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.

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.

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

Advantages:
- A small focal area leads to "decoupling" coupling strength while keeping the ion away from the macroscopic mirror and relays the requirements on the mirror coatings.
- 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.
- Patternning 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 nC linear surface trap is fabricated on a glass substrate
- Trap is patterned in 1-µm thick evaporated gold layer
- Operating condition: ~150V, 39 MHz
- +/−100 nC 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 fiber by applying different voltages to DC electrodes.
- No difference was observed between these two locations.

Possible院iews
- Evalute on a single mode fiber using a micro-mirror

For an ideal cavity with this geometry the photon extraction efficiency can reach 37%. For realistic scattering and absorption losses of the mirrors of 3.5 x 10⁻² the photon extraction efficiency is expected to be more than 30%. In this case, the optimum is reached for a transmission of the output mirror of about 8 x 10⁻³°.

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.

Generally, photons generated by α 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 α transition and reject photons generated by β transition.
- 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.

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

For the planar geometry, the cavity finesse is 

\[ \frac{λ}{\ln(1+\frac{R_1}{R_2})} \]

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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.