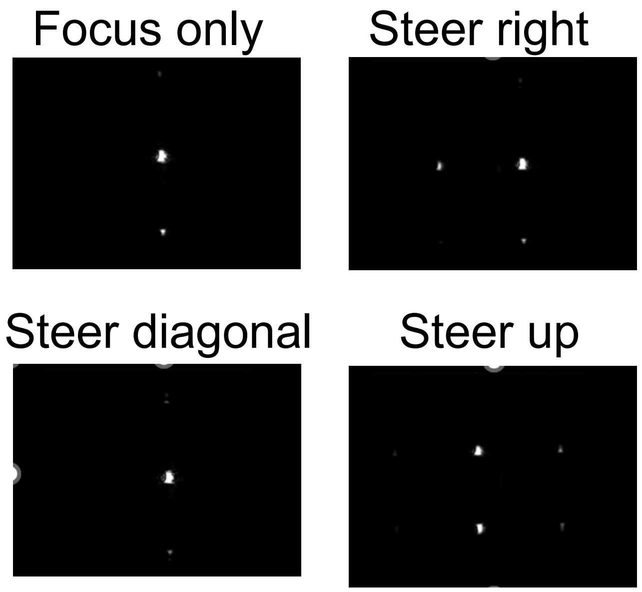
$\Delta H_{extent} = 2\theta_{1st} \sim \frac{\lambda \cdot z}{p}$

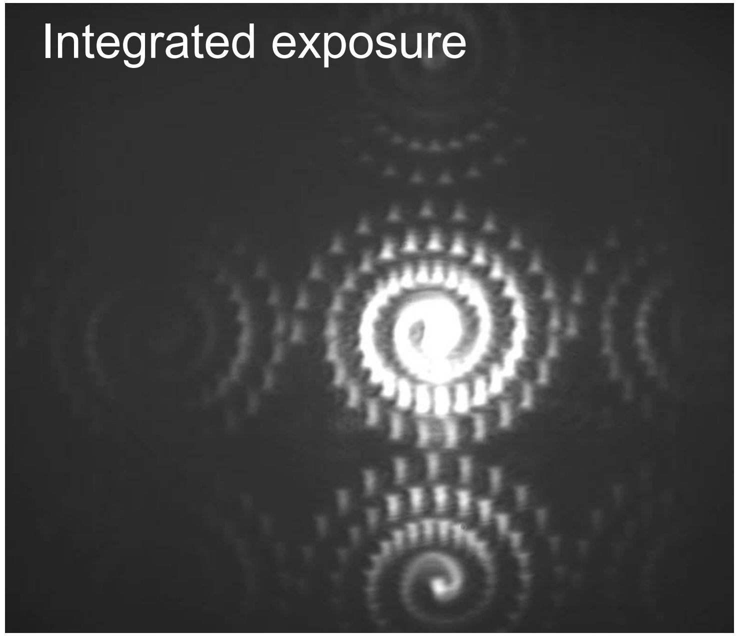
$r_{Rayleigh} \sim 1.22 \frac{z\lambda}{np}$

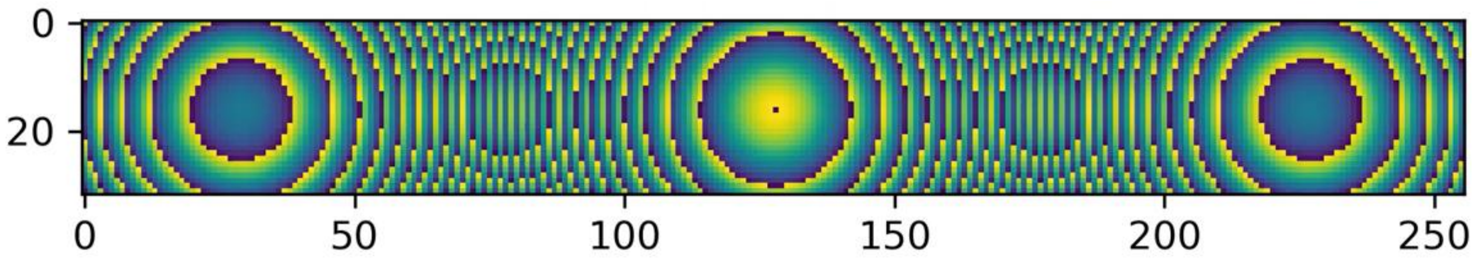
$\eta_{0th} \sim (Fill)^2$

Analytical - Beam Focus & Steering



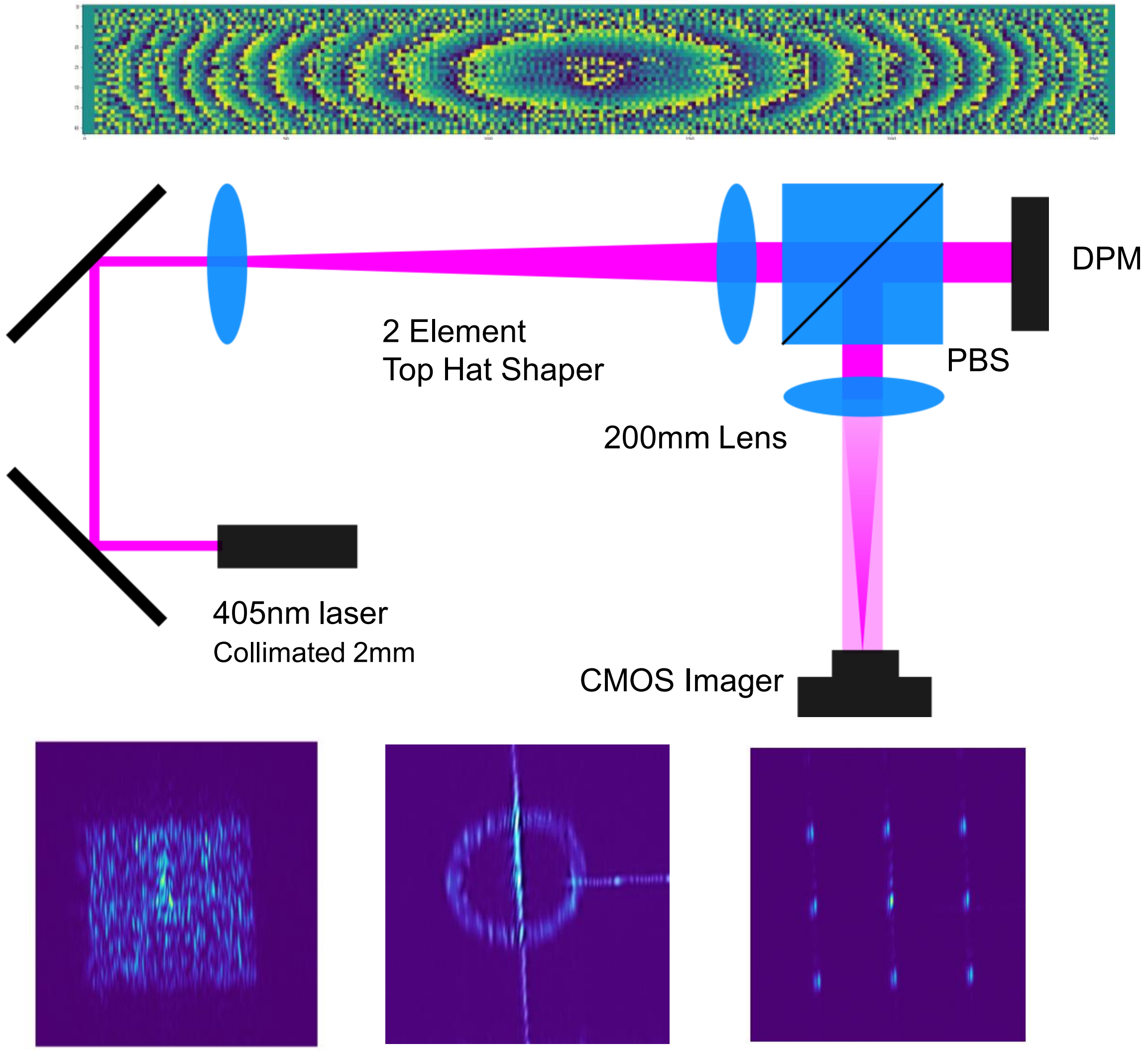






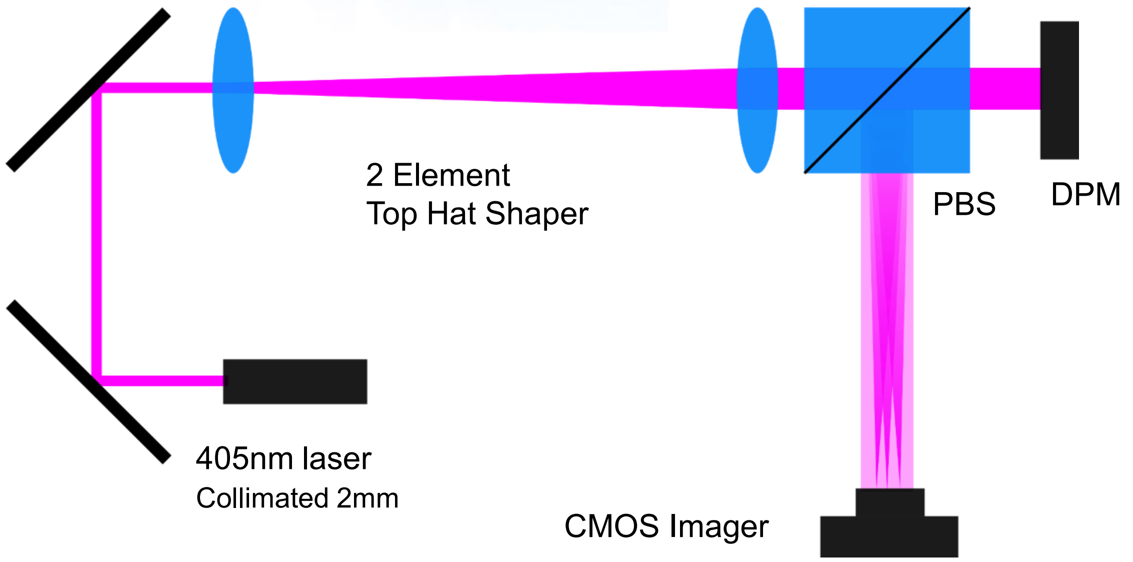
- **Phase modulator programmed with successive Fresnel phase patterns**
- **405nm beam focusing and beam steering at 200 kHz (5us update)**

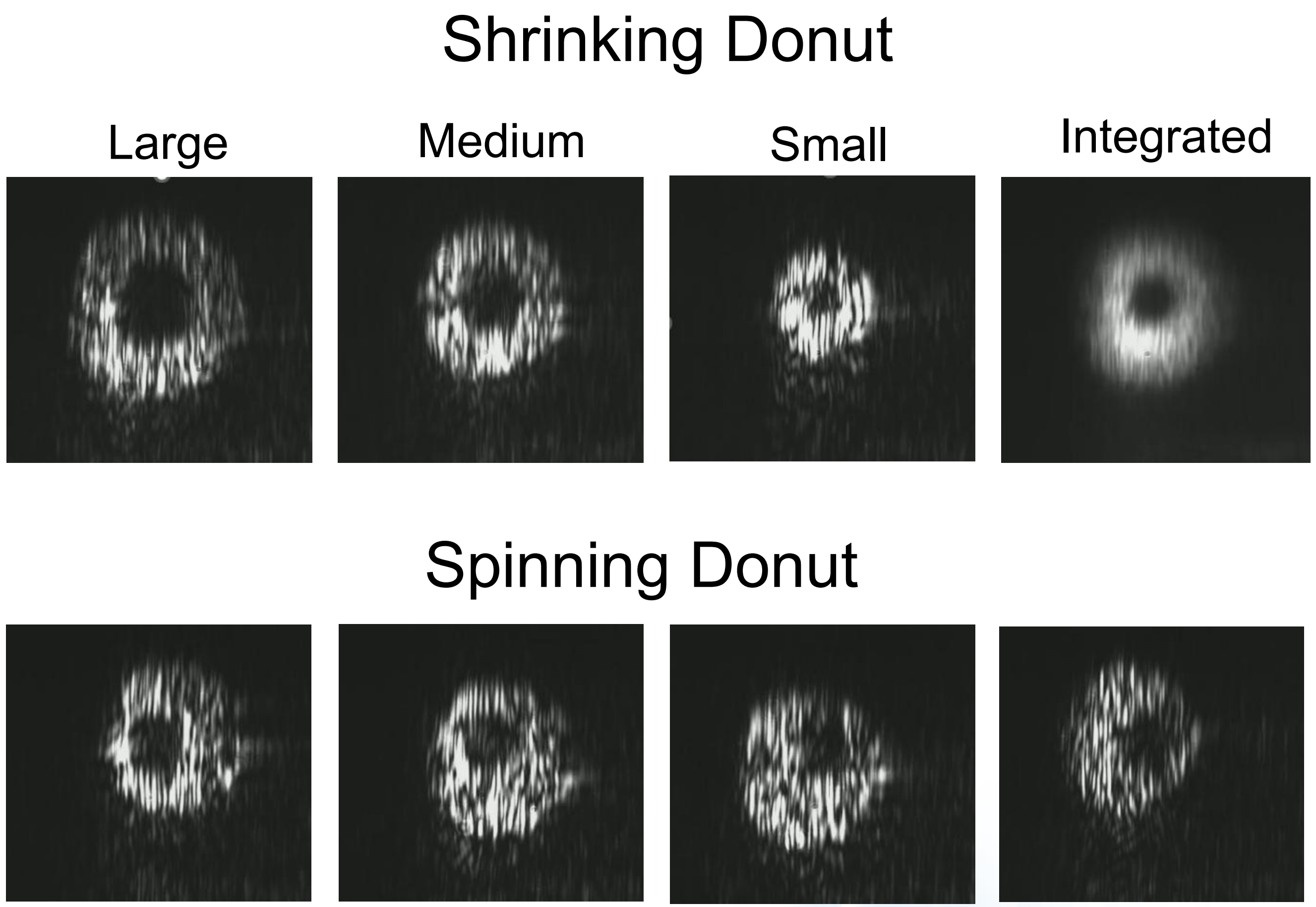
Beam Shaping for Industry - Verified



- **Fresnel hologram beam shaping at TOS**
  - Testing done with Robin Kurth and Jörg Hoffman of TOS, RWTH Aachen; Annika
  - First articles with known issues (fixes coming)
    - Slight backplane bow and faceplate bow
  - Holograms are calculated using an IFTA
- **Initial results show preliminary devices are ready for beam shaping**
  - Slight defocus found from backplane bow
  - **No zero order effects** from faceplate bow
    - Affects efficiency
    - Fix is known and will be incorporated in future builds
  - **No cross talk** in spatial frequency testing
  - Results are visually matching simulation – ***algorithms must take aspect ratio into account***

High Speed Dynamic Holography

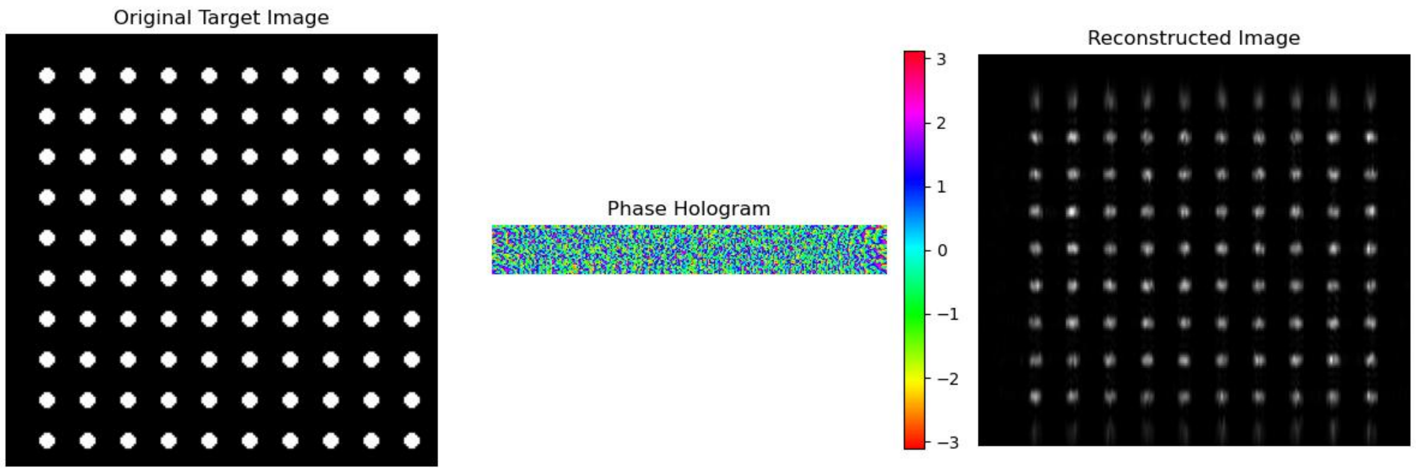




- **Note that a lens is not necessary for holographic beam shaping**
  - 405nm Fresnel holograms @ 400mm working distance
- **Shown right are video captured dynamic results at 400mm**
  - Top frames shows donut changing size, up to 250kHz
    - Integrated shows 400us exposure of 100 sizes
  - Bottom frames show spinning lopsided donut

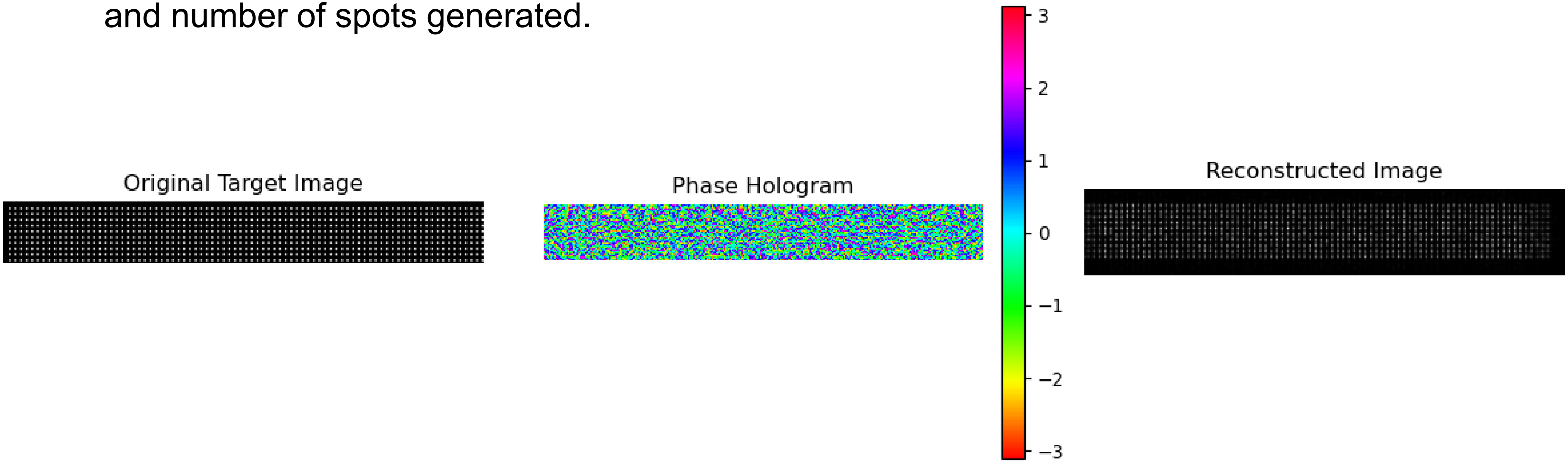
Spot Arrays – 32x256 Non-Anamorphic

- **The square pixel pitch results in a square FOV**
- **The 8:1 aspect ratio aperture results in a 8:1 hologram resolution**
  - Square or round pixels must be at the resolution of the short axis
  - Grid resolution may still be much higher in the long axis dimensions



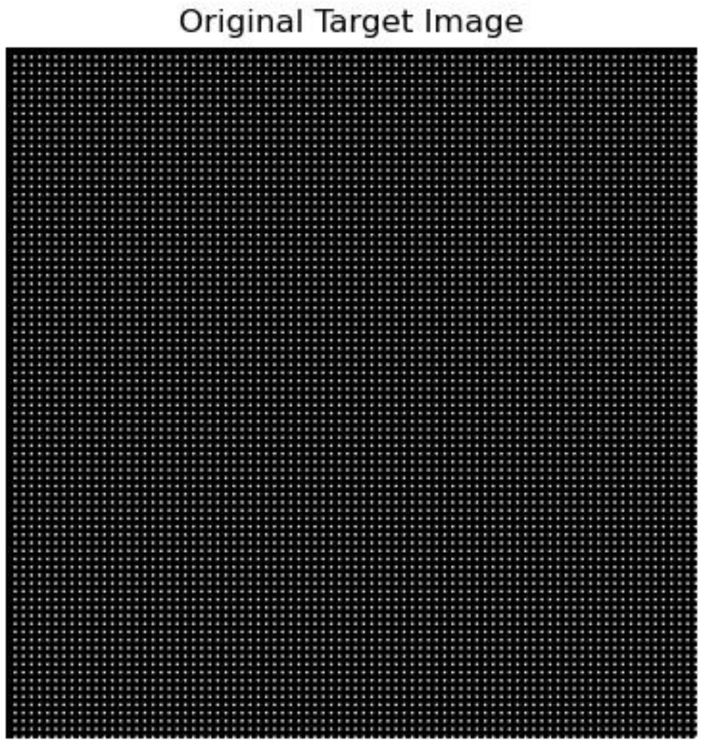
Spot Array – 32x256 Anamorphic

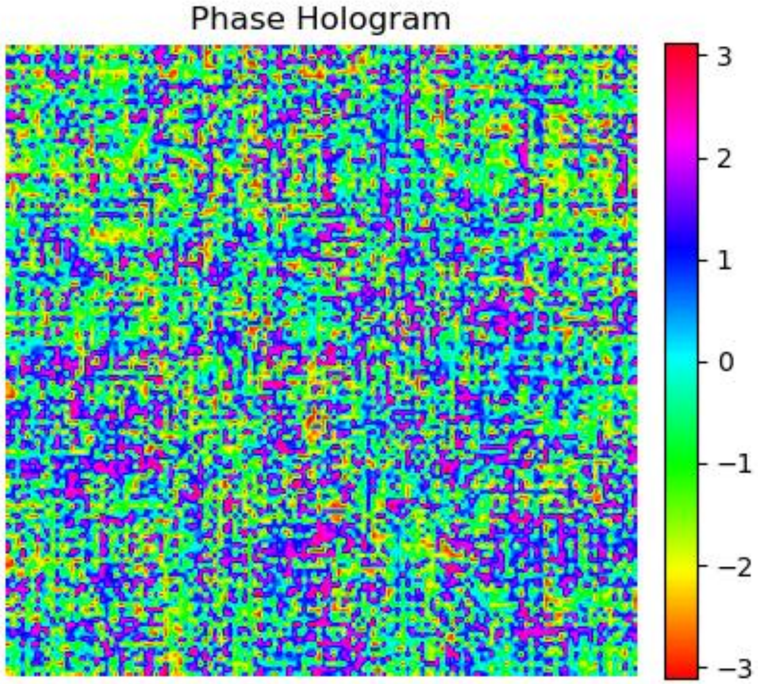
- **Introducing an anamorphic telescope or prism pair may elongate the log axis resolution to create symmetric spots and correspondingly increase the FOV by 8x in that dimension.**
  - Spot uniformity and contrast depends on holographic algorithm, optical system aberrations and number of spots generated.

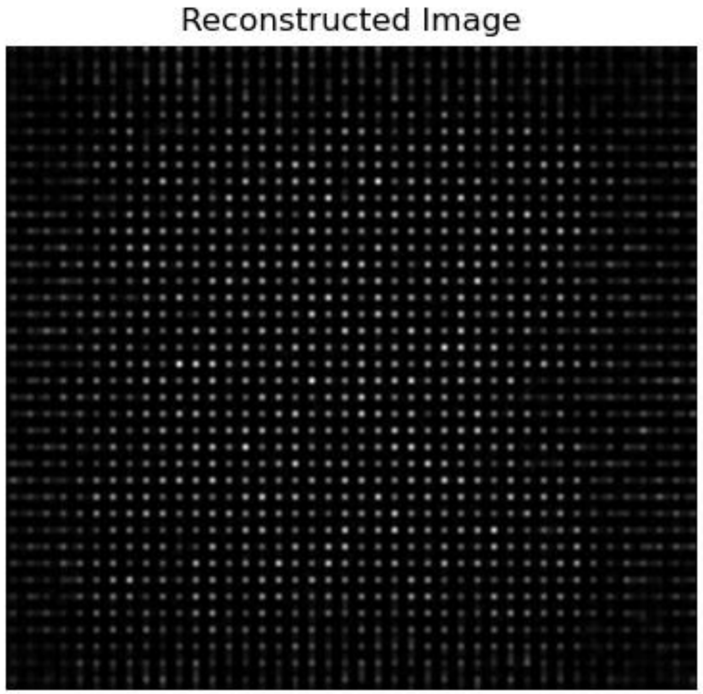


Spot Arrays – 128 x 128 UV-NIR DPM™

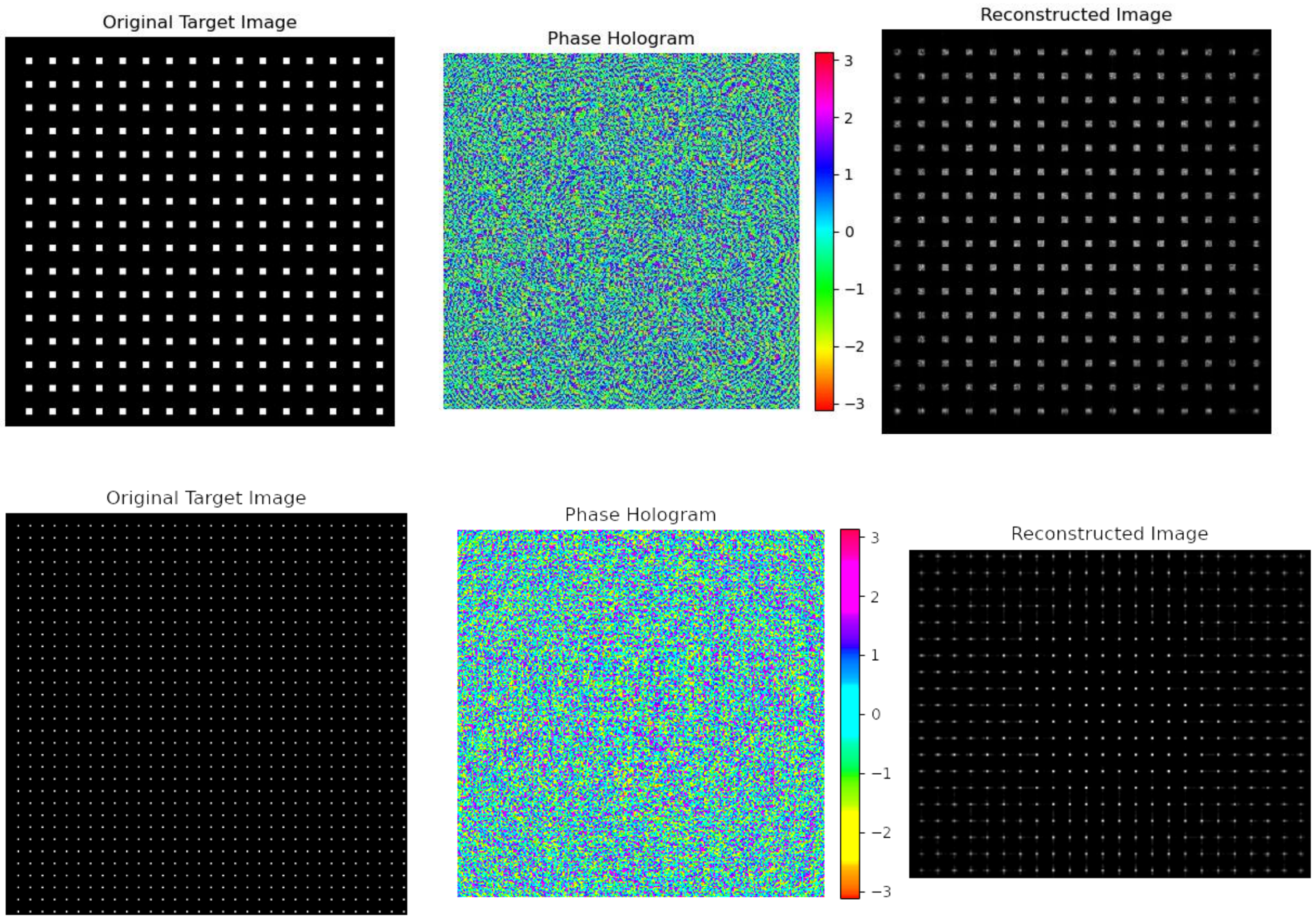
- **SLM is developing a 128x128 device that will enable larger arrays**
  - 100 kHz minimum operating speed
  - Operating wavelength range 343 – 1064nm







Spot Array – Higher Resolutions



- **Higher resolution, wavelength optimized devices are achievable**
  - Increased pixel counts may enable higher spot counts for increased bandwidth, finer grid placement, higher contrast and more uniform spots, or better correction of aberrations within the optical system

Neutral Atom Quantum Computing with DPM™

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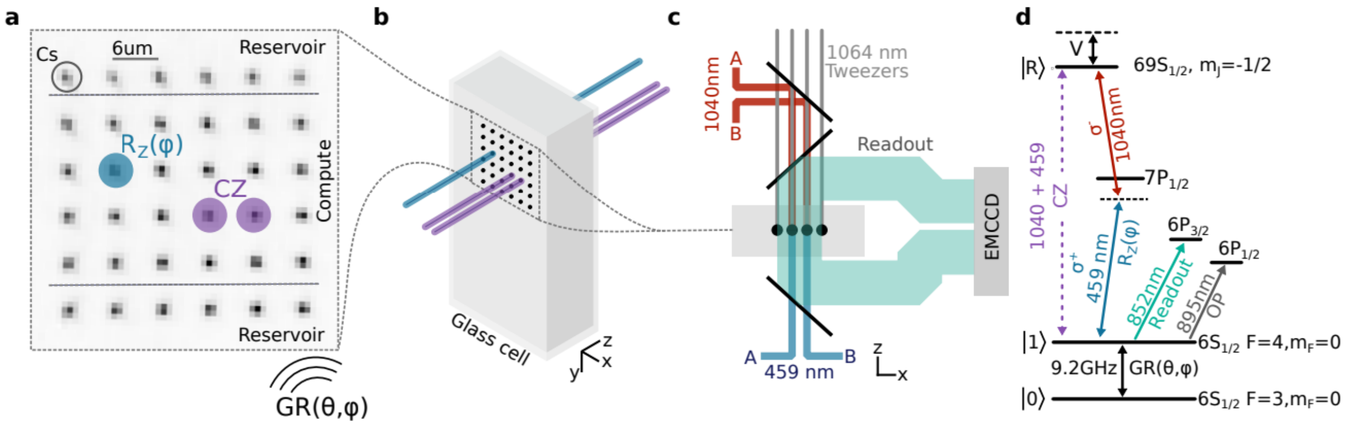
Neutral atom quantum computer overview



- **Neutral atom quantum computers are powered by the interaction of atomic qubits with control laser fields. Lasers are used to trap and arrange the qubits, to initialize the qubits, to implement a universal quantum gate set, and finally to read out the qubit quantum state.**
  a. Image of array of atoms (in this case cesium atoms), trapped in a glass cell.
  b. Locally addressed RZ(ϕ) (beam shown in blue) and CZ (beams show in purple) gates are applied via beams propagating perpendicular to the atom plane. Microwave-based global R(θ, ϕ) gates (labeled GR) address the entire array.
  c. Layout of key lasers implementing trapping and gates. Rydberg excitation is implemented by counter-propagating 459 nm (blue) and 1040 nm (red) lasers. Rydberg illumination for control and target qubits are sourced from separate pulse shaping systems (labeled A and B). An optical tweezer array (1064 nm) is generated via AODs and combined with the 1040 nm light. Readout fluorescence is collected and imaged on an electron-multiplying CCD camera
  d. Atomic levels and addressing fields, including lasers for two-photon Rydberg excitation, readout, and optical pumping (OP). Rydberg beams are circularly polarized (σ+ and σ- for 459 nm and 1040 nm, respectively). Rydberg blockade shift denoted by V .

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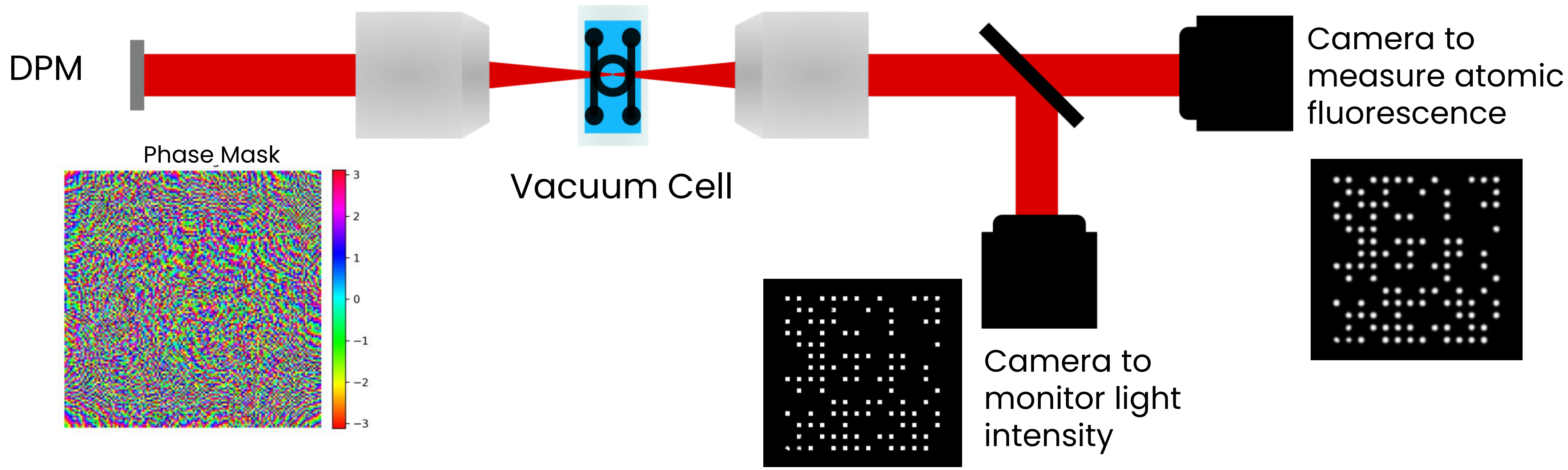
Example Set Up with DPM



- The SLM is patterned with a phase profile that corresponds to illumination of an arbitrary set of atoms enabling parallel execution of quantum gates on those atoms

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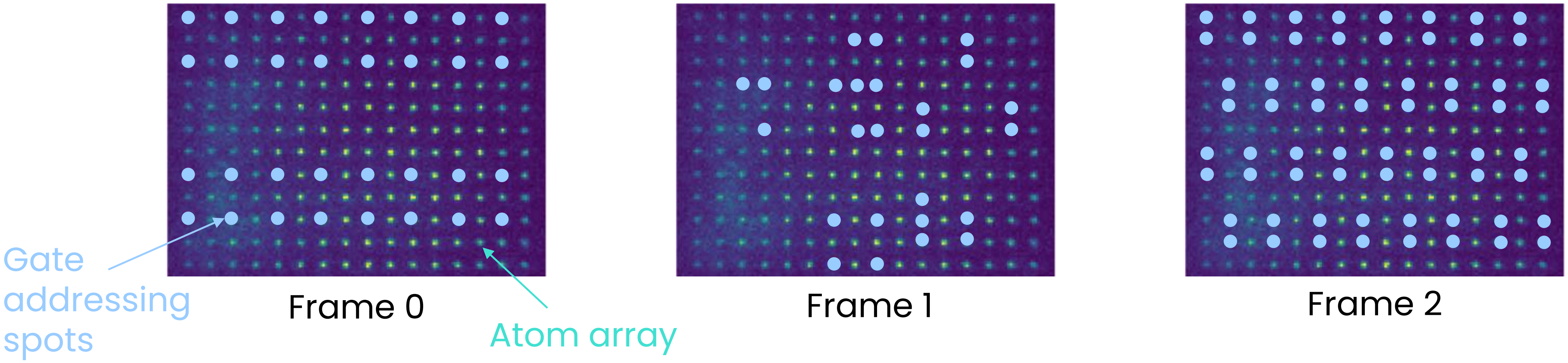
Benefits of High-Speed Modulation



- Neutral atom gates are fast requiring O(100 ns) to complete
- The determining factors for the rate of gate execution are typically technical factors associated with the addressing devices, atomic reconfiguration,
- Fast modulators allow the frame switching time to approach the duration of the gates themselves, vastly improving operational speed

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Further DPM™ benefits for Cold Atom

- **DPM™ can work from UV to NIR**
  - Broad wavelength compatibility is a bonus for atomic systems where many wavelengths from the UV to the IR are used
- **DPM™ has high power handling**
  - Optical power handling considerations are also important for quantum computing applications where the power per spot may be on the mW scale, implying that patterns with many hundreds or thousands of spots may require many watts of power handling
- **DPM™ has high resolution 7-bit linearized DAC**
  - High resolution (both in terms of pixel count and DAC) allows more accurate reproduction of the desired illumination pattern, for example achieving a larger extinction ratio between spatial regions where light is desired to be present vs absent
  - 128x128 (16k) NIR device coming 2026, with higher pixel counts possible

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Conclusion

Conclusion

- **Neutral atom quantum computing is an exciting approach to quantum computing due to its potential for massive qubit scalability, fast and high-fidelity gate operations, and naturally coherent qubits—making it a promising platform for implementing quantum error correction at scale.**
- **Infleqtion's pioneering approach leverages two atomic species and individual laser addressing to minimize error-correction circuit runtime**
- **The high speed of the DPM™ provides flexible, fast, arbitrary laser addressing of atom arrays enabling increased gate execution rate and further reduced circuit runtime**
    - Future devices can be made with larger pixel counts, higher displacement resolution, and increased frame rate
    - DPM™ devices can also be paired with other technologies of complementary strengths
        - Scanners such as galvos or AOMs for increased FOV or sub-resolution adjustments
        - DOE or LCOS spatial light modulators for higher resolutions and multi-planar light converting (MPLC) modalities