

Scalable imaging of trapped ions

E. W. Streed*, A. Jechow, B. G. Norton, M. J. Petrasiusas, D. Kielpinski

Centre for Quantum Dynamics, Griffith University, Nathan, QLD 4111, Australia

*e.streed@griffith.edu.au

Abstract: Wavelength scale imaging of trapped Ytterbium ions was demonstrated using a microfabricated phase Fresnel lens. Near diffraction-limited spot sizes of below 440 nm (FWHM) were achieved, an important precursor to efficient single-mode coupling.

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OCIS codes: 020.3320 Laser cooling, 050.1965 Diffractive lenses, 270.5585 Quantum information and processing,

1. Introduction

The efficient coupling of light from a dipole source into a single optical mode is an important enabling technology for quantum information processing (QIP) [1–4]. This problem extends across a wide range of QIP approaches including trapped ions [5], neutral atoms, and solid state systems [6]. We have proposed the use of microfabricated phase Fresnel lens (PFL) arrays (Fig. 1a) as a solution to this challenge [7] since the ease of microfabricating large PFL arrays make them an attractive optical interconnect for massively parallel trapped-ion QIP [8,9]. Recently our group [10] has shown the successful integration of ion trapping and PFLs, with collection efficiency and image contrast that are competitive with other trapped-ion QIP experiments and suitable for large-scale QIP.

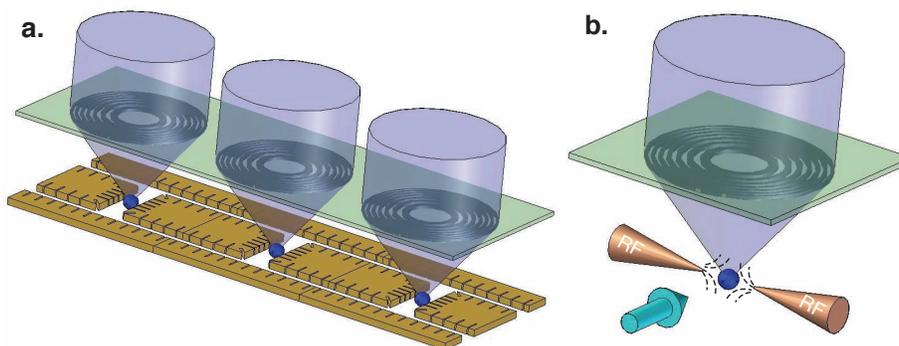


Fig. 1. a. Proposed highly parallel readout of trapped-ion qubits with PFLs [7]. Fluorescence from ions trapped at many sites on a microfabricated trap [8,9] is efficiently coupled into single optical modes by an array of microfabricated PFLs on a single substrate. b. Diagram of the experimental apparatus. A single $^{174}\text{Yb}^+$ ion is trapped in the RF quadrupole field (dashed lines) and illuminated with resonant light at $\lambda = 369.5$ nm (arrow). Light scattered from the ion is collimated with an in-vacuum PFL and imaged onto a cooled CCD camera (not shown).

2. Experimental Results

Ion images with wavelength scale resolution were obtained for the first time, demonstrating near diffraction-limited performance of the PFL [11]. This high resolution enables several applications beyond the simple collection of photons for state detection. These include the possibility of individual addressing and individual readout of the ions by lasers, as required for large-scale ion-trap QIP [5, 12] as well as the efficient coupling of fluorescence photons into the single optical modes of fiber optic cables. To perform the experiment a two-level (binary) PFL (Fig. 2a) was integrated in ultra-high vacuum with a simple yet highly flexible radiofrequency (RF) ion trap. The PFL optic was microfabricated by electron-beam lithography of a fused silica substrate. A series of concentric rings, 390 nm deep, were etched into

the fused silica surface to generate π phase shifts at the Yb^+ cooling laser wavelength of $\lambda = 369.5$ nm. The resulting phase profile approximates that from a point source 3 mm from the lens. The 3 mm focal length of the lens is identical to its working distance. The pattern was written over a diameter of 5 mm, corresponding to 12% of the total solid angle ($\text{NA}=0.64$). Yb^+ ions were trapped in an RF electric quadrupole field formed between two needles [13, 14]. Each needle was attached to nano-positioning translation stages and used to control the position of the trapped ion in all three dimensions. Loading of $^{174}\text{Yb}^+$ ions into the trap was performed through isotope-selective excitation of a neutral ytterbium beam. The $^{174}\text{Yb}^+$ ions were laser cooled on the 369.5 nm $S_{1/2}$ to $P_{1/2}$ transition using light from an ECLD [15] frequency stabilised to Yb^+ ions generated in an electrical discharge [16]. The RF needles were positioned such that the PFL collimated the light scattered from the trapped ions. The ion light was then reimaged with 615 ± 9 magnification onto a cooled CCD camera. Magnification calibration was performed by measuring the distance between two ions for a known trap frequency. To measure the ion spacing we applied a negative DC voltage to the RF needles so that the ions lay in the object plane of the imaging system. An image of a single ion on the CCD camera is shown in Fig. 2b, where the horizontal axis is the needle axis. A Gaussian fit to the data gives an ion spot size (FWHM) of $434 \text{ nm} \pm 9 \text{ nm}$ in the vertical axis and $475 \text{ nm} \pm 9 \text{ nm}$ in the horizontal (needle) axis.

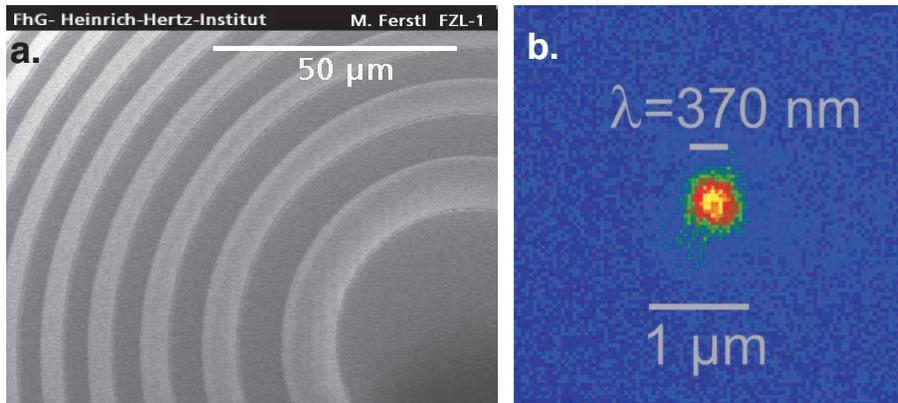


Fig. 2. a. Electron microscope image near the center of the PFL. b. Image of a single ion obtained with a PFL integrated in UHV of a needle ion trap.

3. Conclusion

In conclusion, we have demonstrated imaging of trapped ions with a resolution at the wavelength scale using a micro-fabricated phase Fresnel lens. To our knowledge, this is the highest imaging resolution achieved with an atom in free space to date. The highest resolution previously achieved with imaging of single atoms was reported to be 570 nm [17] at a wavelength of 780 nm. However, in that setup neutral atoms in an optical lattice were investigated. While our approach can be applied to such neutral atomic systems straightforwardly, the working distance in [17] was too short to be applicable to trapped ions. The excellent scalability and high resolution of the PFL architecture render it useful as an integrated optical interconnect in large-scale QIP applications.

This work is funded by the Australian Research Council under DP0773354 (DK), DP0877936 (ES, Australian Postdoctoral Fellowship), and FF0458313 (H. Wiseman, Federation Fellowship), as well as the US Air Force Office of Scientific Research (FA2386-09-1-4015). AJ is supported by a Griffith University Postdoctoral Fellowship. The PFL was fabricated by Margit Ferstl of the Heinrich-Hertz-Institut of the Fraunhofer-Institut für Nachrichtentechnik in Germany.

4. References

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