A Path to Scalable Quantum Computers

The demonstration that ions can be precisely manipulated in a trap containing integrated photonics paves the way for a large-scale trapped-ion quantum processor.

By **Sara Campbell**

Industrially useful quantum computers will require substantially more quantum bits (qubits) and similar or better fidelities for qubit operations, compared to present state-of-the-art systems. So far, some of the best fidelities have been realized in quantum computers whose qubits are trapped atomic ions [**1–3**]. In one such computer design, called the quantum charge-coupled device (QCCD) architecture, the ions are transported between dedicated zones where they interact and qubit operations occur [**4**]. Thanks to their high fidelities and flexible qubit connectivity, QCCD systems have achieved some of the best performances on quantum-computing benchmark tests to date [**5**]. Now Carmelo Mordini and colleagues at the Swiss Federal Institute of Technology (ETH) Zurich have presented potential building blocks for a future scalable quantum computer based on the QCCD architecture [**6**].

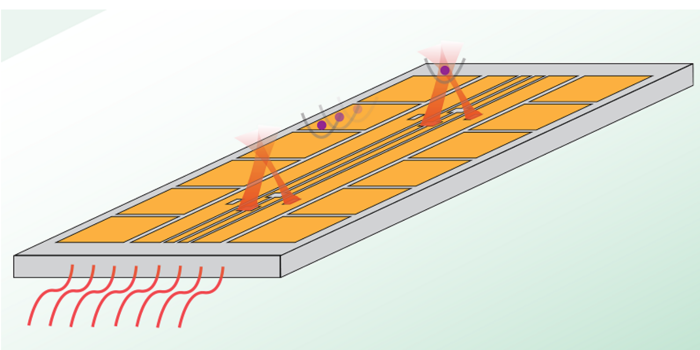

Figure 1: Mordini and colleagues present building blocks for a quantum computer whose quantum bits are trapped ions (purple) [**6**]. Individual ions are transported above surface electrodes (light orange), which are patterned on a dielectric material (light gray) and have integrated photonics underneath. Light enters the system through optical fibers (red) and is sent to two separate zones where it is launched as a pair of crossing beams (dark orange) to manipulate an ion's state.
Credit: C. Mordini *et al.* [**6**]

Atoms of the same species suspended in a vacuum are often called nature's perfect qubits because they are identical to each other and can be well isolated from the outside world. However, atomic qubits also come with a challenge: the inexorable need to use some amount of laser light to manipulate and read out their states. For a scalable QCCD architecture, a promising strategy is to use integrated photonic components in the ion-trap chip to send light to the trapped ions [**7–9**]. This approach avoids the physical limitations and engineering complexity of scaling up free-space optics and laser alignment systems. However, the strategy has been difficult to fully implement, in part because trap-integrated components can distort an ion's trapping potential, leading to problems with ion transport.

Mordini and colleagues overcame this challenge in an ion trap with surface electrodes and integrated photonics (Fig. **1**). The trap contains two zones, each with three optical waveguides leading to devices called grating couplers that shoot laser light out of the trap and focus it on ions confined just above the trap's surface. One of the three waveguides carries light for initializing and detecting the state of the ion qubits. The other two launch crossing beams that create a standing wave, driving an atomic transition that flips between the two qubit states. The grating couplers face the ions through windows in the

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electrodes, leaving the ions exposed to underlying dielectric material, through which laser light also propagates. Voltages applied to the electrodes control an axial electric potential that confines the ions along the trap's length and enables ion shuttling. Shuttling is achieved by changing these voltages over time to produce a trapping potential at multiple locations along the trap's length [**10**].

Qubit connectivity requires the ions to move during a quantum computation while maintaining a carefully controlled quantum superposition of qubit states. However, light-induced charging in the dielectric windows distorts the trapping potential, making the ions go on a rough ride. To determine how badly these bumps in the road jostle the ions during transport, the researchers first cooled an ion to near its lowest-energy motional state in the trap. They then shuttled the ion back and forth between the trap's two zones (zone 1 and zone 2) before measuring its final motional state. Without any compensation, the rough ride caused the ion to have 58 quanta of coherent excitation (back-and-forth wiggling of the ion at its natural frequency) and 25 quanta of incoherent excitation (random jiggling). Such effects would be enough to hamper high-fidelity quantum operations.

Mordini and colleagues next aimed to compensate for these effects. Changes in the frequency at which an ion oscillates in the trapping potential can cause ion heating. Therefore, for zone 1, the researchers developed a protocol for stabilizing this trap frequency along the whole ion trajectory in the presence of the stray charges from the dielectric windows. They modeled these windows as fictitious electrodes, used spectroscopy to measure the changing trap frequency along the trap's length, and then modeled window voltages that would induce such changes. Accounting for the modeled window voltages, the team generated an updated sequence of time-dependent electrode voltages for keeping the trap frequency constant during ion transport [**10**]. After a few iterations of this protocol, the applied voltages achieved the required stabilization.

Although this procedure worked well for compensating zone 1, another method was needed for zone 2, whose dielectric windows underwent more charging. For this zone, Mordini and colleagues moved the ion along the same direction as a laser beam and then measured the ion's velocity by looking at the Doppler shift in the ion's atomic resonance frequency. The researchers still modeled the windows as fictitious electrodes and used the modeled voltages to generate a revised series of applied voltages for ion shuttling. They then picked the modeled voltages that gave the ion the smoothest ride with the smallest changes in velocity. By combining the compensation methods for zones 1 and 2 as the ion was shuttled between the zones, the team reduced the ion's coherent excitation to only 8 quanta and its incoherent excitation to a negligible level.

All this transport work was a prerequisite for Mordini and colleagues to demonstrate coherent qubit operations between the trap's two zones. Using the trap-integrated beams, the researchers placed an ion in a quantum superposition in zone 1, transported it to zone 2, manipulated the qubit state in zone 2, and then sent the ion back to zone 1 for detection. In this multizone protocol, the team achieved a fidelity of more than 99% for single-qubit logic gates, showing that the effects of transporting the ion over the dielectric windows were sufficiently compensated. The researchers also demonstrated parallel, simultaneous qubit operations in the two zones.

As trapped-ion quantum computers continue to scale up in size and complexity, more devices for qubit manipulation and readout will need to be integrated into the ion-trap chips. Thus, it will be crucial to find new ways to both characterize and mitigate the impact of these devices on the ions. Mordini and colleagues' work takes a nice step forward by presenting the first quantitative description of the effects of integrated photonic elements on ion shuttling routines. The work is also the first to map out these effects and compensate for them during ion transport. A future step is to incorporate transparent conducting windows in the trap to enable light transmission while screening unwanted charging effects. A future problem to tackle is how to integrate necessary ultraviolet beams into the trap, for which charging effects have proved even more challenging.

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