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Integrated photonics in trapped ion quantum computing

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The integration of photonic components in surface electrode traps is a novel and impactful technology, representing a promising approach for scalable quantum computing with trapped ions \[Mehta2023\].
In this architecture, photonic waveguides are embedded in a trap layer underneath the electrodes to route light with high efficiency to the position of interest. Integrated gratings output the light from the chip and tightly focus it directly on the ions, creating beam spots with high intensity and the possibility of engineering the light wavefront using suitable photonic structures. Finally, this architecture can be paired with active components such as optical modulators and detectors, representing a breakthrough in integrated technologies for quantum computing.

Here we report on the last results on photonic surface traps developed at ETH Zurich. We used traps equipped with integrated waveguides and passive optical components based on silicon nitride to operate with $^{40}\mathrm{Ca}^{+}$ ions. Laser beams at the wavelengths of 729, 866, and 854 nm are integrated, used to drive the qubit quadrupole transition $4S_{1/2} \rightarrow 3D_{5/2}$ and to repump the ions for cooling and spin reset, respectively. The cooling and detection light at 397 nm and the photoionization beams at 423 and 389 nm are delivered in free-space.

In this platform, we demonstrated the first two-qubit entangling gate controlled by integrated light, in a trap with one 729 integrated beam addressing multiple ions \[Mehta2020\].
As a next step, we demonstrated the use of integrated components to deliver spatially structured light to the ions, engineering the laser-ion interaction to the application of interest \[Ricci2023\]. In our design, the integrated photonic gratings are arranged to produce a passively phase-stable standing wave at the ion location. We characterized the spatial structure of the light field and the optical performance of the device using one trapped ion as a probe. Such a structured light field can be used to enhance the fidelity of quantum logical gates or metrological operations and to generate state-dependent optical potentials in a novel way.
Finally, we demonstrated for the first time the use of integrated photonics in multizone operations as a building block for scalable quantum computing \[Mordini2024\]. We developed techniques to mitigate the influence of the photonic structures on ion transport and implemented coherent operations between distant trap zones and simultaneous control of multiple ion qubits.
To conclude, we present an outlook of the possible research directions using integrated photonic traps on different ion species such as barium, currently in development at the University of Padua.

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