# Integrated Waveguides in Trapped Ion Quantum Computing Chips


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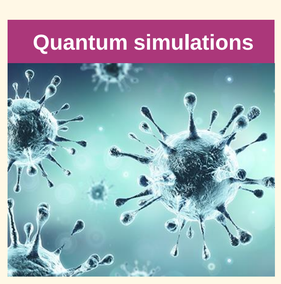
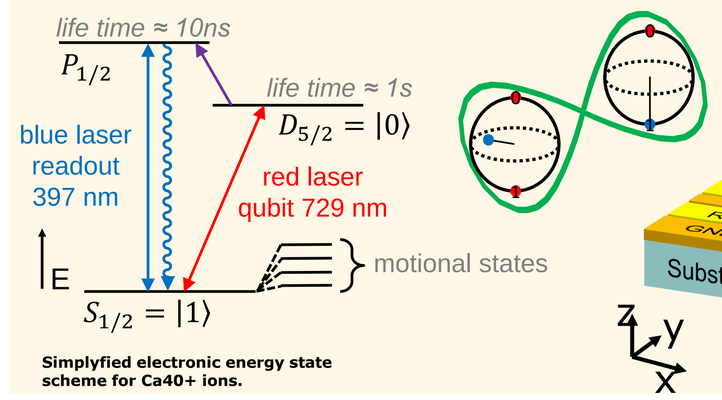
## Why Quantum Computing?

Optimization problems

Quantum simulations

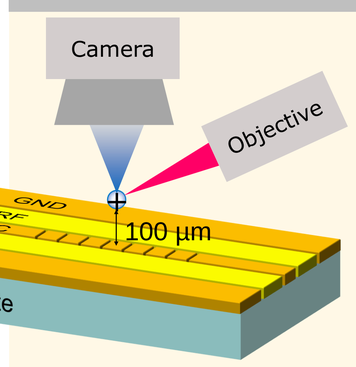


## Quantum Computing with Trapped Ions

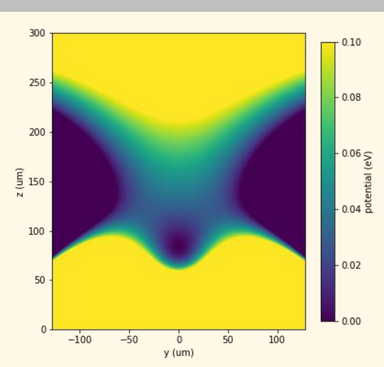



Simplyfied electronic energy state scheme for Ca40+ ions.

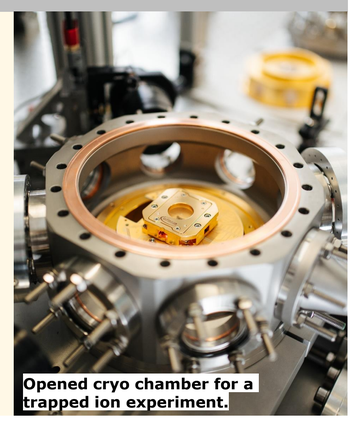
## Surface Ion Traps




Sketch of a trapped ion setup with a surface ion trap on a chip.




Typical pseudopotential for a single trapping site on a surface ion trap.



Opened cryo chamber for a trapped ion experiment.

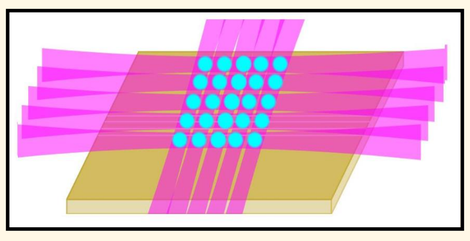
## Why Optical Integration in Ion Traps?

Useful QC requires 1000s of ions to talk to each other.

1000s of DC electrodes for ion control and shuttling

Laser access to **100s of ions @ ~10 nm beam accuracy**

Wavelengths: 400 – 1800 nm

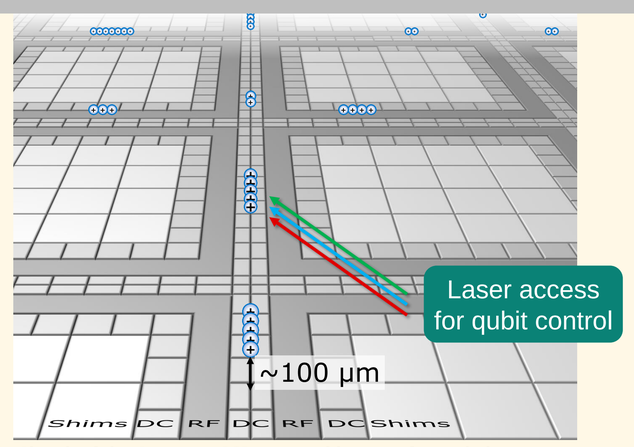


**Standard Setup**
ion trap chip
+ free-space laser beams

**Problems:**

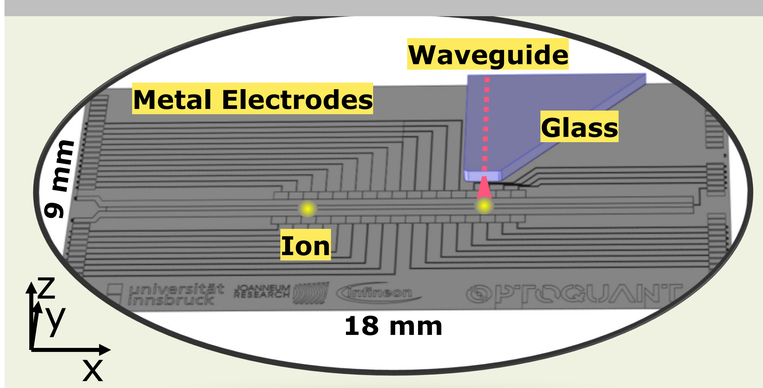
- Vibrations Typical. 1-10 nm
- Drifts Typical 100-1000 nm
- Scalability

**Integrate Photonics in Chip!**




Sketch of the Quantum CCD trap architecture for scaled up trapped ion processors. Ions are shuttled along lines in a grid. Laser access needs to be maintained at specific locations.

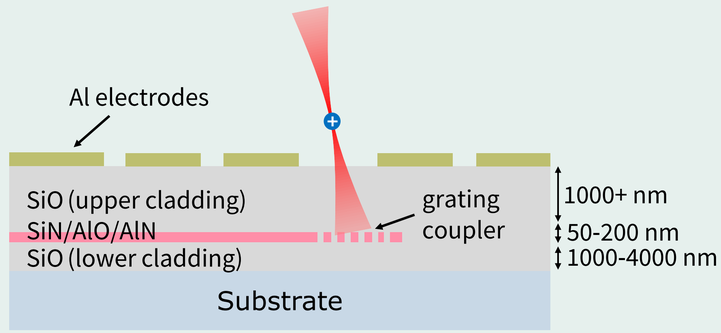
## Optoquant Approach to Optical Integration



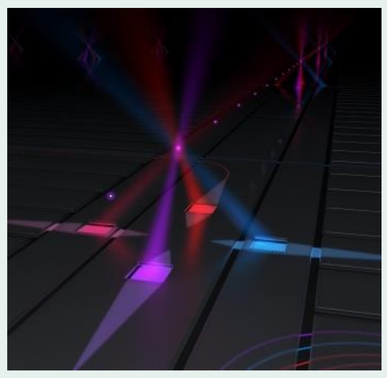

**Idea:**

- Femto-second laser written waveguides in glass block
- Glass block bonded on chip via waferbond
- Butt-coupling via optical fiber
- Optional: Micro lens for beam focusing

## Slab Waveguides and Thin Film Gratings




Schematic cut through an ion trap chip with a slab waveguide and a fokusing grating.



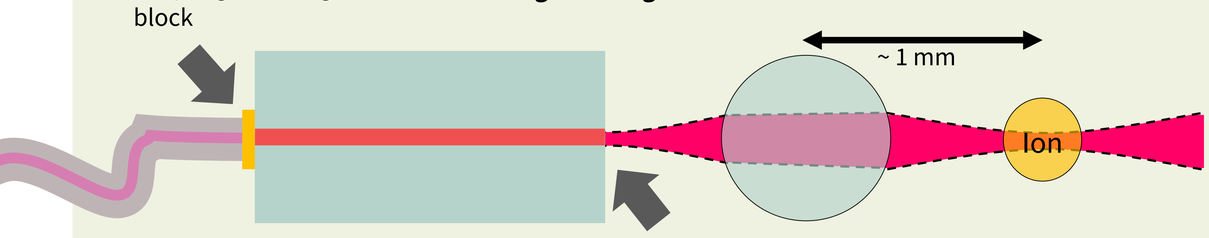
MIT Lincoln Labs, Illustration: Chet Beals

## Integrated Optical Elements

b) Fiber end glued to in-coupling facet of glass block

**c) Femtosecond laser written waveguides in glass**

**e) Microlens placed on substrate**

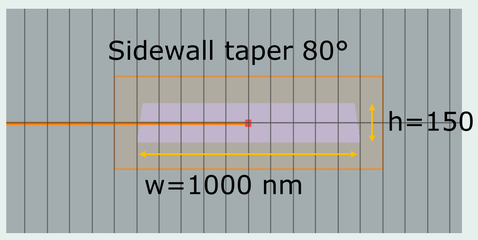



a) Fiber transports laser light to chip

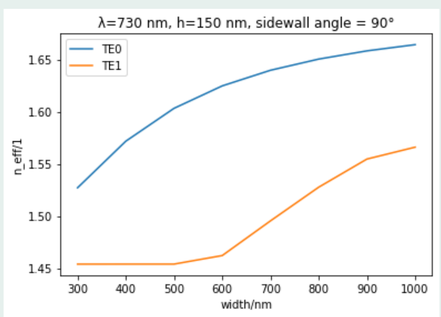
**d) Beam outcoupling at smooth sidewall**

f) Beam waist at ion ~ 30 µm

## Waveguide Simulations

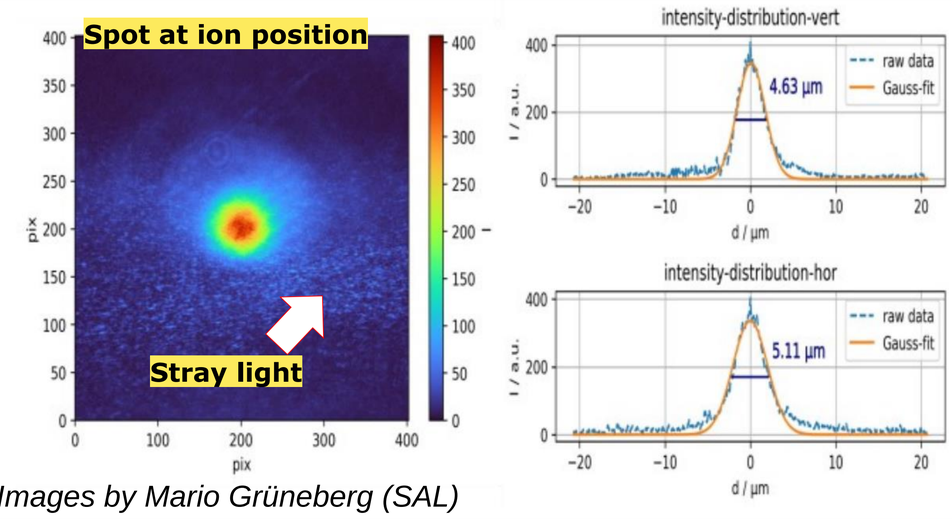



Profile of a slab waveguide with sidewall taper and denoted width and heigth. In the simulation the cladding extends 5 µm to all directions.



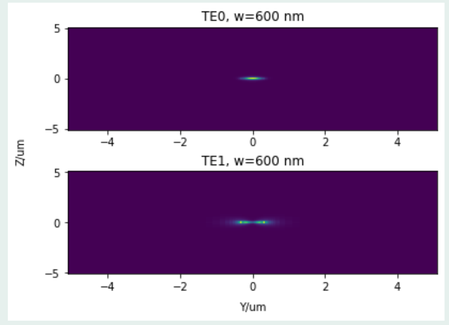

Finite difference eigenmode simulation of the TE0 and TE1 modes. Here the effective index is plotted against the waveguide width at height 150 nm and wavelength 730 nm.

## Characterization of the Spot at the Ion

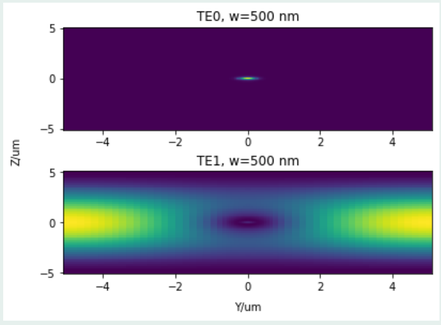



*Images by Mario Grüneberg (SAL)*

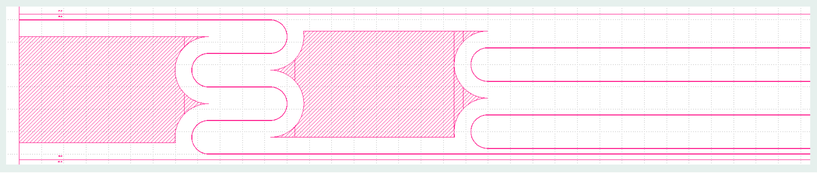
**ToDo: Fabrication and assembly of final design, trapping of ions**
**Problems: stray light, small bending radii**




Field amplitude of a cut through the waveguide/cladding stack of modes TE0 und TE1 at a width of 600 nm. The waveguide is placed in the middle of the image. Here the TE1 is a guided mode in the waveguide.




Field amplitude of modes TE0 und TE1 at a width of 500 nm. The waveguide is placed in the middle of the image. Here the TE1 is not guided in the waveguide. Instead we can see a mode that is guided at the boundaries of the cladding where a reflective metal boundary was placed.



Cutout of test chip design containing waveguide meanders of different lengths for cutback trials to obtain the waveguide losses.

**ToDo: Fabrication of test chips, Characterization of materials and waveguides, Process development and optimization, Grating design and fabrication.**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