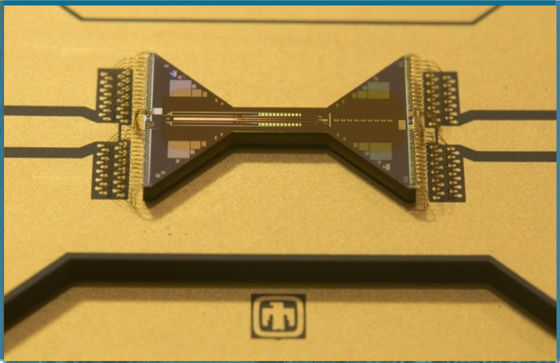
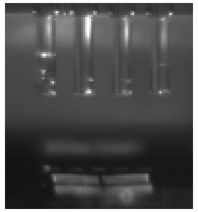
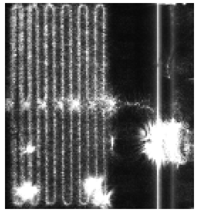
SAND2022-7027C

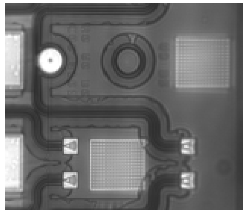
Sandia National Laboratories

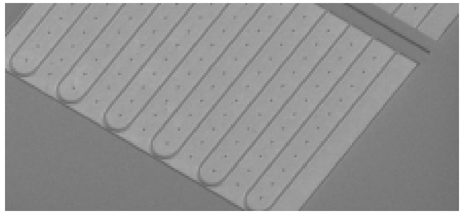
Microfabricated Piezo-Optomechanical Switches for Trapped Ion Quantum Computing

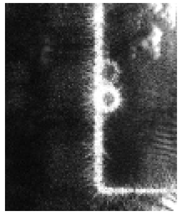












Craig W.Hogle, Hayden J. McGuinness, Daniel Dominguez, Matt Eichenfield, Daniel L. Stick

June 3rd, 2022 DAMOP

U.S. DEPARTMENT OF ENERGY NNSA

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Optical modulator design

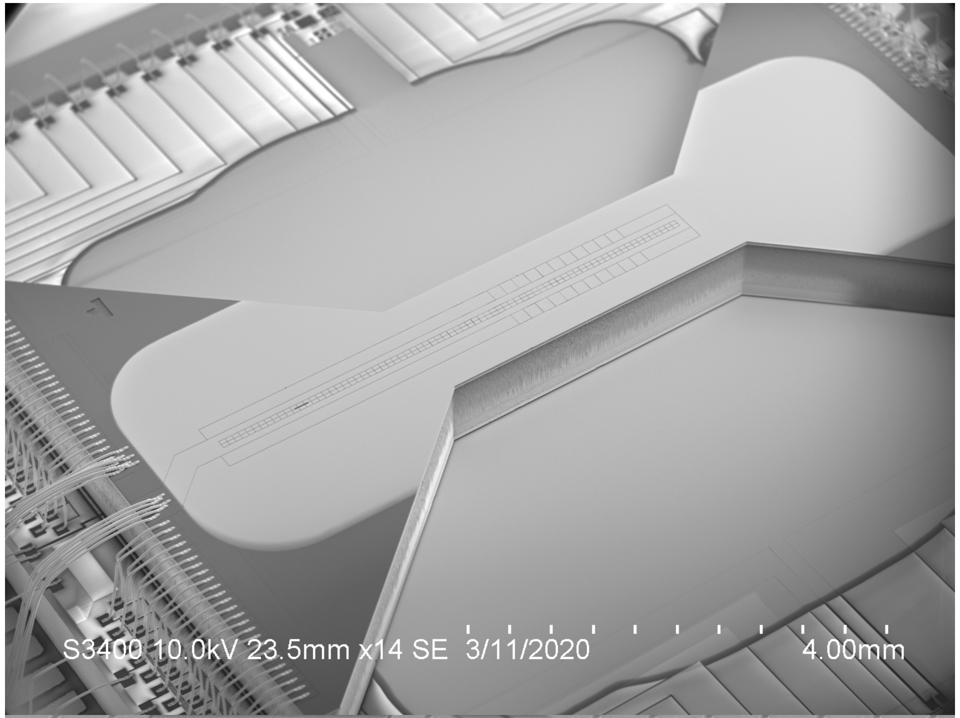
CMOS compatible – integrable with current surface ion trap fabrication techniques

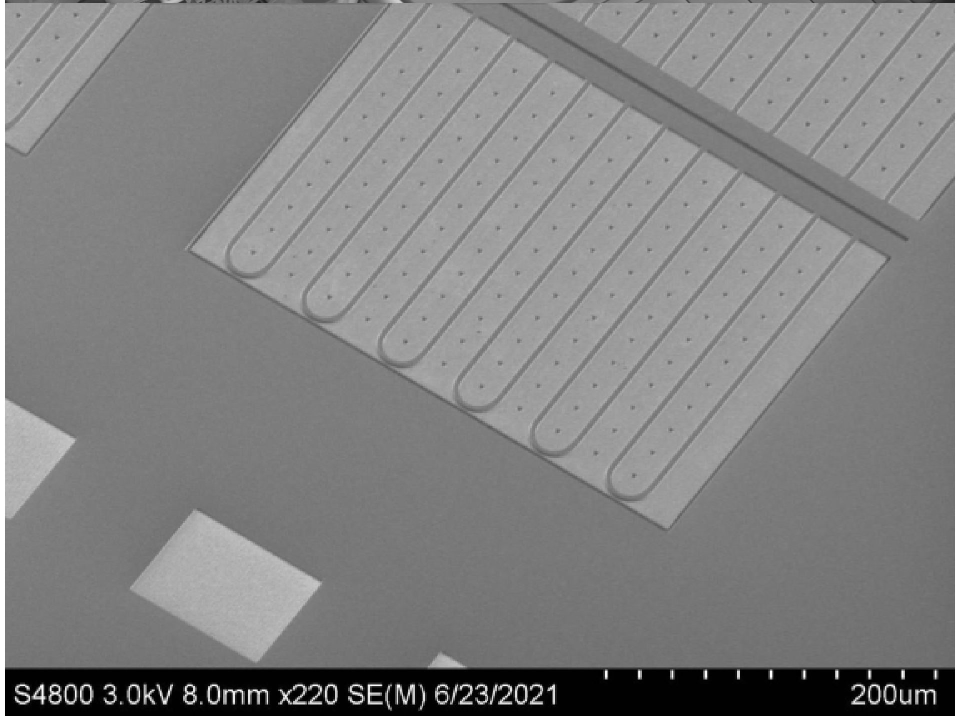
Fast response times – operate in the μs timescales of gate times

Low voltage requirements – desire control limiting to ~10 V

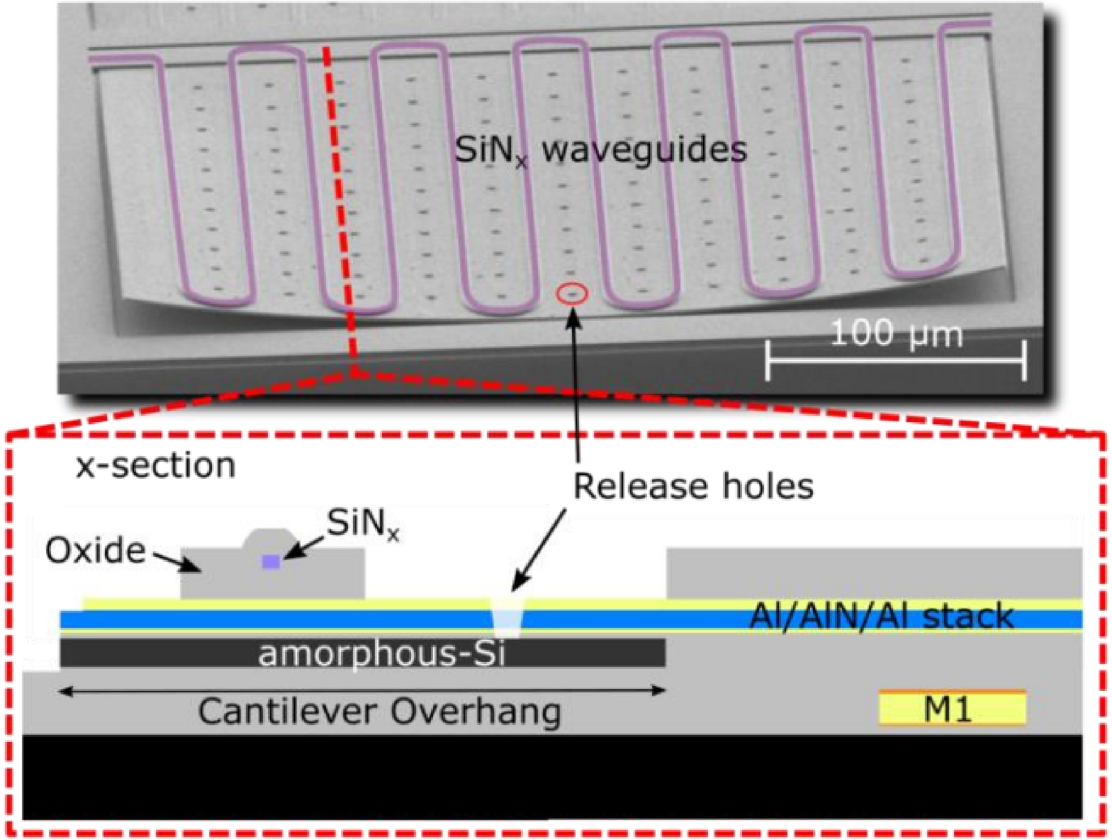
Small form factor – fabricate many modulators on the same ion trap

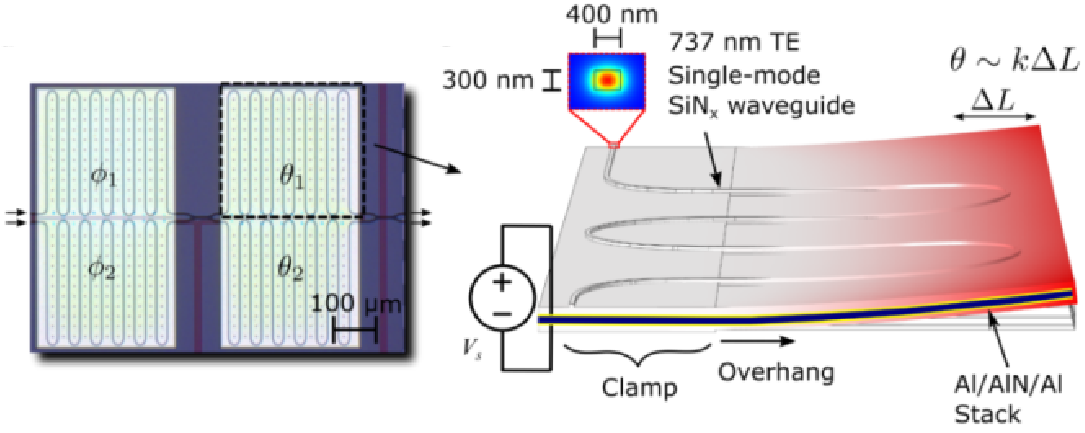
Extinction factor – current modulation techniques set a high standard for full light extinction





Cantilevered Mach-Zehnder interferometers

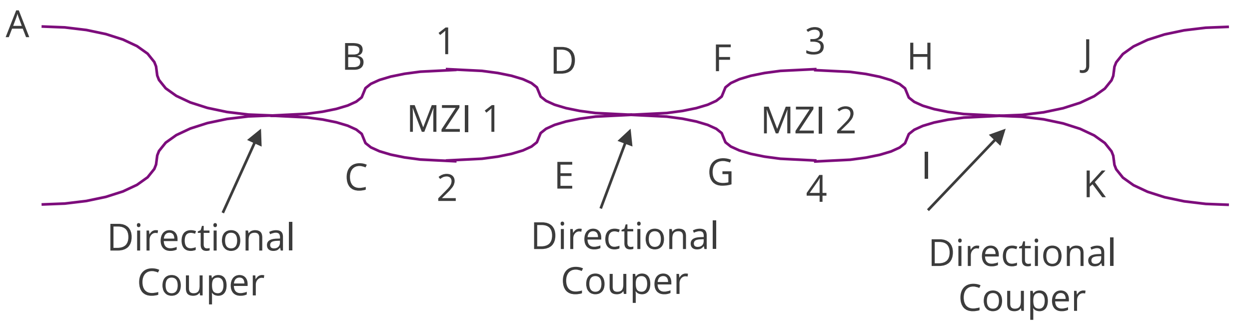




A cascaded Mach-Zehnder interferometer relies on phase control over one arm of the interferometer relative to the other to produce constructive interference at the output port. A serpentined waveguide is flexed by a piezo-actuated material.

Dong, M. et al. arXiv:2201.12447

Analytical Mach-Zehnder Interferometer Calculations



For a given input port, A, the splitting ratio is quantified by T_n, where through-port gets $\sqrt{T_n}$ of the field, and cross port gets $\sqrt{1-T_n}$. For even splitting T_n =1/2. Field after first directional coupler is

$$B = \sqrt{T_1}A \qquad C = \sqrt{1-T_1}Ae^{i\pi/2}$$

After propagating through their respective arms, the fields arrive at D and E with an accumulated phase φ_m

$$D = Be^{i\varphi_1} \qquad E = Ce^{i\varphi_2}$$

Recombination at the second uneven directional coupler results in

$$F = \sqrt{T_2}D + \sqrt{1-T_2}Ee^{i\pi/2} \qquad G = \sqrt{T_2}E + \sqrt{1-T_2}De^{i\pi/2}$$

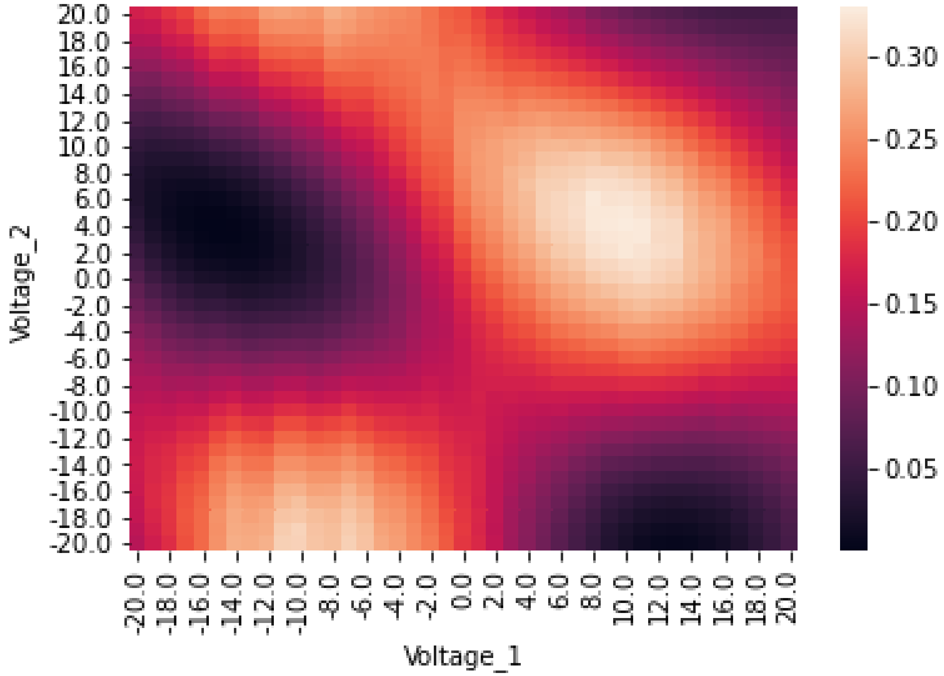
The process repeats

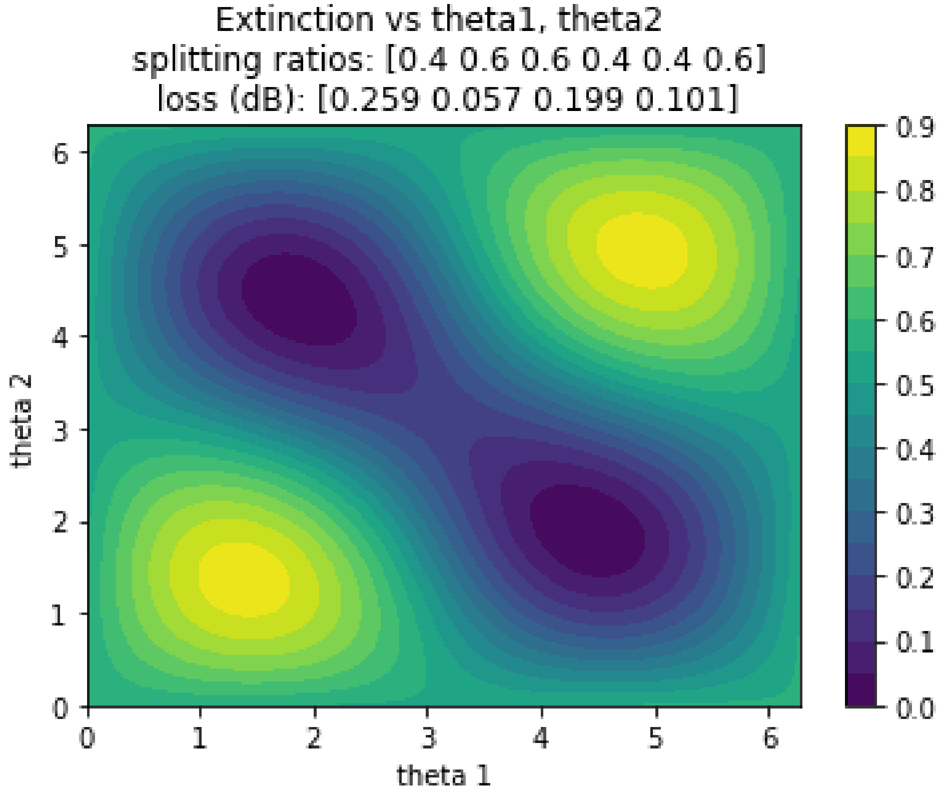
$$H = Fe^{i\varphi_3} \qquad I = Ge^{i\varphi_4}$$

$$J = \sqrt{T_3}H + \sqrt{1-T_3}Ie^{i\pi/2} \qquad K = \sqrt{T_3}I + \sqrt{1-T_3}He^{i\pi/2}$$

$$\frac{|J|^2}{|A|^2} = \left[\begin{matrix} a^2 + b^2 + c^2 + d^2 - (ab)2\cos(\theta_1) - (ac)2\cos(\theta_1+\theta_2) - (ad)2\cos(\theta_2) \\ +(bc)2\cos(\theta_2) + (bd)2\cos(\theta_1-\theta_2) + (cd)2\cos(\theta_1) \end{matrix}\right]$$

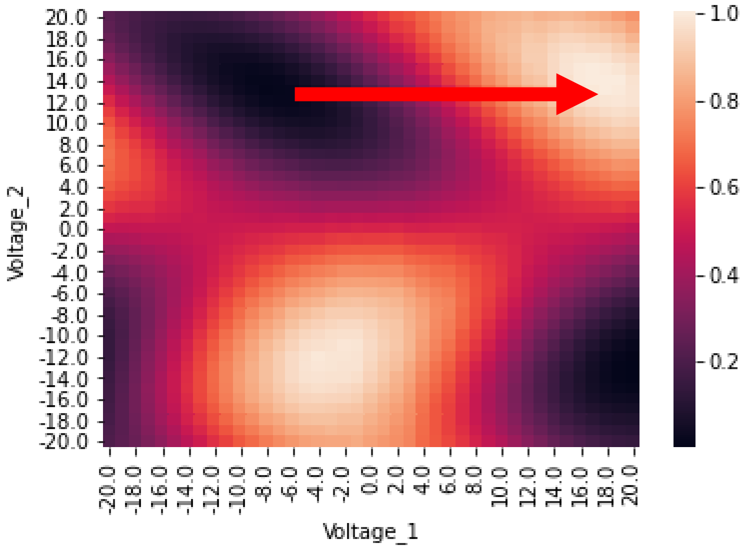
Experimental results agree with analytic simulations

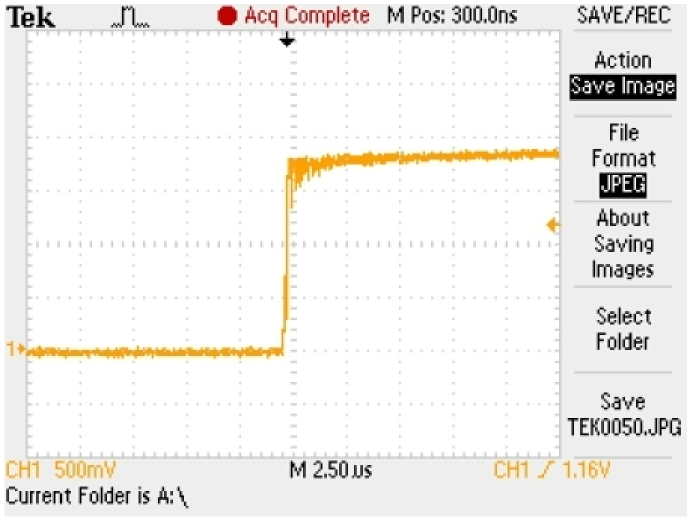


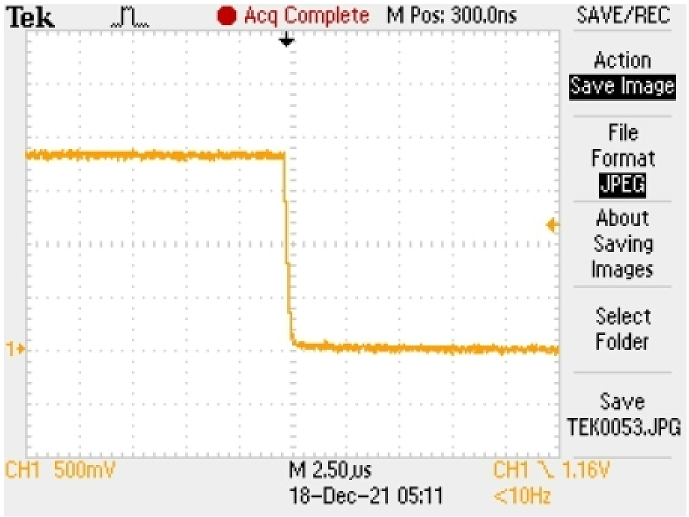


Analytic calculations take into account imperfections of the directional couplers and later included nonlinear effects relevant at higher powers. With moderate voltages we can demonstrate complete change in interference. This simulation proved useful in also understanding nonlinear effects as we went to higher throughput powers.

Using custom electronics for switching





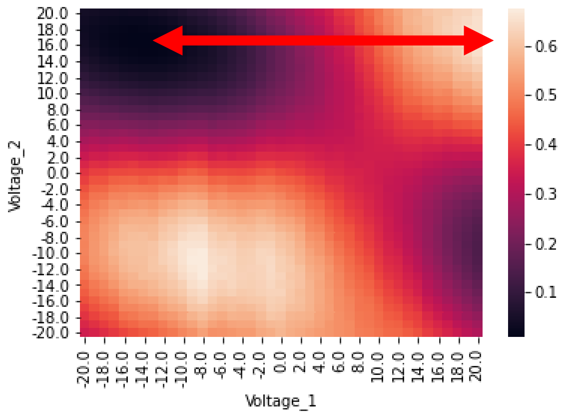


Switching is controlled by a custom mosfet switch where TTL signals from experimental control allows for a fast double poled switch.

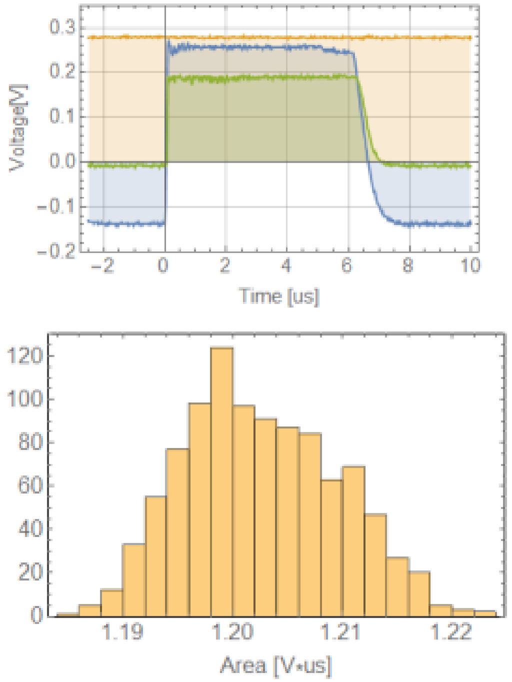
Due to the low throughput of the device, gate times are limited to >10 μs. The noise appears to be reproducible and would not be a current limitation for testing.

Measuring switching performance

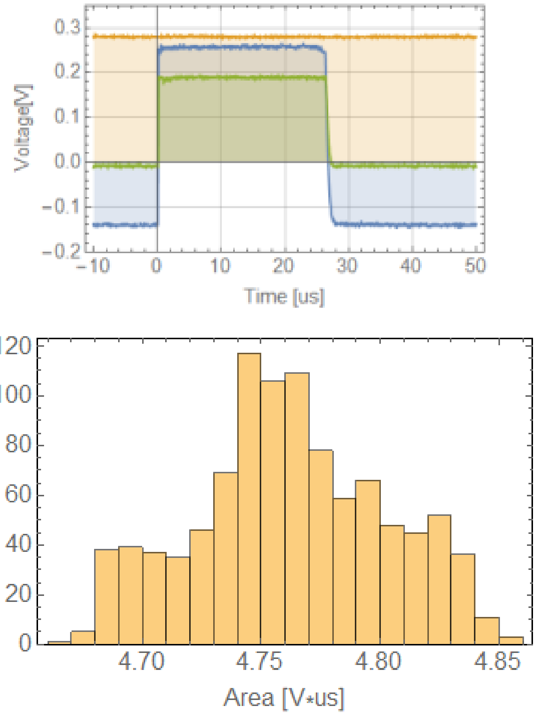
Measuring the pulse area of the switched light through the device to determine amount of noise introduced. Standard deviation of pulse area is less than 1% and may be dominated by technical noise



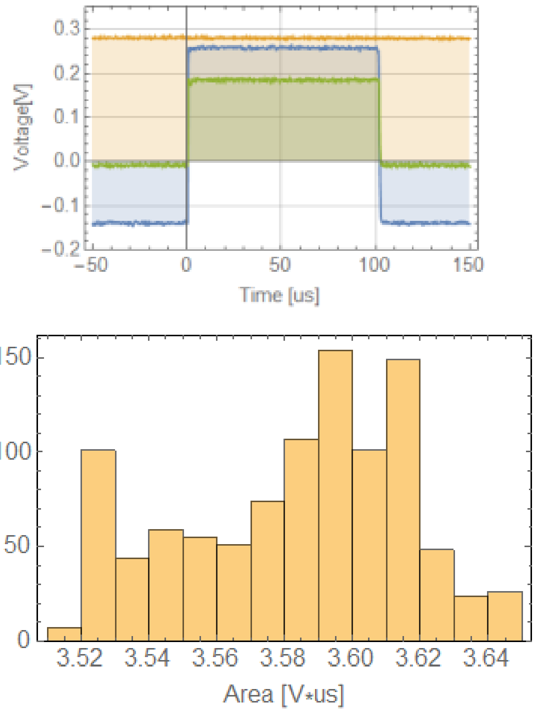
5 us



25 us

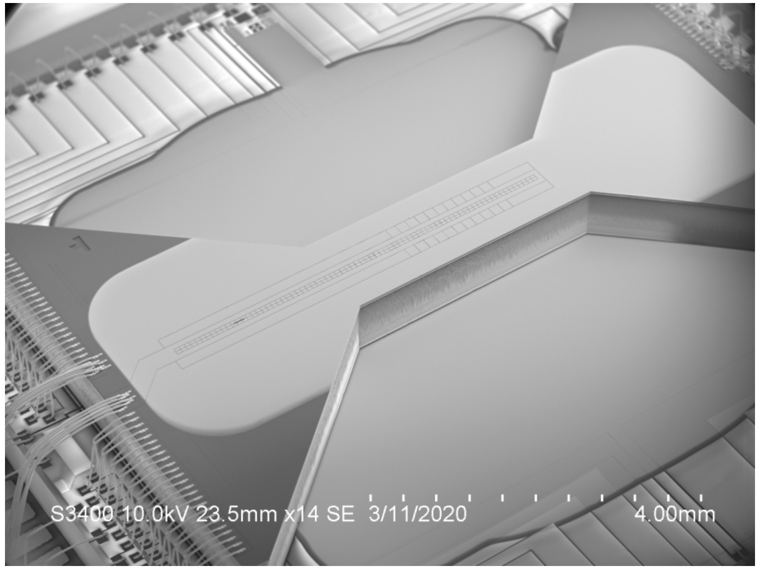


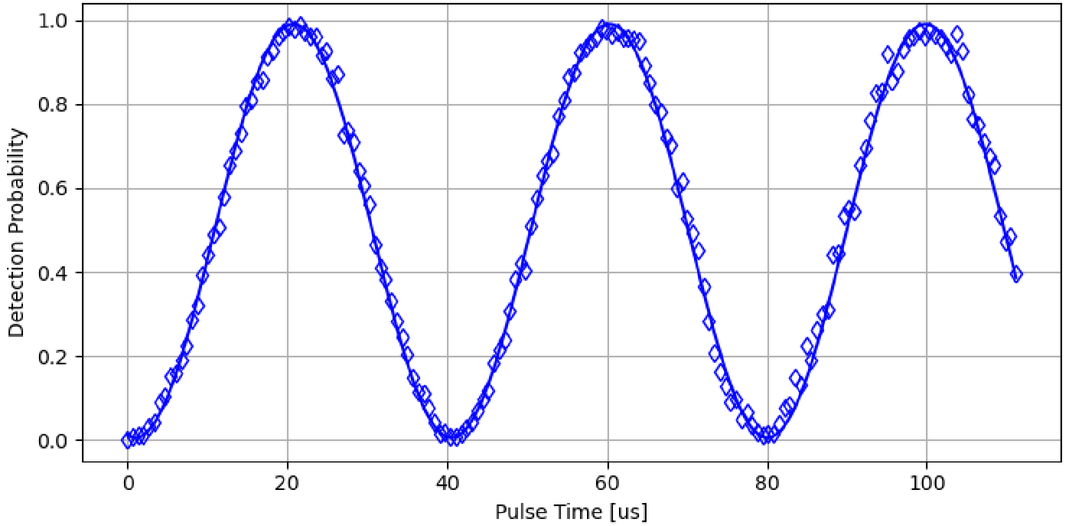
100 us

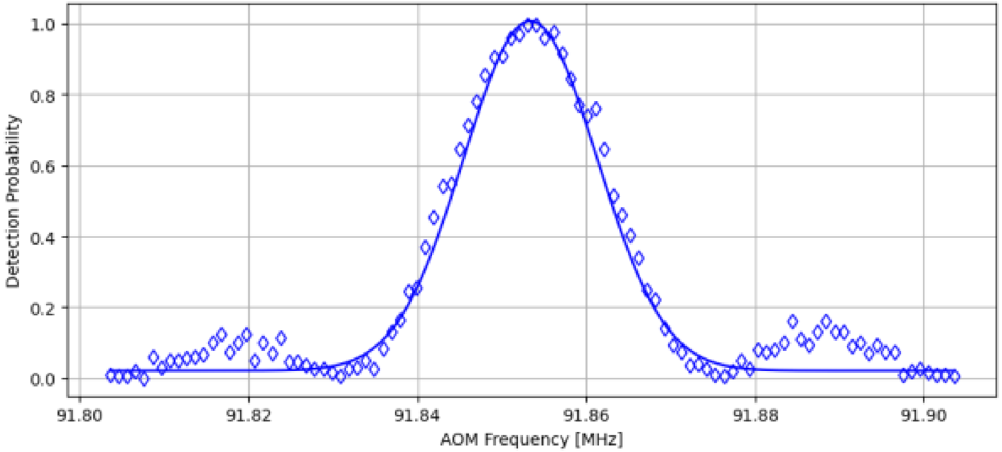


Light delivery to a trapped ion experiment

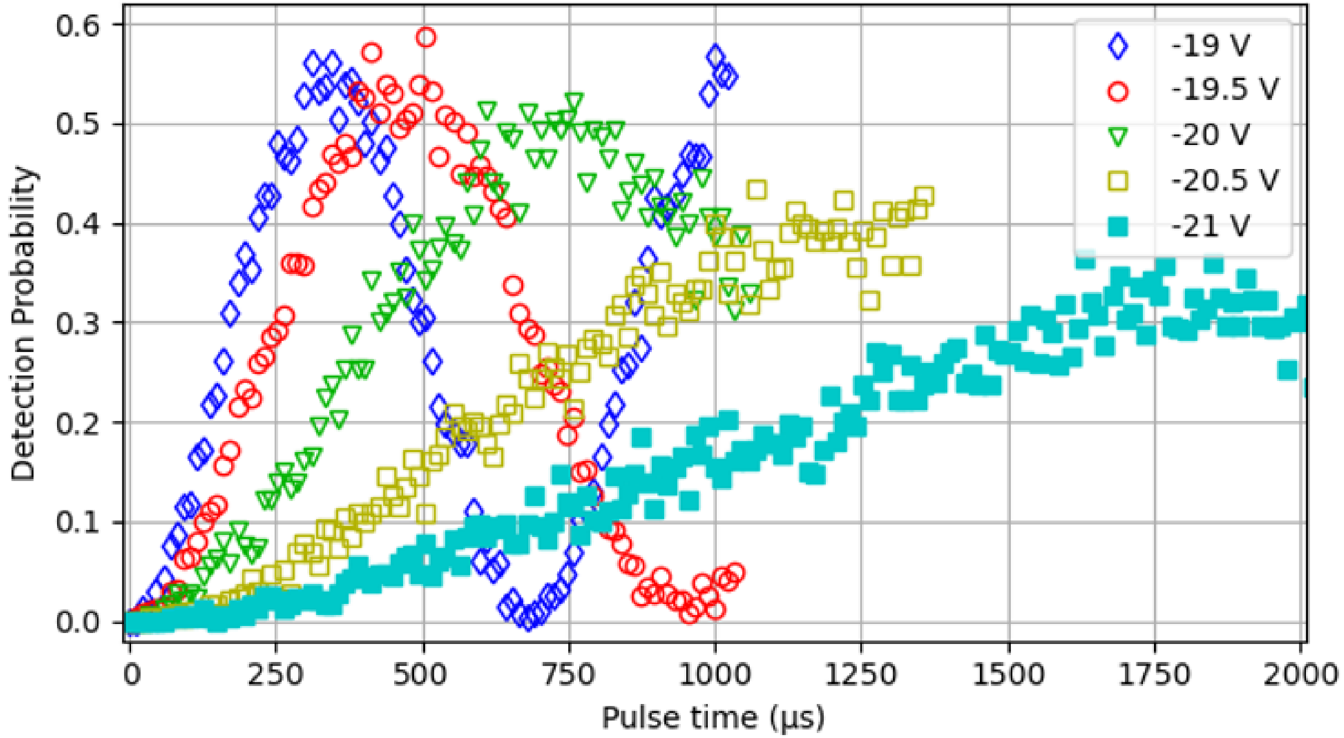
We are able to perform state preparation and Rabi flopping with only the MZI acting as the modulator on a $^{40}Ca^{+}$ ion. Note that a AOM is used to scan for the qubit transition but is not used for extinction during device characterization.

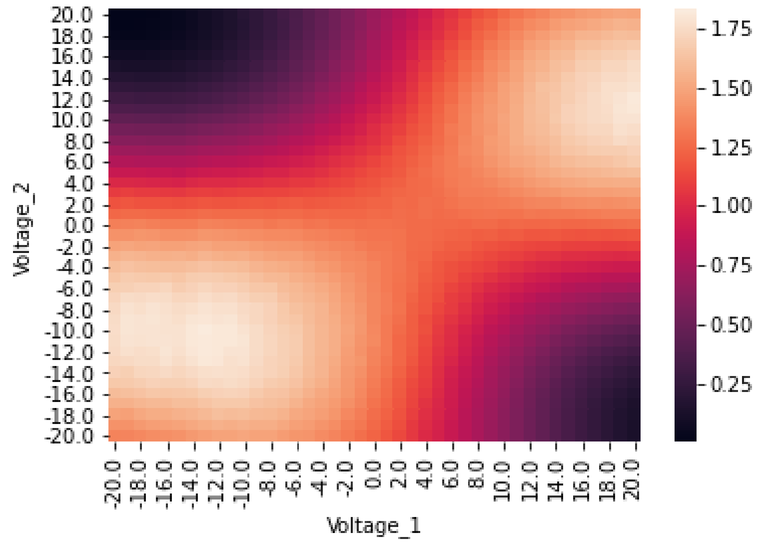




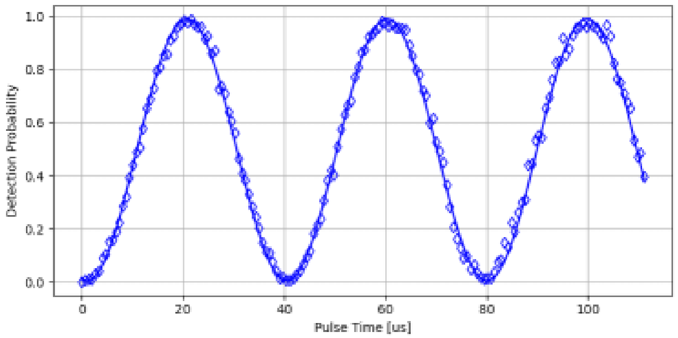


Trapped ions measuring extinction ratio

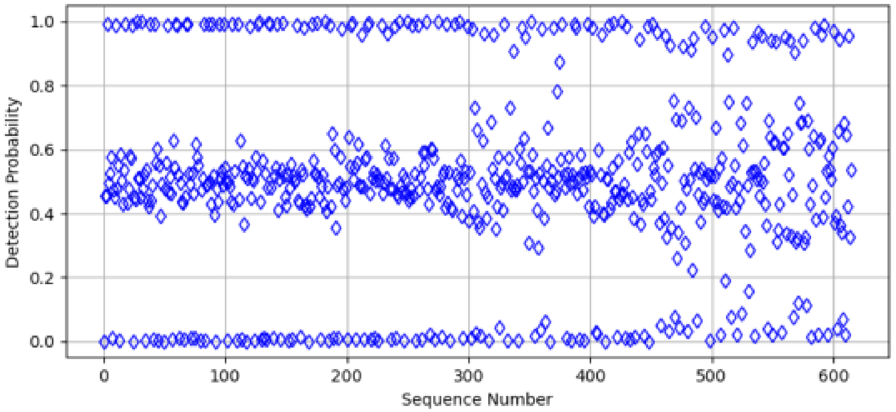




The ion allows for an accurate measurement of the leakage light from the off position (destructive interference) allows for a fine-tuning of the voltage control and has shown an extinction ratio > 38 dB.



Gate Set Tomography – Experimental Results



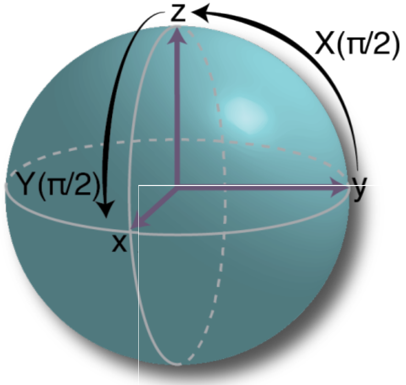
Gate	Entanglement Infidelity	1/2 Trace Distance
[]	0.003834	0.01406
Gxpi2:0	0.001899	0.034446
Gypi2:0	0.002016	0.034076

Fiducials:

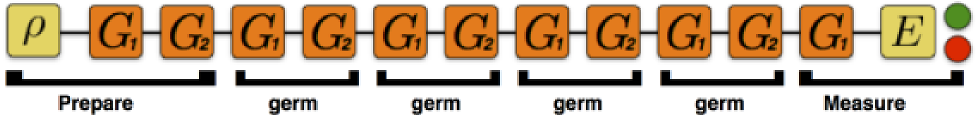
$\{\}$
Gx
Gy
$Gx \cdot Gx$
$Gx \cdot Gx \cdot Gx$
$Gy \cdot Gy \cdot Gy$

Germs:

Gx
Gy
Gi
$Gx \cdot Gy$
$Gx \cdot Gy \cdot Gi$
$Gx \cdot Gi \cdot Gy$
$Gx \cdot Gi \cdot Gi$
$Gy \cdot Gi \cdot Gi$
$Gx \cdot Gx \cdot Gi \cdot Gy$
$Gx \cdot Gy \cdot Gy \cdot Gi$
$Gx \cdot Gx \cdot Gy \cdot Gx \cdot Gy \cdot Gy$

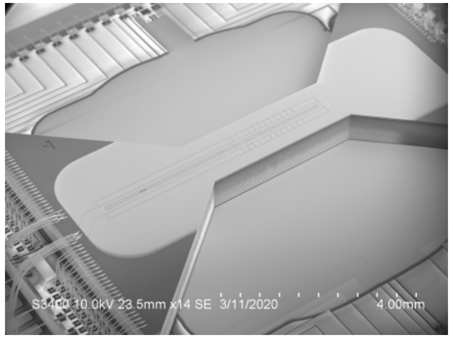


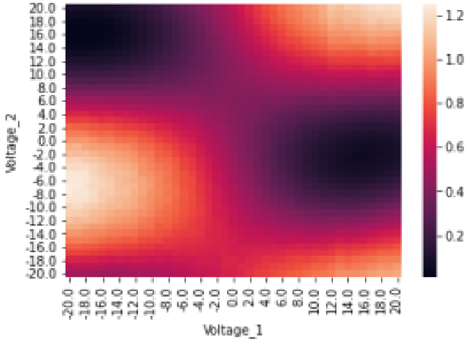
- Measured a gate fidelity of >99.8% using GST performed using only the MZI as the amplitude control
- There is further optimization to explore but this compares favorably to GST results performed with a AOM based set up

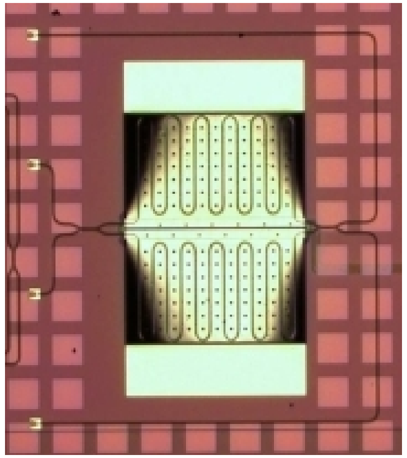


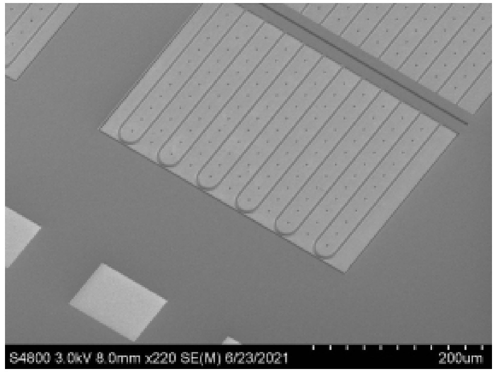
Neilsen, E. et al. Gate Set Tomography. Quantum 5, 557 (2021)

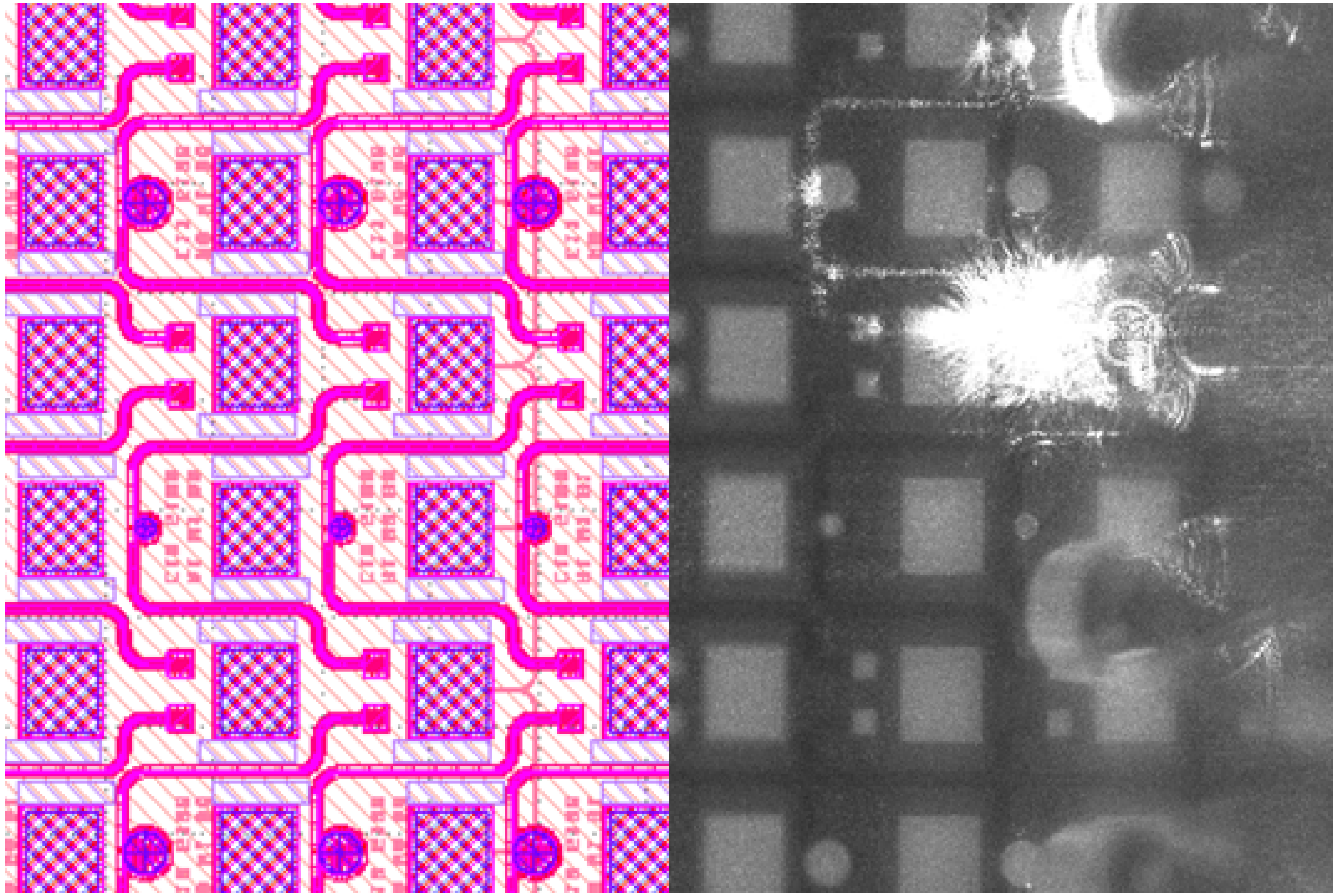
Questions?

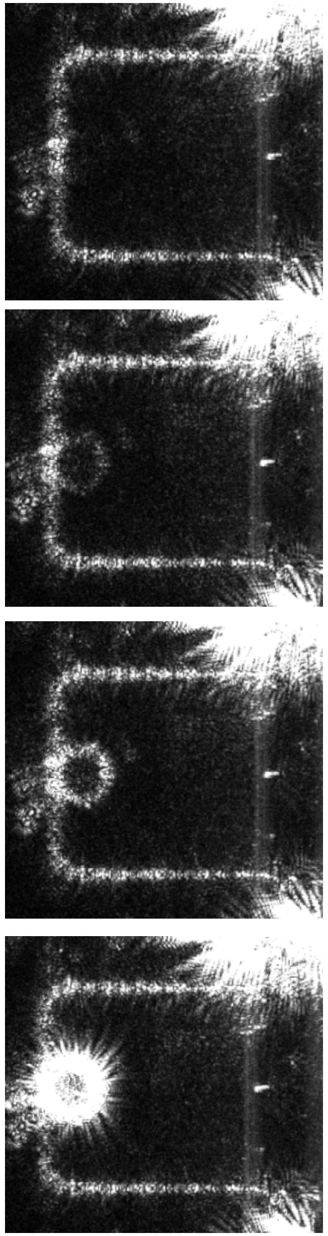

S3400 10.0kV 23.5mm x14 SE 3/11/2020 4.00mm

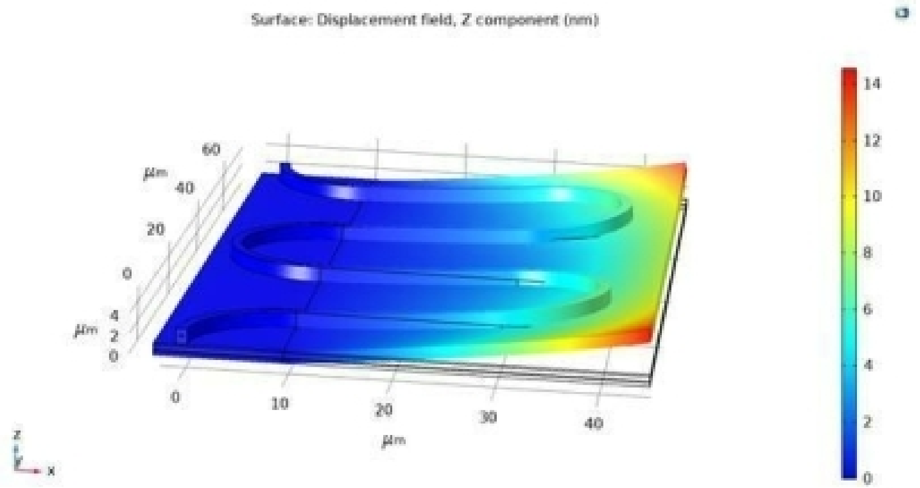

Voltage_2
Voltage_1
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
-18.0
-20.0
1.2
1.0
0.8
0.6
0.4
0.2

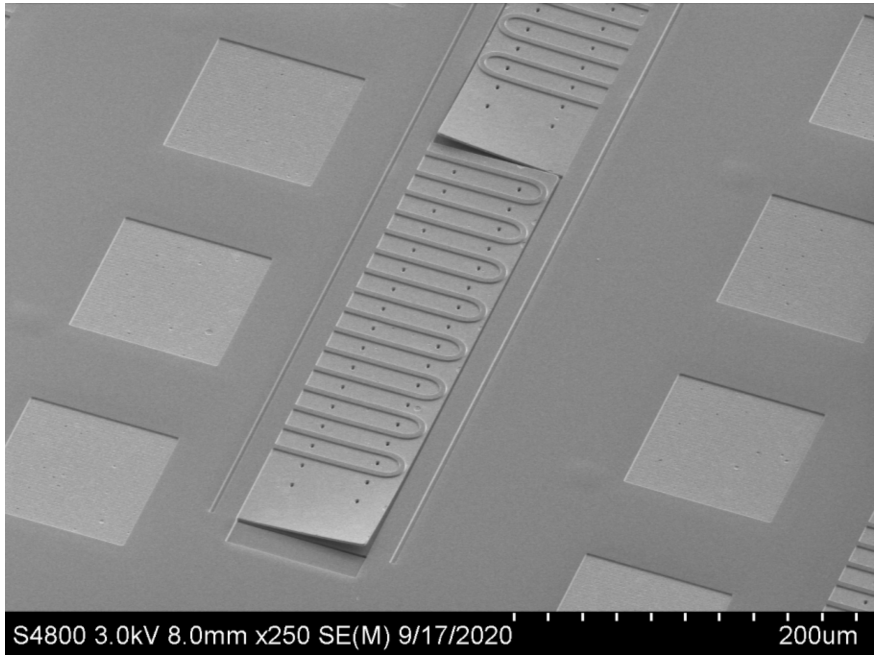


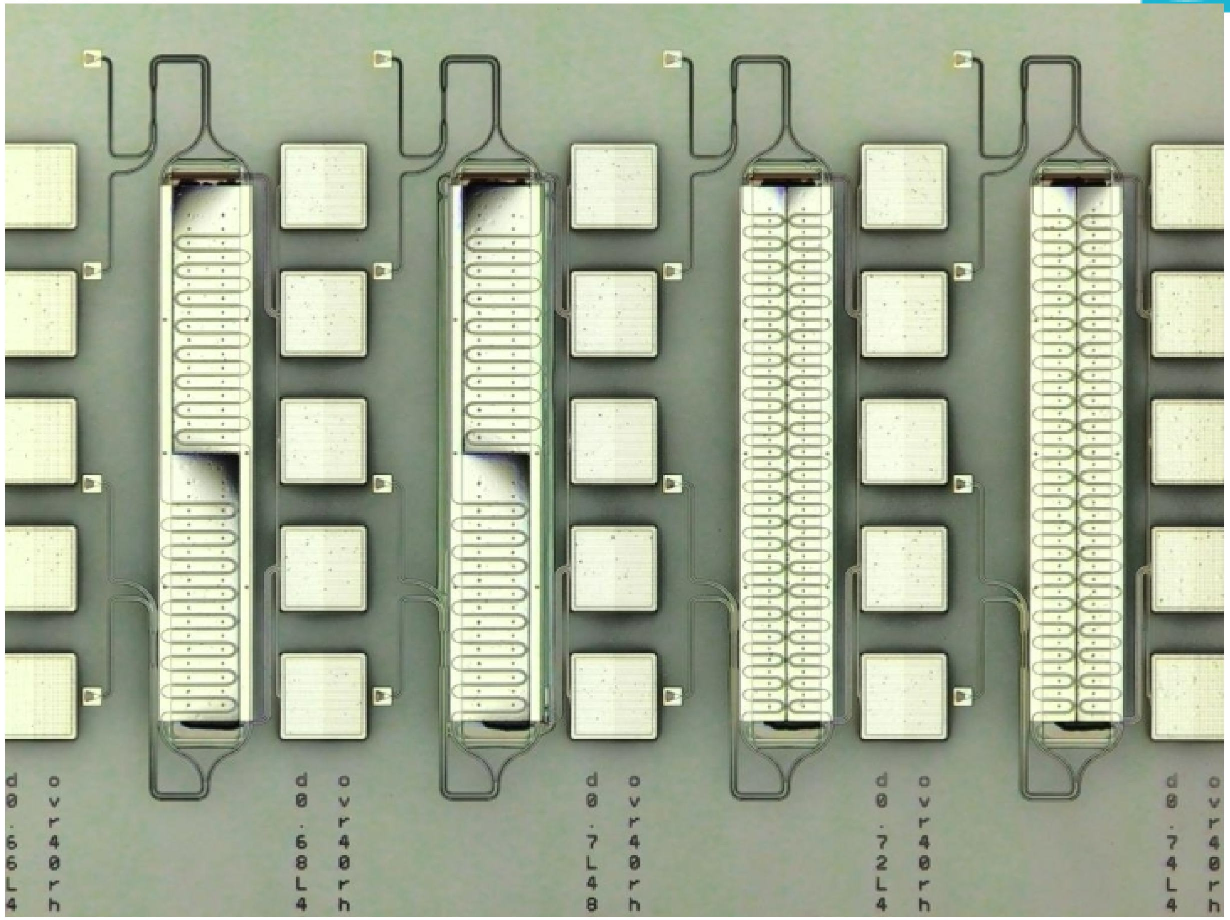

S4800 3.0kV 8.0mm x220 SE(M) 6/23/2021 200um

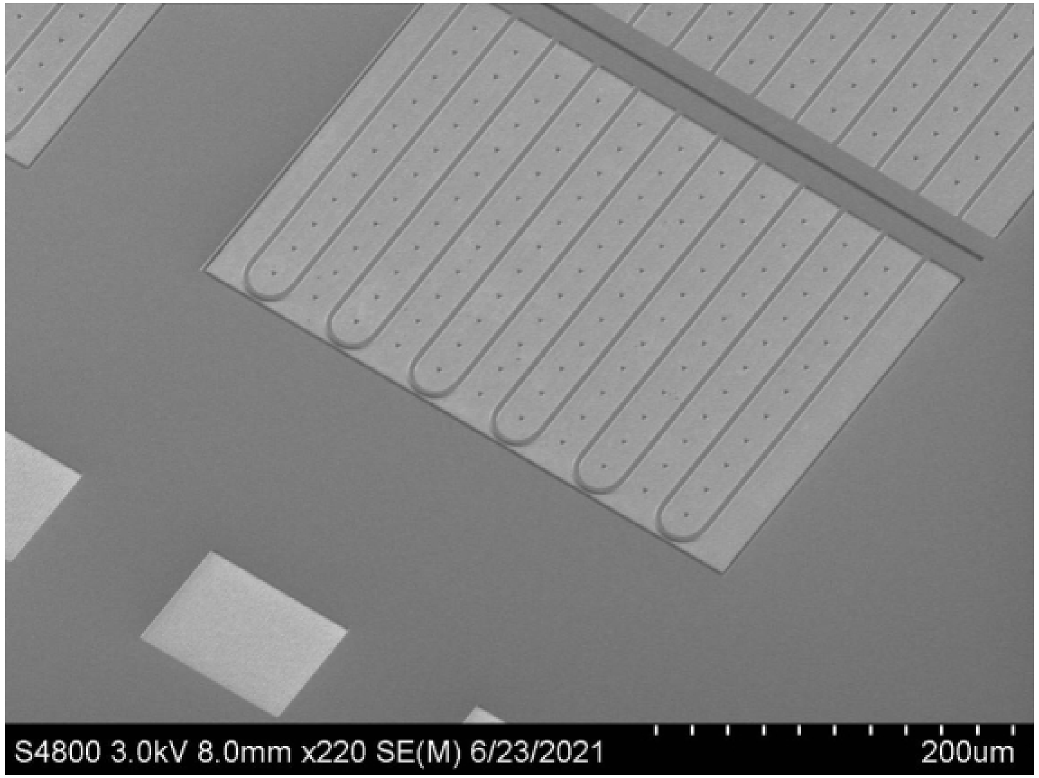


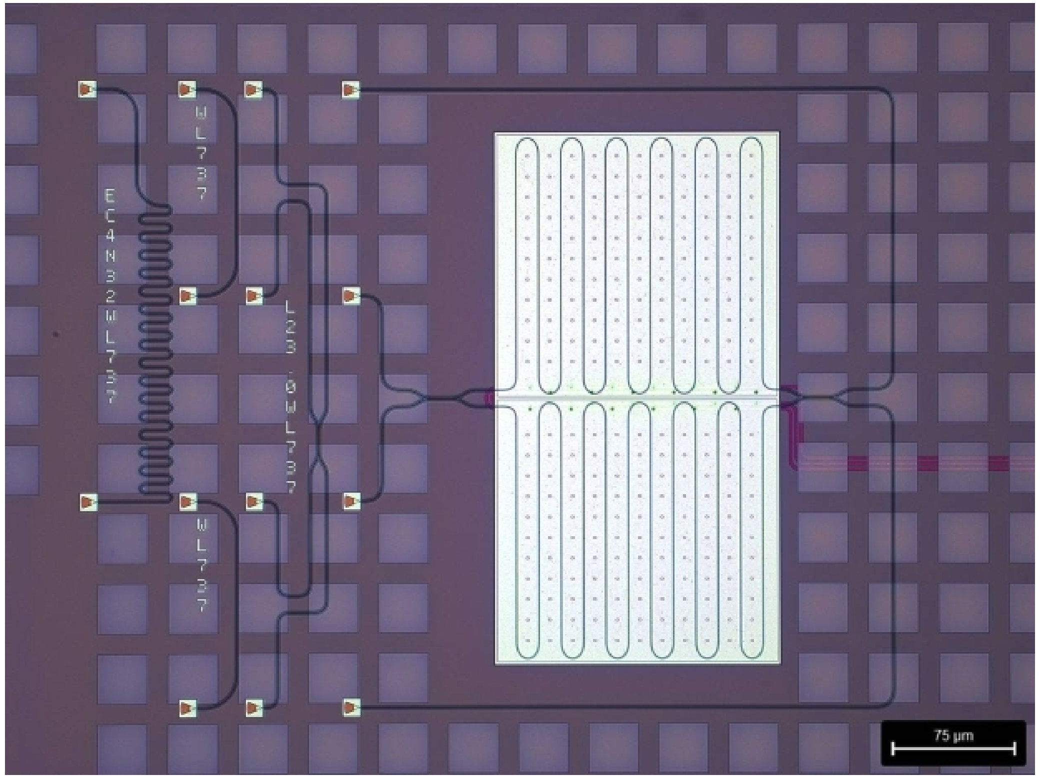



Surface: Displacement field, Z component (nm)
μm
μm
μm
z
x


S4800 3.0kV 8.0mm x250 SE(M) 9/17/2020
200um


d0.66L4
ovr40rh
d0.68L4
ovr40rh
d0.7L48
ovr40rh
d0.72L4
ovr40rh
d0.74L4
ovr40rh


S4800 3.0kV 8.0mm x220 SE(M) 6/23/2021
200um


75 µm

K side

- Calculating Normalized Power for one output port

$= 0$ (built-in Unbalanced Length)

$\rightarrow$

$$\frac{|K|^2}{|A|^2} = \left[\begin{array}{c} a^2 + b^2 + c^2 + d^2 - (ab)2\cos(\theta_1) - (ac)2\cos(\theta_1 + \theta_2) - (ad)2\cos(\theta_2) \\ +(bc)2\cos(\theta_2) + (bd)2\cos(\theta_1 - \theta_2) + (cd)2\cos(\theta_1) \end{array}\right]$$