Integrated Fresnel Mirrors for Scalable Trapped Ion Quantum Computing

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Abstract: Photonic interconnects are a bottleneck to achieving large-scale trapped ion quantum computing. We fabricated a surface trap with diffractive mirrors and achieved sub-wavelength imaging of a trapped ion and $2.0 \pm 0.5\%$ coupling into a single-mode fiber.

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1. Introduction

Trapped atomic ions are a leading system for implementing quantum information processing, demonstrating of all required gates operations for universal quantum computing and a roadmap to realizing large-scale implementations [1]. Micro-fabrication based ion traps (chip traps) with multiple zones that can trap and manipulate multiple ions have been realised [2], however there remains a bottleneck in efficiently coupling ion light into single mode fibers with a scalable solution. Monolithic fabrication of diffractive optics into the surface of a chip trap solves both the scalability problem and the problem of fine alignment between the trap and the optics.

2. Experimental results

Our chip trap (Fig. 1) is a modified version of the Georgia Tech Research Institute microwave chip trap [3]. Reflective diffractive optics were designed to collimate light from a focus at the RF node $58.6 \mu\text{m}$ above the surface of the trap and patterned on the center electrode by e-beam lithograph. The optics are designed for the 369.5nm Yb^+ cycling transition. Each optic was $80 \mu\text{m} \times 127 \mu\text{m}$, the former dimension that of the center electrode rail width and the latter matching the standard pitch of a V-groove fiber array. The optics have an NA of 0.55 (perpendicular to rails) and 0.73 (along the rail), capturing 13.2% of the solid angle and close to the estimated optimal NA for entanglement generation per unit surface area [4]. The grating has a hybrid blaze, multi-level in the center for high efficiency and two level near the edges. The large numerical aperture results in an imaging system with a small depth of focus. To compensate for possible fabrication variation with the introduction of the Fresnel optic, the focal length for different collimator sites were stepped $\pm 2 \mu\text{m}$ from the calculated focus in $1 \mu\text{m}$ steps.

Figure 1. Georgia Tech microwave chip trap [3] modified with integrated diffractive mirrors.

To evaluate the optics $^{174}\text{Yb}^+$ was loaded by isotope selective photo-ionization from a thermal oven (Fig 1 left) and then shuttled to imaging sites. Near diffraction limited sub-wavelength ion images (Fig. 2) were obtained from

the +1 μm site, with observed spot sized FWHM of 338 nm x 268 nm vs. a diffraction limit of 336 nm x 257 nm. To measure the collection efficiency a photon gun protocol was implemented based on an optical pumping protocol. The magnetic field direction was oriented coplanar to the chip along the direction the cooling laser propagation and at 45° from the axis of the RF node. A polarizer was introduced into the imaging system to selectively detect only π photons. By alternatingly exciting on the σ^+ and σ^- transitions, optical pumping ensured a sequence of σ photons was always terminated by a π photon as the ion was pumped into a dark state. The total photon collection efficiency was measured to be $5.2 \pm 1.2\%$. Coupling into a single mode fibre of up to $2.0 \pm 0.5\%$ was observed, limited by mismatch in the coupling optics. Image mode quality indicates coupling up to $\sim 4\%$ may be possible.

Figure 2. Sub-wavelength image of a trapped $^{174}\text{Yb}^+$ ion with near diffraction-limited spot size.

3. Conclusion

We have demonstrated the first high-resolution imaging optics monolithically integrated on a micro-fabricated ion surface trap. Ion light was coupled into a single mode fiber. The configuration of optics used is suitable for scaling to a linear array of sites being coupled into a standard fiber array coupler.

4. References

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