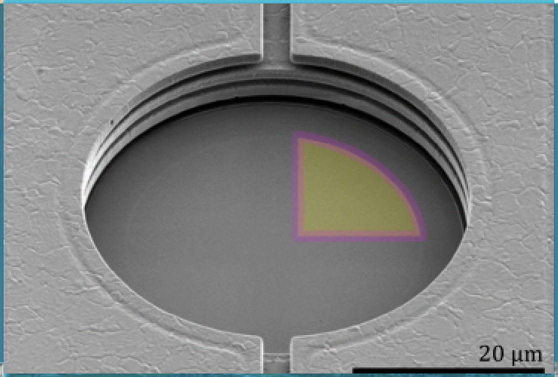
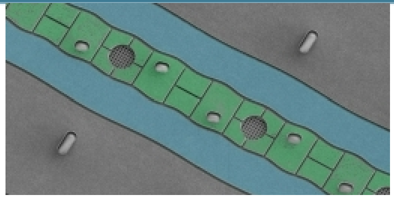
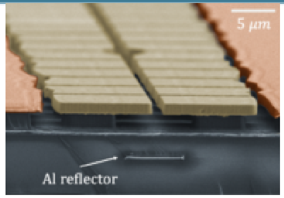
SAND2022-11262C

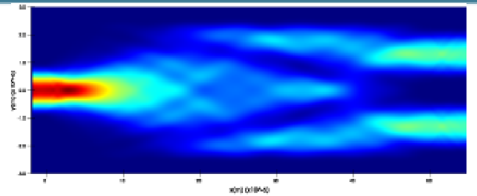
Sandia National Laboratories

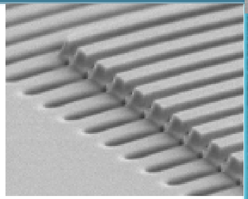
Integrated Photonics for Trapped Ion Quantum Information Experiments at Sandia Labs











Hayden McGuinness, Michael Gehl, Will Setzer,
Nick Karl, Joon Kwon, Craig Hogle, Dan Stick

Quantum Nanophotonic Materials, Devices, and Systems
San Diego
August 23, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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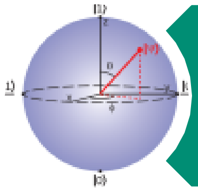
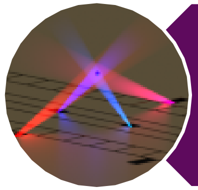
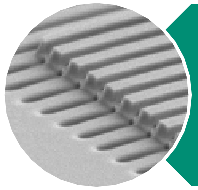
Outline



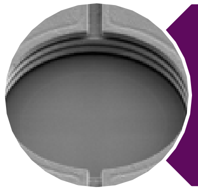
Brief intro to trapped ions for QIP



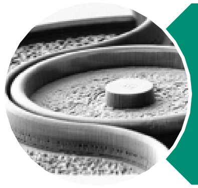
Ion projects employing integrated photonics



Waveguides, gratings, and more



Single-Photon Avalanche Diode



Optical Modulators

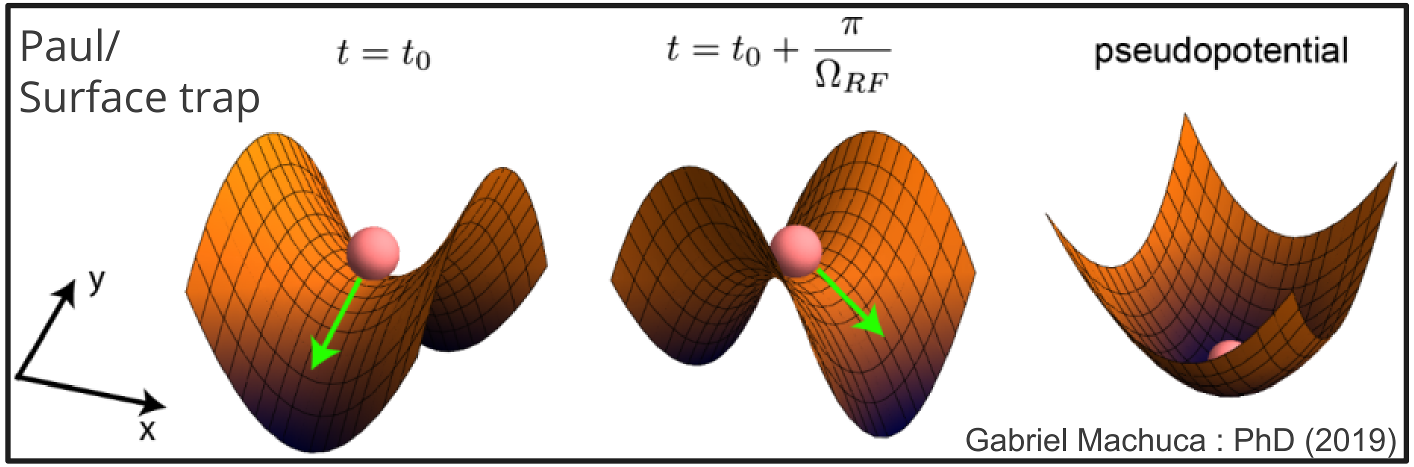
Trapped Ions for Quantum Information and Sensing

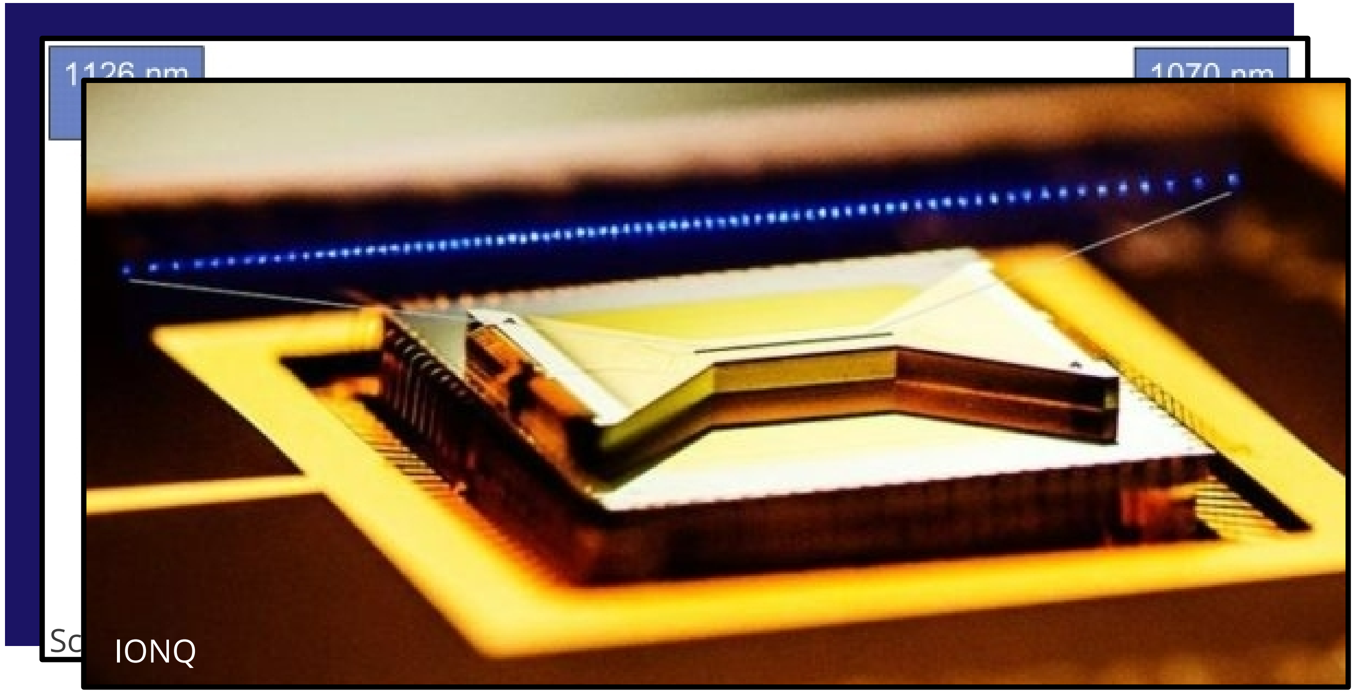
- What is a trapped ion?
  - Neutral atom/molecule stripped of 1+ e^-
  - Confined with RF/DC, E/M potentials

Pros	Cons
Identical qubits*	Slow operation (MHz)
Best fidelities	Multiple lasers
Can be fully connected	Ion loss
Scalability?	Scalability?

- Application
  - Fundamental Physics
  - Sensors (**Clocks**, inertial, EM)
  - **Computation**

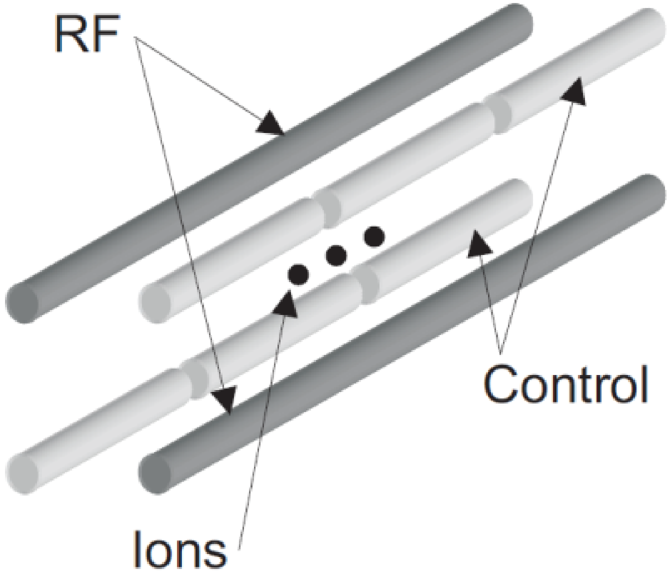
*In identical environments





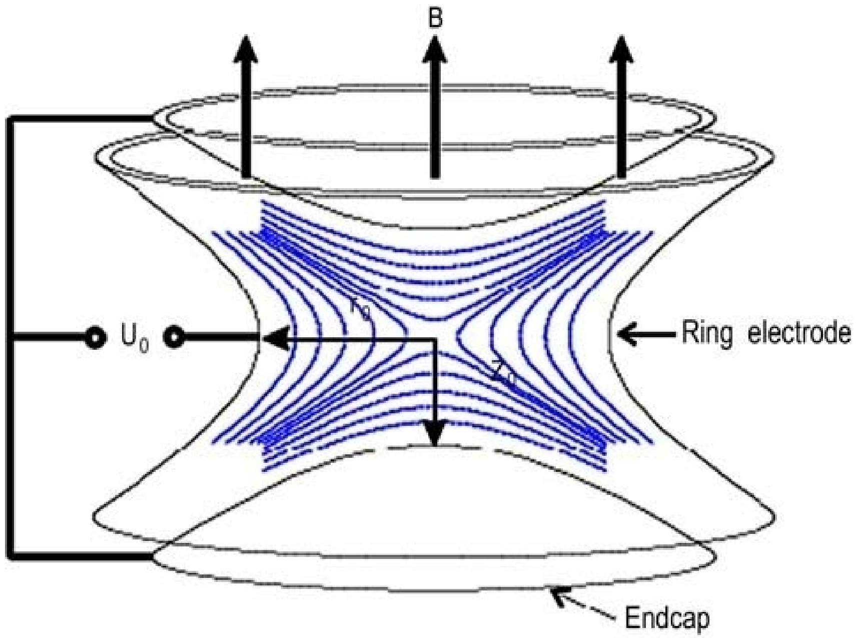
Ion Traps

Paul Trap



- Static and dynamic electric fields
- Simple
- Deep trap depth
- Difficult to Scale

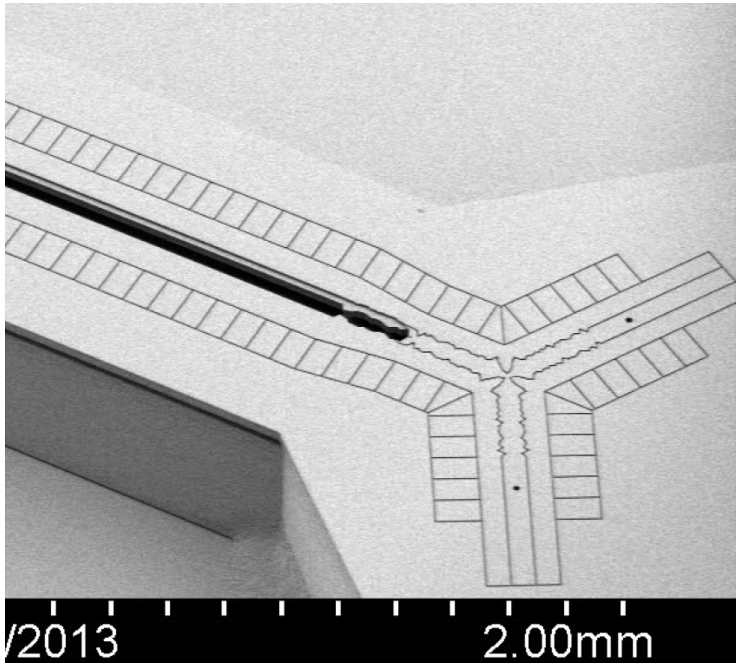
Penning Trap



Plasma Science and Technology **11,** 5, 521 (2009)

- Static electric and magnetic fields
- Simple
- Deep trap depth
- Difficult to Scale

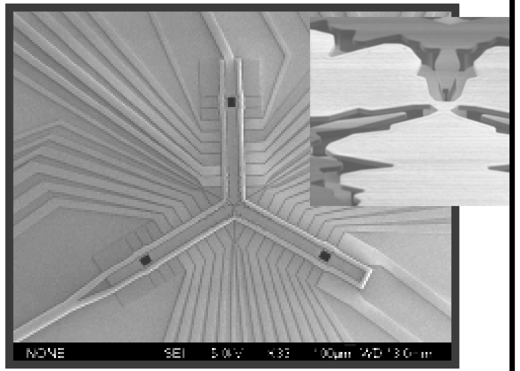
Surface Trap



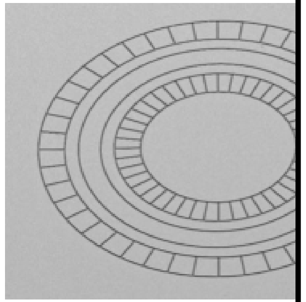
- Static/dynamic E-fields
- Manufacturable, repeatable
- Integrate technologies
- Difficult to make
- Lower trap depth
- Scalable

Some of Sandia's Surface Traps

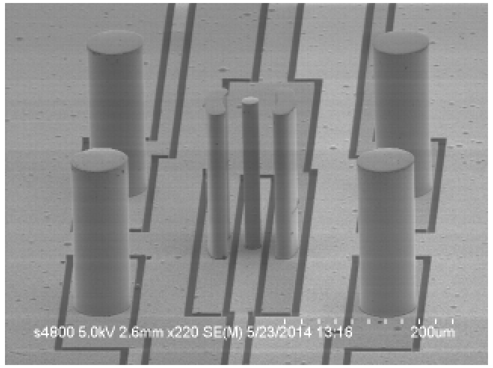
Y-junction traps

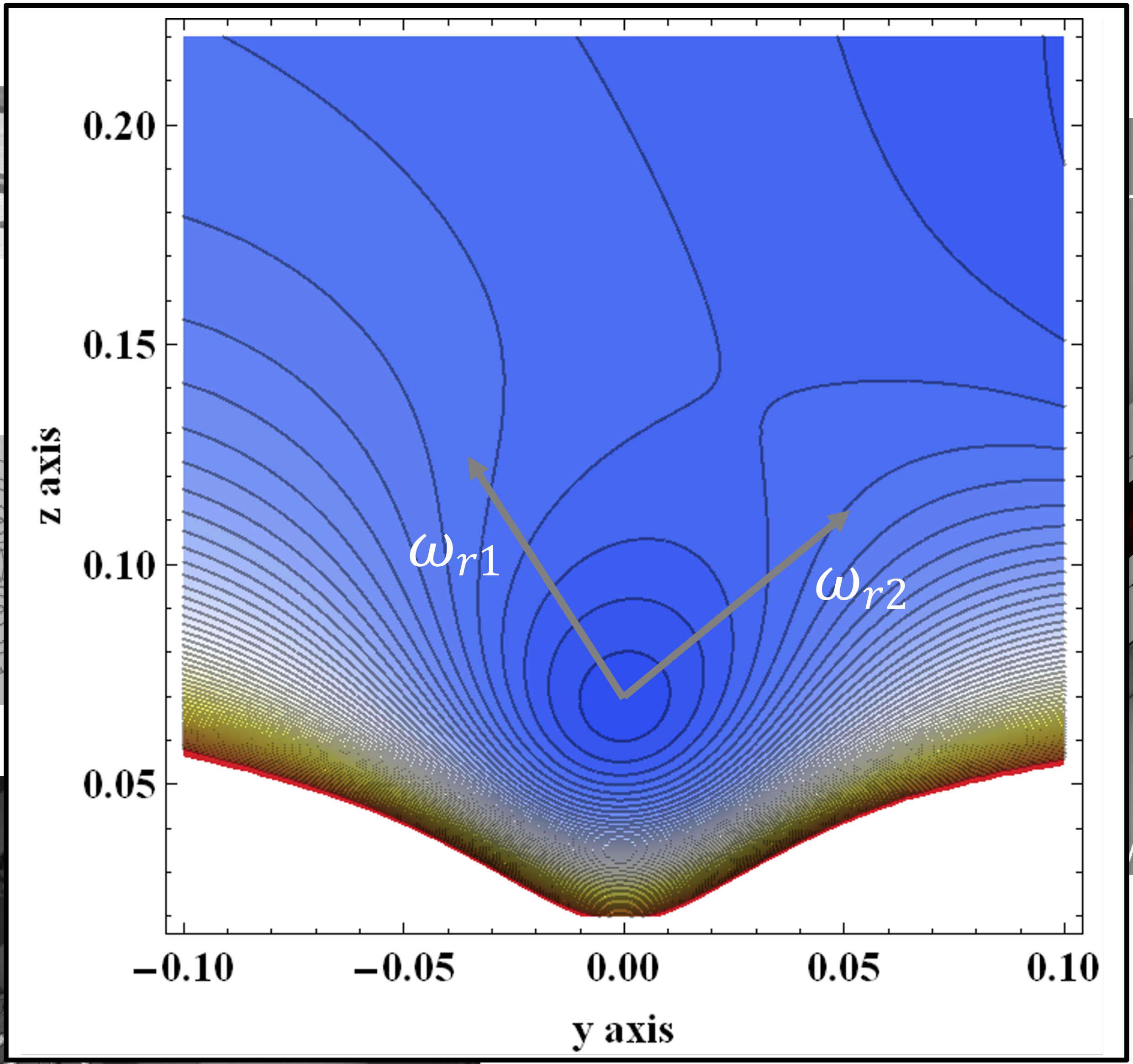


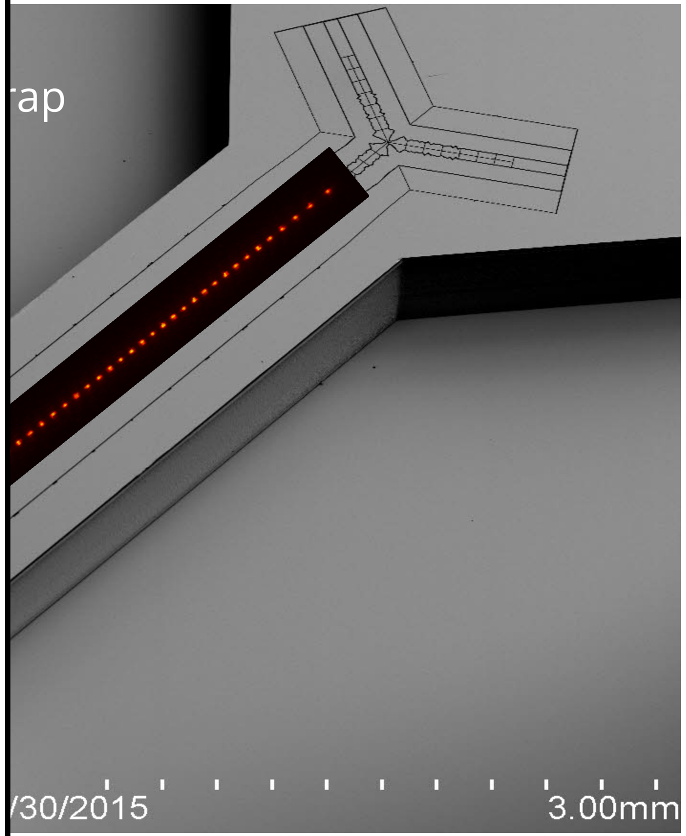
Ring trap:



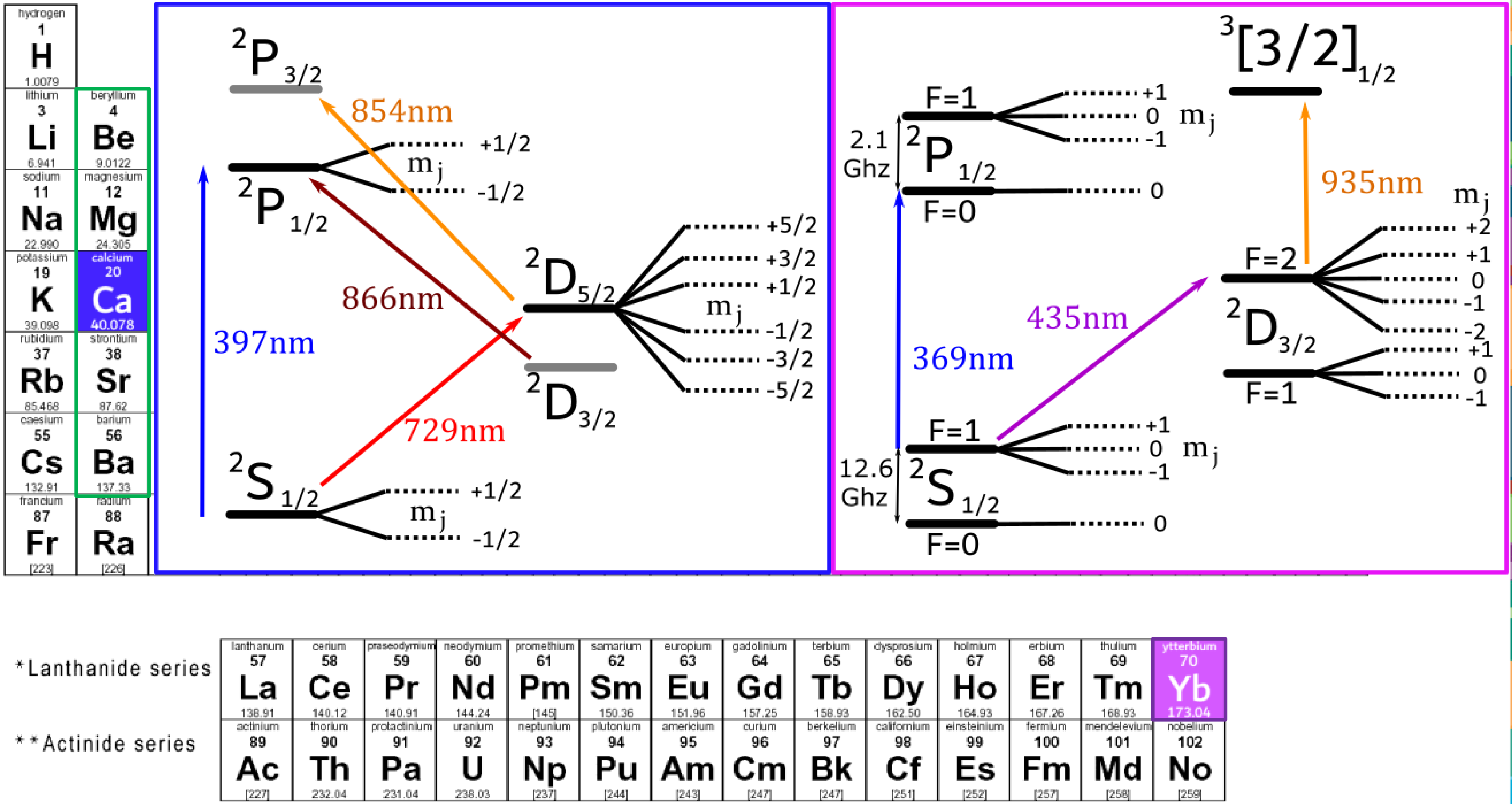
Stylus trap



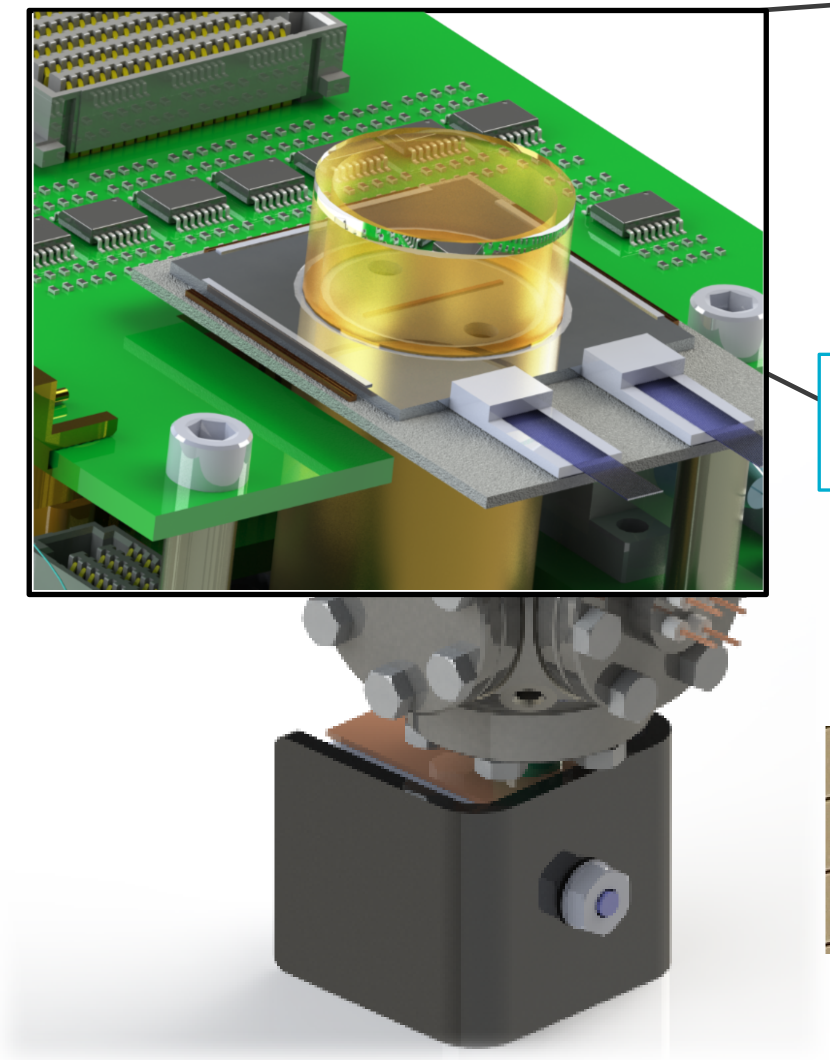




Two Common Ion Species: $^{171}Yb^{+}$ and $^{40}Ca^{+}$

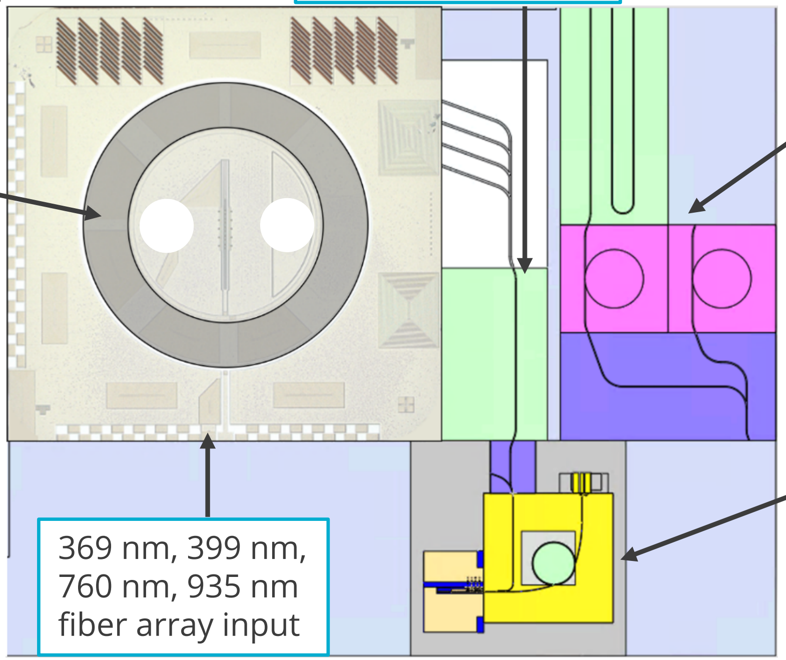


Trapped Ion Clock with photonic Technologies on Chip (TICTOC)



Solder-bonding vacuum cell

200+ thru-vacuum electrical and optical I/O delivered via PIC

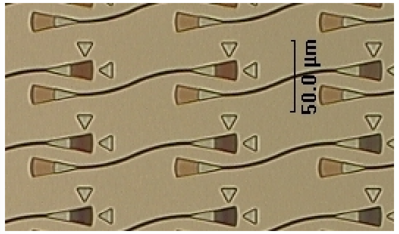


Doubler system

Comb system

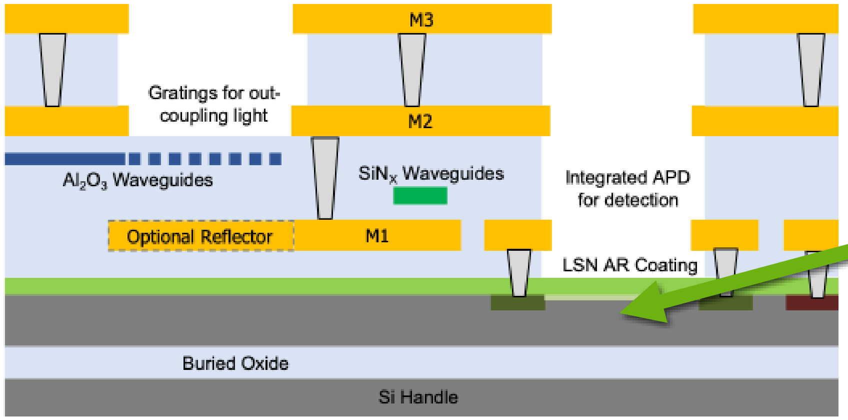
435 nm laser + WGM resonator

369 nm, 399 nm, 760 nm, 935 nm fiber array input

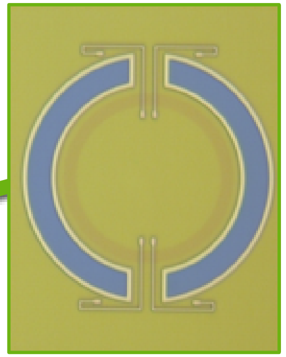


Light delivery with waveguides and grating couplers

Cross section of Ion trap

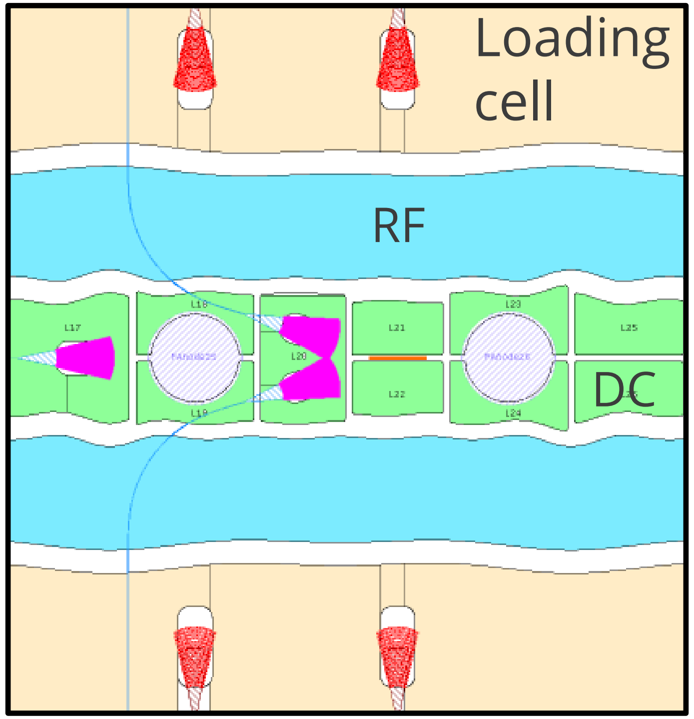


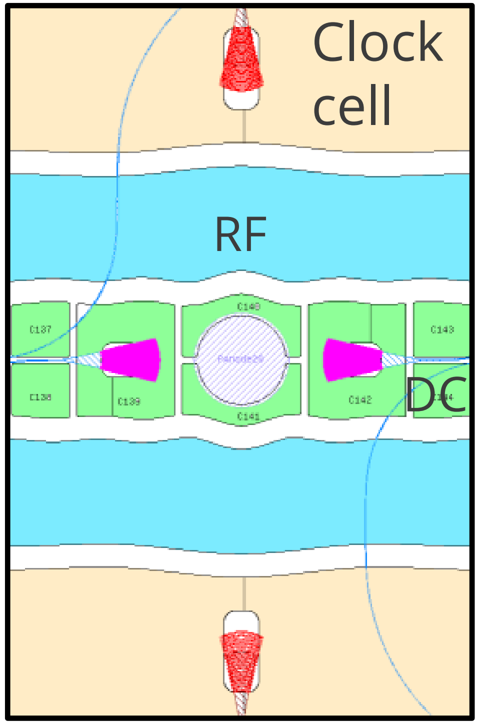
Detection: Avalanche photodiodes

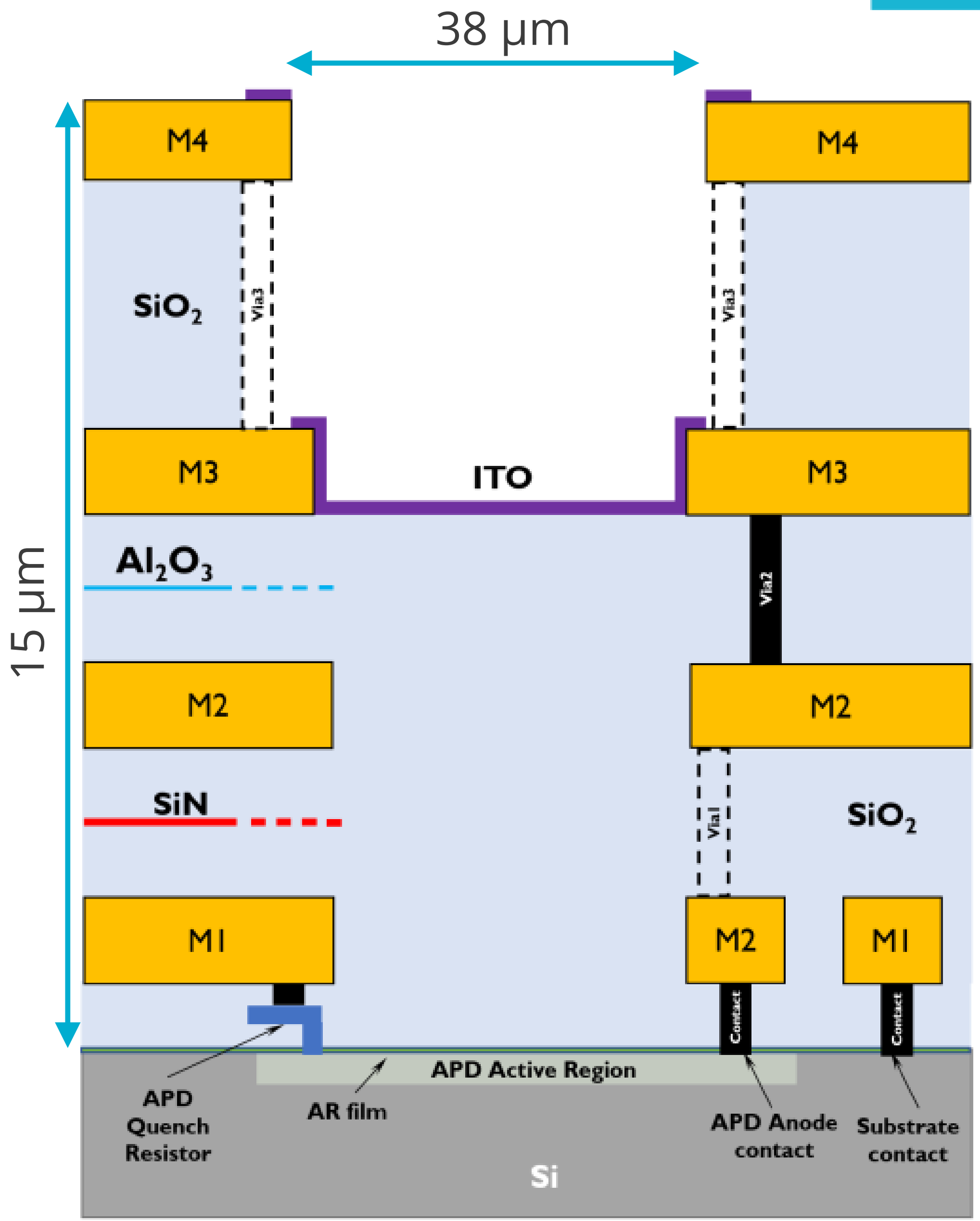


TICTOC 2

- Final TICTOC trap out of fab soon, $^{171}Yb^+$
  - 2 types of cells: “Clock” and “Load”
  - 369, 399, 435, 760, 935 nm light
  - Optimized electrode design, 50 µm height
  - Focusing output gratings, ~ 4 µm UV spot size
  - Loading sites also storage

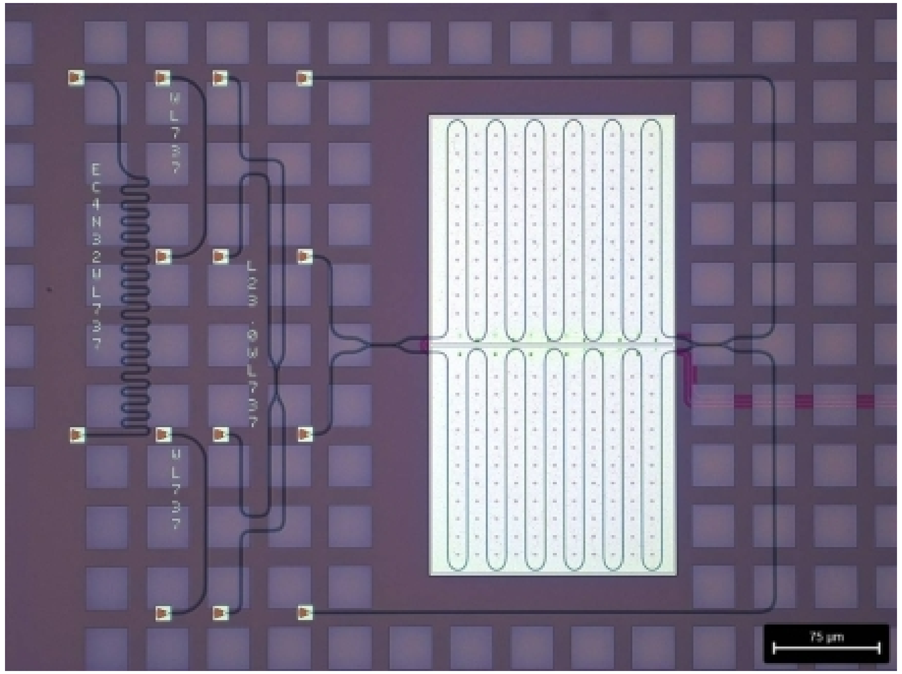


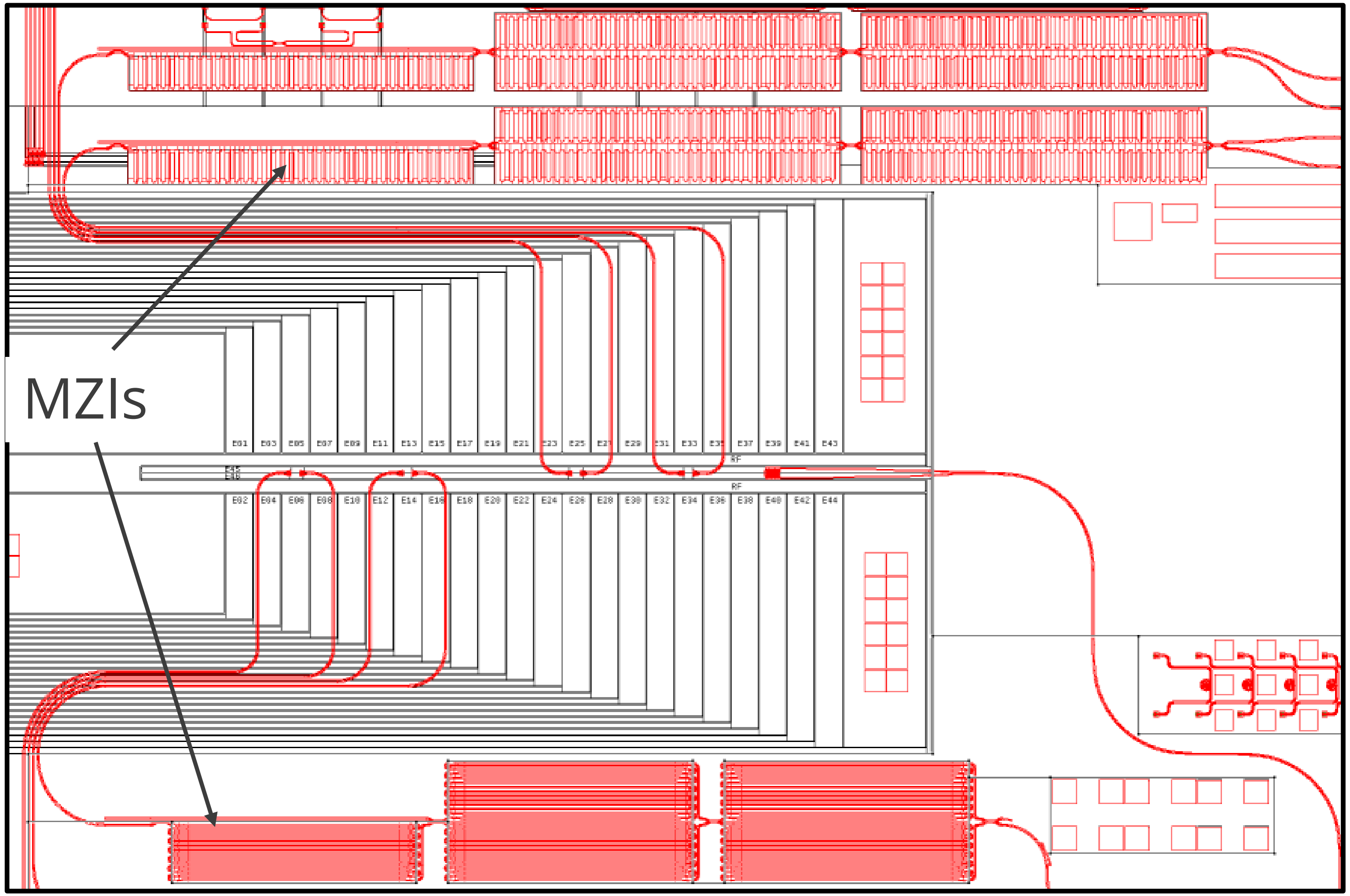




Modulators + Gratings : Malpais

- $^{40}Ca^{+}$, modulators + gratings
  - Multiple MZI designs
  - Edge coupled (off screen)
  - Designed for 729 nm
  - High fidelity 1 and 2-qubit gates

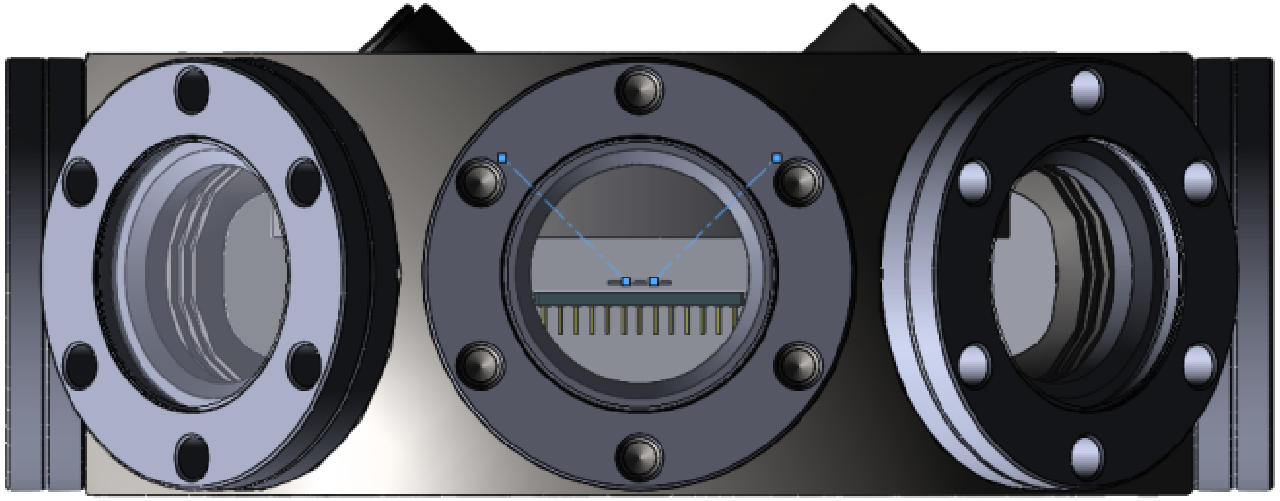


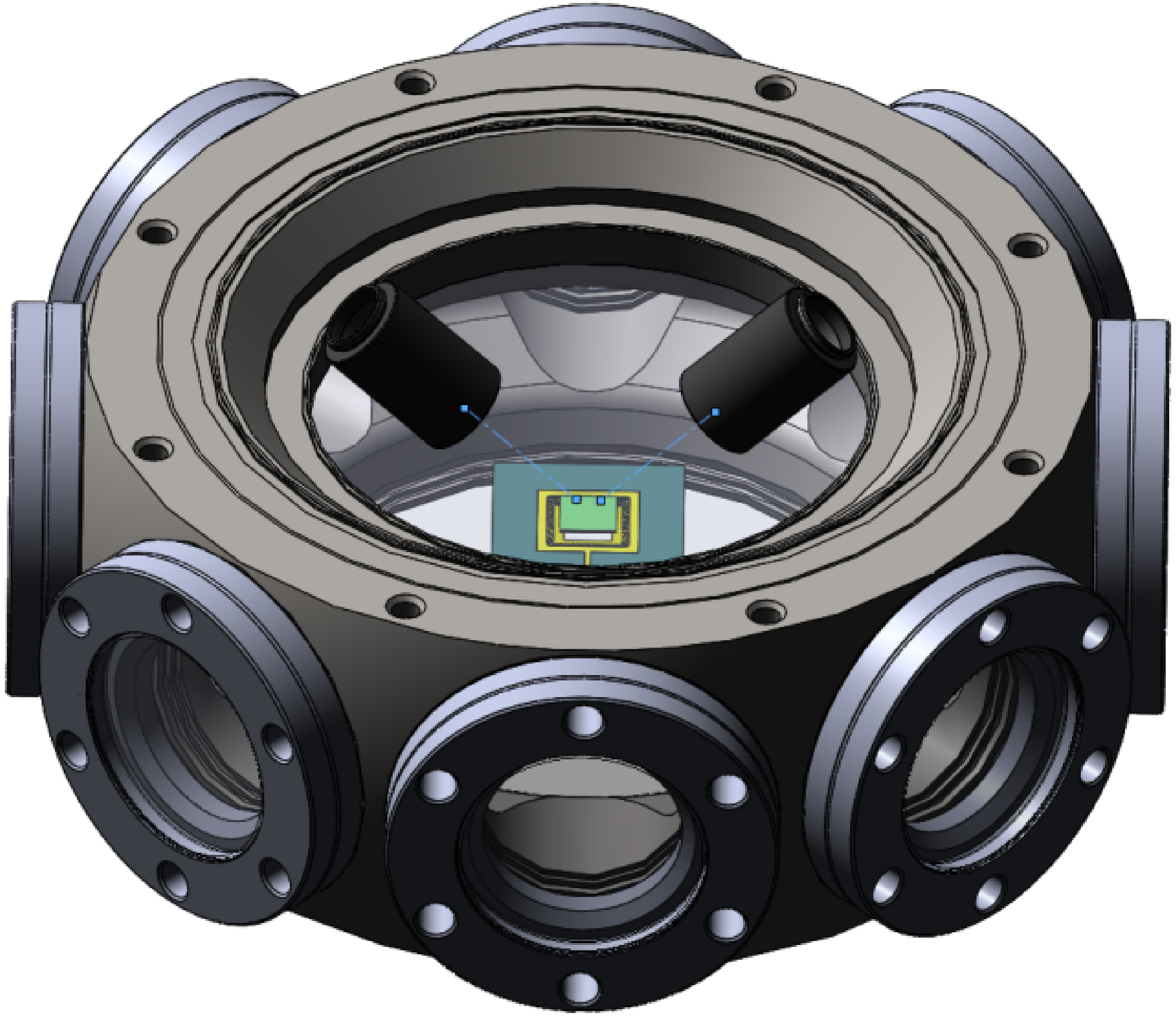


Waveguides, Gratings, and More

Waveguides and Gratings: Coupling In

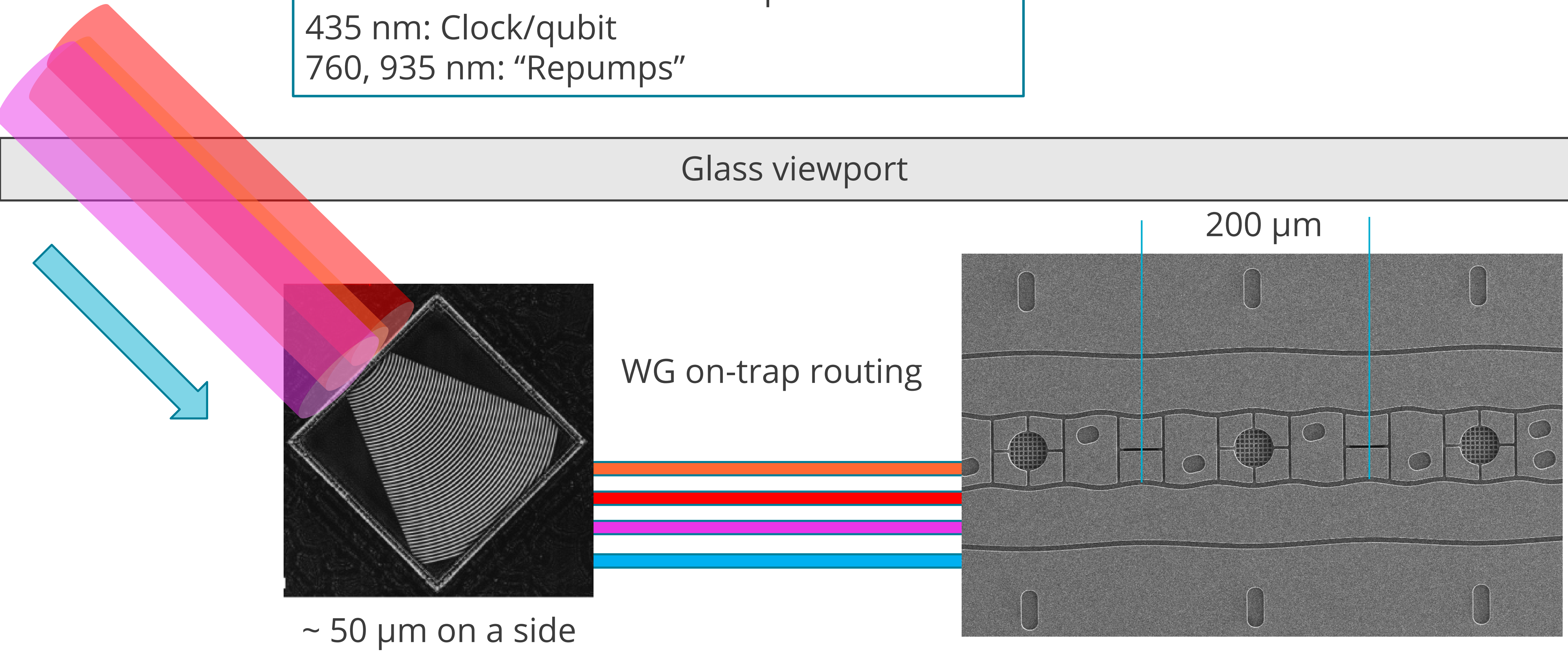
- Requires coupling through vacuum chamber
  - ~ 1E-11 Torr, UHV
  - Room temperature/Cryo
- Mostly top-down grating couple (edge optional)
  - Fiber attach in the works





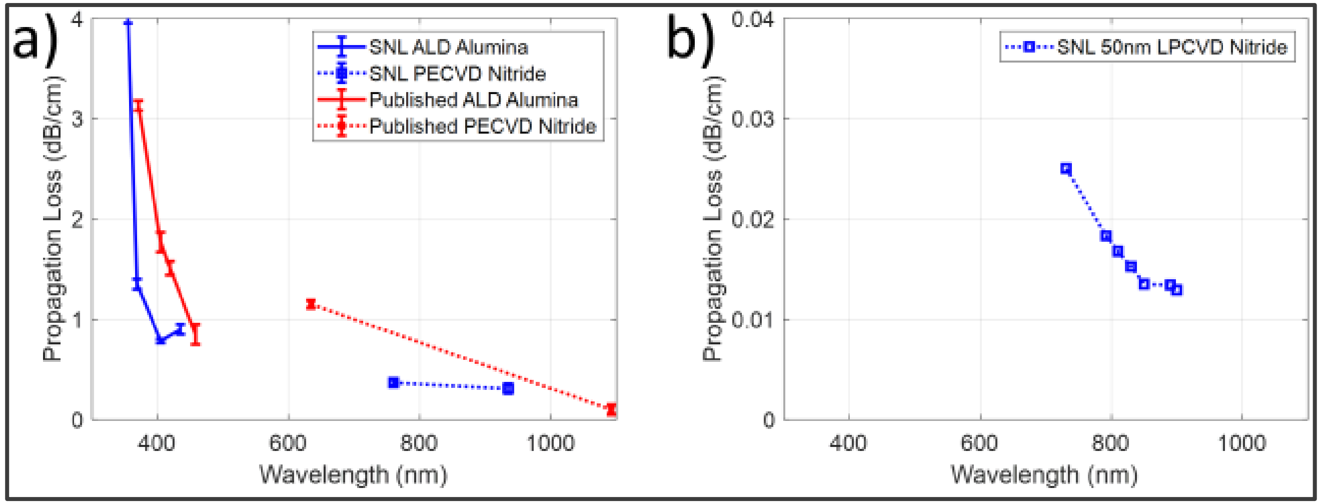
Waveguides and Gratings: Coupling In 2

Input for $^{171}Yb^{+}$:
369 nm: “Doppler” cooling
399 nm: Neutral atoms → strip electron = ion
435 nm: Clock/qubit
760, 935 nm: “Repumps”

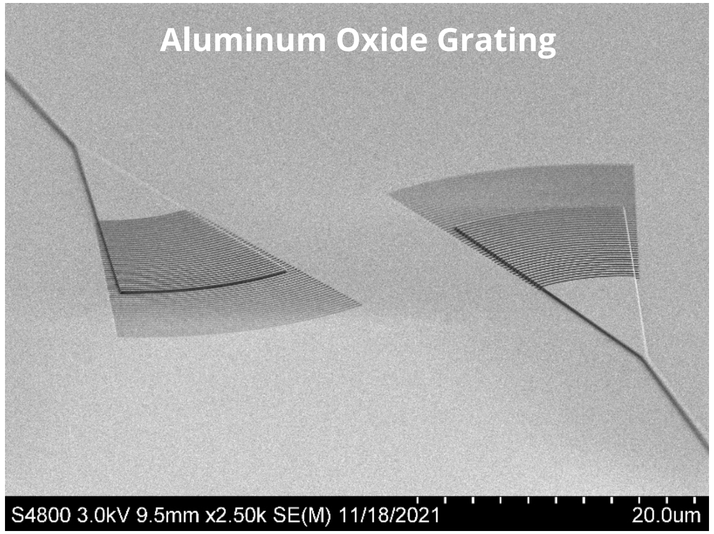


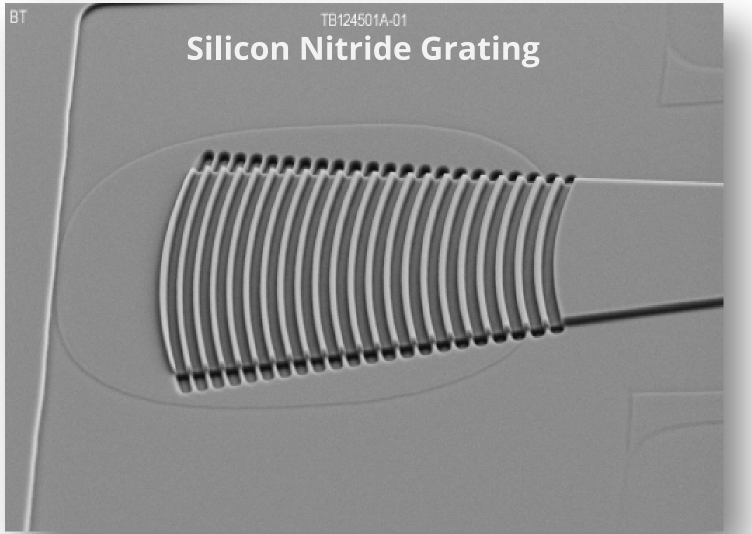
Waveguides and Gratings: Materials

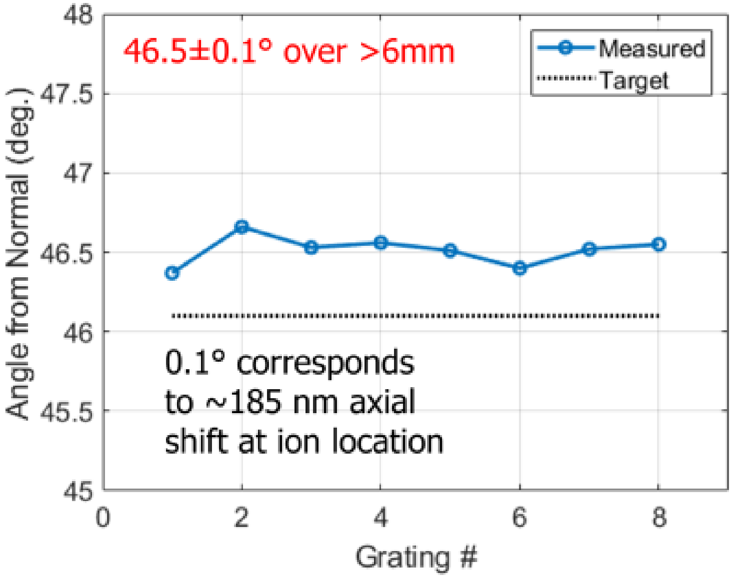
- Silicon Nitride WG material
  - VIS/NIR wavelengths
- New-ish Aluminum Oxide WG material
  - UV/VIS wavelengths
  - ~ 3 dB/cm @ 369 nm
  - Preliminary results at 355 nm: 4 dB/cm



- Angles highly accurate, < 1 μm horizontal error

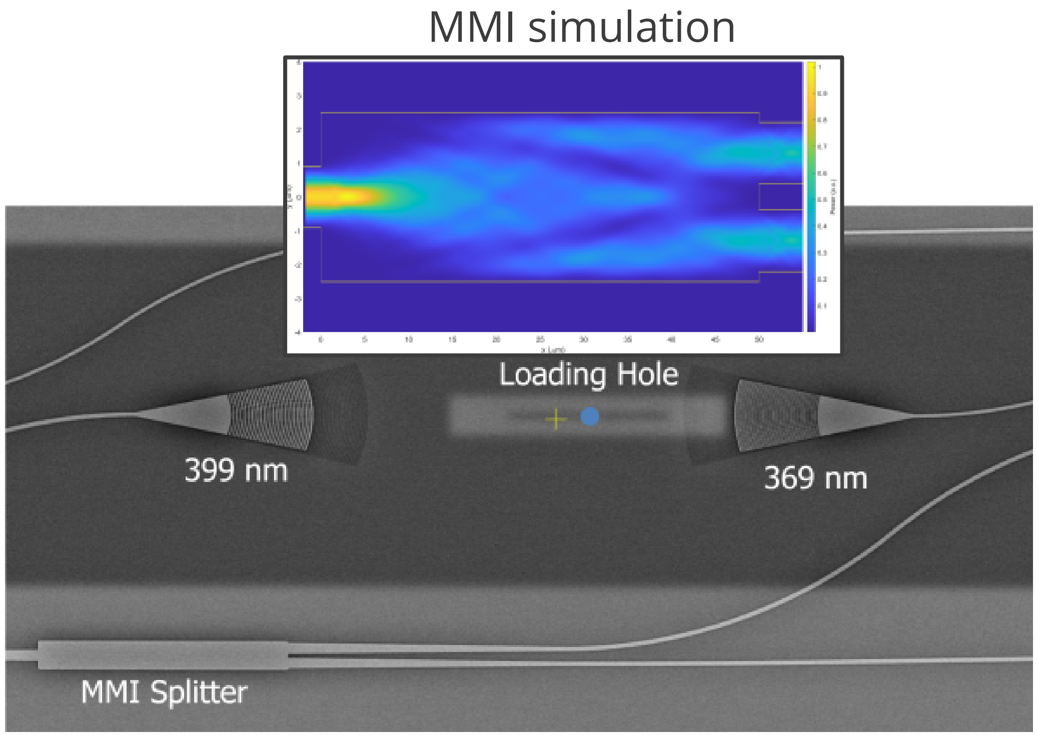


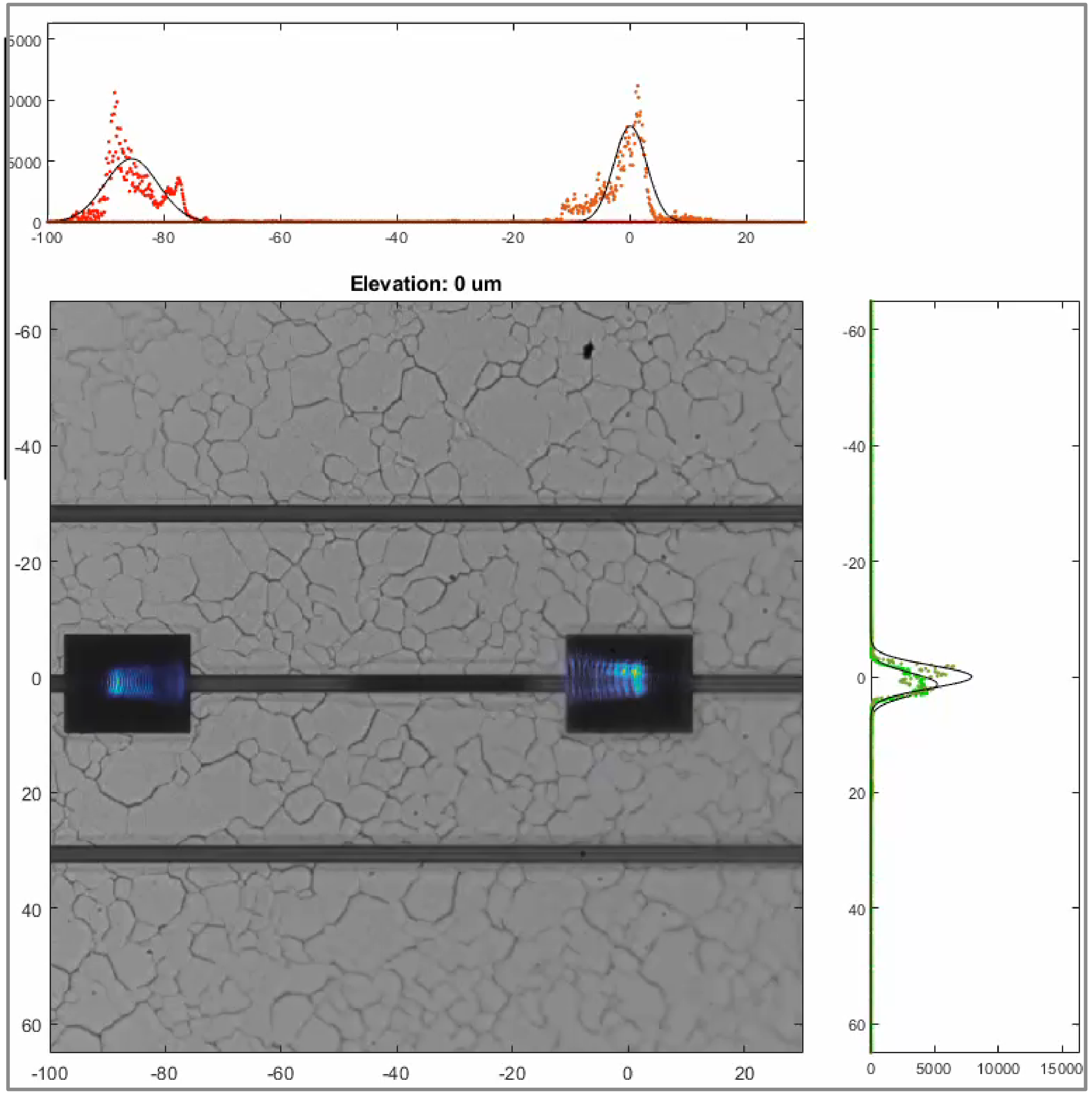




Waveguides and Gratings + Ion Traps

- Focusing Gratings:
  - ~ 4 to 8 μm spot sizes
- Gratings for ion loading
  - Need good overlap
  - Overlap for quantum operations
    - Doppler and Repump beams

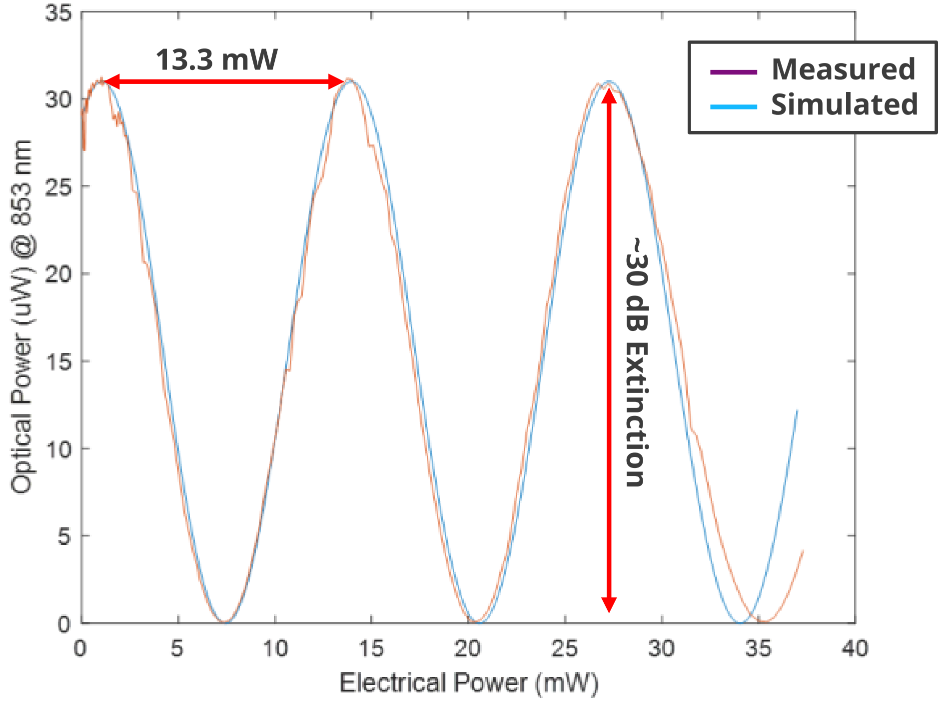




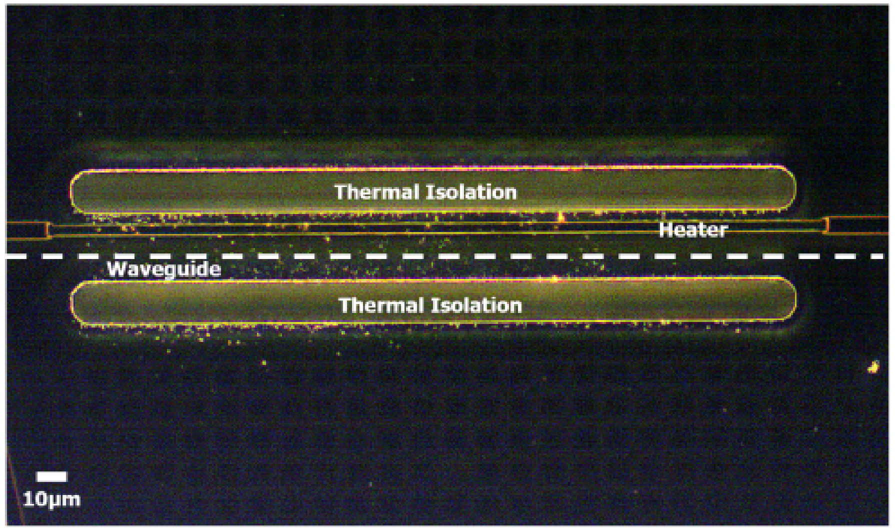
Phase Shifters

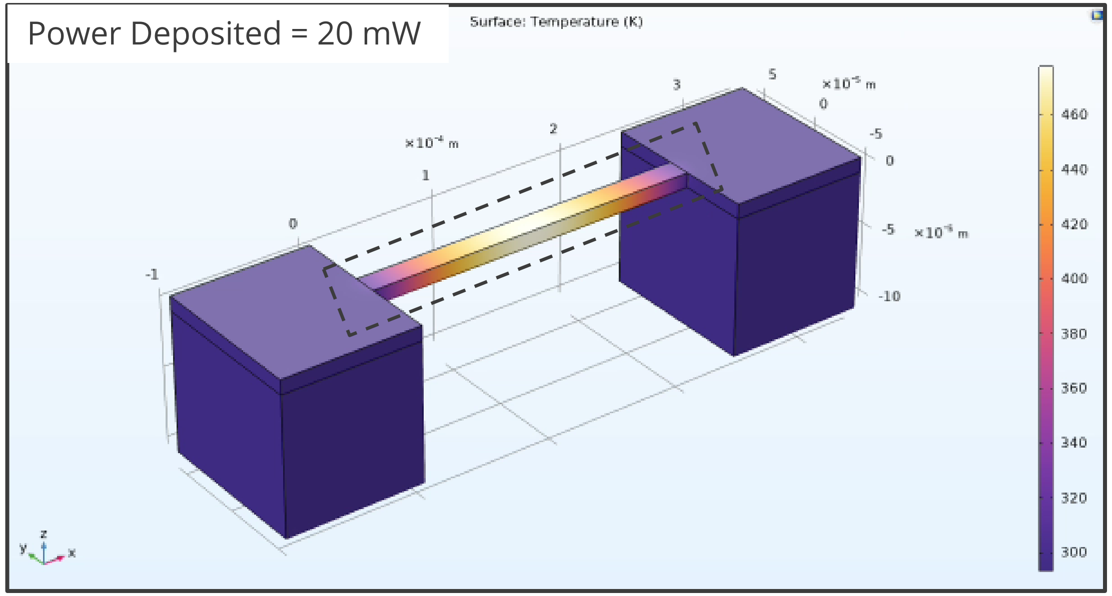
- Thermo-optic phase shifter characterized and show excellent efficiency and range
  - 6.65 mW/π phase shift
  - >5π total phase shift possible before damage
  - ~30 dB extinction on Mach Zehnder test structures

Tuning a Mach-Zehnder Test Structure



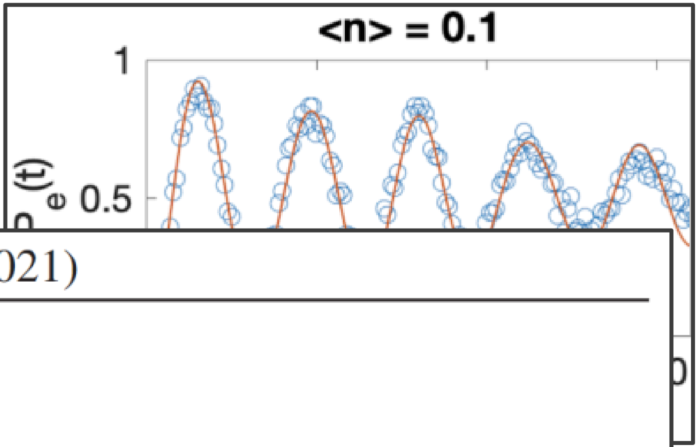
Darkfield Image of Thermo-Optic Phase Shifter





Waveguides + Ions Results

- Waveguide/grating integrated trap
  - L
  - R
  - D
- Heati
  - N
  - N



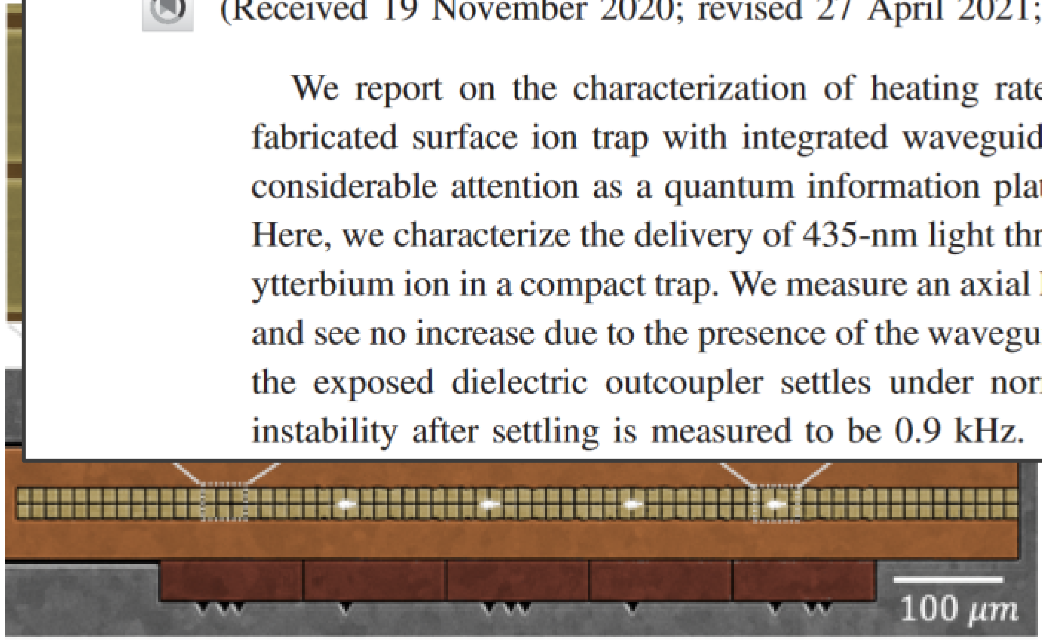
PHYSICAL REVIEW X **11**, 041033 (2021)

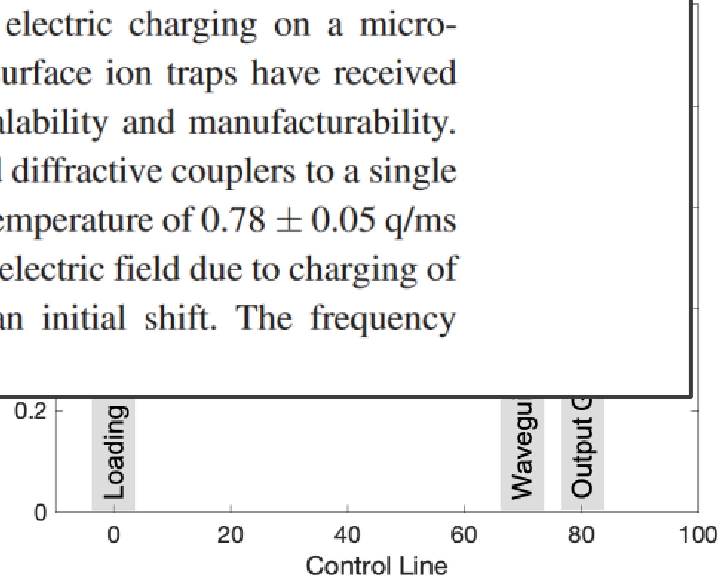
Integrated Optical Addressing of a Trapped Ytterbium Ion

M. Ivory,* W. J. Setzer, N. Karl, H. McGuinness, C. DeRose, M. Blain, D. Stick, M. Gehl, and L. P. Parazzoli
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

(Received 19 November 2020; revised 27 April 2021; accepted 31 August 2021; published 16 November 2021)

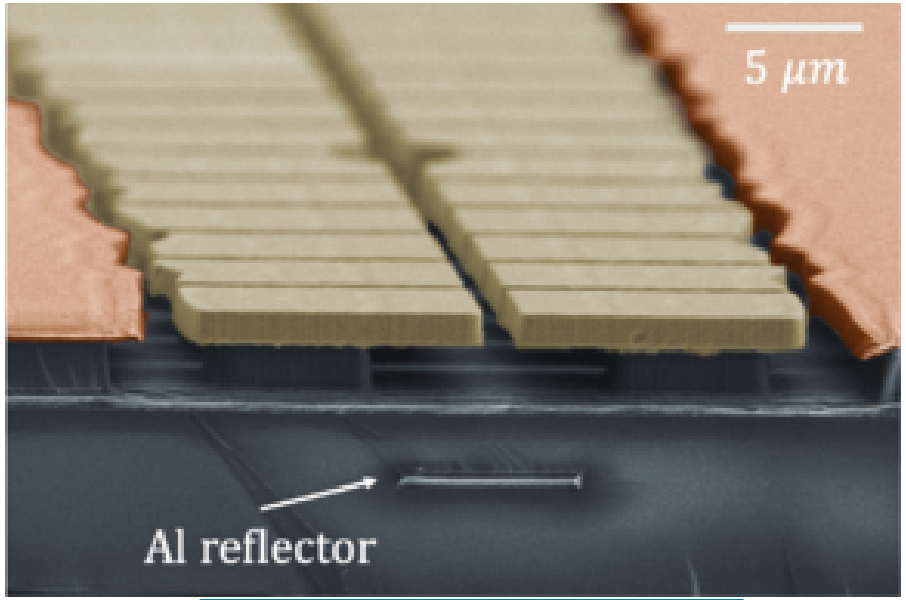
We report on the characterization of heating rates and photoinduced electric charging on a microfabricated surface ion trap with integrated waveguides. Microfabricated surface ion traps have received considerable attention as a quantum information platform due to their scalability and manufacturability. Here, we characterize the delivery of 435-nm light through waveguides and diffractive couplers to a single ytterbium ion in a compact trap. We measure an axial heating rate at room temperature of 0.78 ± 0.05 q/ms and see no increase due to the presence of the waveguide. Furthermore, the electric field due to charging of the exposed dielectric outcoupler settles under normal operation after an initial shift. The frequency instability after settling is measured to be 0.9 kHz.



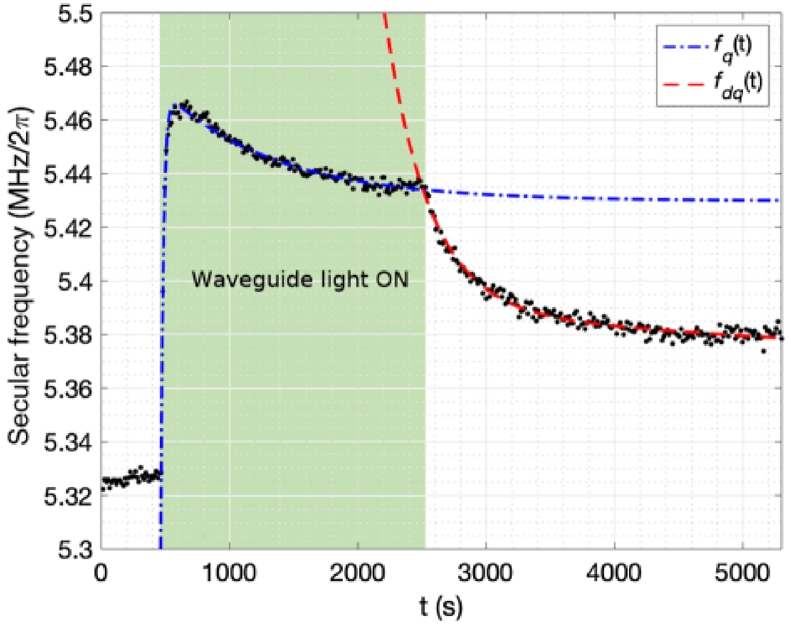


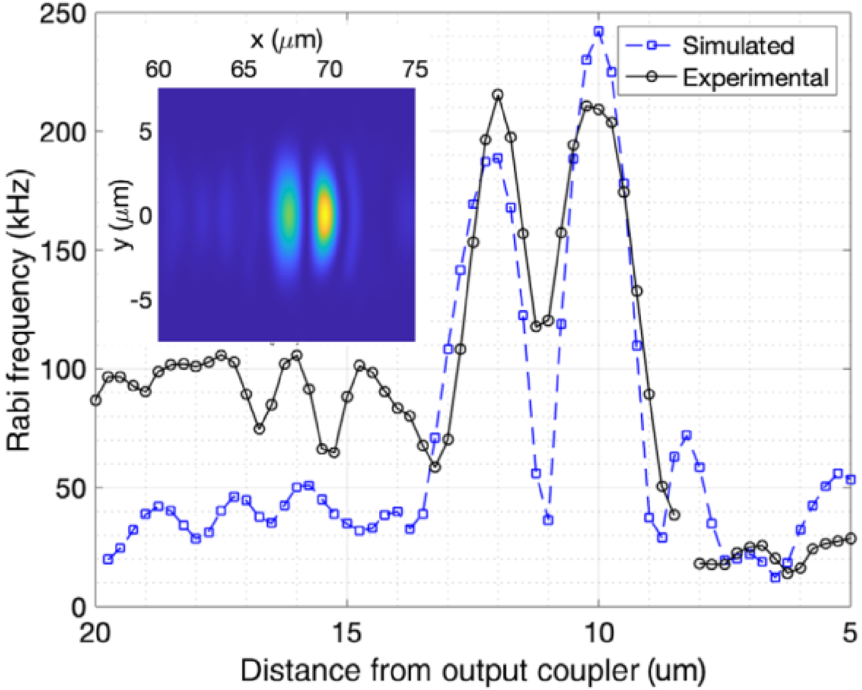
Waveguides + Ions Results 2

- Grating dielectric did have an effect
  - Significant shift of secular frequency
  - Long term drifts
  - Consistent with photoinduced charging models
- Reflector plate impact
  - Meant to redirect downward diffraction to ion
  - On the edge of fabrication resolution: double peak



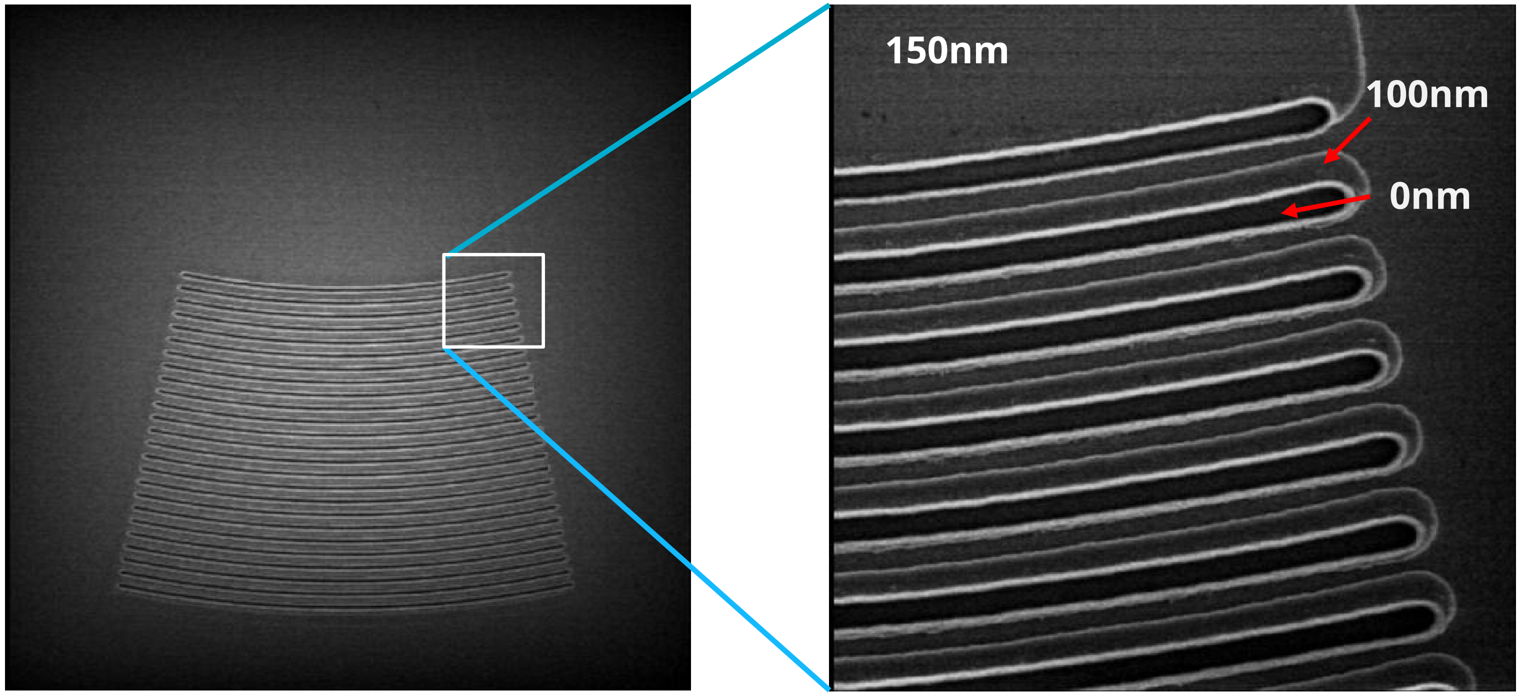
PRX 11, 041033 (2021)

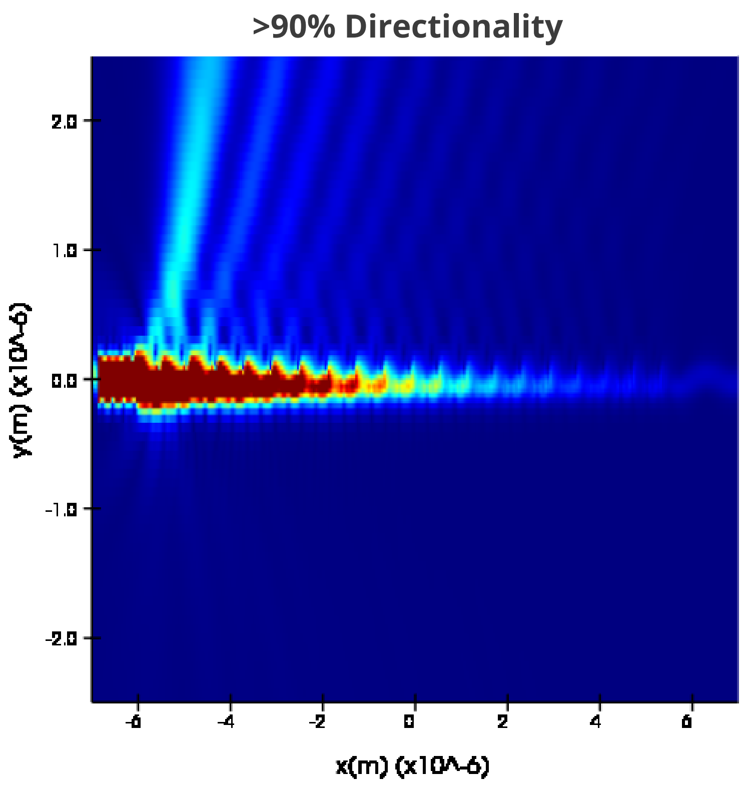




Future Directions for WGs + traps

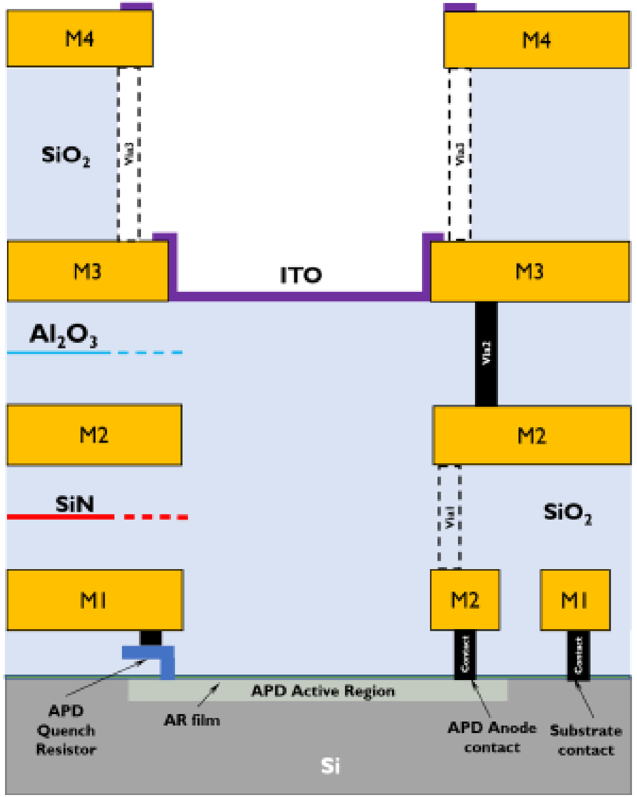
- Highly direction output gratings
  - Send most light towards the ion
  - Enabled by multi-level fabrication
  - Ridge waveguide design and polarization rotation possible
- More Traps
  - Preliminary results for ps pulsed 355 in WGs good.

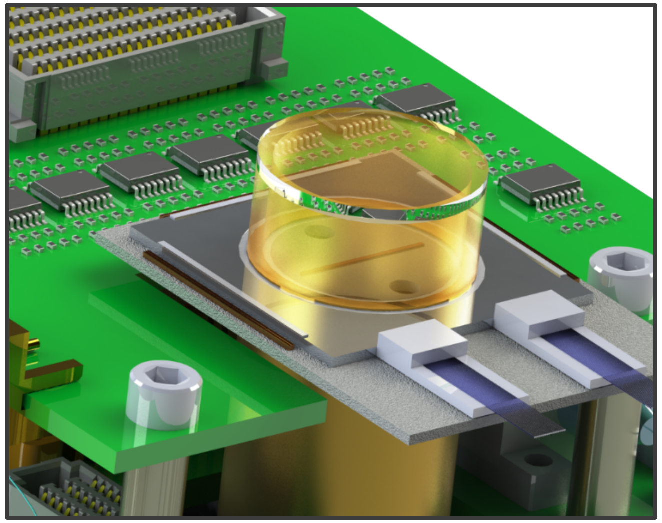


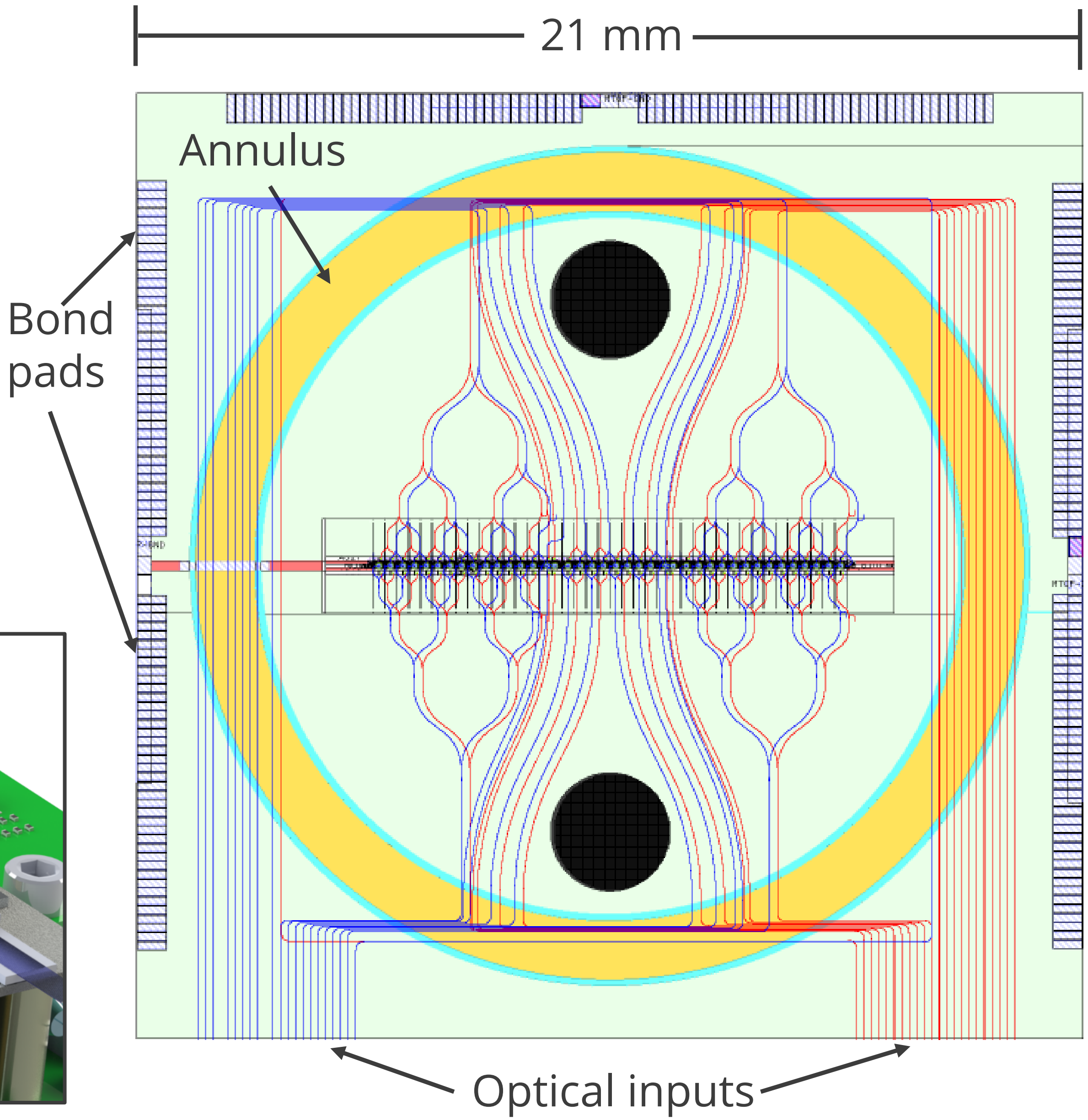


Future Directions for WGs + Traps: Fiber Attach

- Outside chamber v-groove/Trap attachment
  - 26 UV, Visible, NIR channels
  - Trap surface is part of the vacuum chamber
  - 369, 399, 435, 760, 935 nm beams





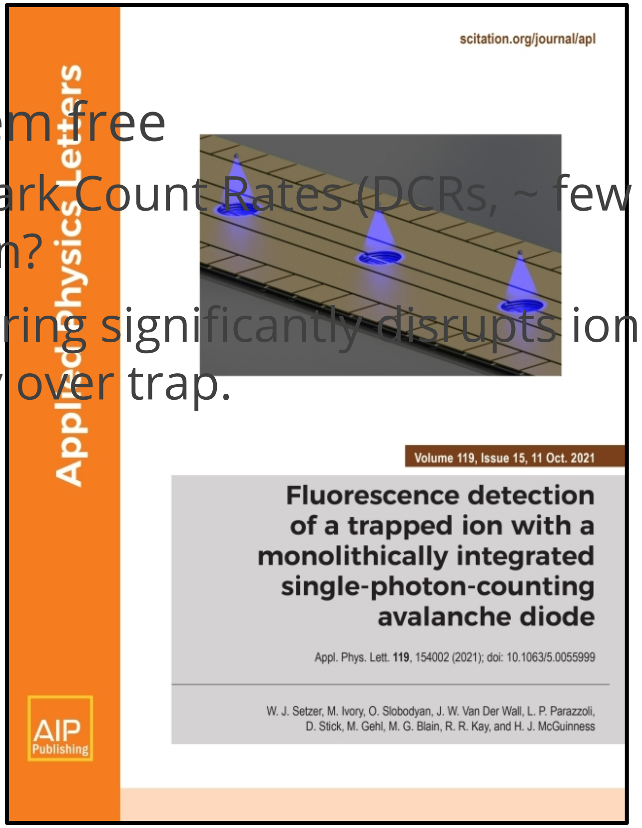


Trap-Integrated Single Photon Avalanche Diodes

Single Photon Avalanche Diodes (SPADs) + Traps

- First demonstration of trap-integrated SPAD
  - Room temperature operation
  - Average efficiency ~ 24% at 369 nm
  - ~ 40 μm diameter

- Not problem free
  - High Dark Count Rates (DCRs, ~ few kHz): defection creation?
  - SPAD firing significantly disrupts ions, couldn't hold ion directly over trap.


scitation.org/journal/apl

Applied Physics Letters

Volume 119, Issue 15, 11 Oct. 2021

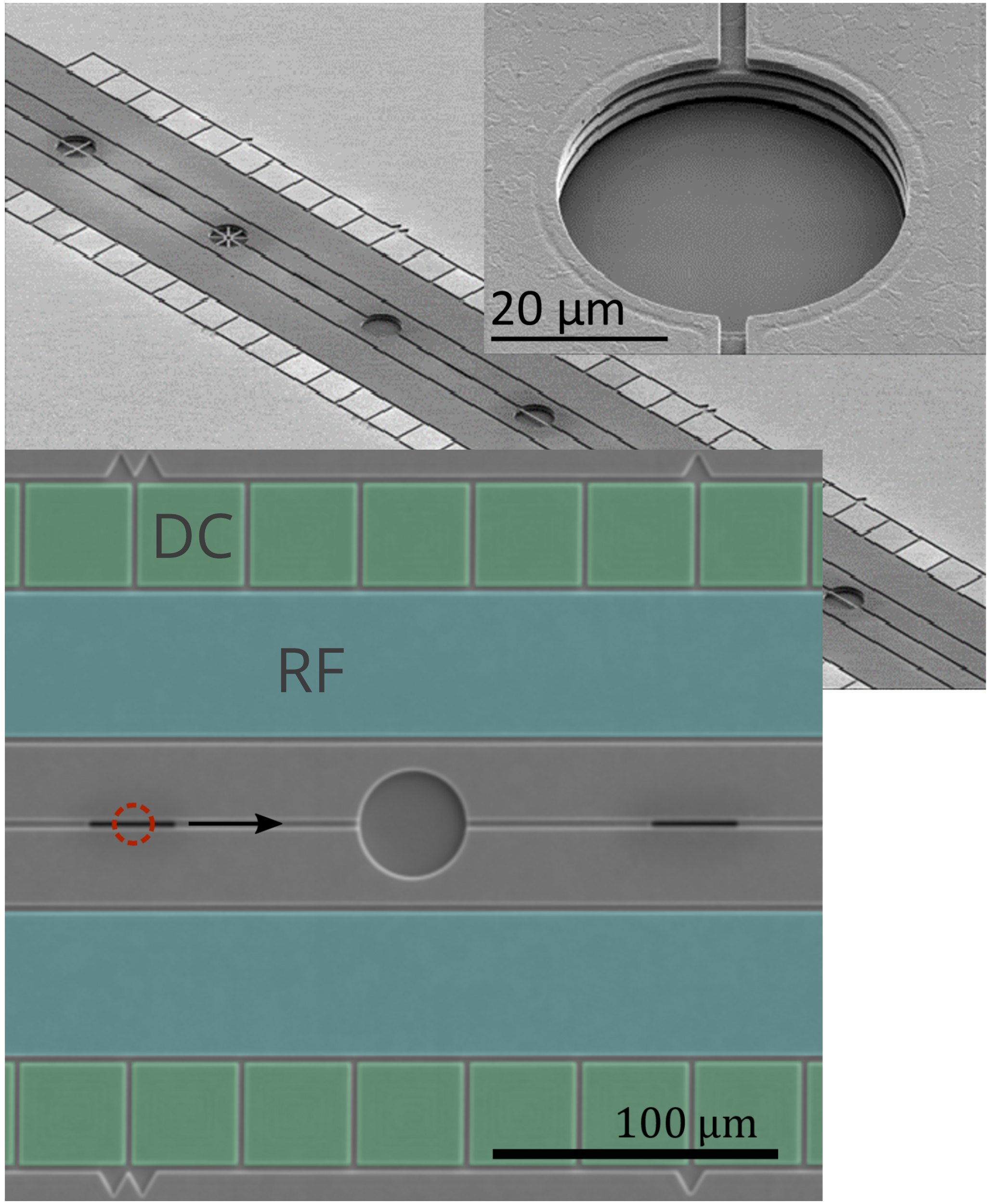
Fluorescence detection of a trapped ion with a monolithically integrated single-photon-counting avalanche diode

Appl. Phys. Lett. 119, 154002 (2021); doi: 10.1063/5.0055999

W. J. Setzer, M. Ivory, O. Slobodyan, J. W. Van Der Wall, L. P. Parazzoli, D. Stick, M. Gehl, M. G. Blain, R. R. Kay, and H. J. McGuinness

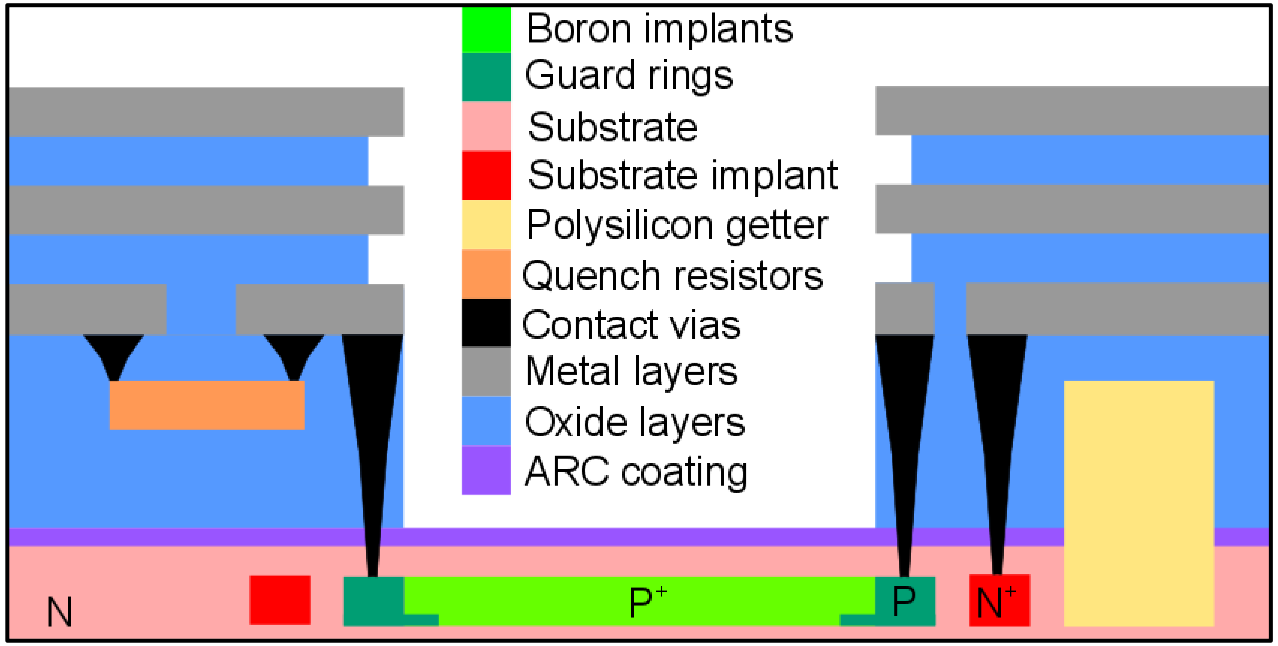
AIP Publishing

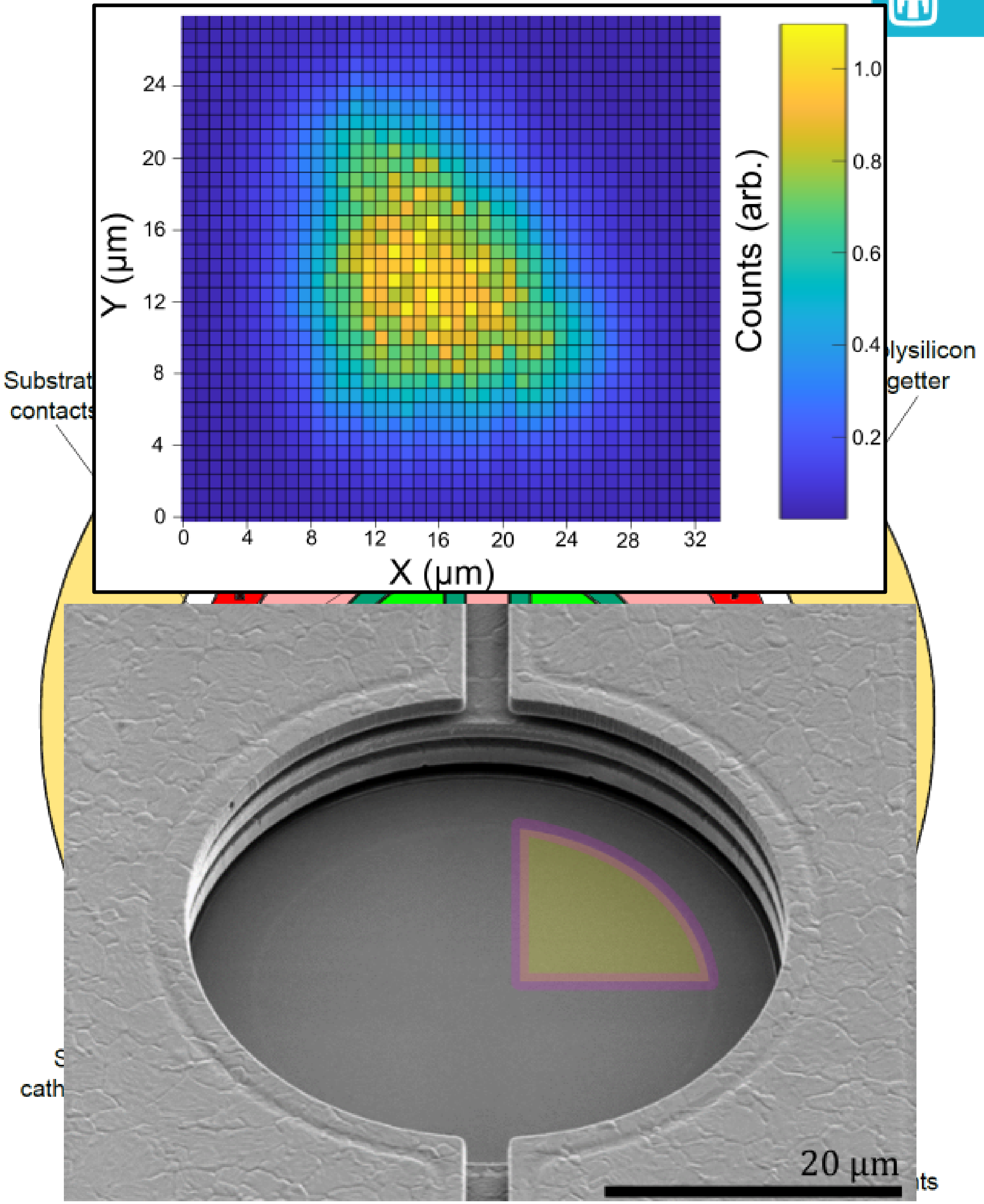
Appl. Phys. Lett. **119**, 1540222 (2021)



SPAD Composition and Design

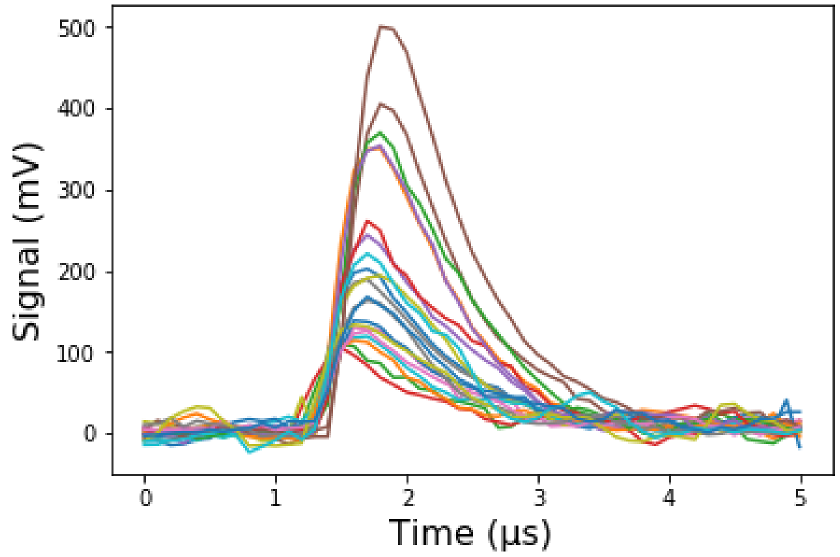
- SPADs Monolithically integrated into surface trap
  - Process flow could be carried out in most CMOS fabs
  - ARC reduces reflections @ 369 nm from ~ 30% to ~ 10%
  - Quartered and halved active area, reduce DCR
  - Active area of quartered area ~ 60 μm^2



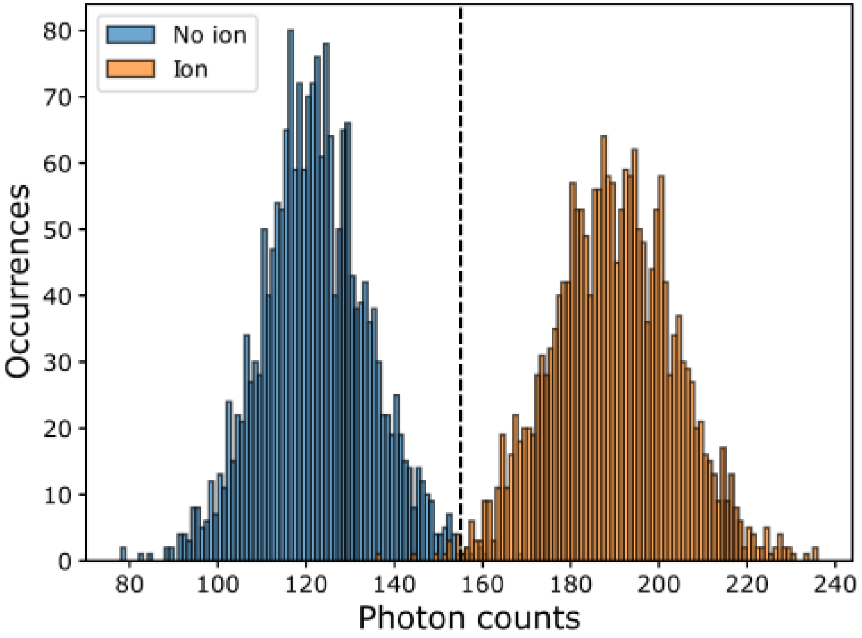


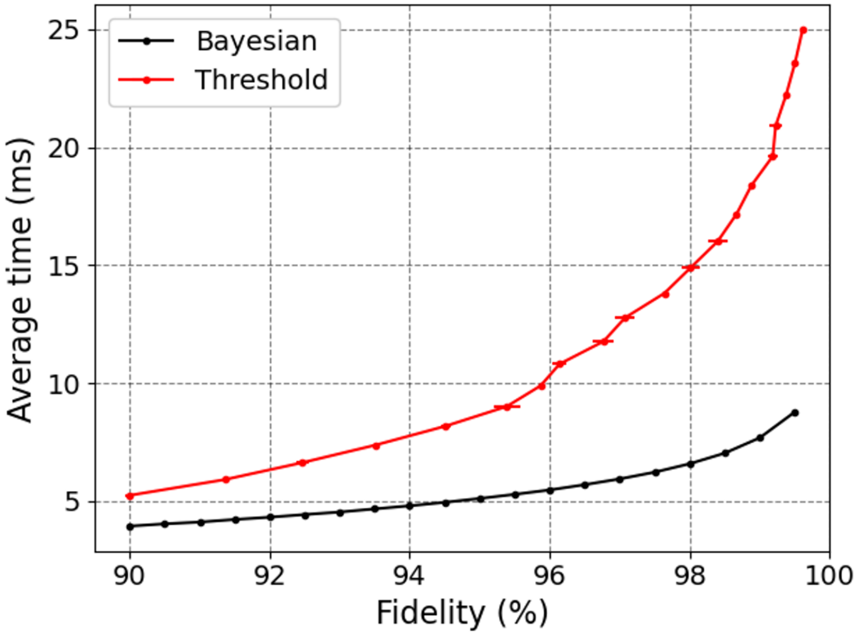
Results with Ions

- SPADs Pulses longer than wanted
  - Likely extra capacitance from long leads
- With $^{174}Yb^{+}$ only ion/no ion
- "Traditional" threshold vs. Bayesian detection
  - Bayesian much faster, but more complex



Source	Counts (kcps)
Ion fluorescence	4.8(1)
935 nm repump	4.0(1)
370 nm Doppler	1.4(1)
Dark counts	1.2(1)
Rf pickup	0.3(1)

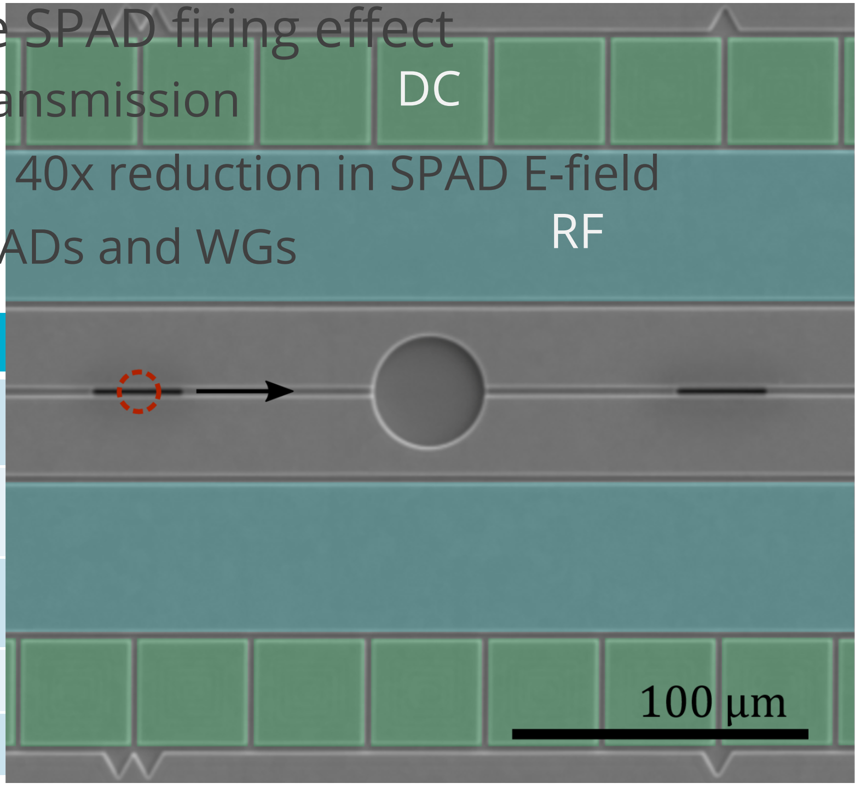




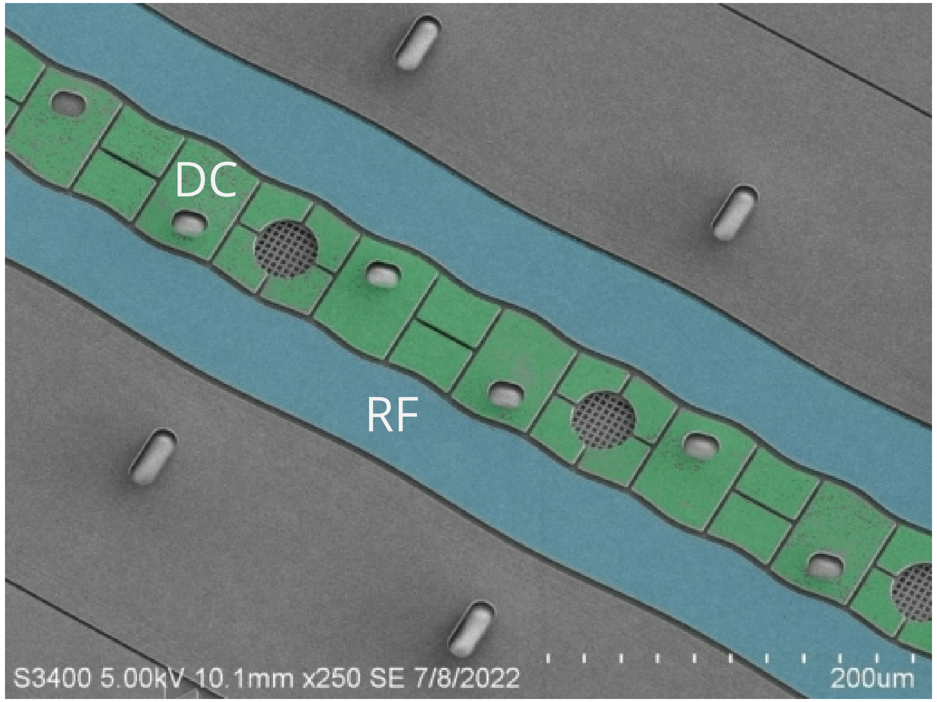
"Enhanced" SPAD/Waveguide Trap

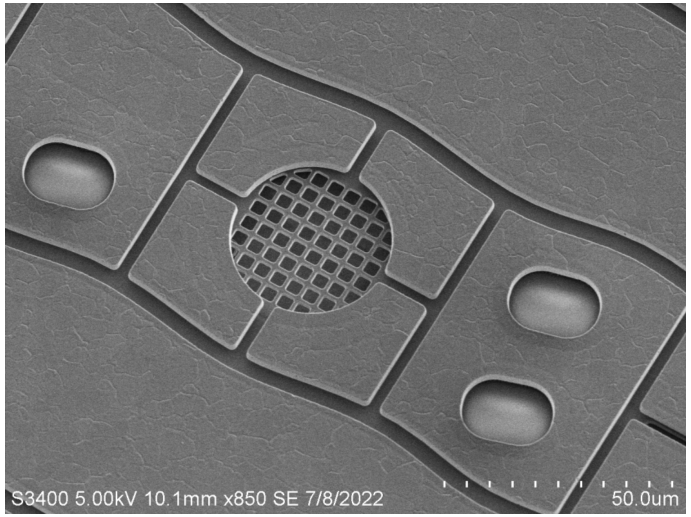
- Version of trap with SPAD covering/waveguides
  - SPADs from previous design, new metal layers
  - "Inner" DC electrodes, much higher trap depth
  - Easier to transport over gratings
  - SPADs or WGs, not SPADs + WGs

- Metal mesh to reduce SPAD firing effect
  - Estimated ~ 56% transmission
  - Simulations show ~ 40x reduction in SPAD E-field
  - ITO in future for SPADs and WGs



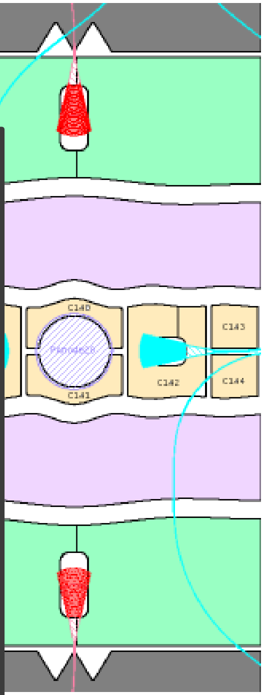
Source
Ion fluorescence
935 nm repump
370 nm Doppler
Dark counts
Rf pickup

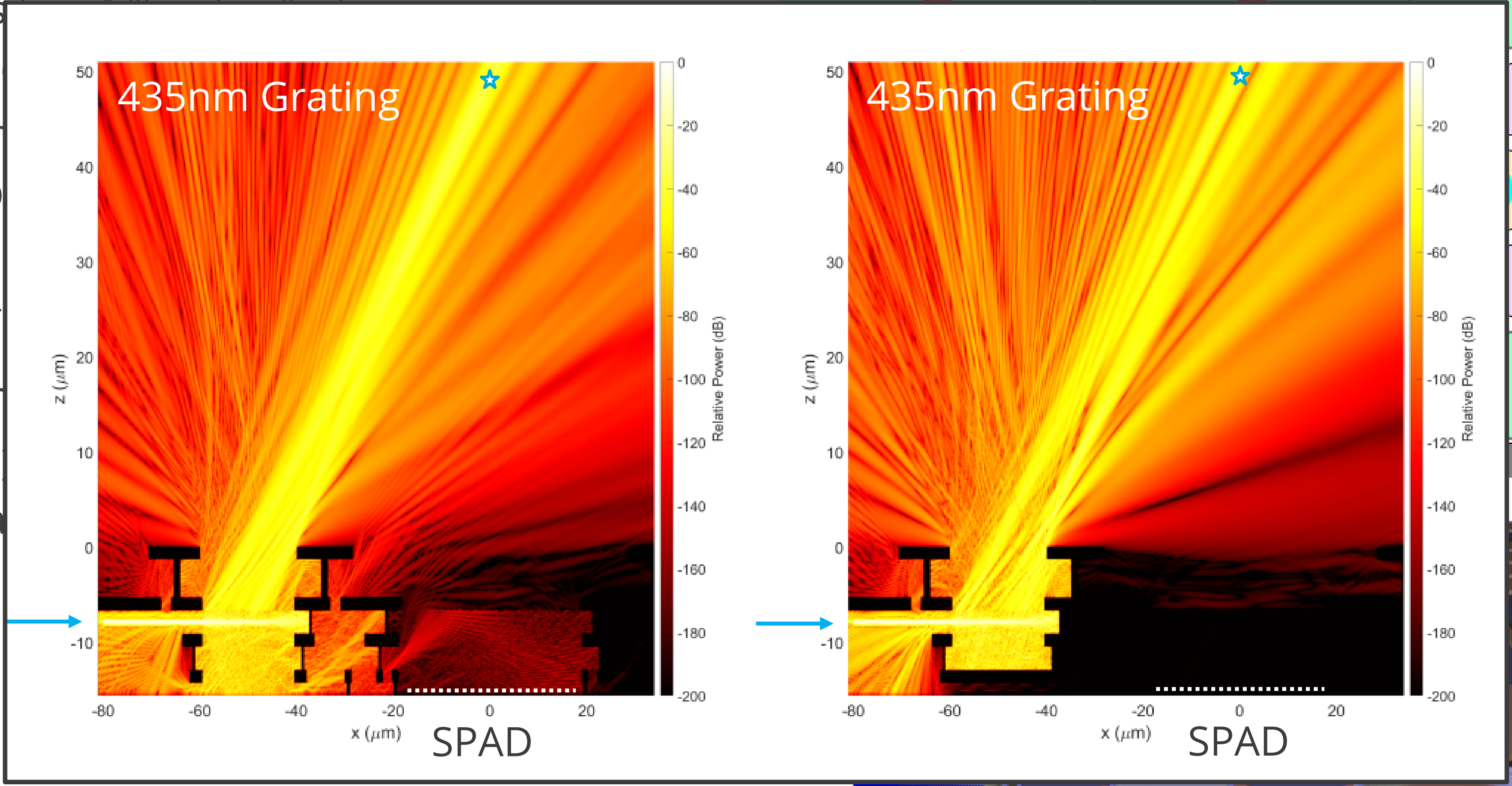


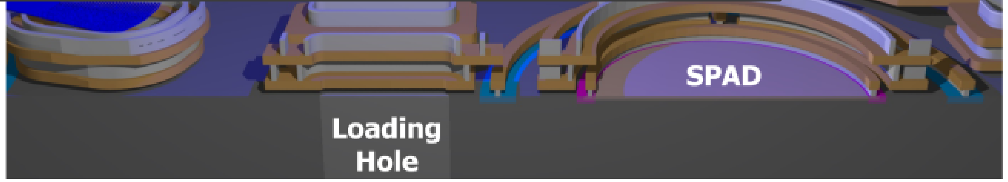


Future Directions: Final Trap!

- Final trap near completion
  - 32 “clock” s
  - SPADs + W
  - ITO coverin
  - “Full” SPAD
  - New SPAD
    - Initial DCR r
- Baffles for sim
  - Significantl
  - Affects bea

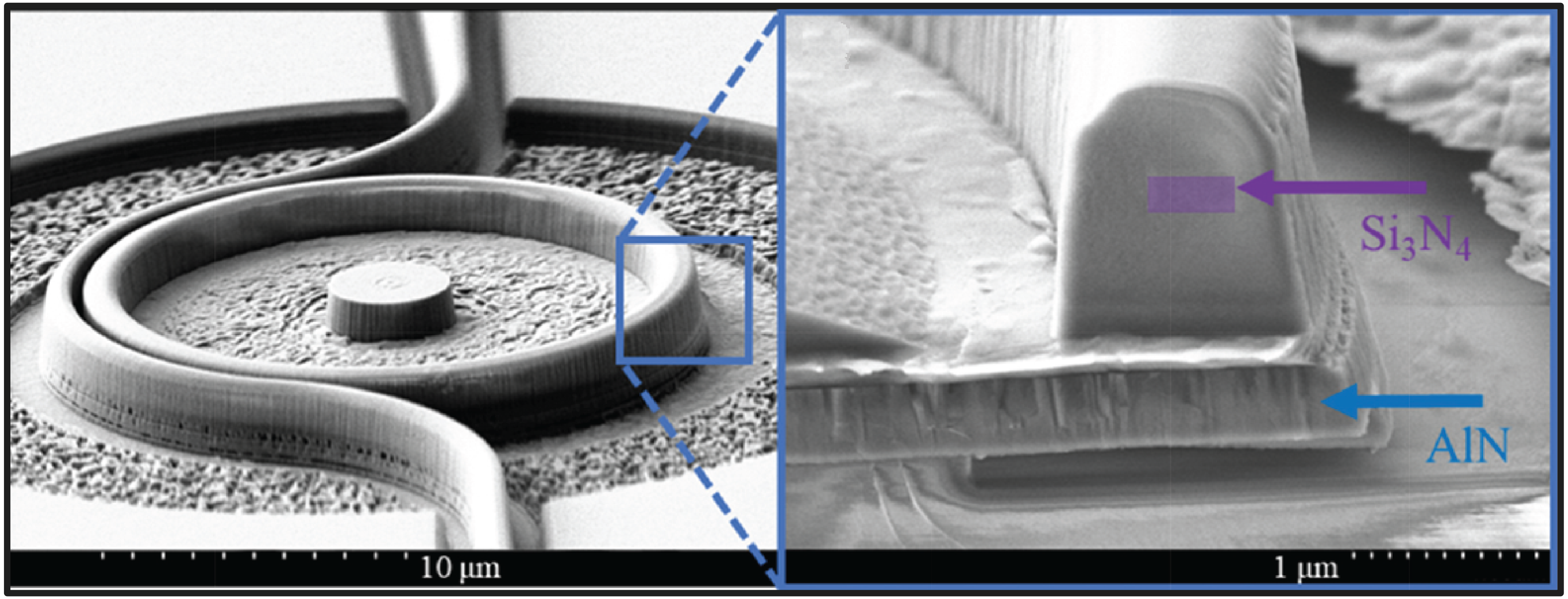






Traps and Modulators

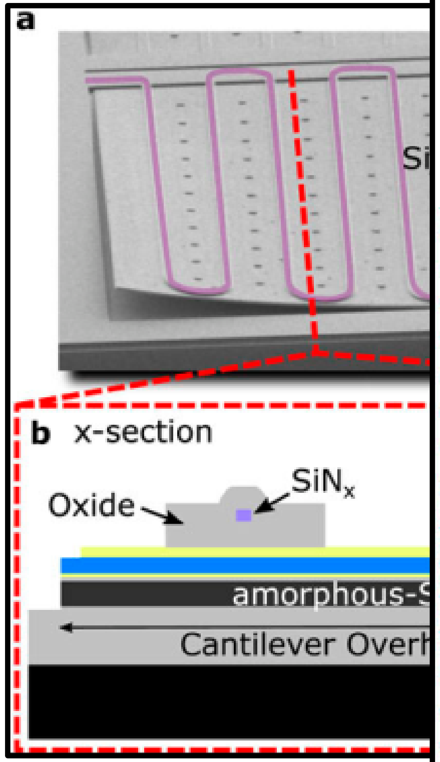
Integrated Modulators Overview

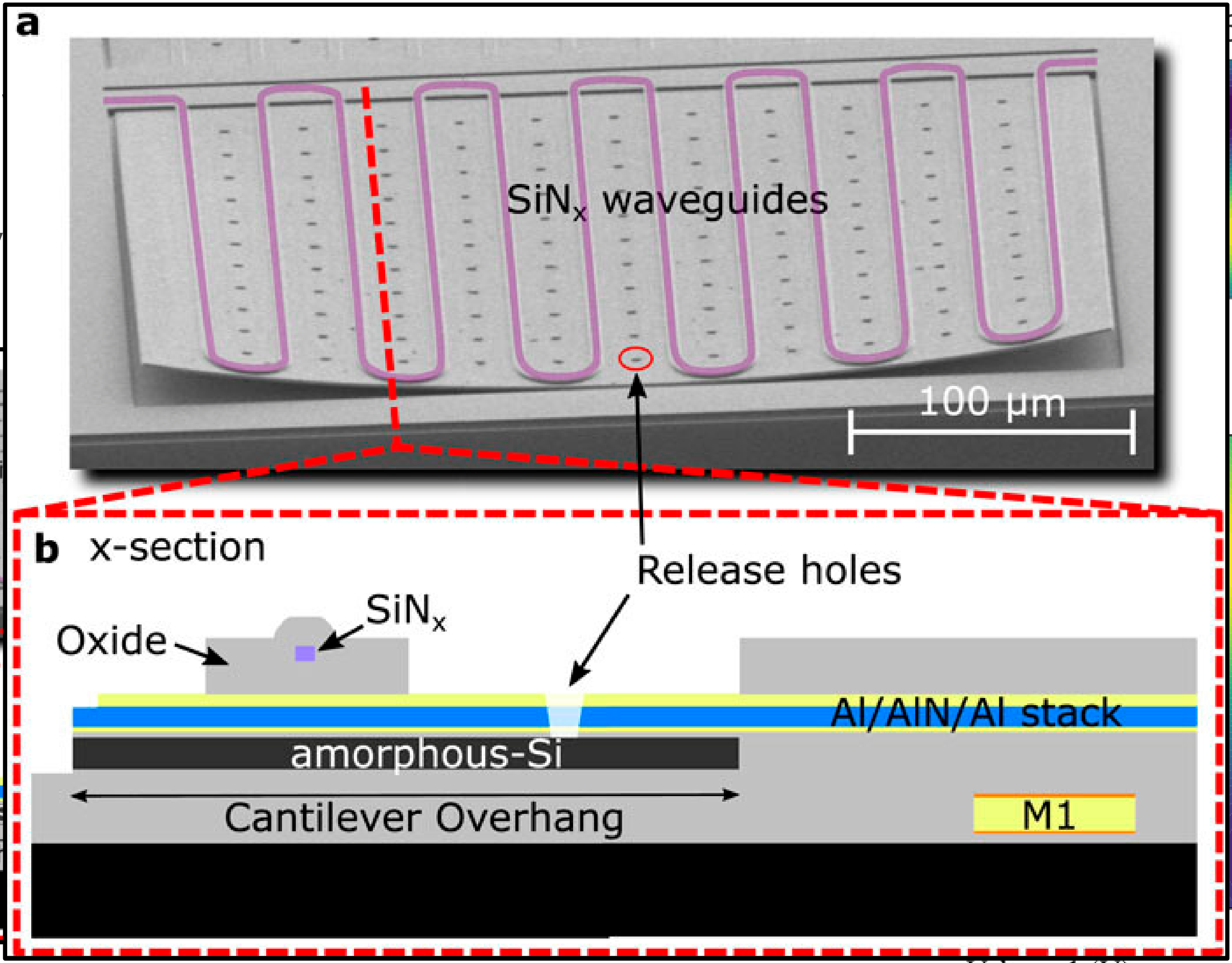


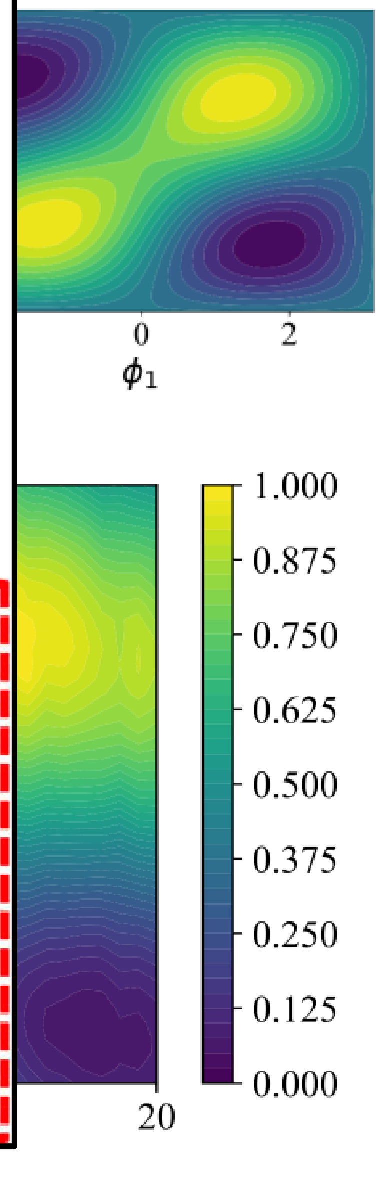
APL Photonics **7**, 051304 (2022)

General Performance Characteristics

- SiNx waveguides on
  - Release holes allo
- Splitting ratio of cou
  - Observed roughly

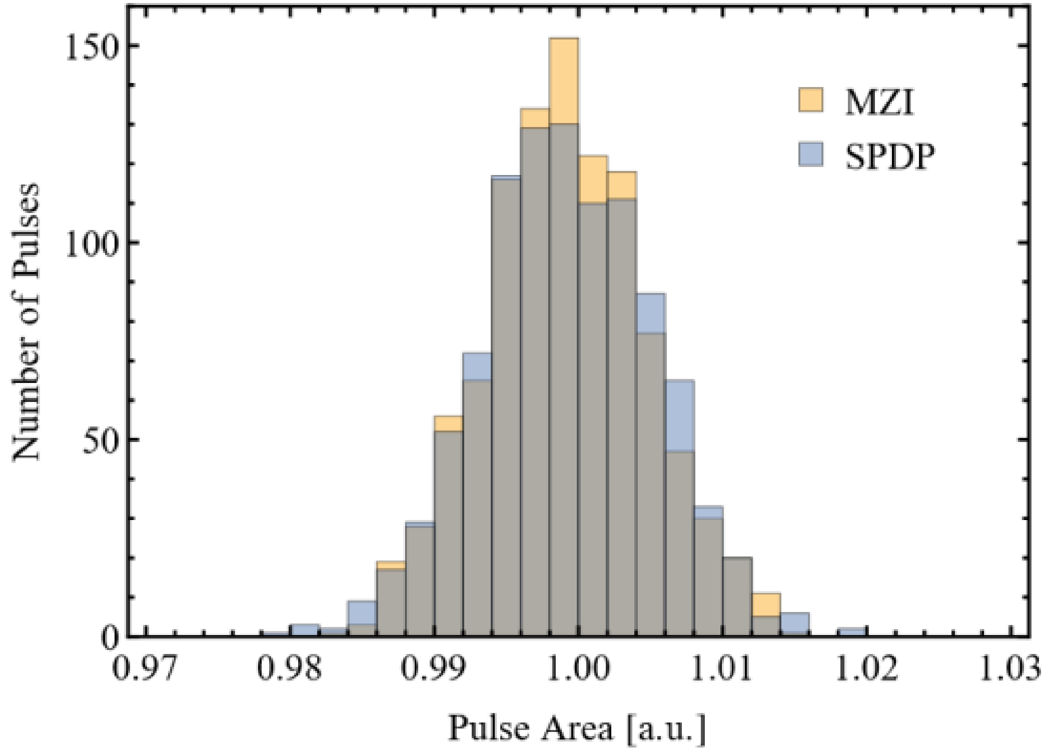


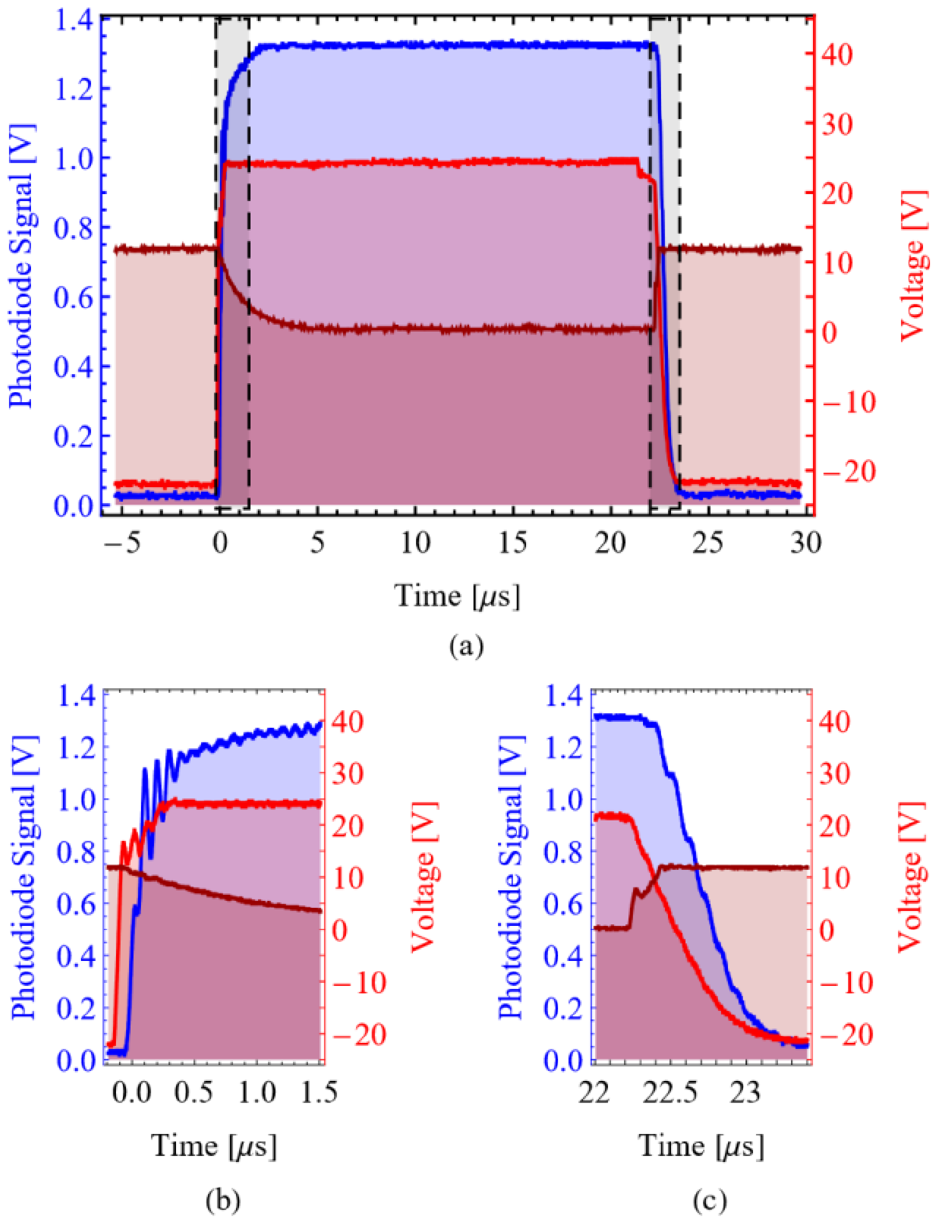




Pulse Timings and Stability

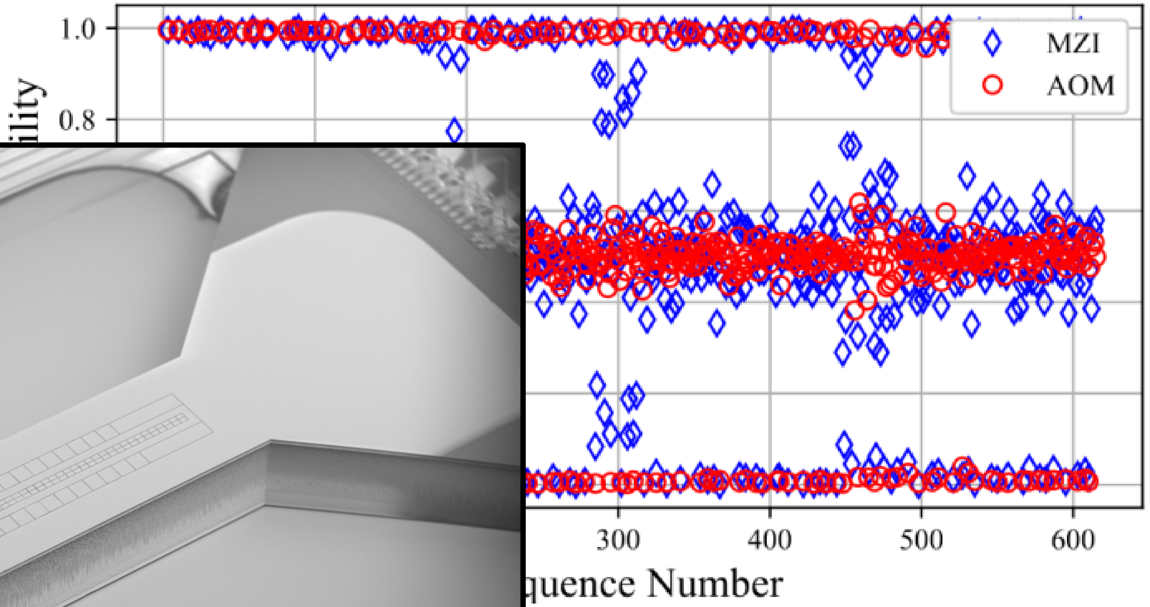
- Compare MZIs to “traditional” AOM switch
  - Single-pass/Double Pass AOMs vs. double MZIs
  - Imperfect electronic switching, but long-ish pulses
  - Integrated pulse intensity similar, detection electronics limited?

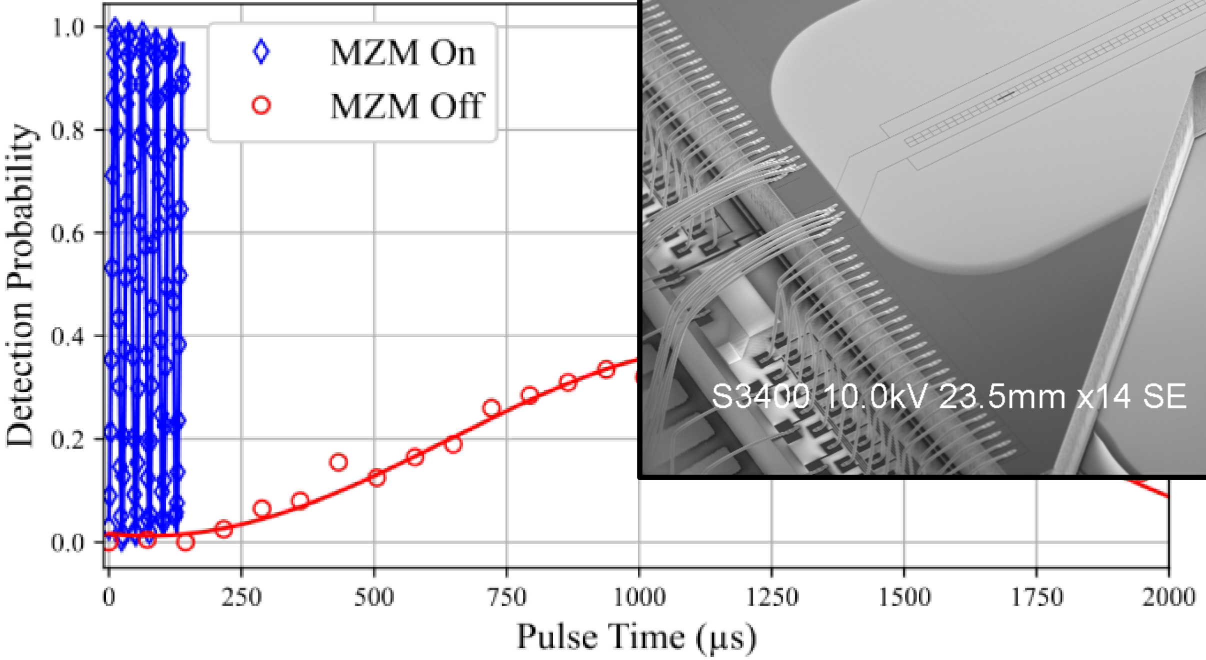


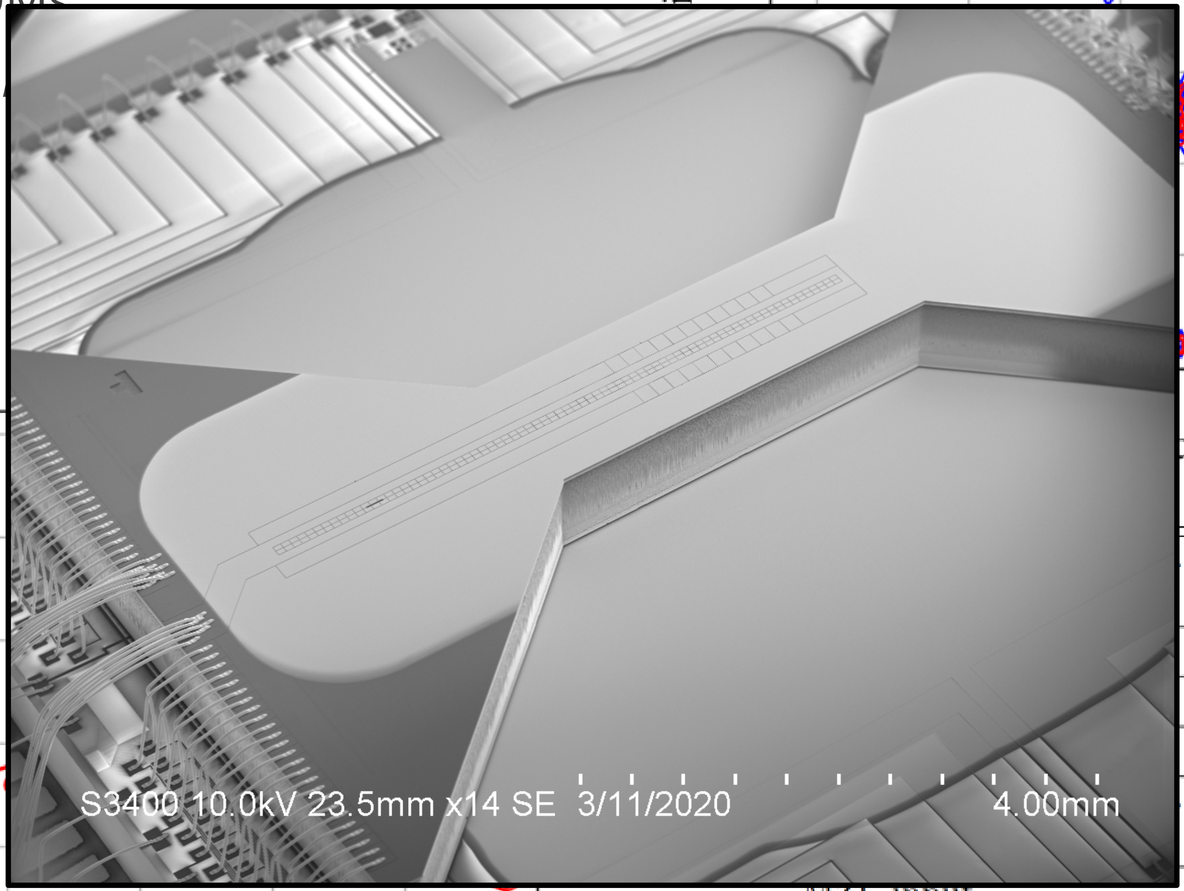


Modulators + Ions

- MZI switch inline with $^{40}Ca^{+}$ quad. beam (729 nm)
  - Rabi flops similar to AOMs
  - Extinction ratio ~ 38 dB
  - GST results: Somewhat
  - Identity gate the worst:







	Process infidelity ($\times 10^{-3}$) **(X/Y/I)**
	$2.6 \pm X$ / $2.4 \pm X$ / $2.6 \pm X$
	$1.6 \pm X$ / $1.5 \pm X$ / $0.7 \pm X$
	$0.7 \pm X$ / $1.0 \pm X$ / $0.1 \pm X$
	Diamond norm ($\times 10^{-2}$) **(X/Y/I)**
MZI, input	$1.5 \pm X$ / $1.4 \pm X$ / $4.7 \pm X$
AOM, input	$2.5 \pm X$ / $2.3 \pm X$ / $0.3 \pm X$
AOM, output	$0.5 \pm X$ / $0.5 \pm X$ / $0.7 \pm X$

Role the Credits

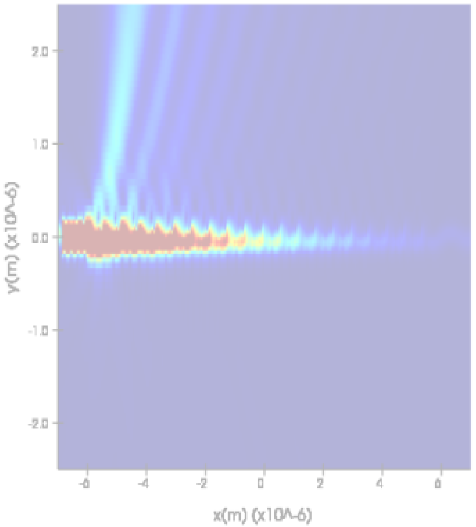
Thanks to:

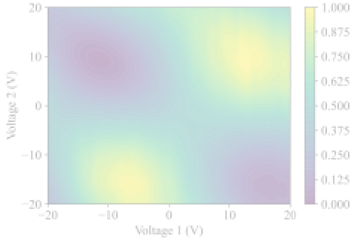
TicToc

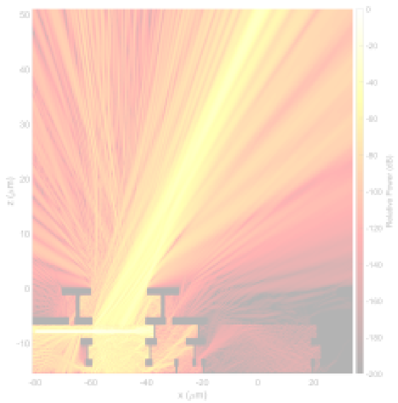
Michael Gehl
Rex Kay
Doug Trotter
Will Setzer
Nick Karl
Joon Kwon
Megan Ivory
Ray Haltli
Justin Schultz

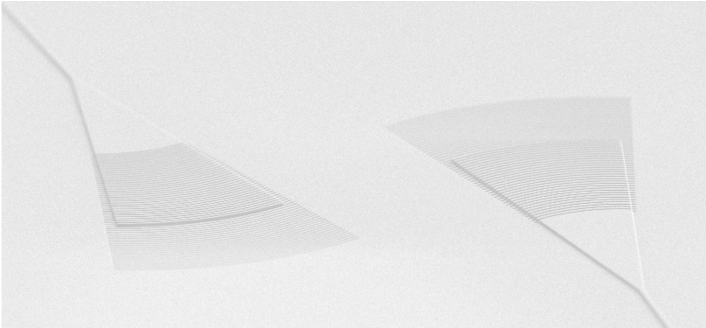
Malpais

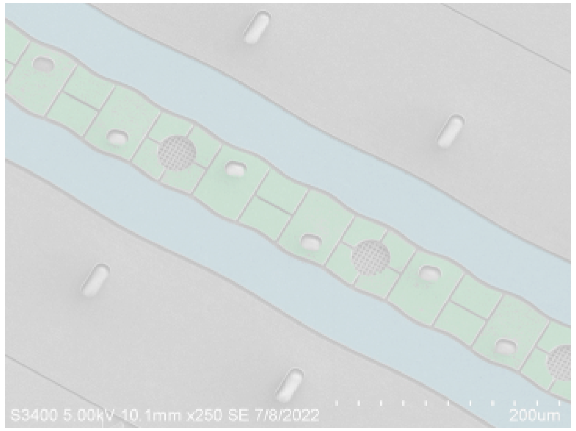
Craig Hogle
Daniel Dominguez
Matt Eichenfield
Dan Stick











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U.S. DEPARTMENT OF ENERGY

Office of Science

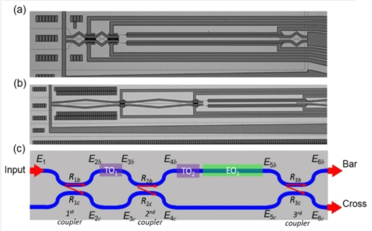
Postdoc Positions Available !

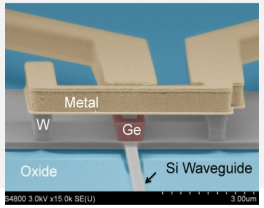
Contact: Hayden McGuinness
hmcgui@sandia.gov

The National Security Photonics Center

Integrated photonics for quantum communications

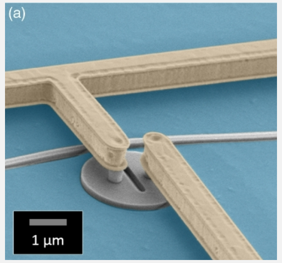
Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms: compact microsystems for telecom and visible wavelengths

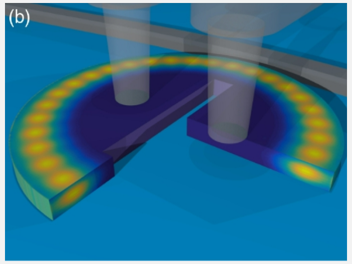




Cryogenic optical interconnects

High-speed low-power resonant modulator operating at cryogenic temperatures (≤ 4 K)

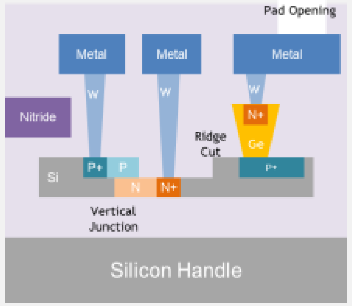


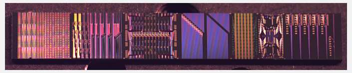


Optica **4,** 374-382 (2017)

Silicon photonics integrated circuits

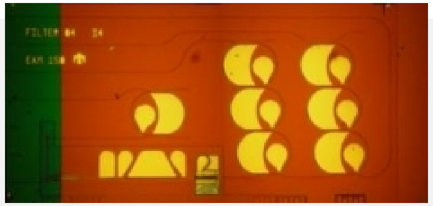
- Leverage CMOS (200 mm SOI)
- 22 passive devices, 20 active devices, design guide and library
- **MPW runs available**, up to passive+active+Ge devices





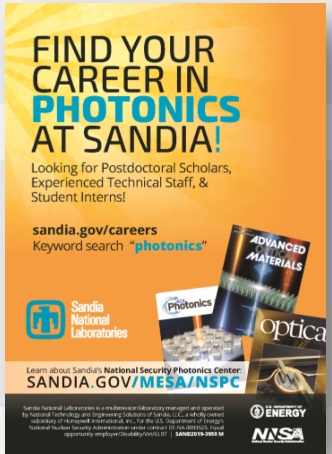
III-V photonic integrated circuits (PICs)

- InP, GaAs, GaN
- Elements: Waveguides, lasers, amplifiers, modulators, detectors, phase shifters
- **MPW runs available**



More information on photonics MPW opportunities:

- National Security Photonics Center: sandia.gov/mesa/nspc
- Contact photonics@sandia.gov



DiVincenso Criteria and Trapped Ions

1) A scalable physical system with well-characterized qubit : ? / YES
2) The ability to initialize the state of the qubits to a simple fiducial state: YES
3) Long relevant decoherence times : ? / YES
4) A "universal" set of quantum gates : YES
5) A qubit-specific measurement capability: YES