Integrated optical control and enhanced coherence of ion qubits via multi-wavelength photonics

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Monolithic integration of control technologies for atomic systems presents a promising route to the development of quantum computers and portable quantum sensors. Trapped atomic ions form the basis of high-fidelity quantum information processors and high-accuracy optical clocks, but currently rely on free-space optics for ion control, limiting portability and scalability. Here we demonstrate a surface-electrode ion trap which delivers all wavelengths required for ionization, cooling, coherent operations, and quantum-state preparation and detection of Sr$^+$ qubits using integrated waveguides and grating couplers. Laser light from the violet to the infrared is coupled onto the chip via an optical-fiber array, creating an inherently stable optical path that we use to demonstrate qubit coherence resilient to platform vibrations. This demonstration of CMOS-compatible integrated-photonic surface-trap fabrication, robust packaging, and enhanced qubit coherence represents a key advance in the development of portable trapped-ion quantum sensors and clocks, and it lights the way toward the complete, individual control of larger numbers of ions in quantum information processing systems.

INTRODUCTION

Trapped ions are natural qubits. They form the basis of a promising physical implementation for quantum information processing (QIP) due to their long coherence times, ease of control and readout, and strong ion-ion interactions, enabling high-fidelity two-qubit gates [1–4]. Recently, quantum processors based on trapped ions have been used to demonstrate relatively complex quantum algorithms in architectures with high connectivity [5, 6]: trapped ions can also be used as precise quantum sensors and as the basis for high-accuracy optical clocks [7–9]. There are nevertheless many challenges to increasing the number of trapped-ion qubits in a quantum processor while maintaining high-fidelity operations, and to developing portable trapped-ion-based quantum sensors. Chief among these are the numerous free-space optical elements used to tightly focus and direct multiple laser beams of varied wavelengths to each ion’s location. Optical beam paths defined by these elements are susceptible to vibrations and drift, causing beam pointing instability that can limit the fidelity of quantum logic operations in quantum computers and the sensitivity of quantum sensors deployed outside of the laboratory [3, 10, 11].

Photonic waveguides and grating couplers [12] integrated into microfabricated surface-electrode ion traps [13] offer a way to overcome the limitations of free-space optics for light delivery to trapped ions, greatly reducing the complexity and experimental overhead of trapped-ion systems. To date, a chip-integrated single-mode waveguide has allowed coherent operations on a trapped ion [14], and a multi-material photonics platform has been developed to allow low-loss light delivery over the wavelength range relevant to commonly-used ion species such as Ca$^+$, Sr$^+$, Ba$^+$, and Yb$^+$ [15]. However, the monolithic integration of optical components for delivery of all light required for basic ion-qubit operations (photoionization, cooling, repumping, state preparation and detection, and coherent operations) has remained an outstanding challenge.

Here, we demonstrate operation of a surface-electrode ion-trap chip where integrated photonic components deliver all required wavelengths, from the violet to the infrared, necessary to control $^{88}$Sr$^+$ qubits. Using these integrated components, we demonstrate operations including photoionization of neutral Sr, Doppler cooling of the $^{88}$Sr$^+$ ion, electronic-state repumping, coherent qubit operations, and qubit-state preparation and detection. In contrast to previous demonstrations, where the input beams were coupled to the chip from free space [14], all laser wavelengths are coupled onto the chip via optical fibers mounted in a glass fiber-array block which is precisely aligned and bonded to the chip, thus enabling a dramatic reduction in the number of free-space optics for delivery of control light to the ion. We also observe significantly reduced sensitivity of ion qubits to external vibrations when the coherent control light is delivered via fiber-coupled, on-chip waveguides rather than via free-space optics. This is because the monolithic integration of the trap and optics eliminates relative vibrations between the beam path and the ion that typically reduce the effective coherence time. The operation of this multi-wavelength photonics ion trap represents a critical step towards robust and portable trapped-ion-based clocks and quantum sensors, while demonstrating the promise of this technology for ion-array-based QIP with many more qubits.
FIG. 1. Ion-trap-integrated photonic elements and experimental set up. (a) Photonic ion-trap cross section (not to scale), showing the integrated waveguides beneath the surface-trap electrodes and light diffracting out of the chip by means of a grating coupler. (b) The external fibers are arranged in a fiber-array block which is aligned to photonic waveguides within the chip. The waveguides route the light to the chip center where vertical grating couplers diffract the light towards the ion trapped above the surface of the electrodes (the paths depicted are only notional). (c) Light is coupled to the integrated photonic trap chip via optical fibers which enter the cryogenic vacuum chamber through a fiber feed-through. (d) Energy level diagram for Sr and Sr⁺ depicting the wavelengths necessary for ion loading and control. (e) Scanning-electron micrograph (SEM) of the center of the trap showing square windows in the electrodes for the underlying grating couplers. Inset: SEM of a grating coupler during fabrication showing the curvature of the grating lines, leading to transverse beam focusing. (f) Photonic ion-trap chip packaged and mounted with strain relief. Inset shows close up of 1-cm-square chip, without full epoxy for clarity.

SURFACE-TRAP CHIP AND INTEGRATED PHOTONICS

A schematic design of our ion-trap chip with integrated photonics is shown in Fig. 1a and b. Laser light, delivered into the ultra-high-vacuum system by means of a custom fiber feed-through (Fig. 1c), is coupled into four fibers, which terminate in a fiber array that is aligned and bonded to the chip’s facet. Light is coupled from these fibers onto the chip via inverse-taper waveguide couplers, sections of waveguide that are narrowed such that the spatial mode more closely matches the optical fiber mode [16]. Each integrated-photonic waveguide then routes light under the metal trap electrodes to a grating coupler that directs the light vertically, through apertures placed in the metal electrodes, to an ion trapped above the surface of the chip.

The optical waveguides consist of a laterally defined silicon nitride (SiN) guiding layer surrounded by silicon dioxide (SiO₂) cladding; this confines the light in similar fashion to an optical fiber. Each waveguide is patterned to have a width that ensures single-mode operation at its design wavelength (ranging from a 250 nm width for a design wavelength of 405 nm, to 1.1 μm for 1092 nm). These polarization-maintaining, single-mode waveguides allow flexible routing of light to arbitrary locations below the chip surface. The SiN waveguides have propagation losses below 0.5 dB/cm for wavelengths above 633 nm, with losses increasing to ~10 dB/cm at 405 nm (for more details see ref. [15]). Near the end of each waveguide, the width is adiabatically tapered up to 18 μm in order to expand the spatial mode of the light before it reaches the grating coupler.

The diffractive grating couplers are created by etching a periodic pattern into the widened waveguide along the direction of propagation (Fig. 1a). This creates a periodic variation of the effective refractive index, causing the light to diffract out of the plane of the chip at an angle dependent on the wavelength, grating period, and effective index. For the designs in this work, the grating efficiencies are approximately 10% (see Methods). To increase the light intensity at the ion location, the grating
teeth are curved, focusing the beam to a few-micron waist in the direction parallel to the trap surface and perpendicular to the grating emission (see inset of Fig. 1e for a scanning electron micrograph (SEM) image of a grating coupler).

The linear-ion-trap electrode geometry is similar to that used previously [17]. A radiofrequency (RF) drive applied to two of the trap electrodes confines the ion radially, at a height of 55 μm above the chip surface, while DC voltages applied to the other electrodes provide axial confinement and allow one-dimensional shuttling of the ion parallel to the trap surface. Four 20 × 20 μm² apertures, displaced in the cardinal directions of the trap 55 μm from the trap’s center, are opened in the trap metal above the grating couplers. (See Fig. 1e for a SEM image of the trap electrodes.) A thin film of the transparent, conductive material indium tin oxide (ITO) is deposited over these apertures to reduce the exposed area of dielectric that could potentially become charged, particularly in the case of blue light [18], adversely affecting the electric field at the ion location.

Fabrication is detailed in Methods. After fabrication, 1 cm × 1 cm trap chips are singulated via wafer dicing. The edge of the chip, to which the inputs of the waveguides are run, is subsequently polished in order to minimize light scattering at the interface between the waveguides and the optical fibers that deliver the light. The fiber array is then aligned and attached to the chip using epoxy (see Methods).

Six wavelengths are needed for optical loading and control of $^{88}$Sr$^+$ (Fig. 1d). Ion loading is achieved by photoionization of neutral Sr from a remote, precooled source [17] and requires 461 nm and 405 nm light. Doppler cooling and detection on the $^{88}$Sr$^+$ $5S_1/2 \rightarrow 5P_{1/2}$ cycling transition requires 422 nm light, as well as 1092 nm light for repumping from the $4D_{3/2}$ state. Coherent qubit operations, quantum state preparation into a single Zeeman sublevel of the $5S_{1/2}$ ground state, and resolved sideband cooling are performed by driving $5S_{1/2} \rightarrow 4D_{5/2}$ electric quadrupole transitions via 674 nm light. In addition, light at 1033 nm is used in the cooling and state preparation processes. The chip contains four separate photonics pathways (waveguides plus grating couplers) for ion control: one for 405 nm/422 nm light, one for 461 nm light, one for 674 nm light, and one for 1033 nm/1092 nm light.

For the cases where two different wavelengths propagate in the same waveguide (405/422 nm and 1033/1092 nm), the different wavelengths result in slightly different angles of emission from the grating couplers. As the beams are only focused in the lateral direction, we find the beams are sufficiently large so that both address the ion despite the slight angular difference.
PHOTONIC ION TRAP CHARACTERIZATION AND OPERATION

We initially characterized each grating coupler by directly profiling its emitted beam with a high numerical aperture (NA) microscope objective and projecting the integrated beam onto a CMOS detector [14, 19] (see Methods for details). We used these images to generate 3D profiles of all of the beams and to determine the precise beam positions relative to the trap electrodes (Fig. 2a). These profiles show that the different integrated beams intersect each other at a height of 65 μm above the chip surface, 10 μm above the chip’s RF null, the line along which the ion is nominally trapped (Fig. 2b). This offset is consistent with a discrepancy between the index of refraction value used during grating design and that measured for the low-loss SiN used in fabrication. Because we cannot move the ion vertically to the point where all integrated beams intersect, we instead demonstrate ion-control operations using up to three integrated beams at a time, shuttling the ion horizontally via the on-chip electrodes to the location of the relevant beam(s).

For ion loading via photoionization, loading was achieved within a few seconds via the integrated 461 nm beam and a free-space 405 nm beam, and in approximately 1 minute via the integrated 405 nm beam and free-space 461 nm beam. (The longer loading time of the latter results from the broad 405 nm transition being unsaturated and from a lower integrated 405 nm beam intensity relative to that available when using the free space beam.) For the infrared beams, we demonstrated quenching of the 4D5/2 state with the integrated 1033 nm beam in less than 10 μs, and repumping from the 4D3/2 state via the integrated 1092 nm beam for Doppler cooling and detection.

We used the integrated 674 nm beam path to perform spectroscopy on the narrow qubit transition, qubit state preparation, including optical pumping and sideband cooling to \( \hat{n} < 1 \) motional quanta in the axial mode, optical-frequency-qubit Rabi oscillations, and Ramsey interferometry. With 10 mW of optical power coupled into the fiber attached to the chip, we were able to perform \( \pi \) pulses on the optical qubit in 6.5 μs. This agrees with a first-principles calculation of the Rabi frequency [20] given the measured beam dimensions, the beam power measured ex-situ, and the determined coupling losses (see Methods).

For ion detection, 422 nm photons emitted from the ion are collected using a high-NA lens and counted via a photomultiplier tube. Using the integrated 422 nm beam, and with spatial filtering of background photons scattered from the 422 nm diffraction grating itself, we achieve count rates of 8600 s\(^{-1}\) from the ion (reduced from typical collection rates due to additional spatial filtering) compared to 1600 s\(^{-1}\) due to background (which is dominated by unfiltered scattering from the grating), leading to \( S_{1/2} \) state detection with 99.7% fidelity in 3 ms. Here, the error is calculated from the overlap of Poissonian fits to the ion-fluorescence and background count histograms. While we did not shelve to the 4D5/2 state as part of this experiment, if we assume the only additional optical-qubit detection error arises from spontaneous decay from the 4D5/2 state (with lifetime of \( \sim 390 \) ms [21], and considering also decay during measurement), this would result in an average qubit detection fidelity of 99.6% for a 3 ms detection time.

In addition to using the high-NA objective to measure the beam profiles emitted from the gratings, we characterized the profiles, as well as the positions of the beams relative to the trap electrodes, in situ using the ion by measuring the strength of the laser-ion interaction as a function of ion position. The location of the ion was varied by changing the voltages applied to the DC electrodes (cf. Fig. 1c), shuttling the ion along the direction of axial symmetry of the trap (\( \hat{j} \)), in steps, through each beam (Fig. 2c–f). For the 674 nm beam (Fig. 2c), the
frequency of Rabi oscillations on the qubit transition was used to determine the beam intensity as a function of ion position. For the 422 nm and 1092 nm beams, ion fluorescence as a function of ion position was used (Fig. 2d and Fig. 2e, respectively). In these measurements, the beam intensities were kept below saturation so that the ion fluorescence rate was approximately proportional to both the 422 nm and 1092 nm intensity. The integrated 1033 nm beam, emitted from the same coupler as the 1092 nm beam, was profiled by applying a short 1033 nm pulse to partially quench the dark state population to the bright state (see Methods). The probability for the ion to have been quenched to the bright state is approximately linear in 1033 nm beam intensity at the position of the ion due to the short pulse duration (Fig. 2f).

These ion interaction profiles agree very well with the beam profiles measured using the microscope objective (see Methods), which gives us confidence that the integrated photonic components can be accurately characterized, independent of the ion, using conventional optical techniques and equipment. In addition, this implies that there are not significant effects on the integrated optics from cryogenic or ultrahigh vacuum operation.

We also used combinations of integrated beams simultaneously by positioning the ion near the intersection of two or more beams, although this effectively reduced the available laser intensity for various operations. Doppler cooling and state detection with the integrated 422 nm and 1092 nm beams were performed, enabling ion trapping for times exceeding multiple hours and measurement and 1092 nm beams were performed, enabling ion trapping for times exceeding multiple hours and measurement of the ion state without the use of any free-space beams. Fig. 3a shows a histogram of bright state ($S_{1/2}$) counts obtained with the ion simultaneously illuminated by integrated 422 nm and integrated 1092 nm beams, and dark counts from when the 1092 nm beam is blocked (causing the ion to be shelved into the dark $D_{5/2}$ state). We detect the $S_{1/2}$ state with 99.5% fidelity in 5 ms; the expected qubit detection fidelity is 99.0%. We also used the integrated 674 nm, 1033 nm, and 1092 nm beams simultaneously to perform qubit state preparation (i.e., optical pumping) and spectroscopy of the $5S_{1/2} \rightarrow 4D_{5/2}$ carrier transition and its first order motional sidebands (Fig. 3b). We note that we did not observe any noticeable effects of charging due to photo-liberated electrons from any of the integrated beams; variation in compensation voltages used to cancel stray fields (resulting in part-per-thousand trap-frequency variations over the course of a day) was comparable to traps without integrated photonics.

**Vibration Resilience**

The inherent stability of optical paths integrated into the trap chip can provide some degree of vibration tolerance of trapped ion qubits, clocks, and sensors. Effective qubit decoherence due to optical phase variation and amplitude modulation arising from vibration of the ion (Fig. 4a) should be significantly reduced, as the vibrations of the ion and the light delivery optics are common-mode due to monolithic integration with the trap (Fig. 4b). To test this hypothesis, vibrations of varying amplitude were intentionally introduced, and we measured the effect on trapped-ion qubit coherence.

We use a cryogenic vacuum system similar to those described previously [17, 22], in which the cryocooler head is normally mechanically isolated from the trap mount. By clamping the vibrating cryocooler head to the trap mount via the upper portion of the vacuum chamber, we can incrementally and dramatically increase the vibrational coupling, causing the chip and ion to oscillate in

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**Fig. 4.** Vibration insensitivity when delivering qubit-control light via monolithically integrated optics and direct fiber-to-chip coupling. (a) Vibrations introduced from the cryocooler attached to the vacuum chamber cause the ion to vibrate relative to the free space optical path. (b) Integrated photonic beams emitted from the chip will vibrate in common with the ion. (c-d) Long-exposure images of increasing vibrational coupling, collected using a high-NA lens and an electron-multiplying CCD camera. Increasing the mechanical coupling increases the amplitude of ion oscillation, and hence ion acceleration for fixed cryogenic-cooler cycle time. (e) The Ramsey-contrast decay time ($1/T_2^*$) measured via the free-space external beam path (red circles) decreases rapidly as the acceleration experienced by the vibrating ion increases. However, the coherence time measured when using delivery via the integrated beam path (blue diamonds) is unchanged.
space with a significant amplitude, as shown in Fig. 4c-d. Here images of the ion fluorescence, acquired using a high-NA lens and an electron-multiplying CCD, are observed as a function of time to determine the approximate induced vibration amplitude. Partially fixing the head to the chamber induces ~6 μm oscillations of the ion, as in Fig. 4c, and directly attaching it excites ~17 μm oscillations, as in Fig. 4d.

As a measure of qubit coherence, the decay of contrast of Ramsey interference fringes was used: first, a $\pi/2$ pulse is applied using 674 nm light to create an equal superposition in the qubit; this is followed by a variable delay time; next, another $\pi/2$ pulse of a varying phase relative to the initial pulse is applied; finally, the probability that the ion is in the lower qubit (bright) state is measured via resonance fluorescence. With the cryocooler head mechanically isolated from the trap, a 1/e contrast decay time of approximately 600 $\mu$s is measured using either the free-space 674 nm beam path or the grating-coupler-delivered 674 nm beam (see Fig. 4e, points at zero acceleration). The contrast decay in these cases is limited by a combination of magnetic-field noise and uncompensated acoustic/thermal noise in fiber optics (~30 m) used to transmit the light from the laser to the optical table housing the vacuum chamber.

Increasing the vibration coupling between the cryocooler and the trap mount as described above has a strong effect on the measured Ramsey-contrast decay when using the externally delivered (free-space) qubit-control beam. As shown in Fig. 4e (red, lower symbols), the Ramsey decay time as a function of the ion acceleration (as extracted from the ion motion) drops rapidly with increasing ion motion. In contrast, the Ramsey decay measured using the grating-coupler-delivered beam remains unchanged as a function of ion acceleration (blue, upper symbols). At this coherence level, the integrated beam path renders the ion immune to even very strong vibrations, suggesting that coherence limited by such perturbation, for instance in a fieldable sensor or clock platform, may be improved by using integrated photonics for quantum control of trapped-atomic systems.

**CONCLUSION**

Recent demonstrations of integration of ion-control technologies in potentially extensible platforms show the promise of ion arrays for scalable QIP [14, 23, 24]. In this work, we have implemented full photonic integration of all of the visible and infrared wavelengths required to ionize, cool, state-prepare, coherently control, and detect Sr$^+$ ions. This represents an important milestone toward the development of practical quantum information processors with trapped ions. Furthermore, the delivery of light directly from fibers to an ion-trap chip was shown to provide the additional benefit of vibration-resilient coherent quantum control, which may be leveraged to enable a new class of robust and portable ion-trap based clocks and quantum sensors deployable in environments beyond the laboratory.

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**AUTHOR CONTRIBUTIONS**

J.M.S. and J.C. conceived of the work. C.S.-A. and S.B. designed the integrated optical components; D.K. oversaw the fabrication of the devices. R.J.N. performed the experiments, with assistance from J.S., C.D.B., D.R., R.M., G.N.W., and W.L.; R.J.N. analyzed the data. All authors discussed the results and contributed to writing the paper.

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Fabrication of the trap chips begins with an 8-inch silicon wafer on which 1 μm of thermally grown SiO₂ is deposited. A 0.5-μm-thick sputtered niobium (Nb) metal layer is then deposited and patterned via optical lithography to form a ground plane for the ion trap [25]. Next, a 5-μm thick layer of SiO₂ is deposited via plasma-enhanced chemical vapor deposition (PECVD) to form the lower cladding of the waveguides. A 100 nm-thick layer of SiN is then deposited via PECVD, patterned via optical lithography, and fully etched to form the waveguide cores. The gratings are patterned in a subsequent optical lithography step and are then formed via a partial (40 nm deep) etch of the SiN. Another 5-μm thick layer of SiO₂ is then deposited via PECVD above the SiN to form the top cladding of the waveguides. The SiN and SiO₂ have indices of refraction of n_{SiN} = 1.89 and n_{SiO₂} = 1.5 measured at λ = 633 nm. Subsequently, a 1-μm thick Nb layer is deposited, patterned via optical lithography, and etched to define the trap electrodes and open the square apertures above the grating couplers. Finally, a 20 nm layer of indium tin oxide (ITO) is deposited and patterned over the apertures in the trap metal to mitigate the potential charging of exposed dielectrics directly below that might otherwise compromise trap stability [18].

Integrated photonic beam characterization

To profile the integrated beams outside of the ion trap vacuum system, we use a custom-built, high-NA beam profiler. This profiler consists of an infinity-corrected 0.9 NA, 60X microscope objective and a 1X tube lens, followed by a CMOS sensor based camera located at the image plane of the lens system. The lenses serve to translate the profile of the beam from the objective plane to the detection sensor (magnified by the lens system’s magnification). The high-NA system allows us to profile beams that are both rapidly diverging, due to tight foci, and travelling at large angles relative to the system’s optical axis. To profile the beams as a function of height above the trap chip, we step the height of the profiler above the surface using a stepper-driven translation stage adjusted with ~1 μm precision and measure the beam profile as a function of the vertical position (Fig. 5). Combining these beam cross sections allows the reconstruction of the full 3D beam profile, providing the beam diameter, focus height, and angle of emission.

The gratings are designed with a uniform period so that they do not focus along their direction of propagation and maintain ~11 μm 1/e² beam diameters at the ion location. However, the gratings are designed with a slight curvature to focus the beams transversely (perpendicular to the beam and parallel to the chip surface) to ~4–7 μm beam diameters.

METHODS

Trap-chip fabrication

Fabrication of the trap chips begins with an 8-inch silicon wafer on which 1 μm of thermally grown SiO₂ is deposited. A 0.5-μm-thick sputtered niobium (Nb) metal layer is then deposited and patterned via optical lithography to form a ground plane for the ion trap [25].
FIG. 5. Integrated photonic beam profiles measured from camera-recorded images. (a) High NA microscope images of the beams are taken while vertically scanning the focal plane above the chip. Laser light is emitted from the grating couplers and imaged at a height of (b) $z = 0$ and (c) $z = 25 \, \mu m$ above the ion trap electrodes.

FIG. 6. Ion interaction profile of 408 nm light, which was used as a proxy for 405 nm. An ion excited to $P_{3/2}$ has a small probability of decaying to the metastable dark $D_{5/2}$ state. Therefore the probability the ion is in the upper qubit (dark) state is proportional to the intensity of the 408 nm at the ion location. To avoid saturation, we chose an input laser power and detuning so that when the ion is in the center of the 408 nm beam, it is in the dark state $\sim 40\%$ of the time. The ion-measured profile of the 408 nm integrated beam agrees well with the ex situ image profile (Fig. 2c). The 408 nm integrated beam angle is such that the beam center is displaced to $y = 15 \, \mu m$ and has a beam diameter of $15.4 \pm 1.8 \, \mu m$ along the axial direction.

On-Chip Coupling and Total Optical Loss

To maximize optical input coupling efficiency, the edge of the chip where coupling occurs is optically polished after dicing. In addition to the waveguides that are designed to deliver light to the ion, we use a “loop-back”
waveguide to monitor coupling efficiency into the chip as we align the fiber array to the waveguide inputs. The fiber array containing six polarization-maintaining single mode optical fibers is aligned by optimizing the optical power through the loopback path, which we found to be a straightforward method to closely optimize the optical power through all four input waveguides that deliver light to the ion. The block is then attached to the chip in a two-step process, first with UV-curable epoxy and then with cryogenic-compatible epoxy to provide additional structural support.

All beams are coupled into the waveguides from fiber with polarization oriented parallel to the surface of the chip. For the 674 nm integrated optical path, we obtain a total loss of $-21.4$ dB from the input of the fiber-block to the output of the grating coupler; this includes the loss due to input coupling from the fiber to the tapered waveguide ($-10$ dB), propagation loss in the routing waveguide ($-0.38$ dB for approximately 0.75 cm), and inefficiency of the diffractive grating coupler ($-11$ dB). For the 422 nm path, we measure $-10$ dB from input coupling loss, $-3$ dB propagation loss, and $-12$ dB grating coupler loss. For 461 nm we measure $-11$ dB from input coupling loss, $-1.5$ dB propagation loss, and $-9$ dB grating coupler loss. For 1092 nm we measured $-6$ dB from input coupling loss, $-0.38$ dB propagation loss, and $-10$ dB grating coupler loss.

During cool-down from room temperature to 7 K, the optical alignment of the fiber block deteriorates, resulting in an additional loss of approximately $-10$ dB to all beam paths. This increases the total loss of the 674 nm path to $-31$ dB, the 422 nm path to $-35$ dB, the 461 nm path to $-32$ dB, and the 1092 nm path to $-34$ dB (the total loss for 1092 nm is an upper bound as light at this wavelength could not be efficiently measured through the chamber windows, and not all light could be collected on a detector).

Despite these coupling losses, we achieved light-ion interaction strengths that were comparable to those obtained when using free space beam paths with similar optical power because the cross-sectional area of the beams in the free-space case is typically over 100 times larger than that of the integrated beams. We believe that all of these loss channels can be significantly improved with new waveguide materials [26], alternative packaging techniques, and improved grating designs [19].