

Large-scale quantum computing with phase Fresnel lenses

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Abstract

Efficient ion-photon coupling is an important component for large-scale ion-trap quantum computing. We propose that phase Fresnel lenses (PFLs) are a favorable optical coupling technology to match with multi-zone ion traps. Both are scalable technologies based on conventional micro-fabrication techniques. Large numerical aperture (NA) PFLs can reduce the readout time for ion qubits and provide good coherent coupling to a single optical mode. From optical characterization of a suitable PFL we predict a coherent coupling efficiency of $>0.64\%$, twice the best experimental efficiency achieved to date. In addition, high NA entanglement fidelity limits can be removed by optical filtering.

Keywords: trapped ion quantum computing, phase Fresnel lens; coherent coupling; diffractive optics; large aperture optics

Introduction

Quantum information processing leverages properties of quantum physics to perform computational and communications tasks at faster rates (Shor-94) or with greater security (Bennett-84) than classical techniques. The electronic and motional states of trapped ions are one of the leading systems for realizing quantum information processing due to their long coherence times, strong yet controllable inter-qubit coupling, and ease in interfacing using established optical and microwave techniques. Many small-scale quantum computation tasks have been demonstrated with trapped ions (Kielpinski-03) and a roadmap exists for larger scale architectures (Kielpinski-02). A common thread in all the proposed large scale ion trap quantum computing architectures is the need for a scalable, efficient method for collecting ion fluorescence. Arrays of phase Fresnel lenses (PFLs) are well suited to meeting these requirements because of their large numerical apertures and scalable production via conventional micro-fabrication techniques (Streed-09). Fig. 1 illustrates the integration of a PFL array with a multi-zone ion trap to create a high-density quantum processor. At large numerical apertures PFLs can maintain diffraction-limited performance ($NA=0.9$, Menon-06) because on-axis geometrical aberrations are engineered out as part of the design process. While the diffraction efficiency of a high-NA multilevel PFL was previously thought to be limited to 20% at deflection angles near 45° , recent vector diffraction modeling of PFLs (Cruz-Cabrera-07) shows efficiencies of 63% could be obtained in this regime with a modified groove structure.

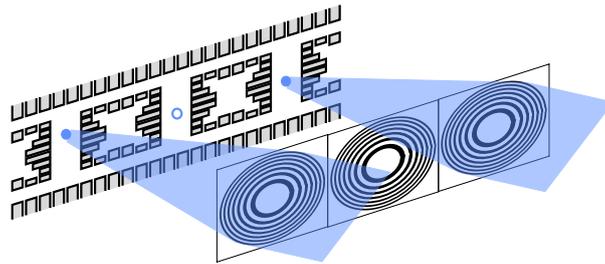


Figure 1: Schematic of parallel optical operations on a multi-zone ion chip trap using an array of phase Fresnel lenses.

Results and Discussion

The probability that a photon is successfully collected by a lens, p_{coll} , depends on its average efficiency, numerical aperture (NA), the transition polarization (σ or π), and the viewing orientation. The beam quality produced by the coupling optic is unimportant in photon counting applications so long as the collected light falls on the detector's active area. However, the probability that light from an ion is coherently coupled into a single optical mode (p_{coh}) does depend on the spatial quality of the beam (M^2) which can be obtained for a particular beam divergence θ . The coherent ion-photon coupling can be estimated by approximating the measured beam as an ideal gaussian, normalizing the intensity with the top hat approximation, and applying this effective divergence angle $\theta_e = \theta/(M\sqrt{2})$ to a

polarization and orientation dependent formula for the fraction of light emitted into a cone. Norton-09 measured a near diffraction limited ($M^2 = 1.08 \pm 0.05$) spot size of $w_0 = 350 \pm 15\text{nm}$ and divergence $\theta = 348 \pm 1\text{ mrad}$ at 369.525 nm with $30 \pm 1\%$ efficiency into the focus on a 0.64 NA binary PFL suitable for integration with a trapped Yb^+ ion system. From these results we can calculate the expected coherent coupling efficiency between the spontaneous emission from single ion and a fundamental gaussian mode (TEM_{00}), which is equivalent to the efficiency for coupling into a cavity, single mode fiber, or interferometer. The total emission collection fraction $f(\theta_m)$ (Eq. 1) as a function of acceptance angle is maximized in two different optical configurations; σ^\pm transitions when magnetic field parallel to the optical axis (a polar view in spherical coordinates, Matsukevich-08) and π transitions when the magnetic field perpendicular to the optical axis (equatorial view, Blinov-04, Moehring-07). Even though the emission pattern is different for polar/ σ and equatorial/ π , the fraction of light captured in an acceptance cone of angle θ_m is identical. For capturing photons in these configurations we predict a coherent coupling of $p_{coh} \geq 0.64\%$, twice that of recent experiments (Moehring-07, Matsukevich-08). From the measured diffraction efficiency and the lens NA the photon collection efficiency should be $p_{coll} = 4.6\%$. Since remote ion-ion entanglement schemes requires coincident detection of two fluorescence photons after interference on a beamsplitter the subsequent the rate of entanglement formation scales as p_{coh}^2 .

$$f_{p\sigma, e\pi}(\theta_m) = \frac{1}{2} - \frac{7}{16} \cos \theta_m - \frac{1}{16} \cos 2\theta_m \approx \frac{3}{8} \text{NA}^2 + \frac{1}{64} \text{NA}^6 \quad (1)$$

A source of error that becomes prominent with large numerical aperture optics is the reduction in polarization contrast (blurring) at large angles. For a polar/ σ^\pm configuration (Matsukevich-08) the polarization fidelity of a photon emitted at an angle θ from the optical axis drops as $\sqrt{1 - \frac{1}{2} \sin^2 \theta}$. Because of this blurring, polarization fidelity greater than 99% is limited to $\text{NA} < 0.27$, while a 90% fidelity requires $\text{NA} < 0.85$ without additional filtering. The application of a sufficient magnetic field to resolve the Zeeman levels allows separation of photons based on their optical frequency as well as polarisation. Photons whose optical frequency and polarisation characteristics do not agree with the entangling basis can thus be selectively filtered to enhance the fidelity. A reduction of 100 in this error rate can be obtained for $^{171}\text{Yb}^+$ ions in a 67 gauss field, producing a 160 MHz Zeeman splitting, and filtered with two etalons of 320 MHz free spectral range and finesse of 16. If purely polarization basis photonic qubits are desired for subsequent processing, acousto-optic modulators can be used to remove the Zeeman splitting frequency shift.

Conclusions

Large numerical aperture optics are crucial to scaling up ion-trap quantum computing. We have shown how phase Fresnel lens arrays can be superior alternative for integration with chip type ion traps. In particular, coincident-detection-based ion-photon entanglement schemes benefit from PFLs since the entanglement rate scales as NA^4 and depends on high spatial mode quality. In addition we have proposed a scheme that eliminates the fidelity loss caused by high NA polarisation blurring effects in a remote ion-ion entanglement scheme. We have demonstrated that large NA PFLs are a good candidate device for collection and coherent coupling optic in ion-trap quantum computing.

Acknowledgements

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