A Fully Fiber-Integrated Ion Trap for Portable Optical Atomic Clocks

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We present a novel, single-ion trap with integrated optical fibers directly embedded within the trap structure to deliver laser light as well as collect the ion’s fluorescence. This eliminates the need for optical windows. We characterise the system’s performance and measure signal-to-background ratios in the ion’s fluorescence on the order of 50, which allows us to perform state readout with a fidelity over 99% in 600 µs. We test the system’s resilience to thermal variations in the range between 22°C and 53°C, and the system’s vibration resilience at 34 Hz and 300 Hz and find no effect on its performance. The combination of compactness and robustness of our fiber-coupled trap makes it well suited for applications in, as well as outside, research laboratory environments and in particular for highly compact portable optical atomic clocks. While our system is designed for trapping $^{40}\text{Ca}^+$ ions the fundamental design principles can be applied to other ion species.

I. INTRODUCTION

Trapped ions are a promising candidate for a wide range of quantum technologies. They are intrinsically reproducible systems, exhibiting long coherence and trapping lifetimes, and techniques to prepare, readout and manipulate their internal and external quantum states are highly mature. This makes them highly suitable to be used in quantum information processing [1, 2], precision spectroscopy [3] and tests of fundamental physics [4, 5] amongst others. While there has been remarkable progress in the development and miniaturisation of novel ion trapping structures and associated vacuum systems [6, 7], the optical system needed to manipulate and detect the state of the trapped ions are still mainly based on free-space optics. This leaves a compact ion trap surrounded by a large volume of optical components, which are often susceptible to drifts and vibrations, requiring regular realignment, since free-space optics can lead to beam-pointing instability and hence a deterioration of the system’s performance. While for laboratory-based research systems this can be acceptable, for the translation towards operation outside research laboratories this poses a significant barrier. In particular, the susceptibility of the beam steering and detection optics to vibrations, temperature fluctuations and drifts hinders the use of trapped ions in fieldable metrology and sensor systems.

In recent years there has been progress in integrating the fluorescence detection optics into the ion trap structure using optical fibers [8–10]. This eliminates the need for large numerical aperture lenses, which are prone to misalignment and drift and allows the easy connection of the photon detector. However, this comes with the disadvantage that the lack of spatial filtering results in a higher sensitivity to light scattered by the trap electrodes or the surrounding structures. Another approach being investigated is to use integrated superconducting single photon detectors [11] and single-photon avalanche photodiodes [12]. While these offer great collection efficiencies they are best suited to planar ion traps, as opposed to end-cap traps, and the requirement to operate at cryogenic temperatures for superconducting devices prohibits their use in highly compact and portable systems. Progress has also been made in the integration of the delivery optics, using optical waveguides embedded into the substrate of surface ion traps [13–15]. Here, diffractive couplers are used to focus the beams onto the position of the ion. This leads to mechanically robust and realignment-free system, but while the diffractive couplers produce good beam quality in the near infrared (IR) wavelength range, the beam quality in the near ultraviolet (UV) range is significantly reduced. Moreover, the overall optical transmission efficiency is quite low.

In this article we present a fiber-integrated ion trap structure, eliminating the need for external free-space optics or optical access. An end-cap style ion trap based on [10] has an optical multimode fiber integrated into one of the rf electrodes for fluorescence collection, and uses in-vacuum optical fibers and focusing optics to deliver the required laser light to the ion. In particular, the laser delivery structure facilitates the flexible alignment

![FIG. 1. Relevant energy levels for the ionisation of $^{40}\text{Ca}$ and operation of a $^{40}\text{Ca}^+$ atomic clock. In this work we cool the ion using the 397 nm transition, together with 850 nm and 854 nm repumpers. The clock transition in $^{40}\text{Ca}^+$ is at 729 nm. Wavelengths have been grouped by colors (blue, orange or red) to represent the beams that can travel through the same type of optical fiber. Solid arrows denote the wavelengths used in this work.](image)
of the individual beam polarisations and angles during assembly. The geometrical arrangement of the multimode collection fiber, its close proximity to the ion and the good beam quality provided by the delivery optics allow us to measure the ion’s fluorescence with high signal-to-background ratios even without any spatial filtering. We have characterised the system’s performance under different temperature and vibration conditions, which allows us to show that it is unperturbed by external environmental changes. The compact size, robustness and flexibility of this trap design make it well suited for applications in single ion sensing outside the research lab, such as portable optical atomic clocks.

II. $^{40}\text{Ca}^+$ ION AND REQUIRED WAVELENGTHS

Our system is designed for trapping calcium ions. $^{40}\text{Ca}^+$ is particularly well suited for applications in portable optical atomic clocks and sensors because all the wavelengths required for ionisation, cooling, repumping, quenching and spectroscopic interrogation of the clock transition are accessible through compact diode lasers. Also, all these wavelengths are compatible with fiber optic components, which is essential for the miniaturisation and ruggedisation of the setup.

The relevant energy levels of $^{40}\text{Ca}$ and $^{40}\text{Ca}^+$ are shown in Fig. 1. In order to ionise neutral $^{40}\text{Ca}$ we use a resonant transition at 423 nm and non-resonant light at 375 nm. We use the cooling transition in $^{40}\text{Ca}^+$ at 397 nm, and repumping can be done with 866 nm light or a combination of 850 nm and 854 nm light. $^{40}\text{Ca}^+$ has a clock transition at 729 nm. The 854 nm transition is also used for quenching out of the D$_{5/2}$ state during the clock interrogation readout step.

III. THE FIBER-INTEGRATED ION TRAP

The trap, schematically shown in Fig. 2, is an endcap style trap, which provides three-dimensional rf confinement. It consists of two sets of cylindrical concentric electrodes facing each other, with the trap center being in the gap between the electrode assemblies. The inner electrodes are connected to the main rf source at the back of the electrodes. The outer electrodes are grounded by connecting them to the main body of the trap through a pair of capacitors. This allows them to
be used as dc electrodes for micromotion compensation in the axial direction, while keeping them ac grounded. Two dc electrodes are utilised to supply micromotion compensation voltages in the radial plane. A resistively heated tantalum tube filled with calcium is mounted inside the copper body holding the trap, and serves as a calcium dispenser. Two pinholes collimate the calcium atomic beam to pass between the inner electrodes.

Integrating the fluorescence collection fiber in the electrode assembly removes the need for alignment, since the fiber is concentric with the rf electrodes and is therefore aligned with the expected position of the trap center. The system is therefore insensitive to small misalignments of the fiber position, making it inherently robust to mechanical vibrations and thermal drifts. The multimode fiber used for fluorescence collection (Thorlabs FG200UEA) has a core diameter of 200 µm and a cladding diameter of 220 µm. The core is made of pure silica, and the cladding is made of fluorine-doped silica. The acrylate protective coating of the fiber was stripped and its end was tapered down to a diameter of 190 µm over ~11 mm to provide a tight fit to the rf electrodes’ inner bore. The multimode fiber is retracted 90-100 µm with respect to the rf electrodes’ front surface. Based on the geometry of the system, the fraction of light captured by the fiber is ~1.2 %, limited by its numerical aperture, meaning a total possible of ~2.4 % if two fibers are used. Light collected in the multimode fiber is sent to a photo-multiplier detector (PMT) with an optical narrow band-pass filter to measure the ion’s fluorescence.

To deliver the necessary laser beams for the ionisation of \(^{40}\text{Ca}\) and for the cooling and repumping of \(^{40}\text{Ca}^+\) ions different standard optical fibers are used for different wavelength groups (refer to Fig. 1). We use a Thorlabs PM-S405-XP UV fiber to deliver the photoionisation lasers as well as the cooling beam, and a single IR fiber (Thorlabs PM780-HP) to deliver the repumper beams at 850 nm and 854 nm. This IR fiber can also be used to deliver light at 866 nm. Additionally, the system is equipped with a second UV fiber for another cooling beam, and a dedicated fiber (Thorlabs PM630-HP) for the future clock laser. The fibers are fed into the vacuum system using optical fiber feedthroughs described in [16].

Anti-reflection-coated gradient-index (GRIN) lenses with a design focal length of 10 mm are employed to focus the fiber outputs into the center of the trap. The delivery fibers sit in a ceramic ferrule just behind the GRIN lenses, with a fiber-to-lens separation of less than 100 µm. These laser delivery systems create close-to-diffraction-limited beams, with a beam waist \(\omega_0\) (1/e\(^2\) radius) of ~5.8 µm for the 397 nm beams, ~9.8 µm for the 729 nm beams and ~11.8 µm for the 866 nm beams. The high beam quality enables high signal-to-background collection of the ion’s fluorescence through the multimode fibers without any spatial filtering, since the scattering background counts due to beam or beam halos clipping on the electrodes are very low.

The beams are aligned to the geometrical center of the rf trap during assembly with a combination of a scattering screen between the inner electrodes and a pair of microscopes to observe the laser beam positions. The alignment of the delivery assemblies was done using micro-positioning stages in three dimensions. Once the alignment was optimised the lenses were glued to the main body of the trap using UHV compatible epoxy (EPOTEK H21D). In order to increase the robustness against misalignment, the beam foci were positioned such that the beam radius was ~25 µm at the expected position of the ion.

### IV. TRAP PERFORMANCE

To characterise the trap we use a vacuum chamber with an optical window. This allows us to use an sCMOS camera (Andor Zyla) to observe the ion during characterisation, but note that this is not required to operate the trap.

The system was pumped down to \(\lesssim 10^{-10}\) mbar using a getter-ion combination pump (Saes NEXTorr). After bakeout and pumping, ions were trapped within the first two days of trying, since no optical alignment was necessary. Both atomic and ionic fluorescence could be observed through the multimode fiber by using an appropriate band-pass filter in front of the PMT.

The trap is driven at a frequency of 13.7 MHz via a resonant transformer. The secular frequencies are kept between 0.6 MHz and 4.5 MHz in the axial direction and between 0.4 MHz and 2.0 MHz in the radial directions. Assuming the trap’s \(a\)-values to be negligible (\(a_{x,y,z} \approx 0\)), the \(q\)-values are within the ranges \(q_{x,y} = 0.08 \sim 0.41\) and \(q_z = 0.12 \sim 0.92\).

Excess micromotion due to external stray fields is com-

**FIG. 3.** Unsaturated cooling transition spectral profile measured at 0.14 µW. The orange solid line is a Lorentzian fit to the red-detuned data, showing a fitted linewidth close to the natural linewidth of the \(^{40}\text{Ca}^+\) cooling transition. The dashed orange line shows the count rate measured without an ion in the trap, i.e. the background scattering count rate.
pensated using a combination of the trap depth modulation method and the photon correlation method [17]. From loading to loading, the micromotion compensation voltage values only change by small amounts (≤5%) and are otherwise stable.

With micromotion compensated, we measured the cooling transition spectral profile. These measurements are performed by scanning the frequency of the 397 nm laser using an acousto-optic modulator while recording the fluorescence PMT counts at the output of the multimode fiber. Fig. 3 shows a spectrum for a cooling laser power of 0.14 µW. Fitting a Lorentzian function to the data we can extract a half width at half maximum (HWHM) of 11.1 MHz (with the natural transition HWHM being 10.8 MHz [18]). Repeating this measurement for different powers shows that the main contribution to the line broadening is power broadening, with the HWHM at zero power converging to the natural half-width. The signal to background ratio $SBR = (S-B)/B$ (where $S$ is the count rate at the peak of the transition and $B$ is the background count rate measured without an ion) will depend on the cooling laser power due to power broadening. The best values were obtained for powers under 0.2 µW, where power broadening is negligible, for a value of $SBR$ on the order of 50. For the typical cooling powers used to operate the trap the $SBR$ is on the order of 10-20.

Next we characterise the state detection fidelity in the trap by preparing the ion in either a bright or a dark state, and comparing the photon counting statistics measured with the PMT. A bright state is obtained by keeping the ion in its cooling cycle, i.e. by keeping the cooling laser on, as well as the repumpers. A dark state is obtained by switching off the repumpers, shelving the ion into the D manifold. In terms of determining the state readout fidelity this is equivalent to preparing the ion in either the $S_{1/2}$ (bright) or the $D_{5/2}$ (dark) state (replicating the shelving that will occur during clock interrogation of the 729 nm transition). The measurement sequence can be seen in Fig. 4(b). Photons arriving to the PMT are counted for a time window of length $\tau_w$ for both a dark and a bright ion. The measurements are repeated multiple times, and two histograms are obtained. An example of these can be seen in Fig. 4(a).

In order to determine the state of an ion a threshold value $n_{th}$ is defined (along the horizontal axis in Fig. 4(a)), above which the ion will be considered to be bright, and below which the ion will be considered to be dark. For the bright state, the detection fidelity is given by:

$$F_B = \frac{\sum_{n=n_{th}}^{\infty} h_B(n)}{\sum_{n=n_{th}}^{\infty} [h_B(n) + h_D(n)]}.$$  \hfill (1)

with $h_{B,D}(n)$ being the bright and dark histograms as a function of the photon number $n$. Similarly, the detection fidelity for the dark state is given by:

$$F_D = \frac{\sum_{n=0}^{n_{th}-1} h_D(n)}{\sum_{n=0}^{\infty} [h_B(n) + h_D(n)]}.$$  \hfill (2)

FIG. 4. (a) State detection measurement for a measurement window $\tau_w = 600 \mu$s. The orange (blue) histogram corresponds to an ion prepared in the dark (bright) state. The lines are Poisson fits to the data, for reference only. (b) Pulse sequence utilised for the state detection measurements. The cooling laser is always kept on, while the repumpers are switched on and off periodically to toggle the ion between the dark and bright states.

FIG. 5. Fluorescence decay rate measurement at room temperature for a cooling laser power of 1.6 µW. The orange line is an exponential fit to the data, from which a decay time constant $\tau_1$ can be extracted. Inset: pulse sequence used for the measurement of $\tau_0$. 

\[\text{Counts} vs \text{time (µs)}\]
The state detection fidelity is then calculated as the average between the two, $F = \frac{1}{2} (F_B + F_D)$.

The optimal $n_{\text{th}}$ value depends on the detection window time, the cooling and repumper laser powers and their detunings with respect to the line centers. We measured the state detection fidelity for a range of detection window times and cooling laser powers, and we can achieve state detection fidelities better than 99% for detection periods as short as 600 $\mu$s (example in Fig. 4). Note that this is directly based on the measured data, without correcting for finite state preparation fidelity, state lifetime or other detrimental effects [19], and that we haven’t made any assumptions about the statistical distribution of the measured histograms.

The stability of the fiber-integrated ion trap against temperature changes is an important factor for its use outside of research laboratory environments. In order to test the effects of changing temperatures in our trap we perform a measurement of the Rabi frequency of the cooling beam while raising the temperature of the trap. For this measurement we prepare the ion in the $S_{1/2}$ state, and then switch on the cooling beam with the repumpers off. Fluorescence will be observed until the ion is shelved onto the $D_{3/2}$ or the $D_{5/2}$ state. Over many repetitions an exponential decay of the fluorescence will be observed (see Fig. 5). The time constant $\tau_{\Omega}$ of this decay is directly related to the Rabi frequency of the cooling beam [20]. If the beam is misaligned the ion will be exposed to a different light intensity, which in turn will result in a different time constant $\tau_{\Omega}$. The inset in Fig. 6 shows the dependence of $\tau_{\Omega}$ with the cooling beam power. In order to have high alignment sensitivity to the temperature dependence, measurements were taken using powers around 0.83 $\mu$W, avoiding saturation of the cooling transition while still having an acceptable count rate on the PMT. Fig. 6 shows the measured $\tau_{\Omega}$ for a range of temperatures between 22 $^\circ$C and 53 $^\circ$C. The variation with respect to the average is consistent with changes in laser power between the different measurements, which is the main contribution to the uncertainty for these measurements. This suggests that thermal expansion and contraction has a negligible effect on beam alignment within the range of temperatures explored.

Another potential issue with changing temperatures is a change in the excess micromotion of the ion, caused by a changing geometry of the trap as it thermally expands or contracts. The micromotion compensation voltages were found to remain within $\sim 3\%$ for all tested temperatures, compatible with the variation observed between different loading runs.

Finally, we test the resilience to mechanical vibrations of the fiber-coupled ion trap. To do so, we attach two different sources of vibrations to the vacuum chamber containing the trap, and evaluate its performance. The first vibrating device generates vibrations at around 34 Hz frequencies and the second device at around 300 Hz. The sCMOS camera looking at the ion is mounted on a floated optical table, therefore being fairly well decoupled from the mechanical vibrations induced in the ion trap, which is loosely clamped to the table. From the camera images (see Fig. 7), assuming the motion of the ion trap is sinusoidal, the apparent peak acceleration can be calculated in each case. When using the first device at 34 Hz the apparent peak acceleration is around 0.05 g. For the second device running at 300 Hz the apparent peak acceleration is around 1.1 g. In either case, no significant difference is observed either in the ion’s fluorescence rate, the micromotion compensation voltages, the cooling transition spectroscopic profile or the fluorescence decay constant $\tau_{\Omega}$.

![FIG. 6. Fluorescence decay constant as a function of the trap temperature. The horizontal orange line is the averaged $\tau_{\Omega}$ between all the measurements. Inset: fluorescence decay constant as a function of laser power measured at 22 $^\circ$C. The shaded blue area denotes the power range at which the data in the main figure were taken.](image)

V. CONCLUSIONS

In conclusion, we have presented a compact, fully fiber-integrated, single-ion trap, where optical fibers inside the
vacuum chamber are used for beam delivery as well as ion’s fluorescence collection. The delivery beams are focused onto the expected position of the ion during assembly using GRIN lenses monolithically attached to the trap’s body. This makes the system robust against mechanical vibrations and thermal variations, and completely eliminates the need for beam realignment over time. The multimode collection fibers are housed directly inside the trap electrodes, allowing them to sit close to the ion, therefore granting a good solid angle capture. We have performed a basic characterisation of the ion trap, including state detection fidelity measurements, and we have subjected the system to a range of temperatures and mechanical vibration conditions, showing no deterioration of the trap performance.

We believe this is a step forward towards miniaturisation of ion traps for their use in compact and robust integrated systems for applications outside the research laboratory, and specifically for their use in portable optical atomic clocks. Finally, while we use $^{40}\text{Ca}^+$ as our ion of choice, the design principles presented here can be extended to other species by choosing fibers and lenses appropriate to the required laser wavelengths.

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