Towards Photonic Integrated Ion Traps for high-performance Quantum Computing and Atomic Clocks

(Student paper)

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Ion traps are a promising platform for the realization of high-fidelity quantum information processors and high-accuracy optical clocks. Integrated photonic components are essential for scaling ion trap systems to large numbers of qubits. We will present our work on ion traps with integrated light guidance and manipulation. Keywords: *Ion traps, Quantum computing, Photonic integrated circuits, Microfabricated outcoupling gratings, Waveguides, Atomic clocks*

INTRODUCTION

Trapped ion quantum computers are one of the most promising platforms for efficiently solving classically intractable problems, such as combinatory optimization problems, material design, and drug delivery, just to name a few [1,2,3]. Currently, the world leading trapped ion quantum computers operate with around 20 qubits, offering high fidelities of >99% for single and two-qubit gate operations [4,5,6]. The number of qubits is not sufficient to solve classically intractable problems. Integrated photonics in ion traps will allow making the decisive step to scale up to higher numbers of qubits [1]. Photonic integrated circuits (PICs) enable laser light delivery with high pointing stability and customized spot size to each ion qubit at wavelengths ranging from ultraviolet (UV) to near-infrared (NIR) range.

Trapped-ion-based optical clocks serve as highly stable frequency standards that can be applied for timing information in navigation, very long baseline telescopes, tests of fundamental physics, and geodesy [7,8,9]. The physics package that provides the reference frequency will greatly benefit from integrated optics. The systems will consume less energy, get more compact, portable, easier to maintain, and more affordable.

In our research projects, we work on the development of photonically integrated ion traps for quantum computing and optical clocks. We design ion traps with passive optical devices such as waveguides, focusing grating outcouplers and tapers for incoupling from optical fibers. We characterize the fabricated PICs based on the outcoupled light using beam tomography. The integrated traps will be characterized in a dedicated test setup.

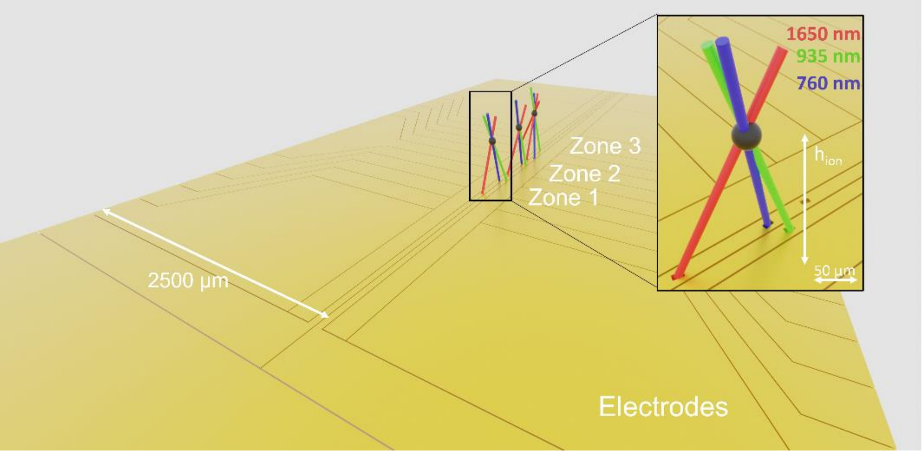

Fig. 1. Surface Ion trap with integrated photonics to control outcoupled beams for addressing the ions (black spheres) in different trap zones. The colored beams display the different wavelengths implemented (Blue: 760 nm, Green: 935 nm, Red: 1650 nm).

Beam geometry and ion trap requirements

We use $^{172}Yb^+$ ions to design and characterize our prototype ion trap with integrated optics. The $^{172}Yb^+$ level scheme (Figure 2 a)) shows all the relevant transitions and their corresponding wavelengths which cover the range from UV to NIR. Specific angles, beam waists, power, and light polarization are required to drive the transitions. Moreover, crosstalk between the different zones and scattering must be avoided. Figure 2 b) shows a basic design of our linear surface ion trap. With the same working principle as a typical Paul trap, the surface trap uses DC electrodes (blue) and RF electrodes (red) to generate a dynamic potential to trap ions in space. In our configuration, the ion height h_{ion} is designed to be 100 µm above the surface. With $\Omega_{RF} = 2\pi\cdot 20$ MHz and $U_{RF} = 200$ V, we obtain a radial secular frequency of $2\pi\cdot 3.03$ MHz and a trap depth of 264.78 mV. Three of the trapping zones are provided with different beam geometries for the NIR transitions (see Fig. 1). To enter a specific zone the ion will be shuttled. The integrated trap design is inspired by *Karan Mehta et al.* [11]. Furthermore, opening windows in the gold electrodes are necessary for beams to not get backreflected from the gold layer. Their influence on the trapping potentials and the possibilities to coat them with ITO are under investigation.

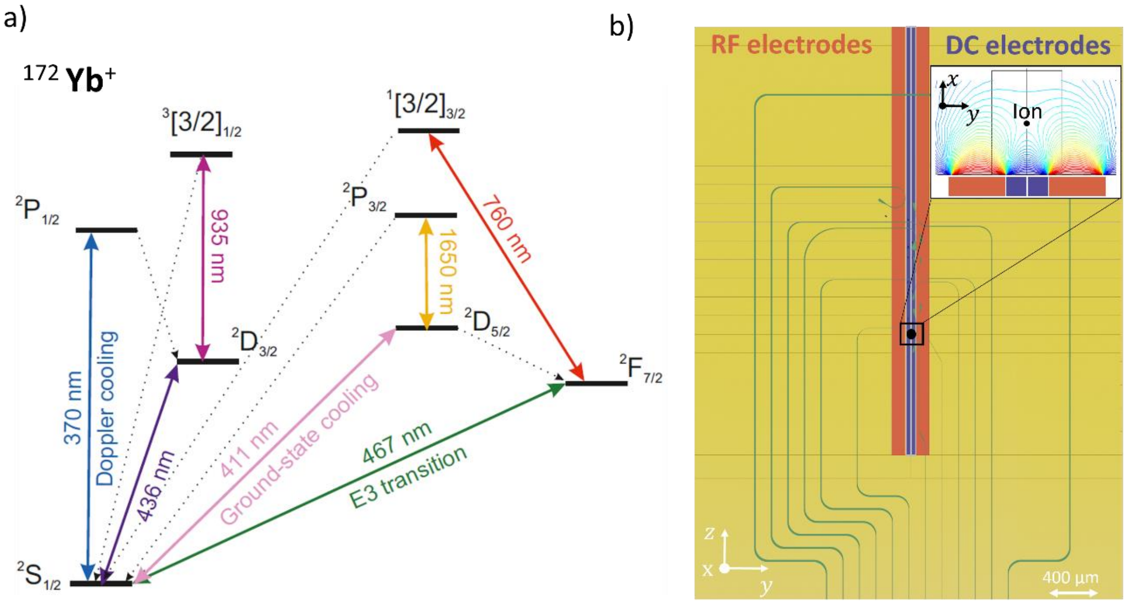

Fig. 2. a) $^{172}Yb^+$ level scheme (based on [12]) b) Sketch of a surface ion trap, the electric potential trapping the ion, and the PIC (green).

Light delivery

To guide the laser light on the chip, different passive optical elements are utilized. The light is coupled in from a fiber array using a two-layer butt coupling scheme. It is sent to the ion for optical control via tailored waveguides and focusing grating outcouplers. The waveguides are designed to provide single-mode operation and high confinement of the fundamental quasi-TE mode. The grating coupler design aims for a Gaussian beam with µm-beam waist by changing the duty cycle, the period, and the grating curvature. Besides that, other passive optical components like MMI splitters and mode converters are utilized. The material of choice for the NIR wavelengths is Si_3N_4. To further address the UV wavelengths, AlN- and Al_2O_3-based PICs are under investigation. The cladding material is SiO_2 and the substrate is Si. Our simulations are carried out with Lumerical FDTD, Lumerical MODE, and COMSOL Multiphysics.

Optical characterization setup

A characterization setup is used to evaluate the performance of the designed integrated optical components. Our setup is designed to target the needed wavelengths ranging from UV to NIR. It consists of three major parts:

1. A *laser system* able to address the wavelengths required to work with $^{172}Yb^+$-ions. The seven lasers are selected to secure a narrow bandwidth operation that avoids dispersive influences of the grating outcouplers (see Tab. 1). This leads to entirely fiber-coupled setups for the IR lasers and free-space setups for the UV wavelengths.
2. A *hexapod* with an attached nanopositioner that aligns the fiber arrays to the chip. Six degrees of freedom and the smallest step size of 2.5 nm serve to maximize the incoupling efficiency.

3. A *microscope* for monitoring the grating coupler emission. The hexapod holding the fiber array and the sample holder is hereby mounted on the microscopes x-y-stage. To reconstruct the beam, emission at different heights above the chip is measured with the help of an automated focusing unit. Four different objectives and a dual-camera port with a CMOS and an InGaAs camera enable measurements from 350 to 1700 nm.

Wavelength [nm]	**Power [mW]**	**Linewidth [MHz]**	**Range [nm]**
370	13	0.15	1
399	>50	1	4
411	23	0.1	5
467	~15	0.1	3
760	9	1	2
935	13	8	2
1650	20	0.1	2

Tab. 2. Different laser types are used to cover the required wavelengths for $^{172}Yb^{+}$. The power values correspond to the specified output powers of the laser sources.

DISCUSSION

The integration of photonics in surface electrode ion traps for scalable quantum computers and optical clocks faces some major challenges. To address the relevant ion transitions photonics from UV to NIR are required which results in different material platforms to integrate into a chip. Furthermore, the beam must be delivered with certain characteristics to interact with the ion effectively, so the focussing grating couplers have to be designed in a way that avoids stray light and provides single-ion addressing. Moreover, standard grating couplers are limited to the emission of linear polarization, however, circular polarization is desired for state preparation in trapped ions. Finally, we have implemented a characterization setup for PICs capable to work from UV to NIR

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References

[1] C. D. Bruzewicz et al., Trapped-Ion Quantum Computing: Progress and Challenges, Appl. Phys. Rev. vol. 6, no.2, pp. 021314 (2019)
[2] J. Benhelm, G. Kirchmair, C. Roos, et al. Towards fault-tolerant quantum computing with trapped ions. Nature Phys 4, 463–466 (2008)
[3] B. Bauer et al. Quantum Algorithms for Quantum Chemistry and Quantum Material Science, Chemical Reviews , vol 120, no.22, pp. 12685-12717, (2020)
[4] IonQ, IonQ Aria: Practical Performance (Part One), https://ionq.com/posts/july-25-2022-ionq-aria-part-one-practical-performance (accesssed 16.01.2023)
[5] Quantinuum, Major Upgrade for System Model H1-1, Powered by Honeywell, https://www.quantinuum.com/hardware/n20 (accessed 17.01.2023)
[6] Access 20 fully-connected qubits using a 19” rack., AQT, https://www.aqt.eu/pine-system-20-qubit-control/ (accessed 17.01.2023)
[7] A. D. Ludlow, et al., Optical atomic clocks, Rev. Mod. Phys., vol. 87, pp. 637 (2015)
[8] J. Stuhler, et al., Opticlock: Transportable and easy-to-operate optical single-ion clock, Measurement: Sensors, vol. 18, pp. 100264 (2021)
[9] T. E. Mehlstäubler, et al., Atomic clocks for geodesy, Rep. Prog. Phys., vol. 81, no. 6, pp. 064401 (2018)
[10] D. Allock, Surface-Electrode Ion Traps for´ Scalable Quantum Computing, PhD thesis, Oxford University, UK (2011)
[11] K. Mehta, C. Bruzewicz, R. McConnell, et al. Integrated optical addressing of an ion qubit. Nature Nanotech 11, 1066–1070 (2016)
[12] T. Burgermeister, Development and characterization of a linear ion trap for an improved optical clock performance. Hannover: Gottfried Wilhelm Leibniz Universität, PhD thesis (2019)