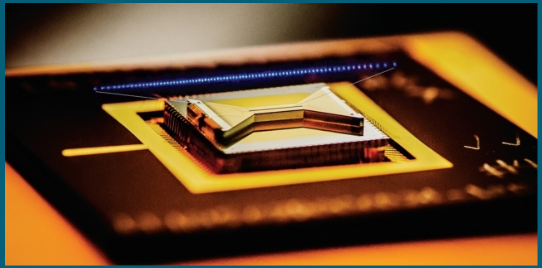
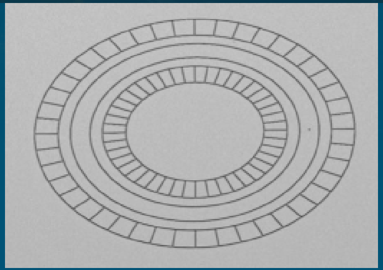
SAND2023-03474C

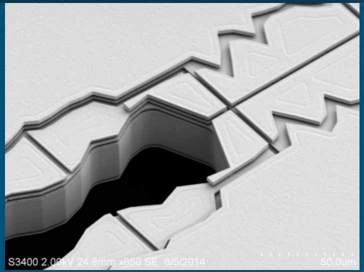
Sandia National Laboratories

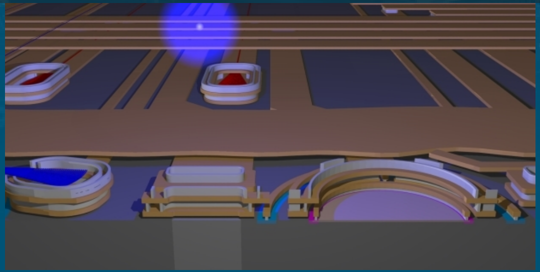
Scalable control systems for trapped-ion quantum computing

QNM Exchange









Daniel Stick

March 3, 2023

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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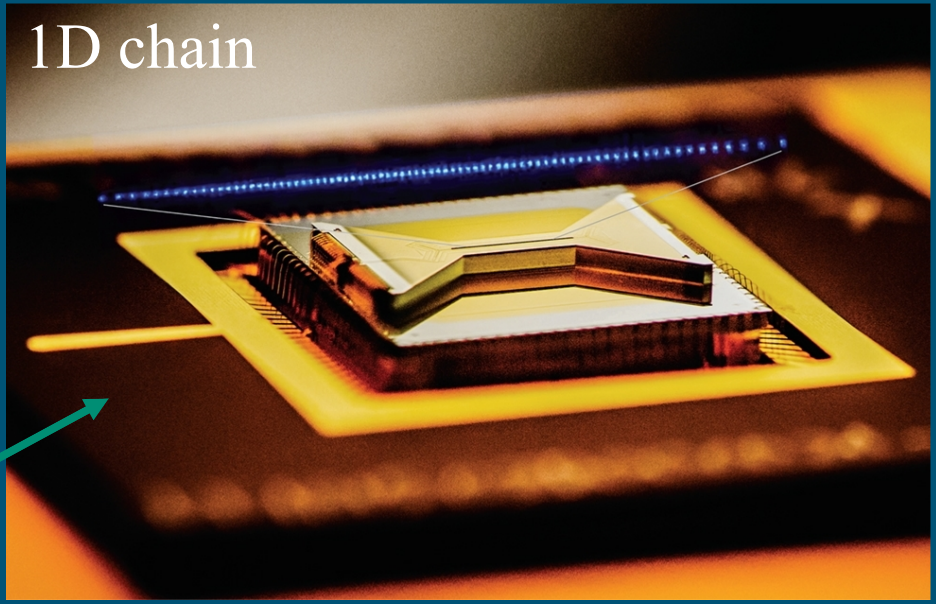
How to define “scalable” & why is it important for QC?

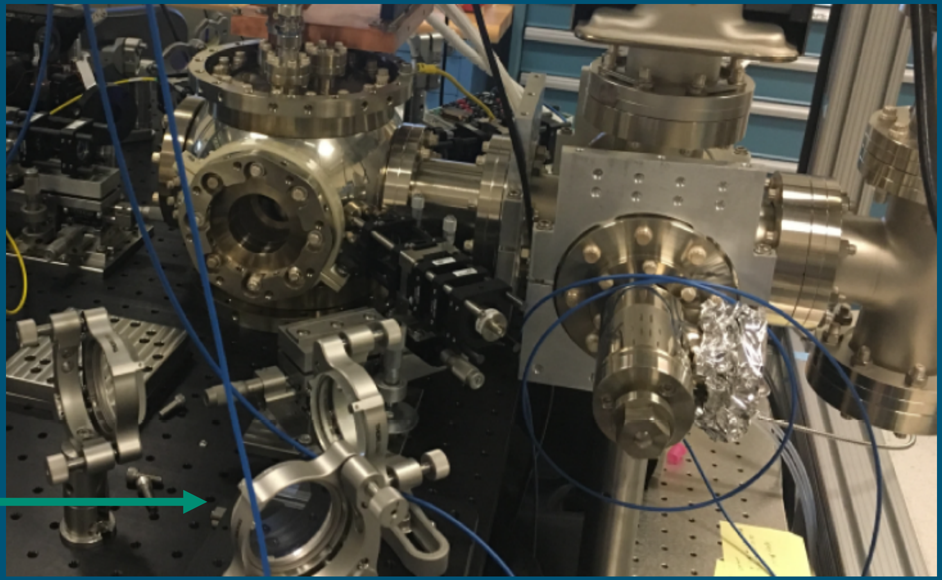
Scalable – the ability to add a qubit using the same hardware as previous qubits and without degrading fidelity.

Scalability **depends on the scheme and concept of operation** for the quantum computer.

Examples of **non-scalable** hardware:

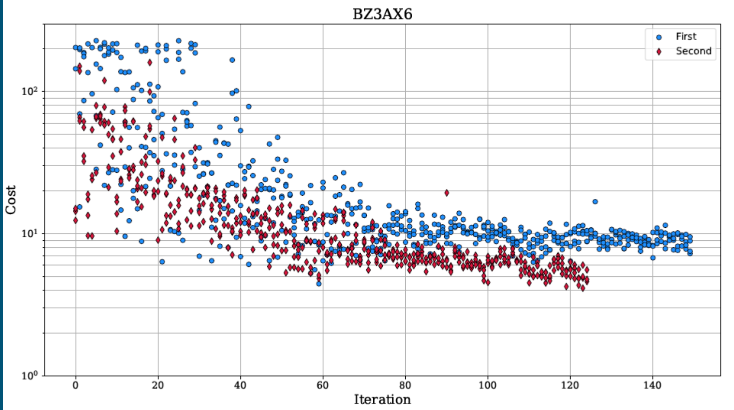
- Bulk optics for delivering lasers to ions
- Bulk optics for counting photons



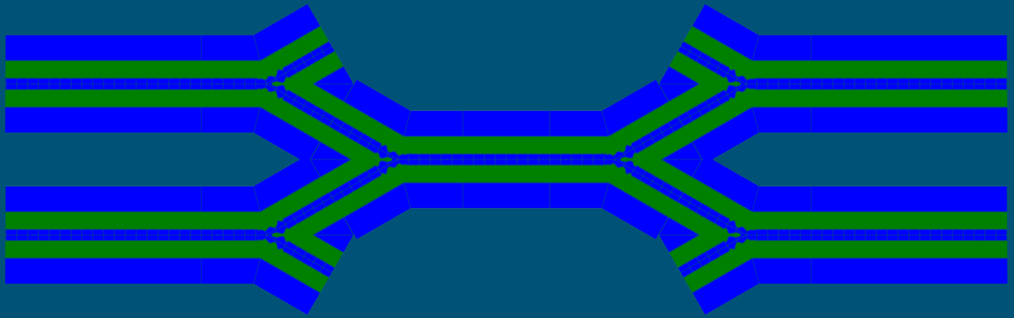


Experimental technology development to support the scaling of trapped-ion quantum systems

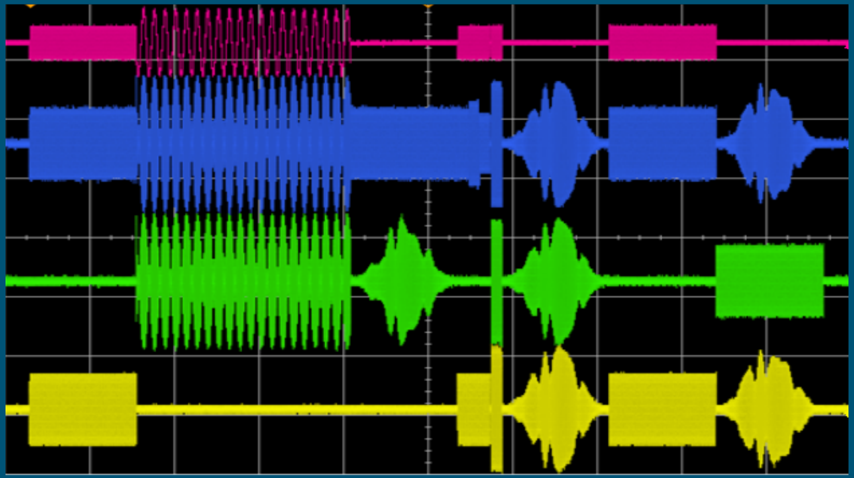
1. Low excitation transport



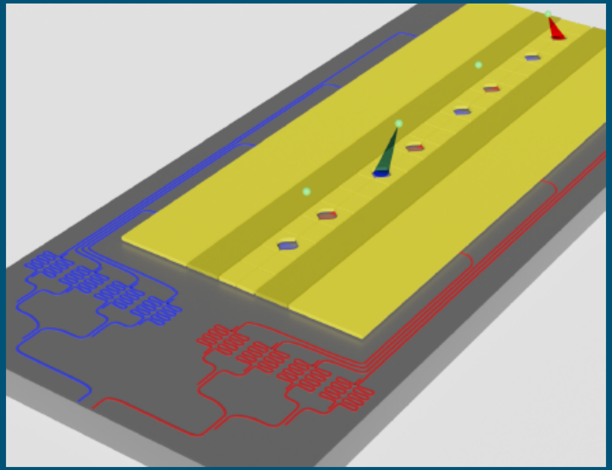
2. Large(r) scale trap arrays



3. SoC control electronics



4. Microfabricated optics

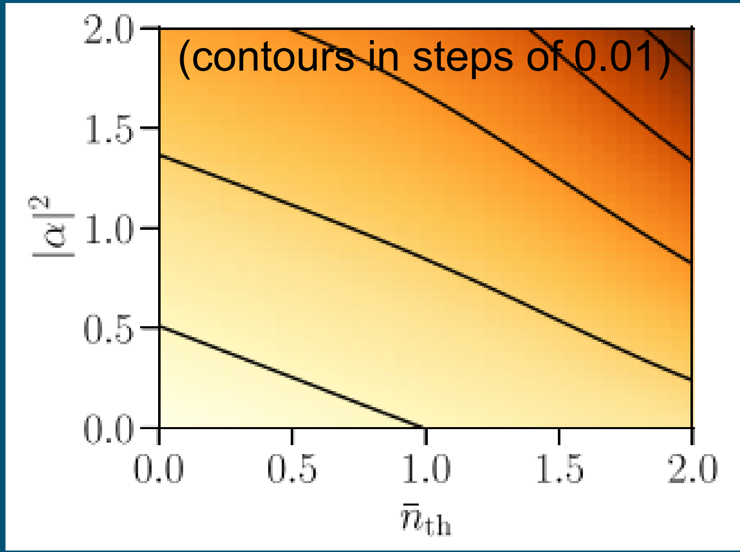


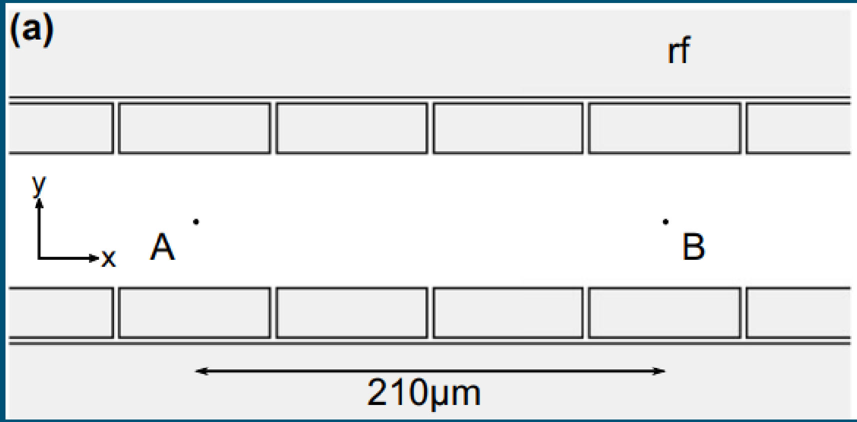
Funded by DOE/ASC

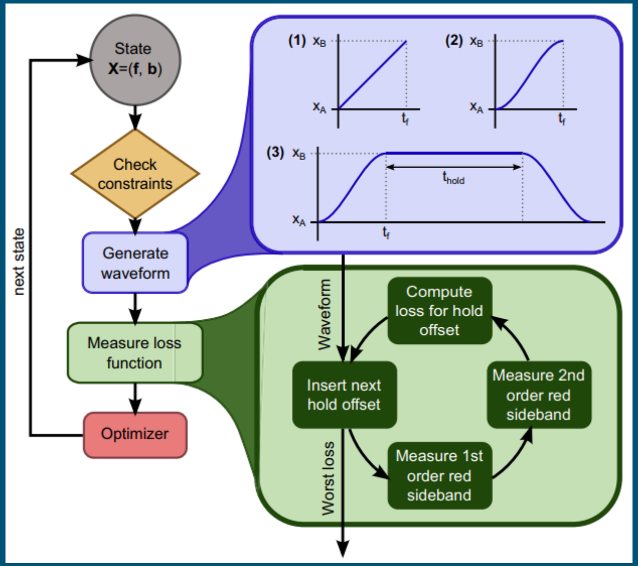
Low excitation ion transport

- **Thermal excitation during a gate** is one of the top contributor to 2Q gate infidelity, but **coherent excitation prior to the gate** must also be considered, especially for larger scale systems*
- We transport an ion 3 electrodes (constituting one well) and back at **35 m/s** with an initial transport waveform generated by simulation
- Loss function (based on 1st and 2nd red sidebands) is a faster and more robust measurement compared to sideband thermometry.
- **Nelder-Mead optimization over 9 waveform parameters**

2Q gate error vs. motion





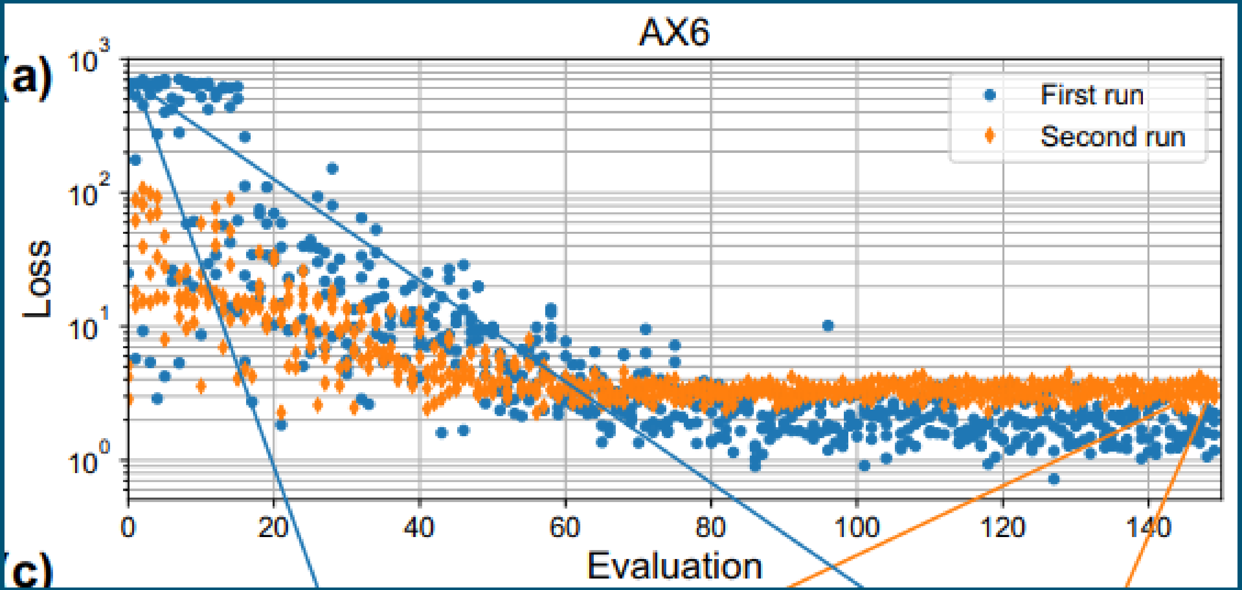


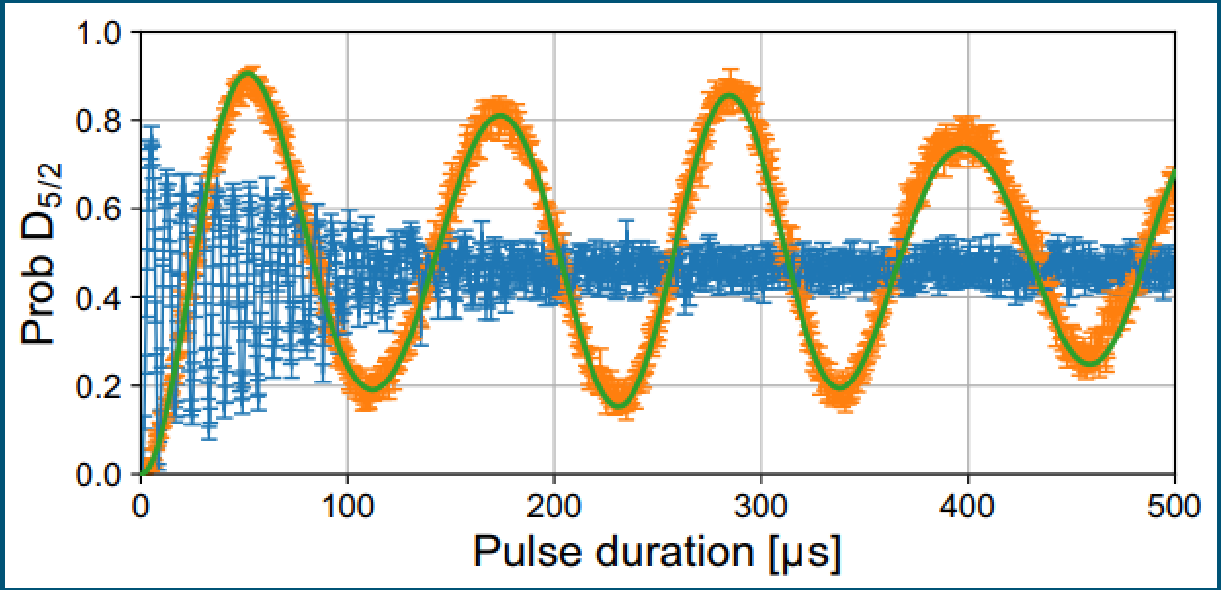
* "Entangling-gate error from coherently displaced motional modes of trapped ions", Phys. Rev. A 105, 052409

Low excitation ion transport

Funded by DOE/ASCR

- Optimizer finds solution that achieves transport with **0.36 q per round trip***
- This experiment used custom DACs with 12 MHz bandwidth. If we artificially slow the DACs and re-run the optimization, we are unable to achieve the same final excitation.



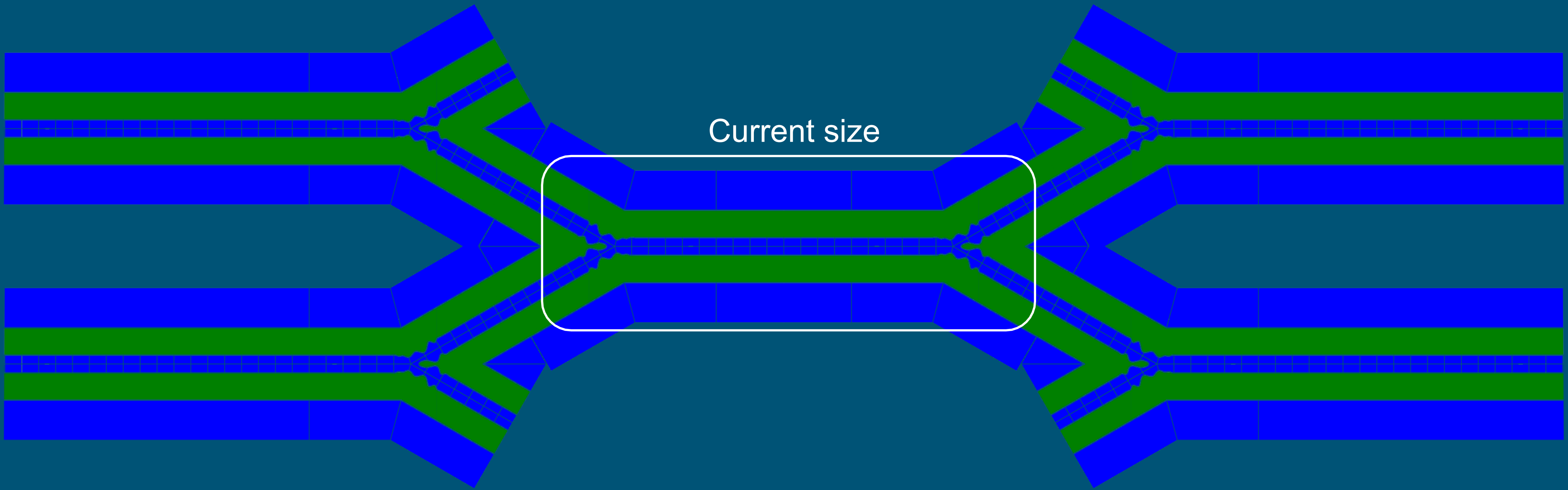


* “Closed-loop optimization of fast trapped-ion shuttling with sub-quanta excitation”, npj Quantum Information 8, 68 (2022)

Funded by DOE/ASCR (QSA

Large(r) scale trap arrays

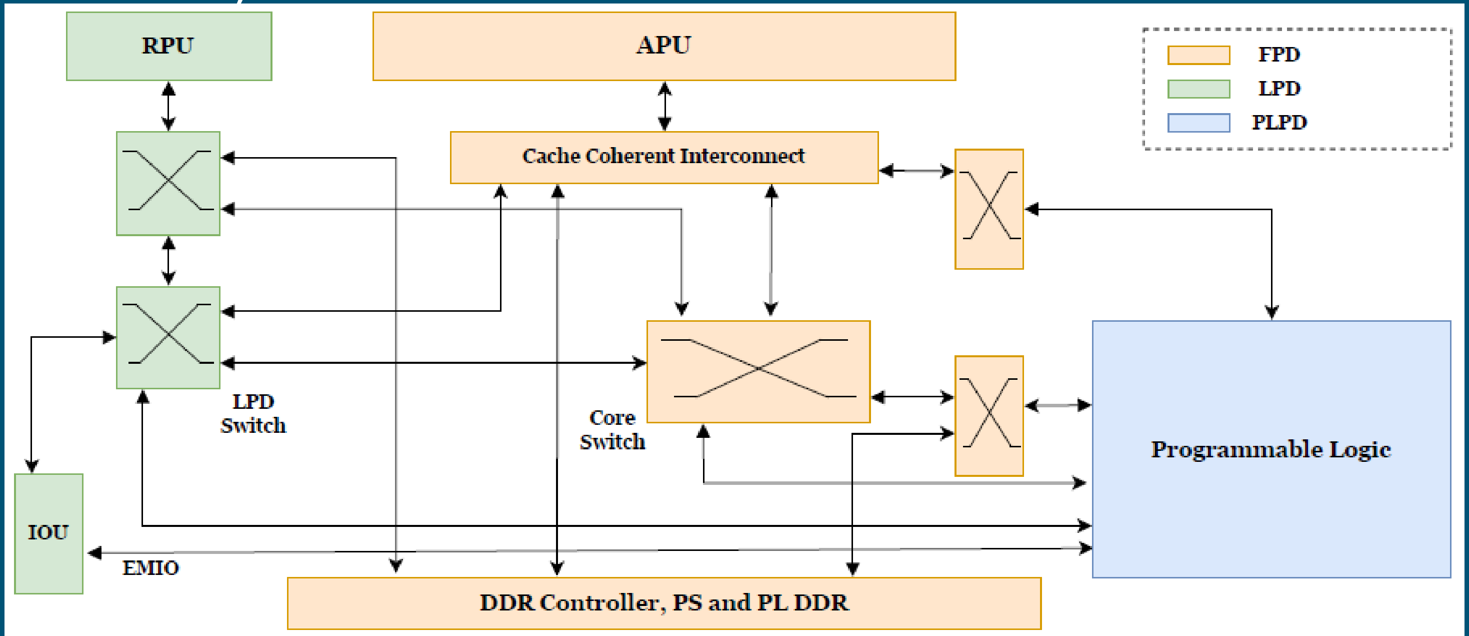
- Designed and are currently fabricating a trap that can **store up to 200 ions in collaboration with Duke**
- >300 top surface electrodes
- Trap would have ~4x capacitance of previous largest trap, but by perforating dielectric and raising the RF rails we are able to keep the capacitance constant

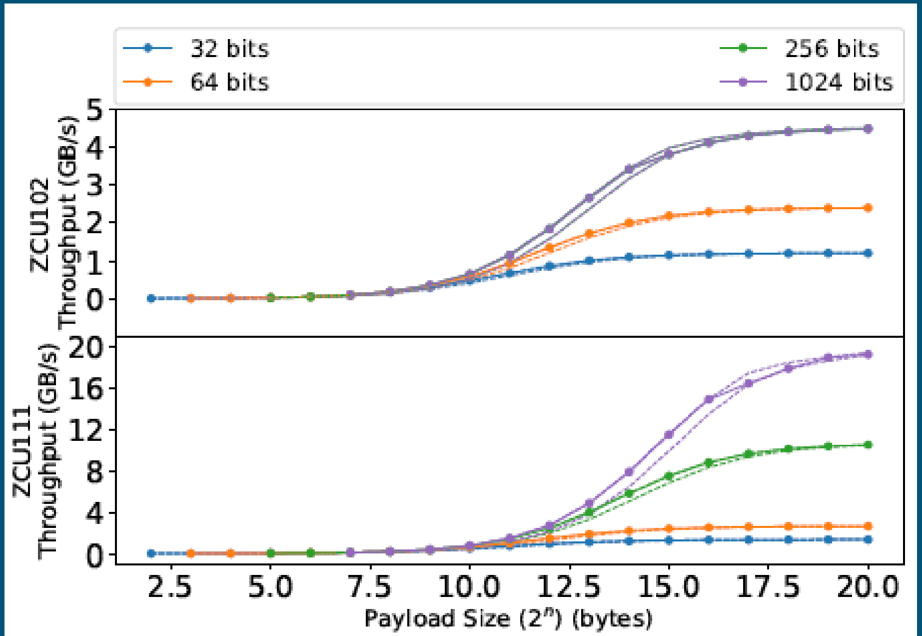


Funded by NSF (QSENS

Control electronics using an SoC

- Collaboration with **UNM (Eirini Tsiropoulou, Jim Plusquellic, Nafis Irtija, Tiamike Dudley)**
- Analysis of fastest reconfiguration time, with goal of achieving times on the order the 1Q gates.*
- Based on a particular encoding for the gates and measured communication rates in a **Xilinx Zynq UltraScale** SoC
- Communication in FPGA leads to a minimum 1.8 μs reconfiguration of all gates (**DMA between RPU and PL**)





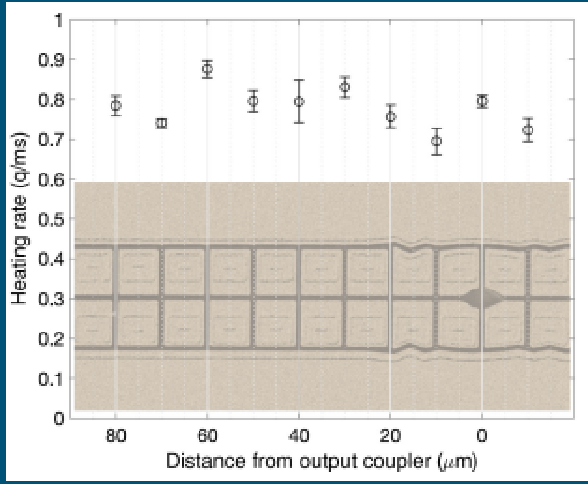
* "Design and analysis of digital communication within an SoC-based control system for trapped-ion quantum computing", IEEE Transactions on Quantum Engineering 4 (2023)

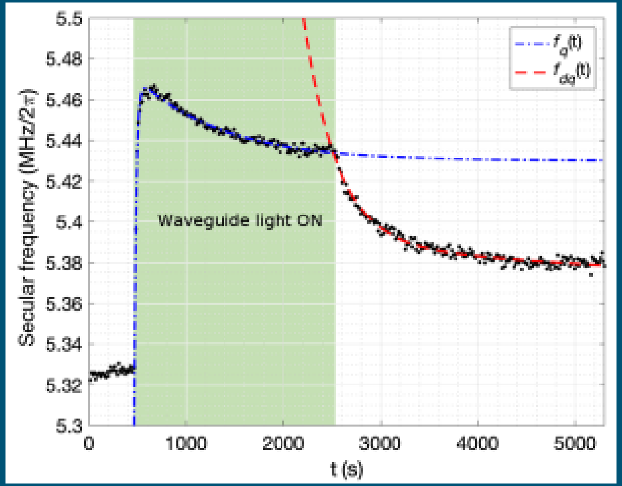
Integrated waveguides and detectors (clocks → QC?)

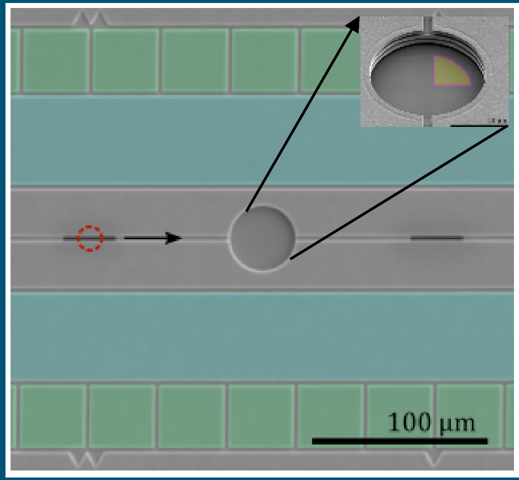
Funded by DARPA

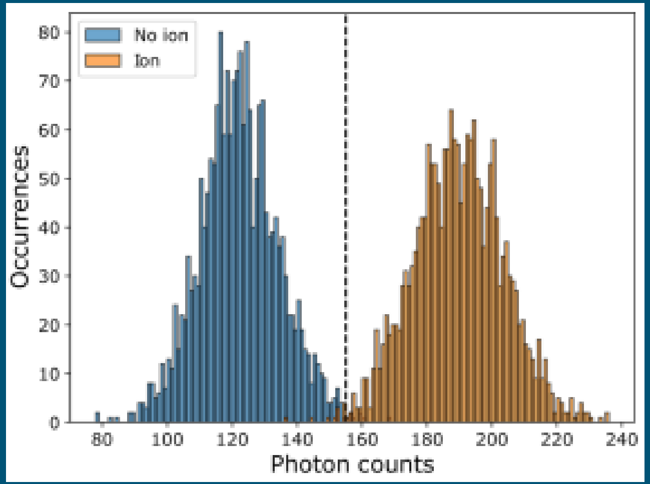
- **Waveguides used to deliver UV light** (435 nm) to grating out couplers between electrodes* and focused on ions above the trap
- This enables delivery to 2D arrays, but introduces new concerns: electric field noise, charging

- **Single photon avalanche diodes (SPADs)**** placed directly under ions break the long-term challenge of having an objective lens that is much larger than the array it images.
- Improvements needed in efficiency, dark counts, background counts









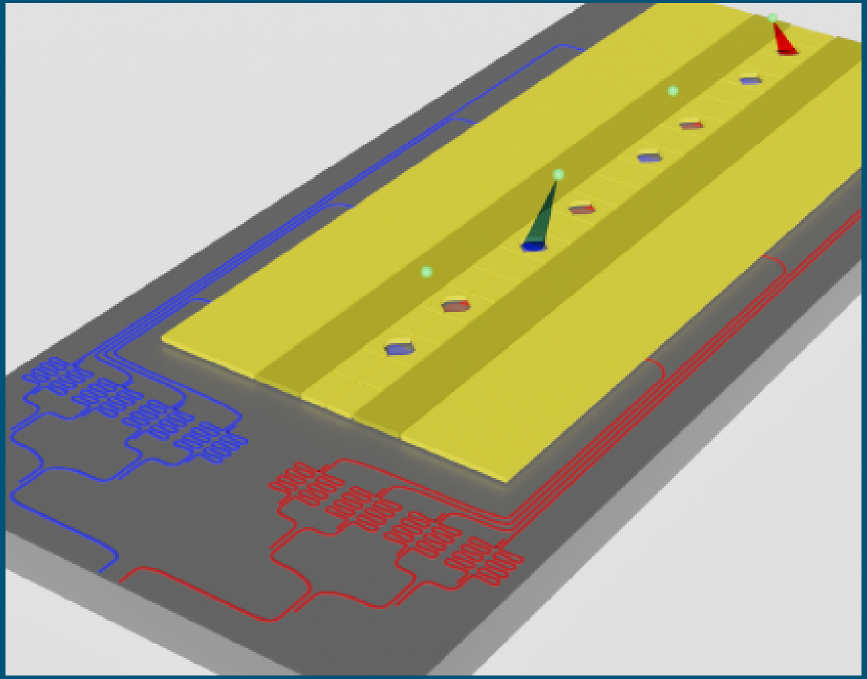
* Ivory, *et al.* "Integrated Optical Addressing of a Trapped Ytterbium Ion". PRX 11, 041033 (2021)

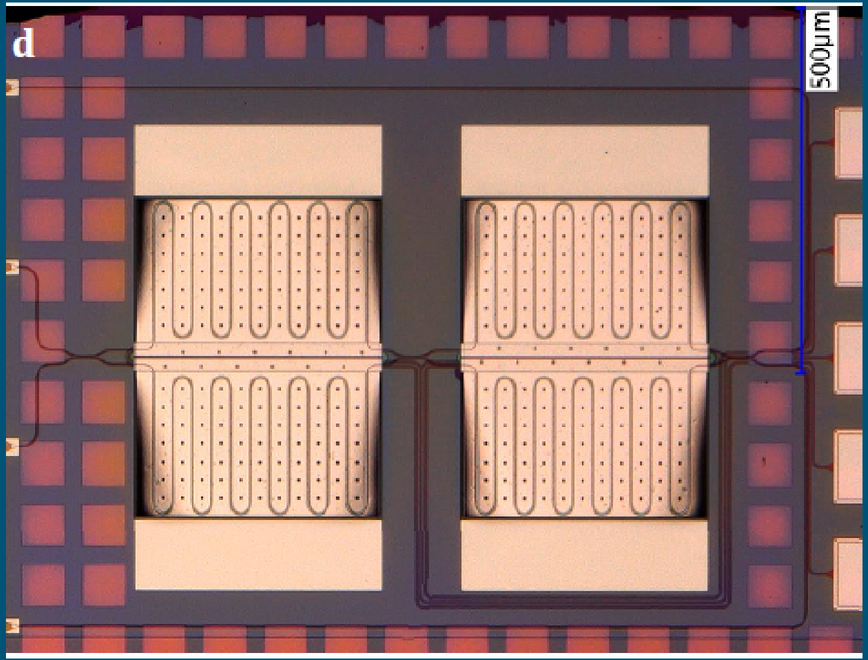
** Setzer, *et al.* "Fluorescence detection of a trapped ion with a monolithically integrated single-photon-countering avalanche diode". APL 119, 154002 (2021)

Funded by DOE/ASCR

Microfabricated optical modulators

- Optical modulators are also important to integrate because they alleviate some of the **I/O challenges** with controlling ions in larger trap arrays
- Desire to be **CMOS compatible, operate from 4K to 300K, accommodate many wavelengths of light, small footprint, modest voltage, switching speeds > 1 MHz**
- Piezo-activated modulators based on AlN are a good candidate based on these criteria
- Use strain induced by applying voltage across an AlN layer to shift the phase in the waveguides and activate a **Mach Zehnder Interferometer**

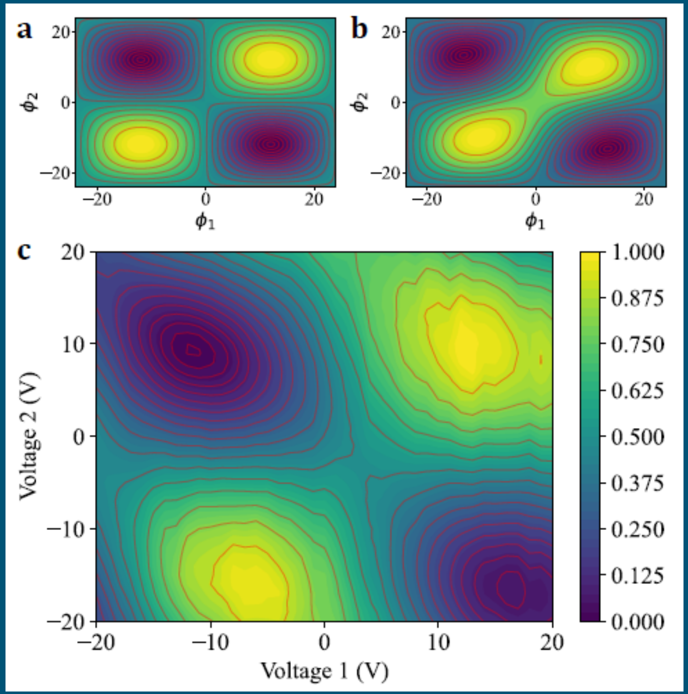


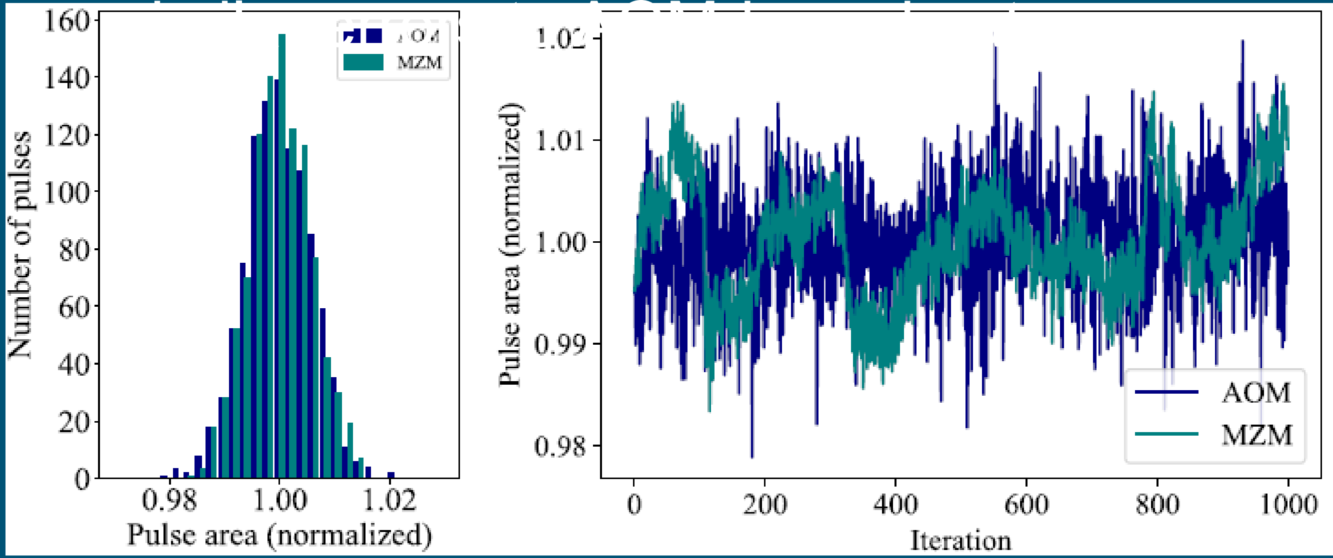


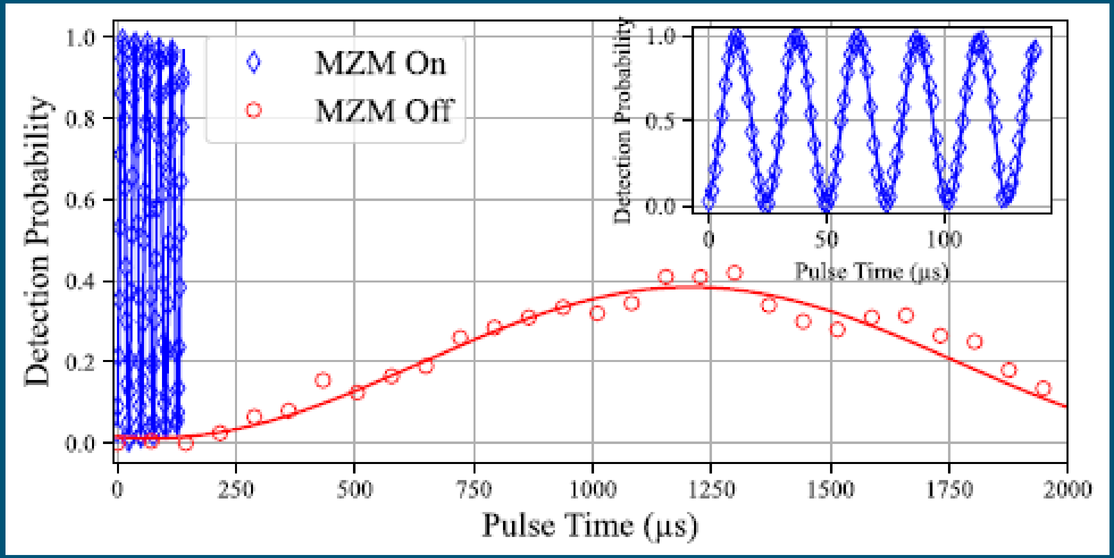
Funded by DOE/ASCR

Microfabricated optical modulators

- <0.5 us turn on/off time
- Similar variations in pulse area between AOM and MZM
- Extinction ratios of **38.7 dB measured with drift of a few dB/hour**
- ~1.5 dB loss per MZI (2.5 mm waveguide)
- Measured single qubit gate fidelities with GST,







Acknowledgments

U.S. DEPARTMENT OF ENERGY
Office of Science

https://www.sandia.gov/quantum/trapped-ions/

Fabrication:
Matt Blain (now at Quantinuum)
Matt Delaney
Ray Haltli
Ed Heller
Tipp Jennings
Nick Jimenez
Becky Loviza
Zach Meinelt
Eric Ou
John Rembetski

Rex Kay
Oleksiy Slobodyan

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Megan Ivory
Ryan Law
Hayden McGuinness
Brian McFarland
Will Setzer
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Daniel Stick
Jay Van Der Wall

Theory:
Brandon Ruzic

Photonics:
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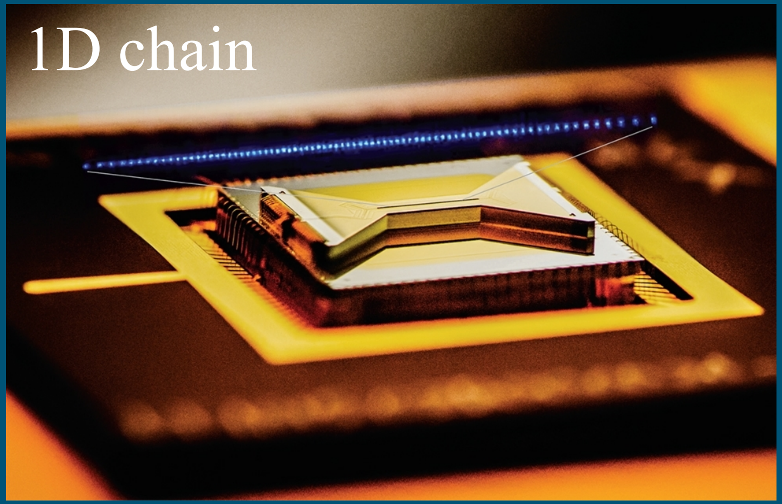
Daniel Dominguez
Mike Gehl
Nick Karl
Andrew Leenheer

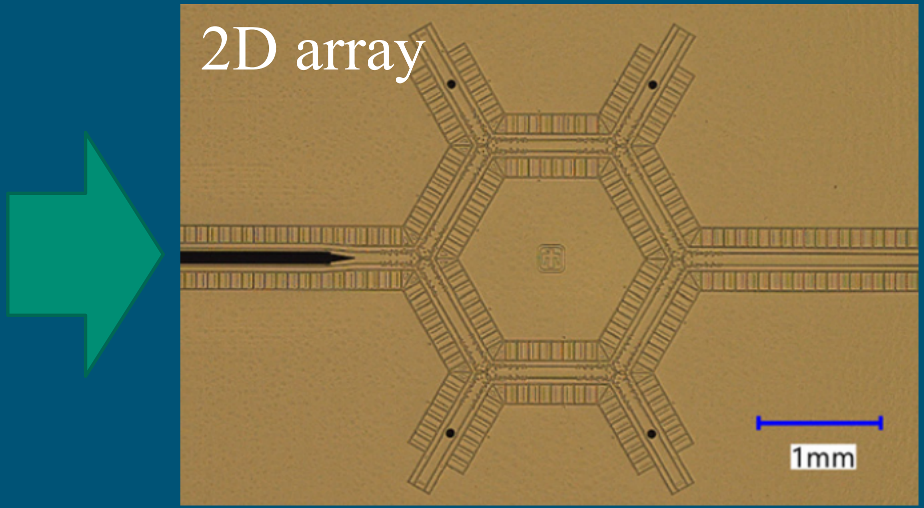
Electronics:
Dan Lobser
Josh Goldberg
Jim Plusquellic (UNM)
Eirini Tsiropoulou (UNM)
Nafis Irtija (UNM)
Tiamike Dudley (UNM)

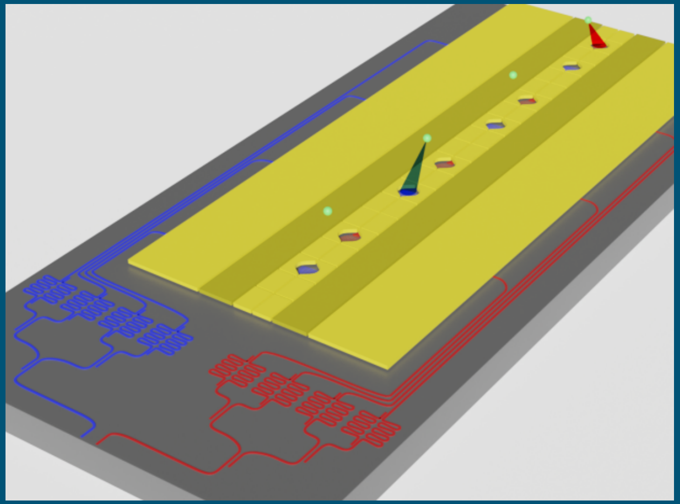
Using PICs to support 2D ion arrays

Funded by DOE/ASCR

- Almost all current ion QC's and other platforms use 1D chains of ions, due to **optical delivery**, ion shuttling complexity, and trap fabrication
- Increasing the number of ions that can be stored ***AND*** individually addressed and manipulated requires **optical signals delivered via PICs**
- This introduces other challenges:
  - Loss in waveguides
  - Waveguide light scattering into detectors
  - **I/O: coupling light onto the chips, can be mitigated using beam splitters and on-chip modulators**







Low excitation ion transport

- Thermal excitation during a gate is one of the top contributor to 2Q gate infidelity, but excitation prior to the gate must also be considered, especially for larger scale systems
- Here we analyze the impact of coherent excitation prior to a gate*

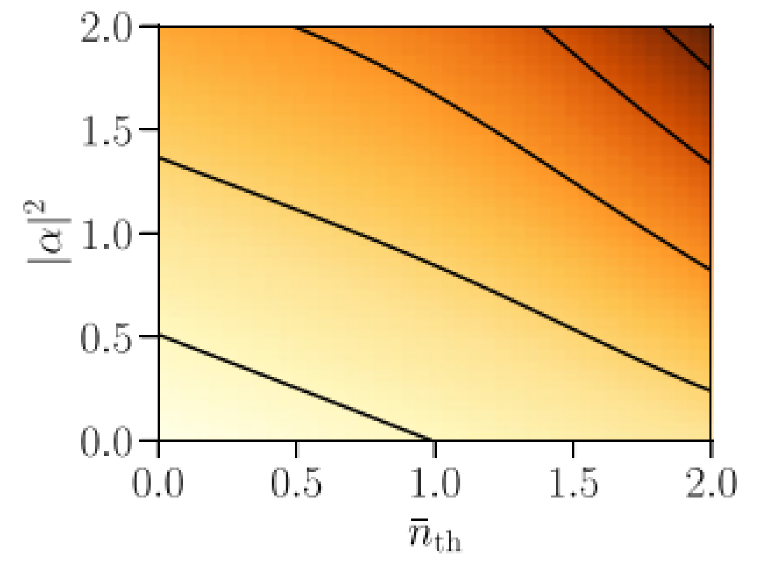
2Q gate error vs. motional energy
(contours in steps of 0.01)

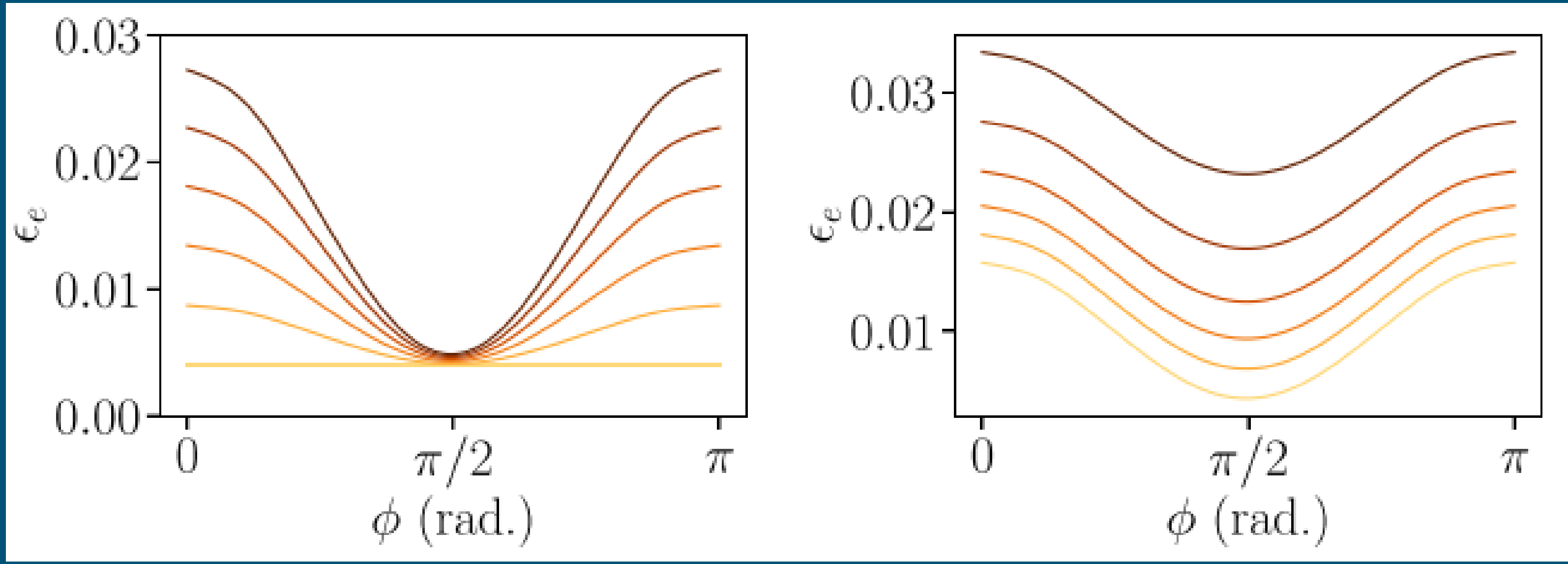
$|\alpha|^2 = 0$ to 2

$\bar{n}_{th} = 0$

$\bar{n}_{th} = 0$ to 2

$|\alpha|^2 = 1$





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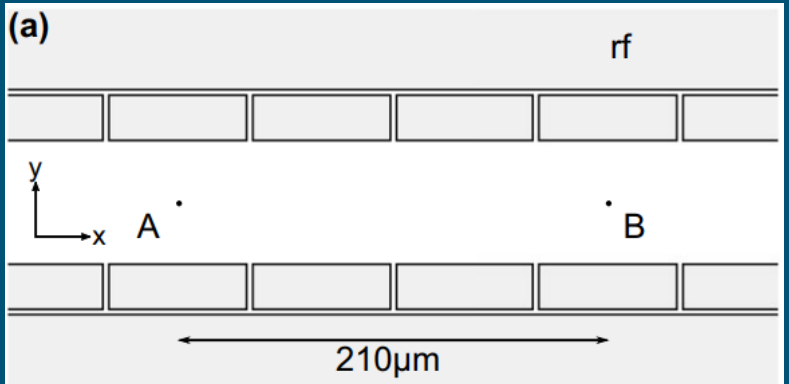
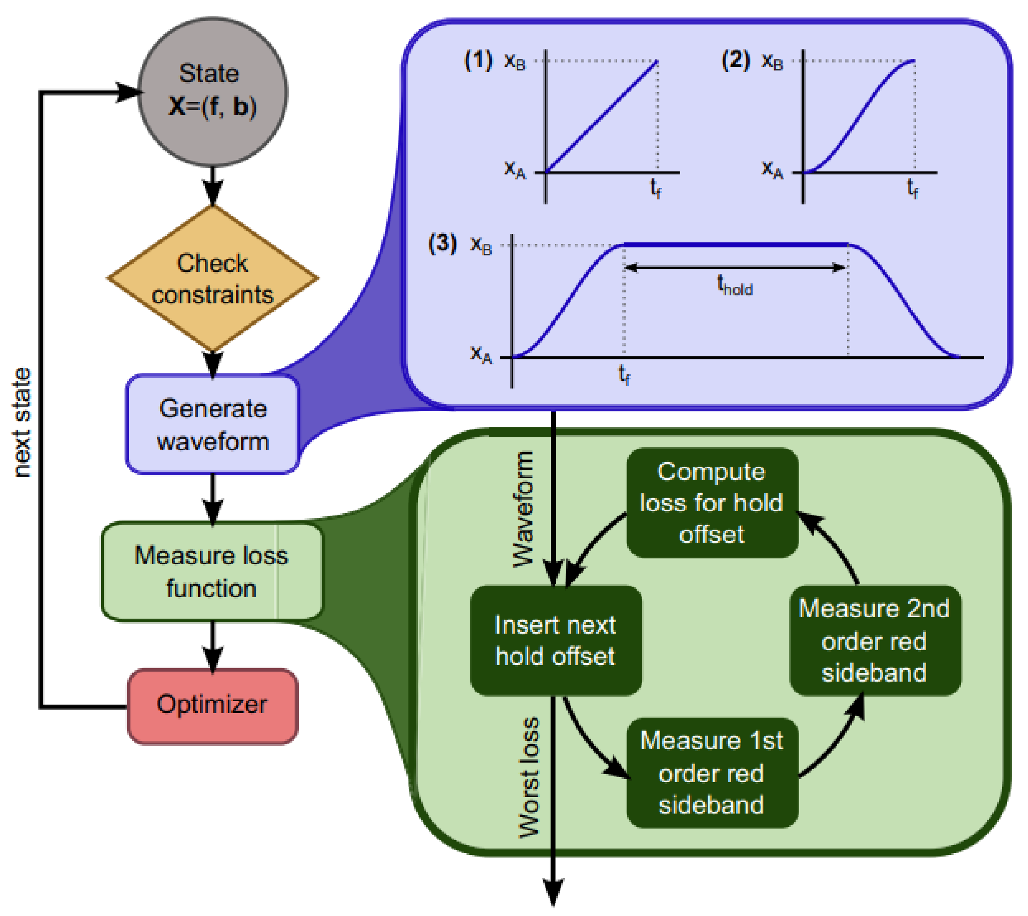
- Loss function is a faster and more robust measurement compared to sideband thermometry. Uses 1st and 2nd red sidebands
- Multiple delay times
- Nelder-Mead optimization over waveform parameters

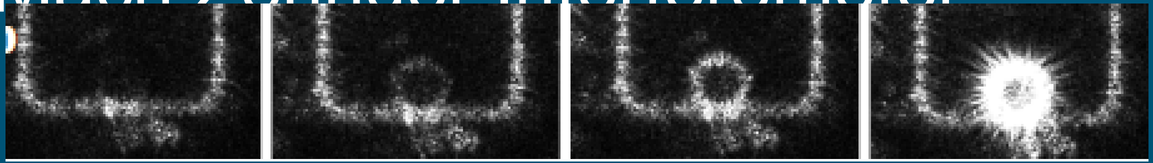


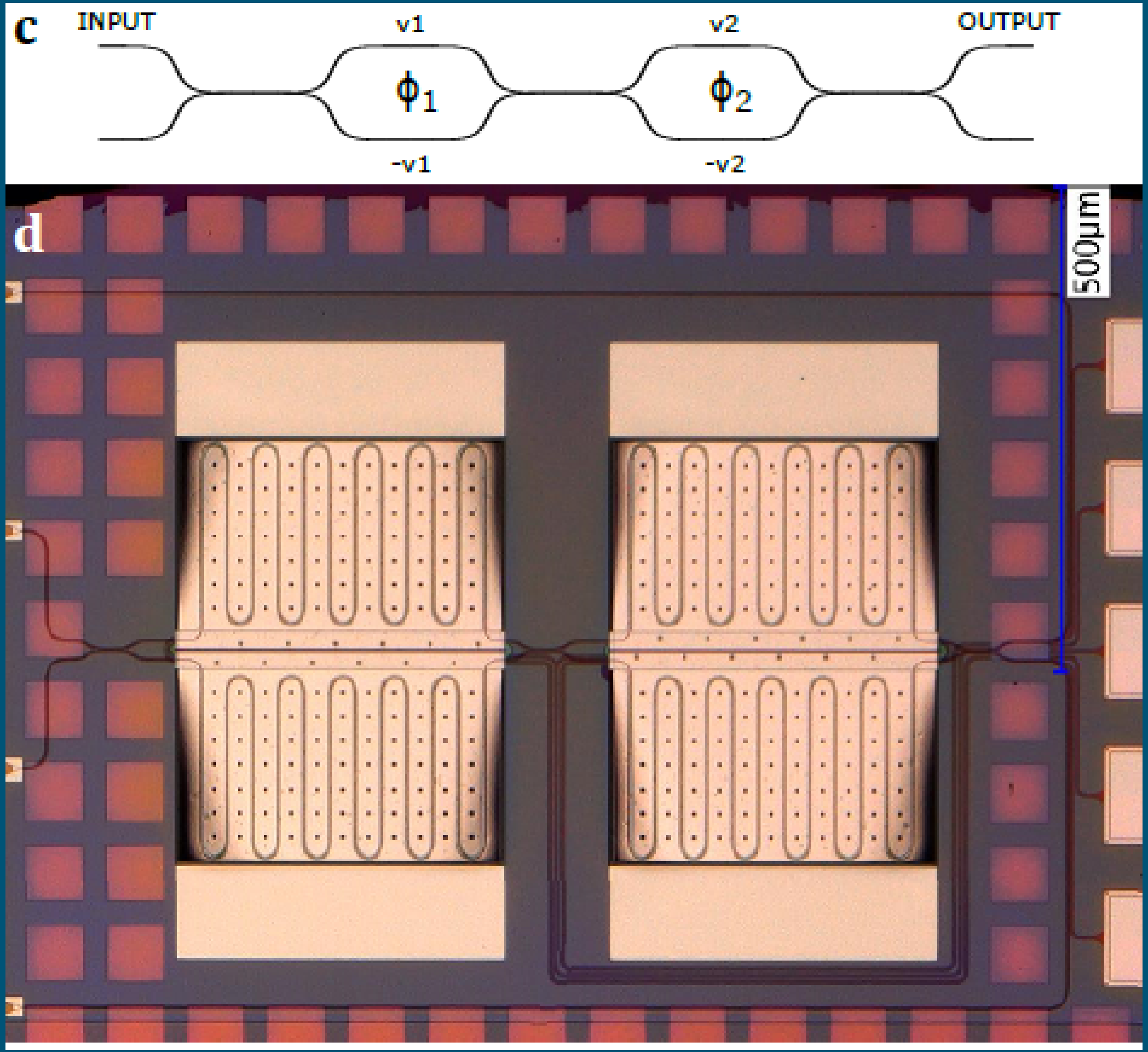


* “Closed-loop optimization of fast trapped-ion shuttling with sub-quanta excitation”, npj Quantum Information 8, 68 (2022)

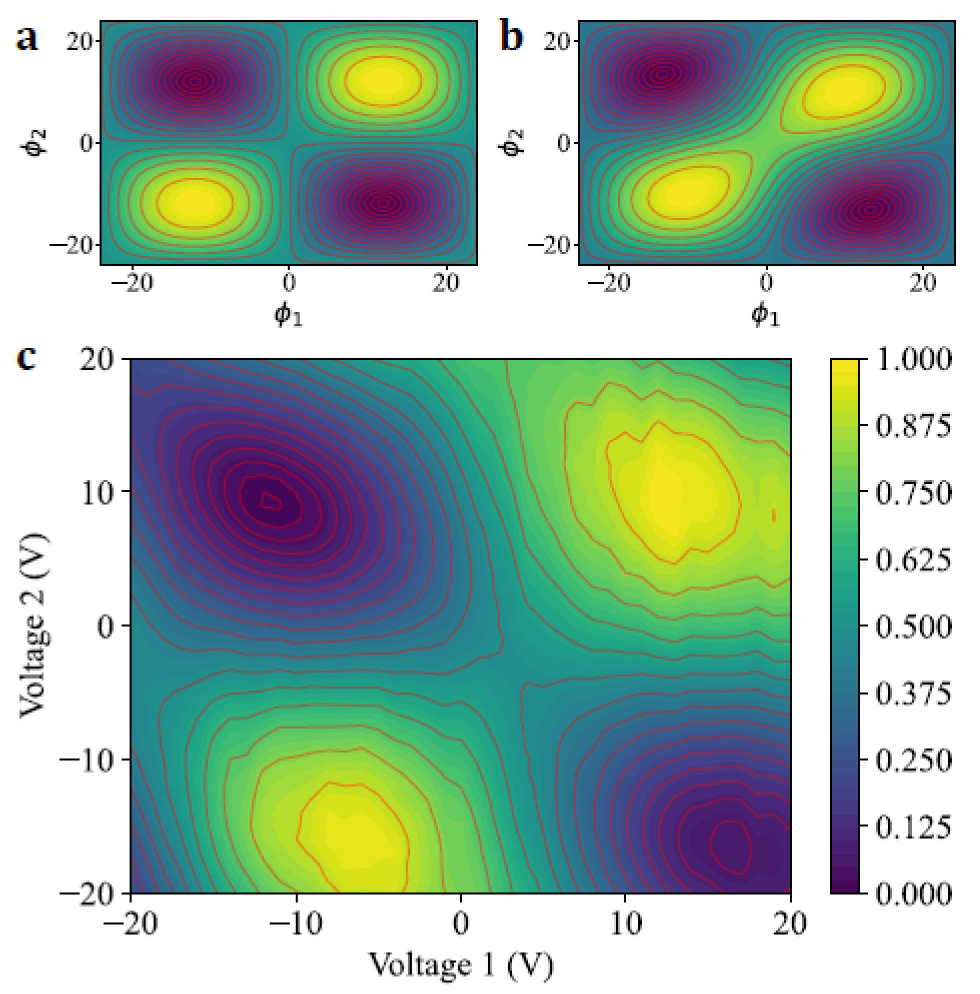
Microfabricated optical modulators

- Piezo-activated modulators based on AlN are a good candidate based on these criteria
- Use strain induced by applying voltage across an AlN layer to shift the phase in the waveguides and activate a resonant ring structure or a Mach Zehnder Interferometer





Microfabricated optical modulators



- Extinction ratios of 38.7 dB measured with drift of a few dB/hour
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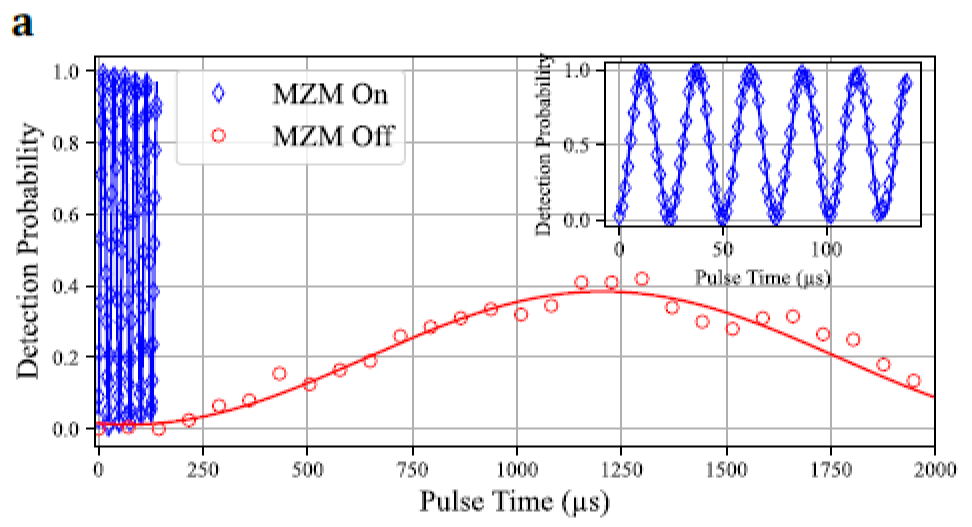

Microfabricated optical modulators

- Coupled to a trapped ion in a microfabricated surface via fibers
- Measured single qubit gate fidelities with GST
- Similar errors to AOM-based gates
- Physical GST variant developed to identify errors due to imperfect extinction

Modulator (GST, stabilization)	**Process infidelity** ($\times 10^{-3}$) $\sqrt{X}$ / $\sqrt{Y}$ / I
MZM (standard, in)	2.64 ± 0.06 / 2.42 ± 0.05 / 2.64 ± 0.06
MZM (physical, in)	0.23 ± 0.01 // 1.62 ± 0.02
AOM (standard, in)	1.6 ± 0.1 / 1.5 ± 0.1 / 0.7 ± 0.1
AOM (standard, out)	0.73 ± 0.07 / 1.05 ± 0.08 / 0.1 ± 0.1
Modulator (GST, stabilization)	**Diamond error** ($\times 10^{-2}$) $\sqrt{X}$ / $\sqrt{Y}$ / I
MZM (standard, in)	1.5 ± 0.04 / 2.15 ± 0.03 / 4.78 ± 0.03
MZM (physical, in)	1.52 ± 0.02 // 4.03 ± 0.02
AOM (standard, in)	2.83 ± 0.07 / 2.33 ± 0.06 / 0.30 ± 0.04
AOM (standard, out)	0.53 ± 0.06 / 0.73 ± 0.06 / 0.69 ± 0.04