Towards single ion-single photon strong coupling for quantum networking

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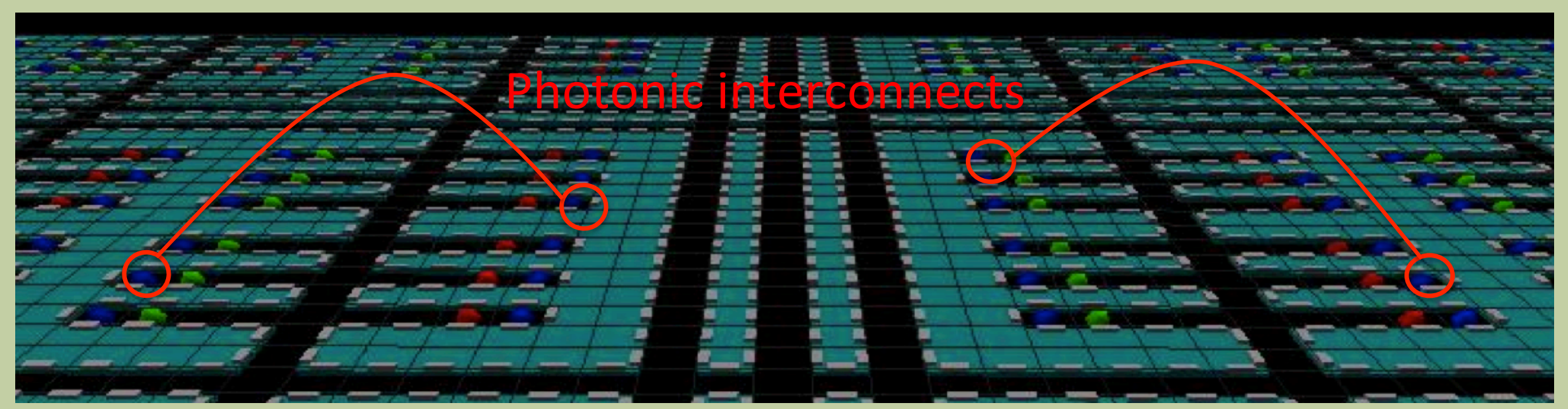
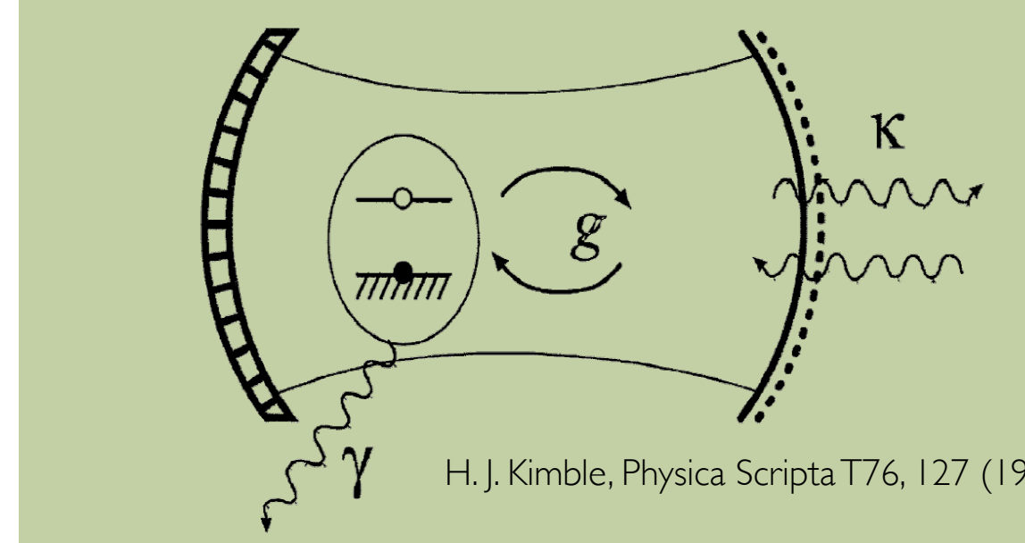
Micro mirror cavity for single ion cavity QED



A large-scale quantum computer can be realized by trapped ion memory qubits confined above a microfabricated array of surface electrode traps. Photonic interconnects can act as buses if ion states can be well-mapped to photon states in the framework of strong coupling cavity QED:

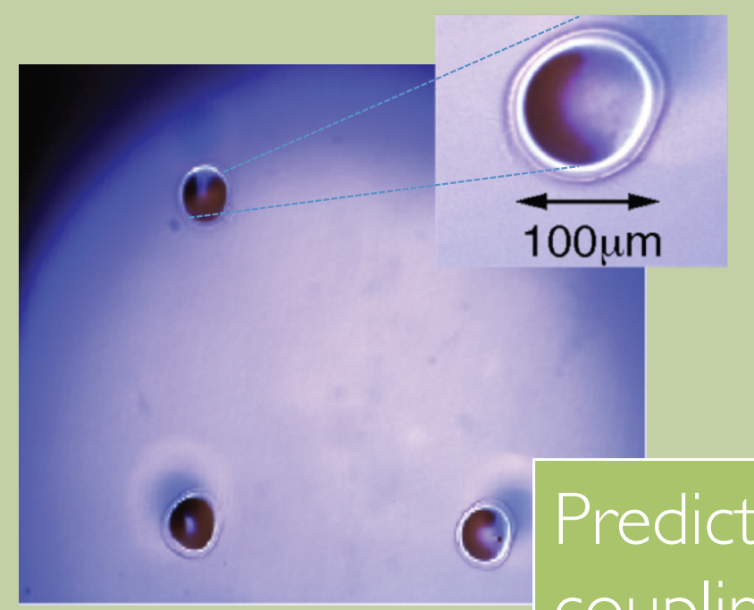


H. J. Kimble, Physica Scripta T76, 127 (1998)

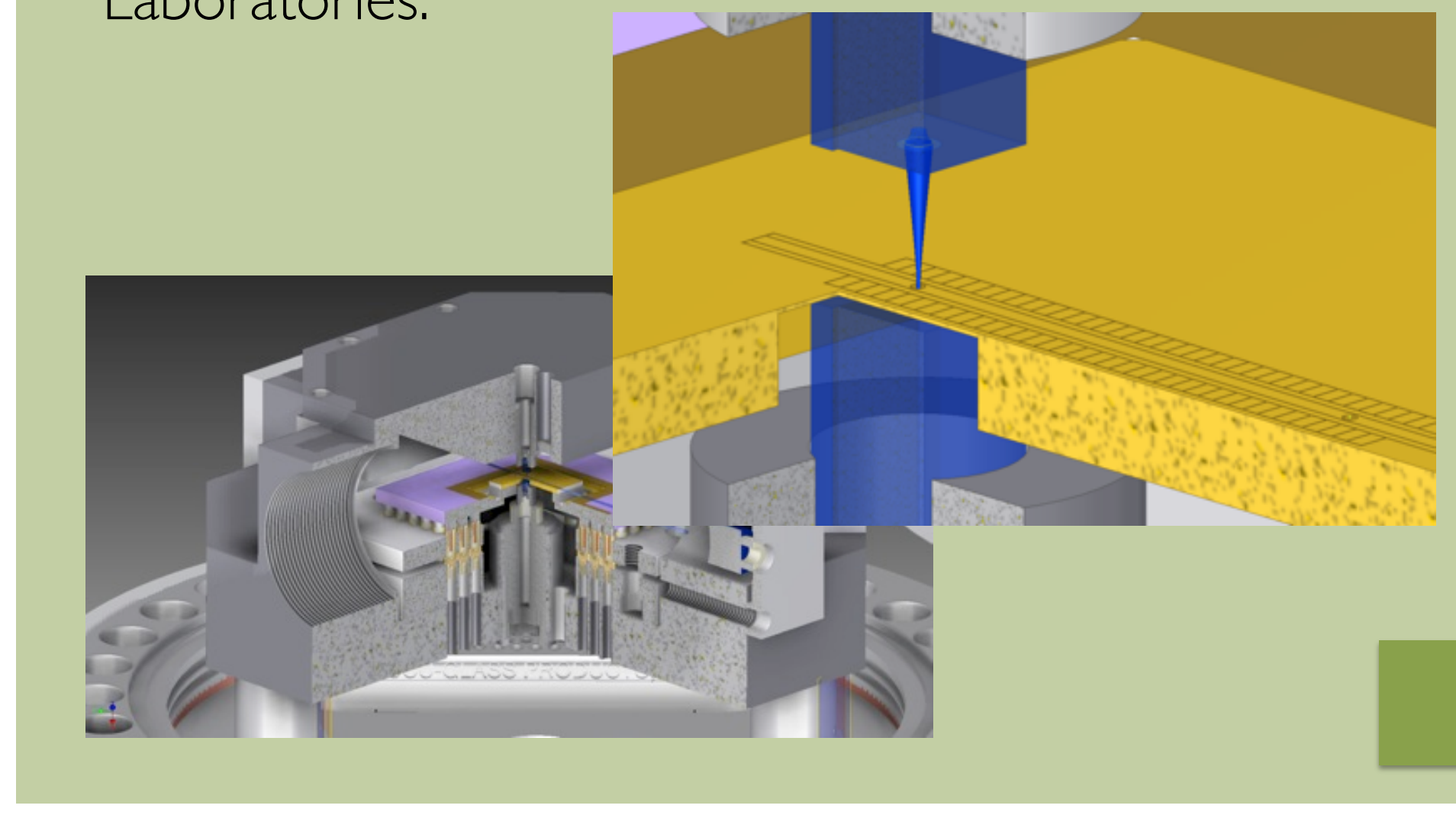
g: Coherent ion-photon coupling
κ: Cavity field decay rate
γ: Atomic dipole decay rate
Cooperativity: $\mathbf{g^2/\kappa\gamma}$
Fidelity of ion-photon mapping: **C/(C+1)**

Such quantum devices would require small ion-dielectric distances, which affects the trapping potential and may show different electric field noise and charging properties than conventional metal traps.

We investigate one approach to reduce the ion exposure to dielectric surfaces by incorporating a highly reflective optical cavity with an apertured planar trap from Sandia National Laboratories:

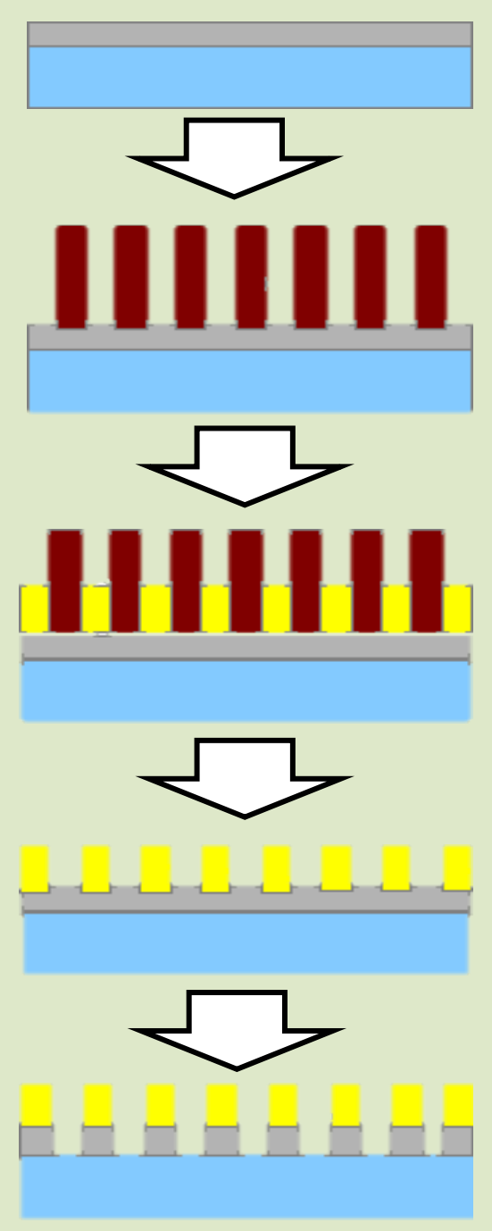


Ultra-low ROC (900μm), laser-machined micro-mirrors with low scattering loss ~140 ppm

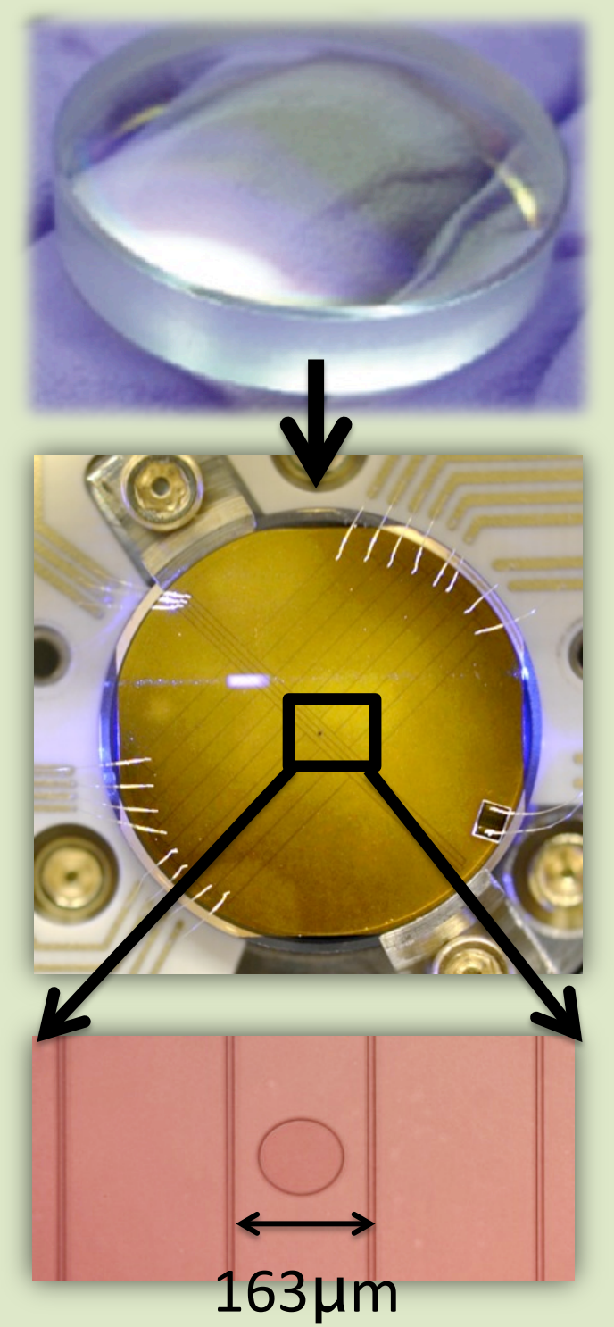


Predicted strong coupling parameters:	
Cavity length	1.1 mm
Cavity waist	3.75 μm
Top mirror ROC	260 μm
Bottom mirror ROC	1000 μm
Finesse	20,000-30,000
Linewidth	4.5-6.7 MHz
Cooperativity	48-73

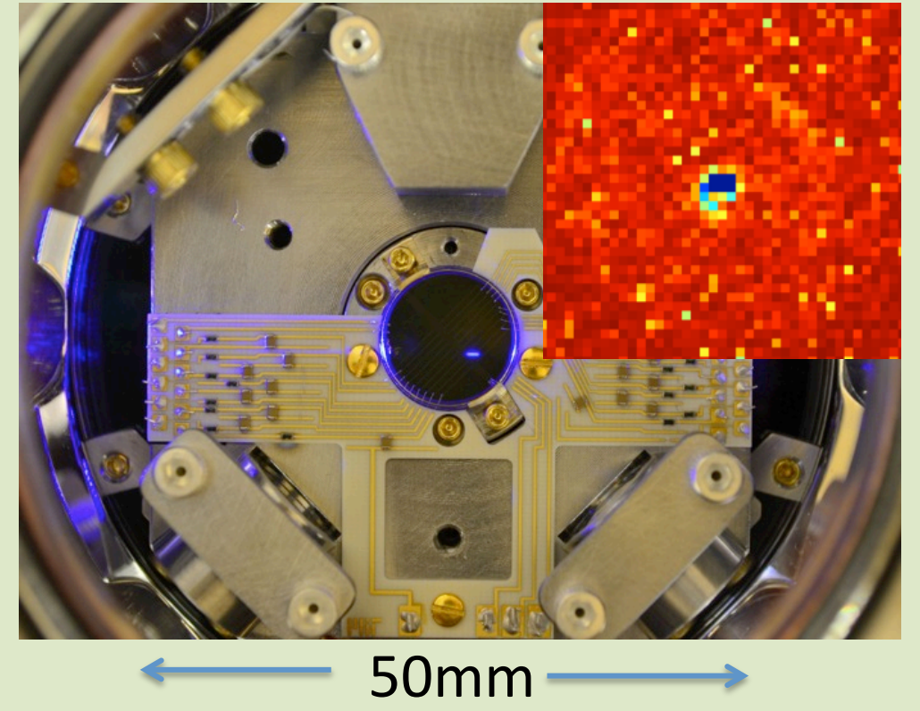
To test the contribution of the dielectric surface to motional heating rate in the proposed ion trap-cavity system, we fabricated a test ion trap on top of a mirror substrate where ions can be shuttled between different trapping zones with metal ground or dielectric[1].

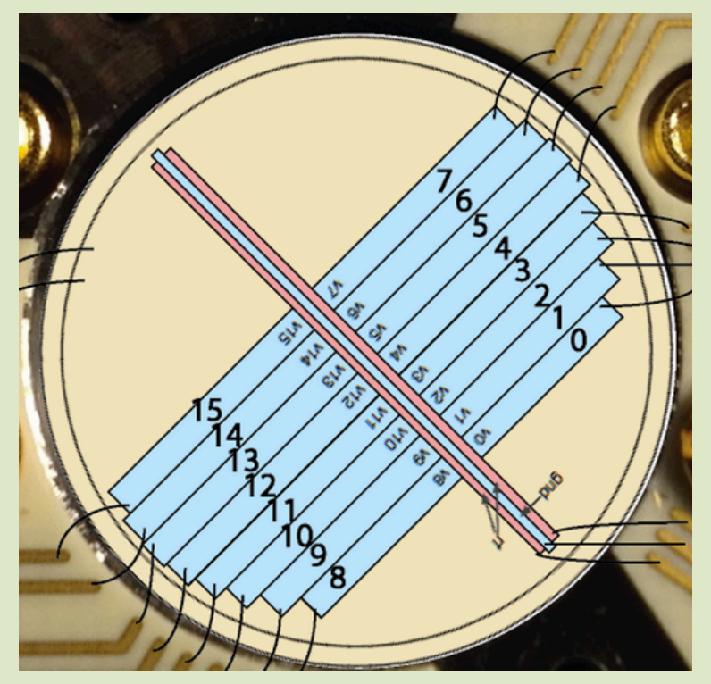


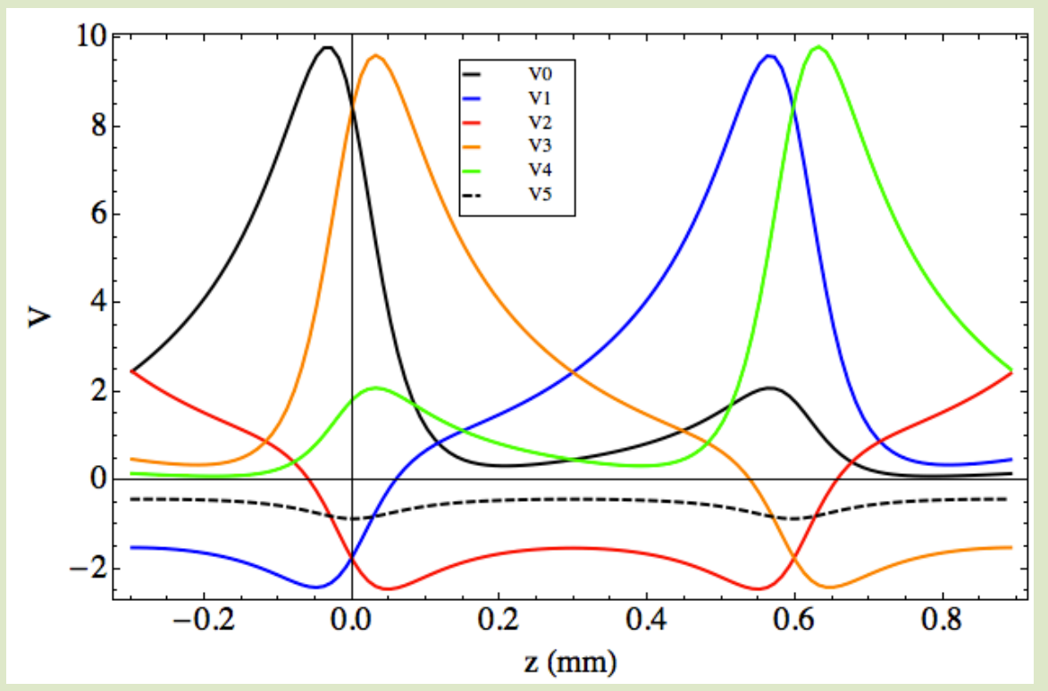
Evaporated silver layer on mirror substrate
Photoresist patterning
Electroplated gold layer as trap electrodes
Photoresist removal
Silver seed layer etching



Observed stable trapping of single $^{88}Sr^{+}$ ions with bright lifetimes of several hours. Secular frequencies of 0.925 and 0.940 MHz were measured using tickle spectroscopy. Ion can be shuttled multiple DC electrode lengths.







1. P. F. Herskind *et al.*, Opt. Lett. **36**, 3045 (2011).

Transparent ion trap with integrated photodetector

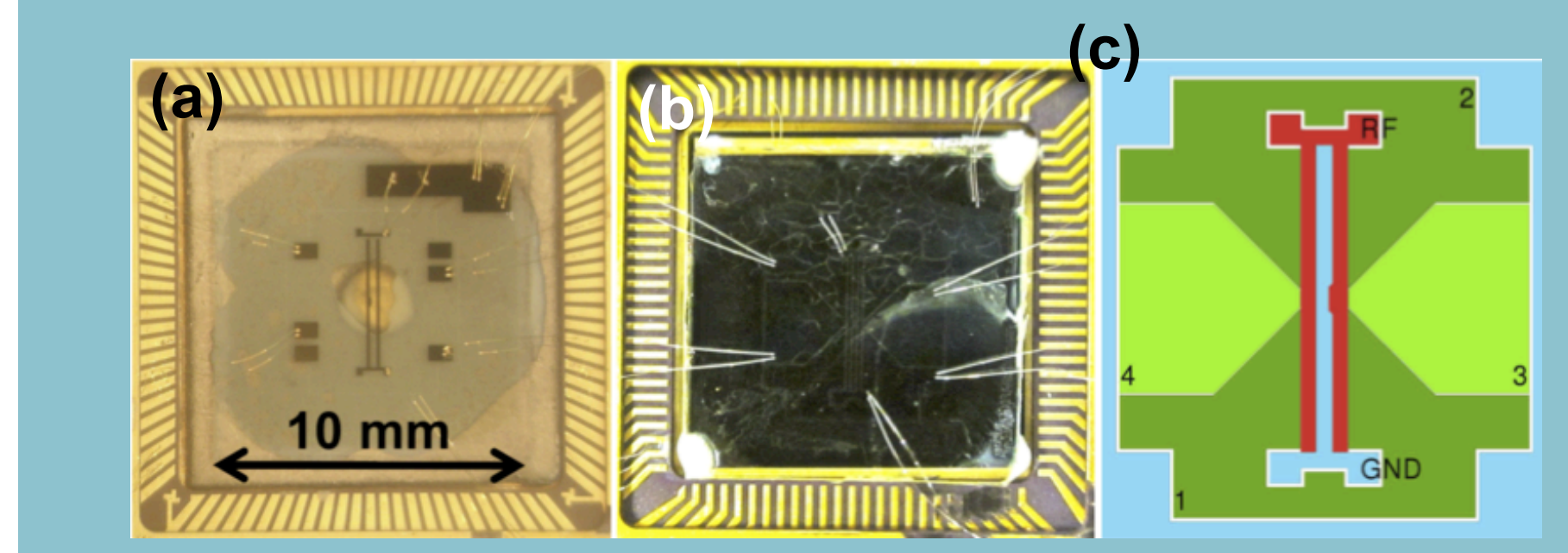
Fluorescence collection sets the efficiency of state detection and the rate of entanglement generation between remote trapped ion qubits. Scaling-up to dense arrays of ions will require efficient light collection from many ions in parallel. Various optical elements have been used to enhance atom-photon coupling, but combining large solid angle capture with scalability has not happened yet.

We present a new approach in which light is collected through a transparent ion trap using a photodetector attached beneath[1].

Fabrication on quartz substrate:
- Pattern using NR9-3000PY photoresist
- Deposit 400 nm of ITO by RF sputtering
- Deposit thin layer of Au on RF electrodes only

Resulting trap properties:
- Optical transmission: ~60% at 422 nm
- Resistivity of DC electrodes (ITO): 1×10^{-5} Ωm
- Resistivity of RF electrodes (ITO + Au): 2×10^{-8} Ωm

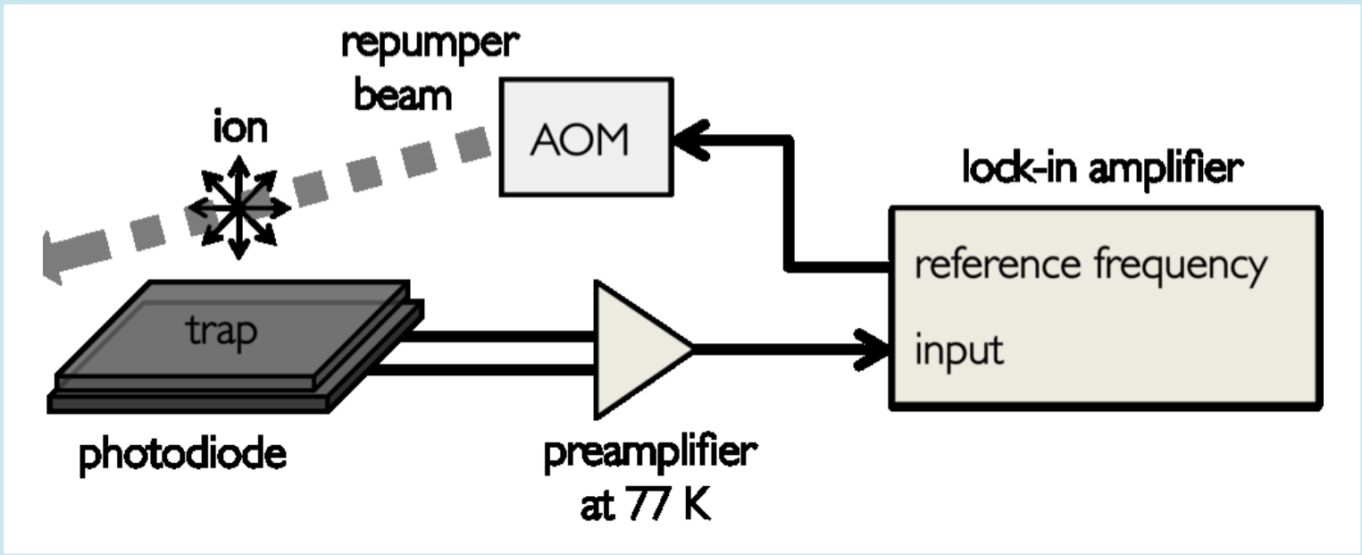
Well-established 5-electrode trap geometry[2]:
- RF frequency: 35 MHz
- Trap frequencies: 0.8 – 1.3 MHz
- Trap depth: ~300 meV



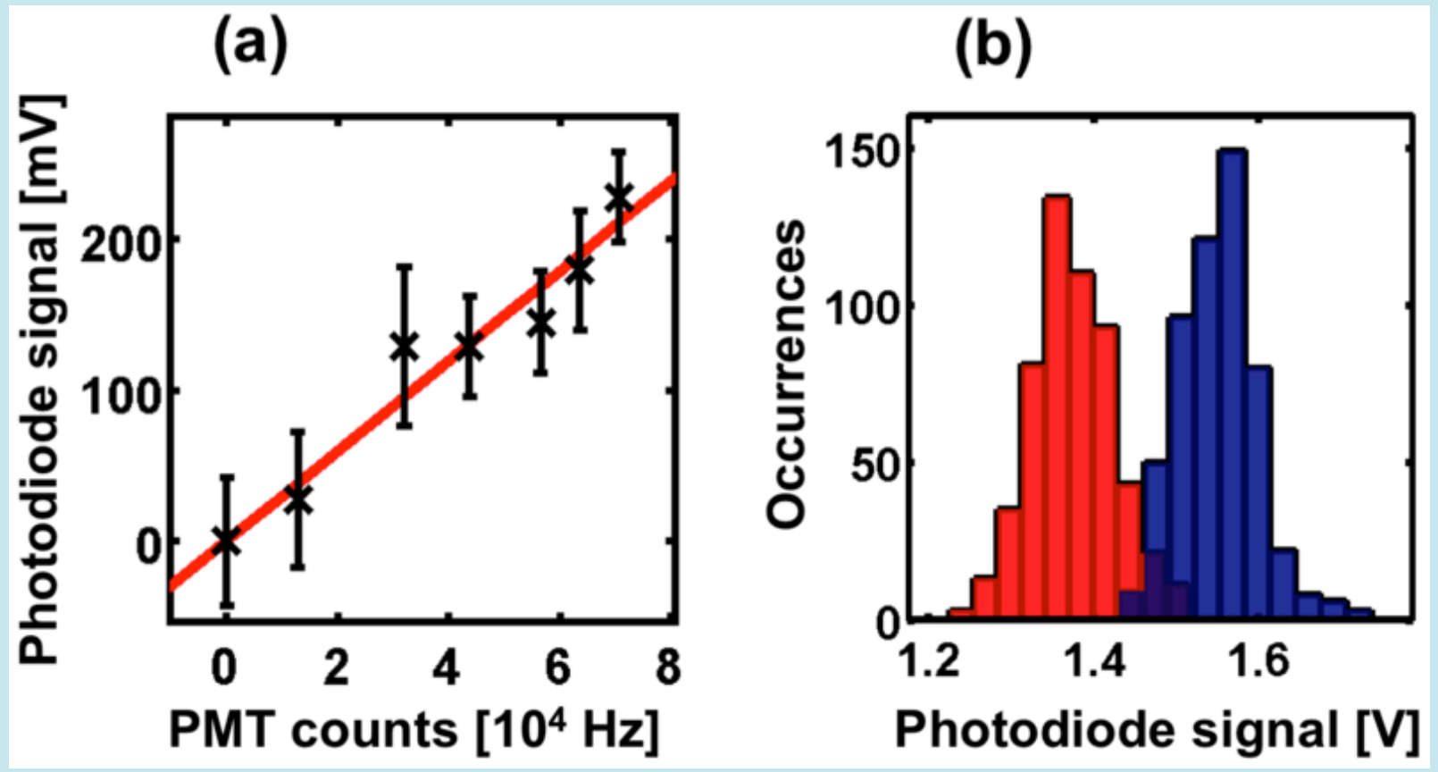
(a) **ITO-4K trap**: 400 nm of ITO plus 50 nm of Au on the RF electrodes
(b) **ITO-PD trap**: 400 nm of ITO plus 5 nm of Au on the RF electrodes, mounted on a photodiode
(c) Diagram showing trap geometry

Experiments:

Single $^{88}Sr^{+}$ ions were stably trapped above ITO-4K trap in a bath cryostat at 4 K.



A large ion cloud (~50 ions) was trapped and detected above an ITO-PD trap with a commercially available PIN photodiode at 77 K:



(a) Photodiode voltage and photomultiplier count rate during loading of an ion cloud
(b) Histogram of photodiode voltages over a period of several minutes without ions (red), and after loading an ion cloud (blue)

Expected signal values for ~50 ions:	Light collection efficiency	Power at the detector	Detector quantum efficiency
ITO trap + PD	30%	60 pW	30%
Bulk objective + PMT	5%	10 pW	20%

1. A.M. Eltony *et al.*, Appl. Phys. Lett. New J. Phys. **102**, 054106 (2013).
2. J. Labaziewicz *et al.*, Phys. Rev. Lett. **100**, 013001 (2008).

Sensitive compensation of micromotion in 3 dimensions for a surface-electrode ion trap using lock-in detection

Micromotion - the driven motion of an ion displaced from the null of the RF trapping field - broadens and shifts atomic transitions, leaks in noise from the RF supply, and interferes with ion coupling to integrated trap elements. Because stray electric fields readily build-up from charge deposition during ion loading or photoelectric charge creation from laser fields[1], micromotion is exacerbated as traps are miniaturized and dielectric materials introduced.

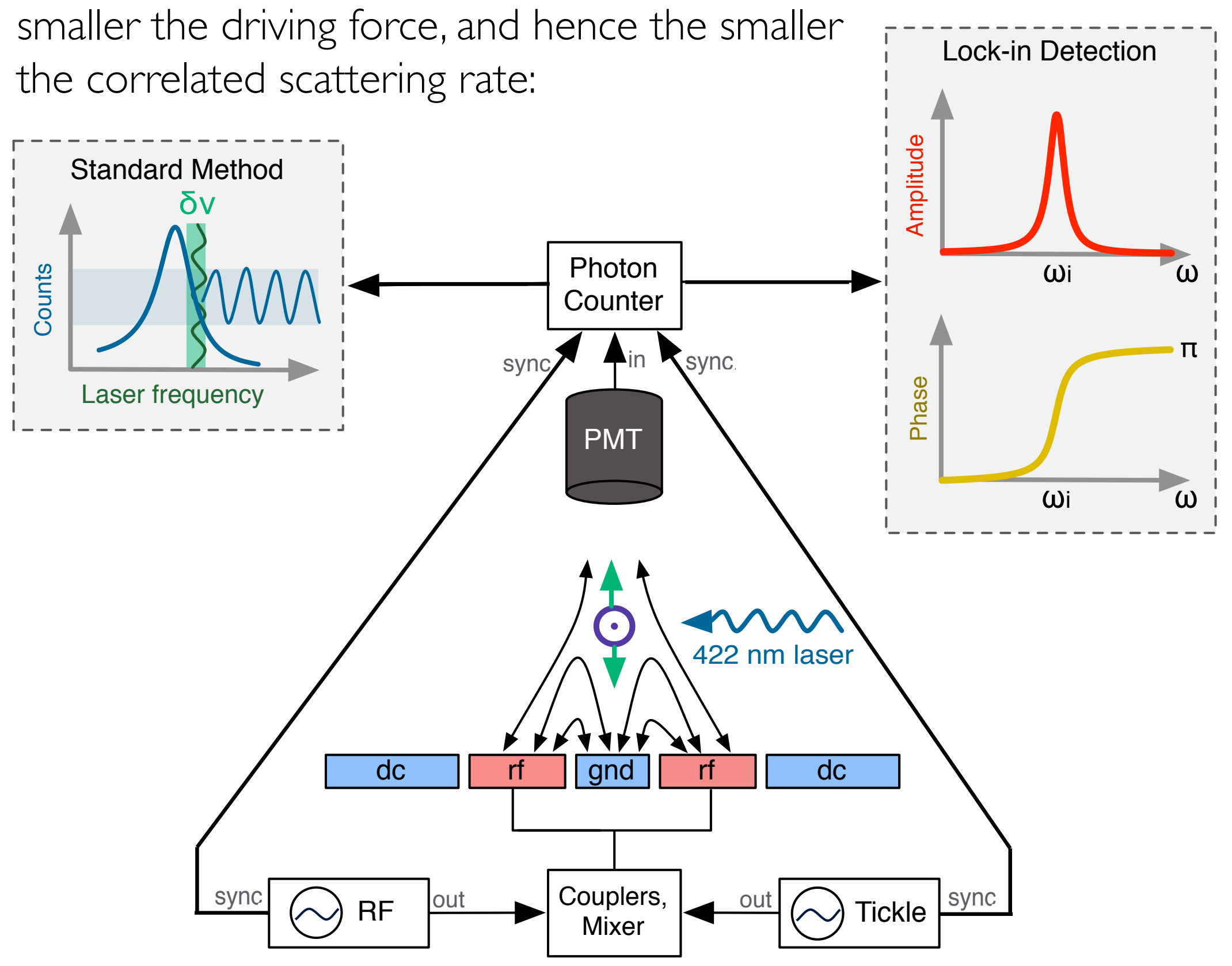
Precise compensation of stray electric fields is essential for a trapped ion qubit:
<1% broadening of Doppler-cooling transition ➔ **need ion within ~0.7 um** of RF null
<1% reduction in strength of carrier transition (for qubit rotations) ➔ **need ion within ~400 nm** of RF null

Resolved sideband spectroscopy on a narrow atomic transition can extract the micromotion amplitude by comparing the Rabi frequency of the first micromotional sideband and the carrier transition[2]. A simpler scheme detects the modulation of the fluorescence at the RF frequency due to the varying Doppler shift of the cooling beam over an RF cycle. However, neither of these techniques can detect offsets out of the trap plane:

Micromotion measurement technique:	Out-of-plane compensation?	Compensation without access to narrow transition?	Integration time required for 10 nm positioning accuracy:
Resolved sideband	no (a)	no	~40 ms
RF correlation	no (a)	yes	~300 ms
Synchronous tickle	**yes**	**yes**	**~6 ms** (b)

(a) Typically (unless the RF trapping potential is tilted)
(b) Assuming a tickle voltage of 1 V is applied

Building on previous work[3,4], we add sidebands to the RF voltage at one of the radial trap frequencies and detect fluorescence in phase with the added voltage. The closer the ion is to the field null, the smaller the driving force, and hence the smaller the correlated scattering rate:



We have developed an FPGA-based photon counter which is used for digital lock-in detection of the ion's driven secular motion.

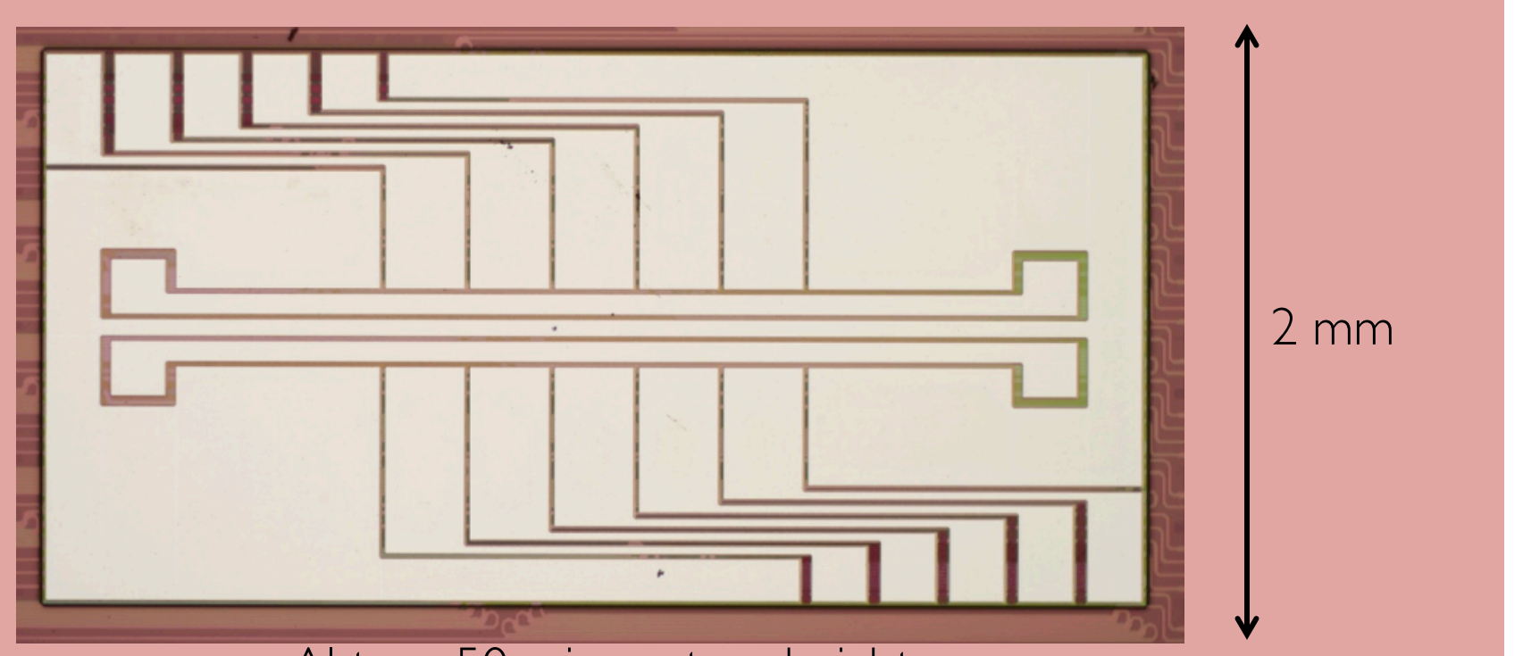
1. S. X. Wang *et al.*, J. Appl. Phys. **110**, 104901 (2011).
2. D. Berkeland *et al.*, J. Appl. Phys. **83**,10 (1998).
3. N. Daniilidis *et al.*, New J. Phys. **13**, 013032 (2011).
4. M. Drewsen *et al.*, Phys. Rev. Lett. **93**, 243201 (2004).

CMOS trap (Collaboration with Karan Mehta and Rajeev Ram)

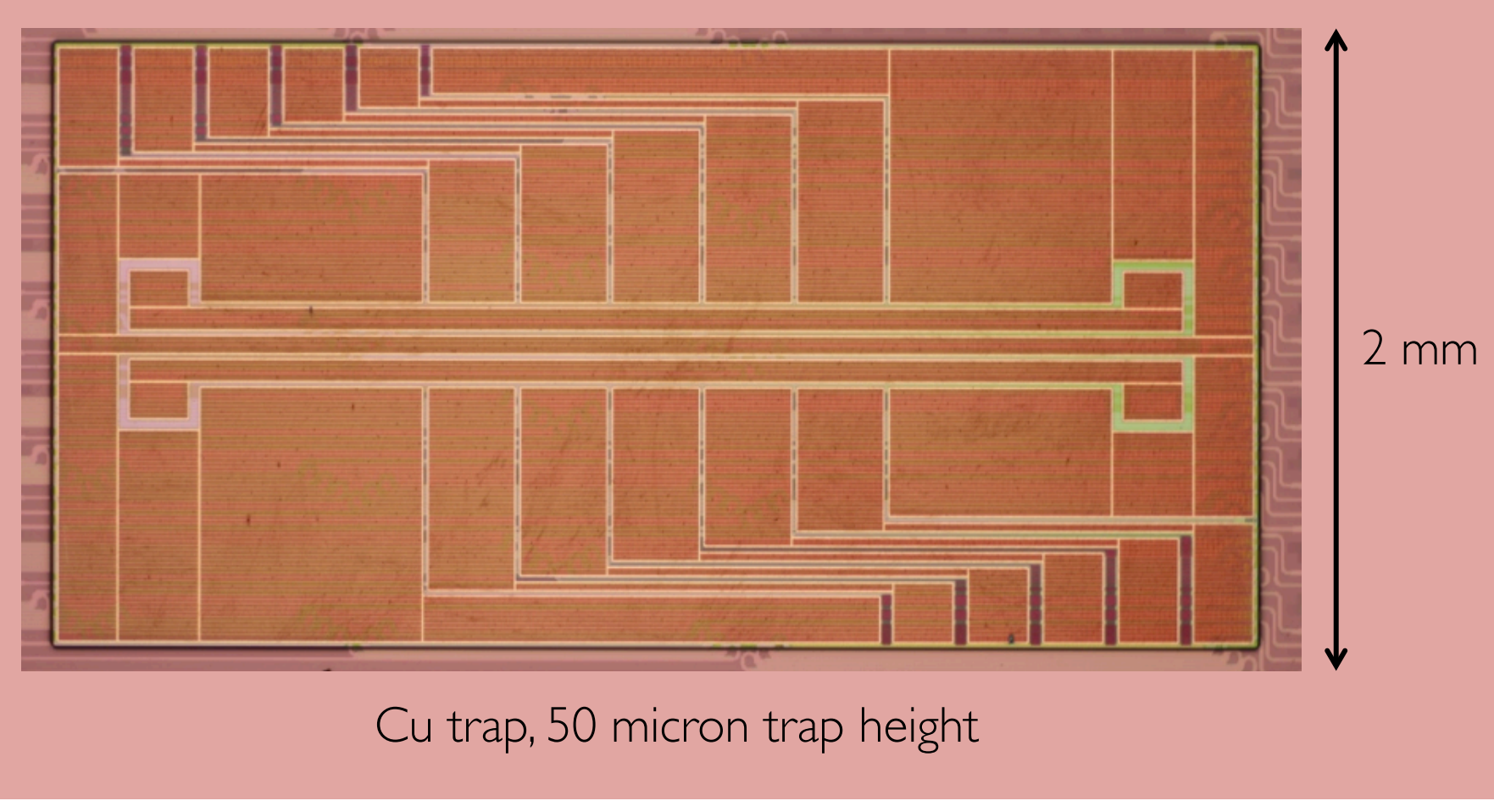
Can ion traps be manufactured with the same process as an IBM processor? A "trap-on-a-chip" CMOS (complementary metal-oxide-semiconductor) fabrication process is the ultimate platform in terms of reproducibility and precision for open source ion traps as well as scalability and integration with other CMOS photonic devices.

We have produced a first run of ion traps fabricated on top of silicon waveguides, using both the top copper layer and the aluminum interconnect layer.

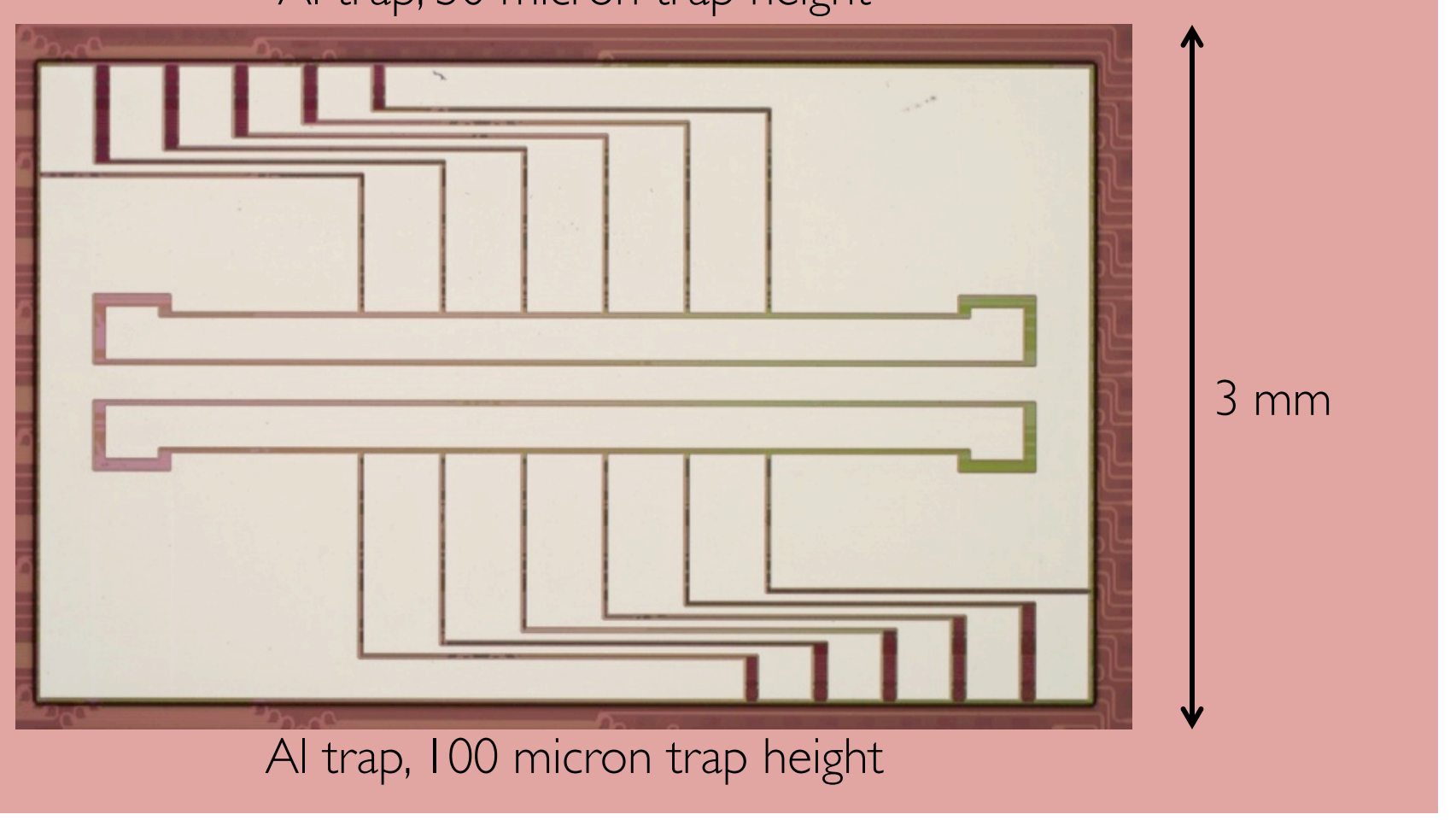
Trap design considerations:
- Possible excess RF field due to shortened electrodes
- Laser-induced charging due to smaller trap size
- Buried metal layers beneath trap



Al trap, 50 micron trap height



Cu trap, 50 micron trap height



Al trap, 100 micron trap height