Integration of Micro-Optics with Ion Traps towards Efficient Entanglement Generation between Remote Ions

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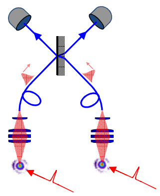
Motivation



- Entanglement of remote ions can add an additional layer of scaling to quantum information processing (QIP).
- Remote ions can be entangled by interference and coincidence detection of two photons emitted by the ions. (C. Simon and W. Irvine, PRL **91**, 110405 (2003); S. Olmschenk *et al.,* Science **323**, 486 (2009))
- The success probability of this heralded scheme scales as the square of the single photon detection efficiency.
- In current experiments, the success probability of this protocol is very small and limited by a small collection solid angle and poor fiber coupling.

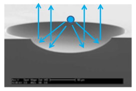
$$p=\underbrace{\frac{1}{4}}_{\text{probability of having a singlet Bell state}}\overbrace{\left[(0.995)(0.8)(0.95)(0.2)(0.15)(0.013)\right]}^{\text{probability of 1 photon emitted and detected}}{}^{2}=2.2\times10^{-8}$$

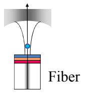
branching to $^2D_{3/2}$ state; losses; excitation probability; fiber coupling efficiency; detector efficiency; solid angle

(From Chris Monroe's group)

- Our goal is to enhance the photon collection efficiency into a single mode using an integrated optics approach.

Possible Approaches

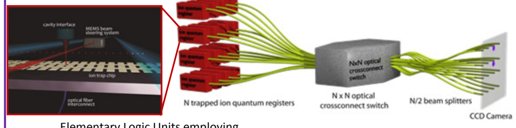




- Increasing the solid angle by using reflective optics (R. Noek *et al.*, Opt. Lett. **35**, 2460 (2010); N. L. Lindlein *et al.*, Laser Physics **17**, 927 (2007)).
- Coupling the ion to the mode of cavity (e.g. M. Trupke *et al.*, APL **87**, 211106 (2005)).

Scalable Quantum Network

- Each quantum register can process quantum information using motional quantum gates and shuttling of the ions.
- A large-scale optical switch reconfigures connections to enable the generation of N/2 entangled pairs of quantum registers in parallel.



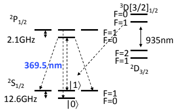
Elementary Logic Units employing deterministic Quantum computing

Remote Photonic link

J. Kim and C. Kim, Quant. Inf. Comp. 9, 181 (2009)

Integration of ion trap and optical cavity on a single-mode fiber

Advantages:
A small focal area leads to "decent" coupling strength while keeping the ion away from the macroscopic mirror and relaxes the requirements on the mirror coatings.

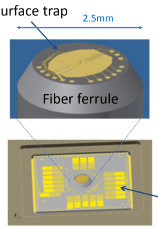


$^{171}Yb^+$ energy diagram

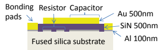
Challenges:

- To minimize scattering loss super-polished surfaces at the fiber tip and the mirror (with small radius of curvature) are required.
- High-reflection coatings on both non-conventional surfaces
- Fabrication of trap on the fiber tip

Fabrication of a surface trap on a fiber tip

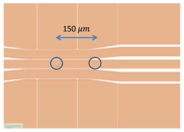


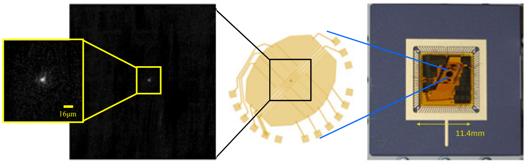
- A linear surface trap will be fabricated on a fiber and ferrule using a gold lift-off process.
- Patterning process on the fiber and ferrule tip has been under development
- Sub-mount for integrated low-pass filter and wire-bonding the trap on the fiber to the chip carrier



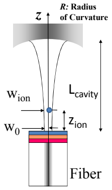
Characterization of surface trap on glass substrate

- A 5-rail linear surface trap is fabricated on a glass substrate
  - Trap is patterned in 1-μm thick evaporated gold layer
  - Operating condition: ~150V, 39 MHz
  - $^{174}Yb^+$ ion trapped 50 μm above the trap surface
  - Lifetime of trap with Doppler cooling: > 1 hour on average
  - Lifetime of trap without Doppler cooling: > 1 min
- Effect of exposed dielectric material near trap location
  - Fiber cavity will have exposed dielectric surface at the center of the trap to form a cavity mode between high-reflection coatings on the glass substrate and a curved mirror.
  - Glass surface is exposed to trapped ion through 10 μm diameter opening.
  - To estimate the effect of exposed dielectric material right under the trapped ion, we trapped an ion right above the exposed dielectric material and also 150 μm away from the center by applying different voltages to DC electrodes.
  - No difference was observed between these two locations.



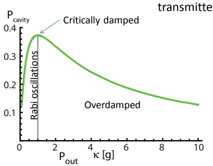


Photon collection into mode of a cavity

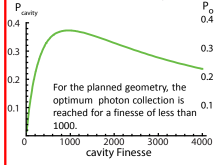


Geometrical Design Parameters:
mode waist w_0 = 1.6μm
cavity length L_{cavity} = 5mm
ion height z_{ion} = 50μm
result in:
waist at ion pos. w_{ion} = 4μm
coupling g = 2π 15.7 MHz

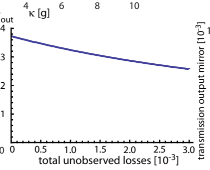
- κ : cavity half linewidth
- P_{cavity} : probability for an initially excited atom to emit a photon into the cavity mode and the photon leaving the atom-cavity system via the cavity decay channel.
- P_{out} : probability for an initially excited atom to emit a photon into the cavity mode and the photon being transmitted through the outcoupling mirror.

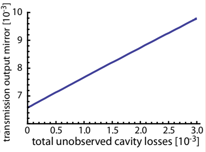


P_{cavity} reaches its maximum in the critically damped case where κ = g. In the underdamped case the system shows Rabi oscillations which modulate the wavepacket of the emitted photon.

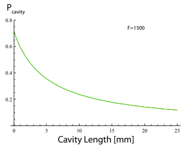


For the planned geometry, the optimum photon collection is reached for a finesse of less than 1000.

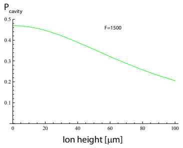




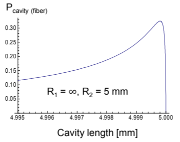
For an ideal cavity with this geometry the photon extraction efficiency can reach 37%. For realistic scattering and absorption losses of the mirrors of 1.5×10^{-3}, the photon extraction efficiency is expected to be more than 30%. In this case, the optimum is reached for a transmission of the outcoupling mirror of about 8×10^{-3}.



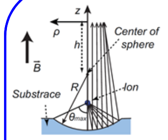
The photon collection efficiency could be improved by reducing the cavity mode volume. Or by pulling the ion closer towards the waist of the cavity mode.



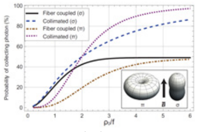
In case of planar-concave cavity, the radius of Gaussian mode at the fiber tip strongly depends on the distance between two mirror surfaces.



Photon collection into a single mode fiber using a micro-mirror



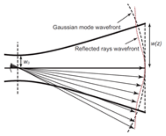
- Photons emitted by a trapped ion can be collimated by a mirror and eventually can be coupled into a single mode fiber.
- "Ideal" parabolic mirror with an infinite aperture can couple as much as 50% of emitted photons into a single mode fiber.



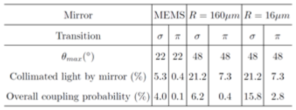
Parabolic mirror

- Generally, photons generated by π-transition cannot be coupled into a single-mode fiber due to radial polarization after reflection, but a spiral phase plate (Opt. Exp. **12**, 3548 (2004)) can be used to couple photons generated by π-transition and reject photons generated by σ-transition.

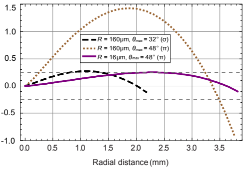
Spiral phase plate

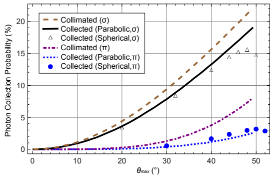


- Large optical path difference (OPD) due to spherical aberration severely limits the collection efficiency using a spherical mirror.
- Curved wavefront of the collimated light due to a non-parabolic micro-mirror can be approximated by a spherical wavefront of Gaussian beam.
- Residual OPD can be reduced by decreasing dimensions of the micro-mirror.



Mirror	MEMS		$R=160\mu m$		$R=16\mu m$	
Transition	σ	π	σ	π	σ	π
$\theta_{max}(^\circ)$	22	22	48	48	48	48
Collimated light by mirror (%)	5.3	0.4	21.2	7.3	21.2	7.3
Overall coupling probability (%)	4.0	0.1	6.2	0.4	15.8	2.8





- Residual OPD can also be reduced by using a phase plate whose thickness varies in radial direction.