

Low-crosstalk silicon-fabricated optical waveguides for laser delivery to matter qubits

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Reliable control of quantum information in matter-based qubits requires precisely applied external fields, and unaccounted-for spatial crosstalk of these fields between adjacent qubits leads to loss of fidelity. We report a CMOS foundry-produced microfabricated silicon nitride (Si_3N_4) optical waveguide for addressing a chain of eight unequally spaced trapped barium ions, with crosstalk compatible with scalable quantum information processing. The crosstalk-mitigation techniques incorporated into the chip design result in a reduction of the measured optical field by at least 50.8(1.3) dB between adjacent waveguide outputs near 650 nm and similar behavior for devices designed for 493 nm and 585 nm. The waveguide outputs near 650 nm, along with a global laser near 493 nm, have been used to laser cool a chain of eight $^{138}\text{Ba}^+$ ions, and a camera has imaged the resulting fluorescence at 493 nm.

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I. INTRODUCTION

Laser-controlled matter-based quantum bits (qubits) are promising hosts of quantum information because these quantum memories (e.g., trapped ions [1–3], neutral atoms [4–6], nitrogen-vacancy centers [7,8], and quantum dots [9]) can possess long coherence times [10–12], have high-fidelity single-qubit control and two-qubit gates [13–16], and can be networked to increase their processing power

[17–20]. Scaling these qubits requires the delivery of well-focused laser light to many closely spaced sites. Utilizing visible-wavelength transitions, especially with irregularly spaced qubits, presents an optical-engineering challenge [21–23].

The use of bulk optical components in combination with waveguide systems to address qubits is often difficult to scale, as it is common to integrate a single bulk optical component with each waveguide, complicating assembly of such designs. Methods utilizing digital-micromirror devices [24] have shown considerable promise to control large two-dimensional (2D) arrays with low crosstalk, but individual output-beam control may be limited by the reliance of these systems on relatively slow mechanical motion.

Integrated diffractive optics can deliver lasers to address qubits within widely spaced trapping zones [25–28], and

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laser-written waveguides (in glass) have delivered light to multiple qubits in a single trapping zone with low crosstalk [29,30]. Foundry-compatible Si-based waveguides with high index contrast are very promising scalable platforms for both modulating and delivering light to ion qubits [23].

In this work, we detail our efforts to fabricate a silicon nitride based (Si_3N_4 -based) waveguide that splits an input laser into multiple outputs for addressing an array of ion-based qubits while minimizing the crosstalk between the output channels. The low crosstalk is achieved using bends, trenches, and output tapers to mode match to typical ion arrays confined within a single trapping zone (ion spacing of order 5–10 μm). We verify chip performance directly by measuring the crosstalk of the waveguide outputs near 493 nm, 585 nm and 650 nm. As a demonstration of the viability of the waveguides, the separate outputs have been used to perform Doppler cooling of a chain of eight $^{138}\text{Ba}^+$ ions by driving the $D_{3/2} \leftrightarrow P_{1/2}$ repumping transition (see Fig. 1). Addressing the ions in this way serves as a model

application of this photonic chip technology. This technology is extendable to individual qubit manipulations [26,31], midcircuit measurements [32,33], and quantum networking with efficient light collection [34].

II. PHOTONIC CHIP DESIGN AND FABRICATION

The requirement of interacting with closely spaced qubits drives the optimal design of our waveguide device. In particular, we have focused on ensuring that minimal quantities of stray light leak through the photonic chip between the waveguide outputs and providing good mode matching to close but unequally spaced qubits in a single trapping zone.

The reduction in stray light primarily stems from strategically placed 90° bends in the waveguides and trenches etched between the outputs, as shown in Fig. 2. The mode-matching capabilities come from tapering the waveguide outputs and patterning their spacing to reflect the

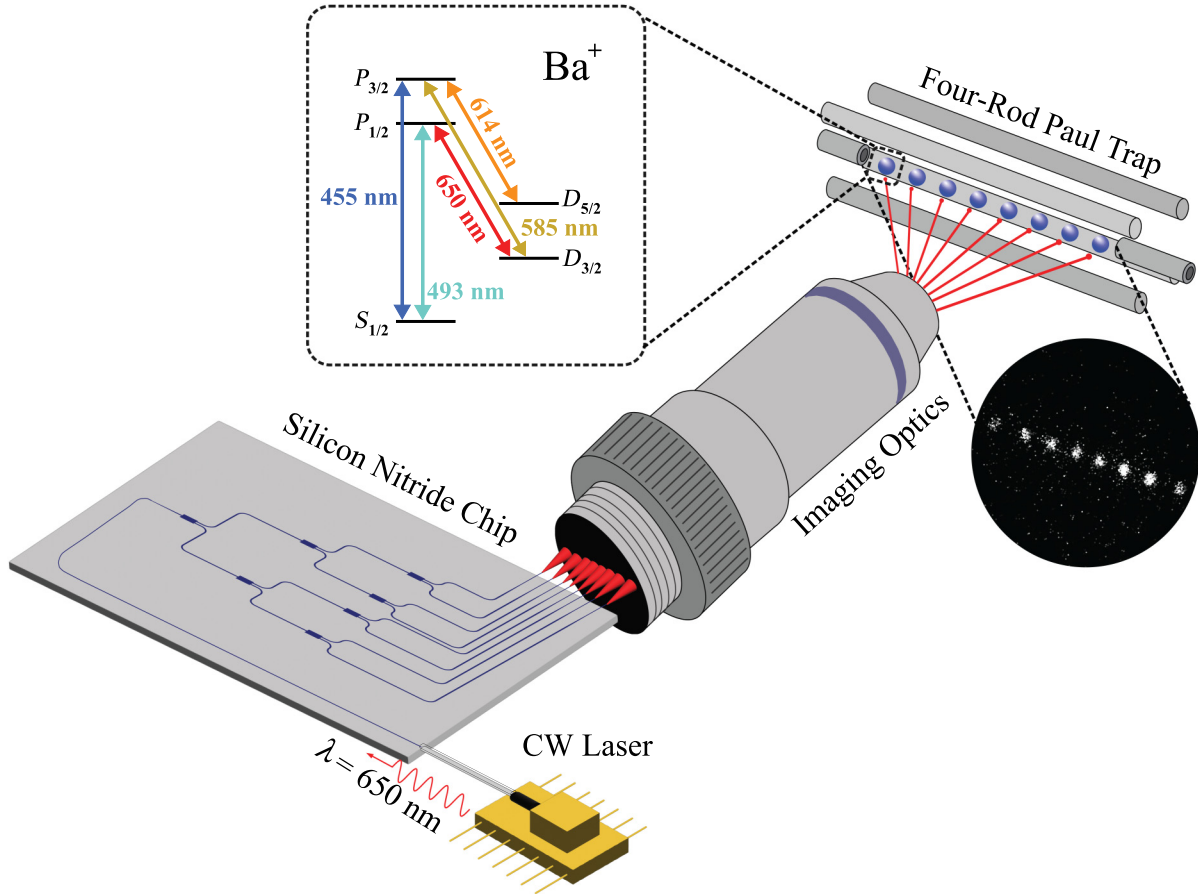


FIG. 1. An illustration of a photonic chip to deliver light to and collect light from an array of qubits. The waveguide edge couplers and lens system are selected to mode match to individual qubits in the array. This enables the low-crosstalk output light from the chip to be focused onto individual qubits as well as the efficient parallel collection of each of their optical emissions. The use of low-loss bends, trenches, and spot-size conversion in a foundry-produced high-index-contrast photonics chip results in low crosstalk between waveguide outputs. The fluorescence from a chain of trapped ions at 493 nm, shown in the inset, requires the delivery of light near the $D_{3/2} \leftrightarrow P_{1/2}$ transition (650 nm).

relative spacing between the qubits. There is a trade-off between optimizing mode-matching capabilities and limiting crosstalk, as increasing waveguide spacing reduces crosstalk but requires higher-magnification imaging optics to match the ion pitch. In addition, focusing the waveguide outputs through high-magnification optics complicates matching the output mode field diameter to the ions.

A. Foundry platform

We have fabricated the integrated photonic chips on 300-mm silicon wafers using a commercial complementary-metal-oxide-semiconductor (CMOS) foundry, from AIM Photonics [35]. Due to the 1.1-eV band gap, standard silicon waveguides absorb wavelengths below $\lambda \sim 1100$ nm, precluding their use for applications in the visible range. However, Si_3N_4 waveguides deposited on silicon wafers provide a method to extend the spectral range to the near-UV region while maintaining compatibility with standard CMOS tooling [36–39]. Our platform consists of 150-nm-thick Si_3N_4 waveguides deposited on silicon

wafers through low-pressure chemical vapor deposition (LPCVD). The chosen waveguide thickness realizes high modal confinement, enabling compact device footprints with small low-loss bends [39]. A 5- μm layer of buried oxide (BOX) isolates the waveguide mode from the silicon substrate and 5 μm of SiO_2 is deposited as the top cladding of the waveguide, as shown in the cross-section schematic in Fig. 2(b). The Si_3N_4 waveguides are patterned using 193-nm deep-UV argon fluoride (DUV ArF) excimer-laser immersion lithography and then etched [40,41].

B. Waveguide design

Finite-difference eigenmode (FDE) simulations have indicated that the optimal waveguide width for 650 nm is 500 nm, which ensures that the design is below the single-mode cutoff while maintaining a high confinement and low modal sidewall overlap. Waveguide dimensions for other wavelengths have been similarly developed. The simulated electric field profile of the fundamental transverse-electric (TE) mode for a nominal waveguide is shown in Fig. 3(a).

Due to the high modal confinement of the waveguide geometry, compact 10- μm -radius bends with simulated losses below 0.1 dB/90° bend are used to route the photonic circuits. The fundamental TE mode has a measured loss of 1.7 dB/cm through a long section of waveguide. Light has been equally distributed to the outputs using a splitter tree. Directional-coupler-based four-port splitters [42,43] have been tested along with multimode interference (MMI) Y junctions for differences in crosstalk mitigation, especially in regard to polarization stability as the TM mode was not confined in the waveguide as well as the TE mode. However, they both display a large polarization dependency in the transmission efficiency as well as the ratios between output waveguides. The designs have

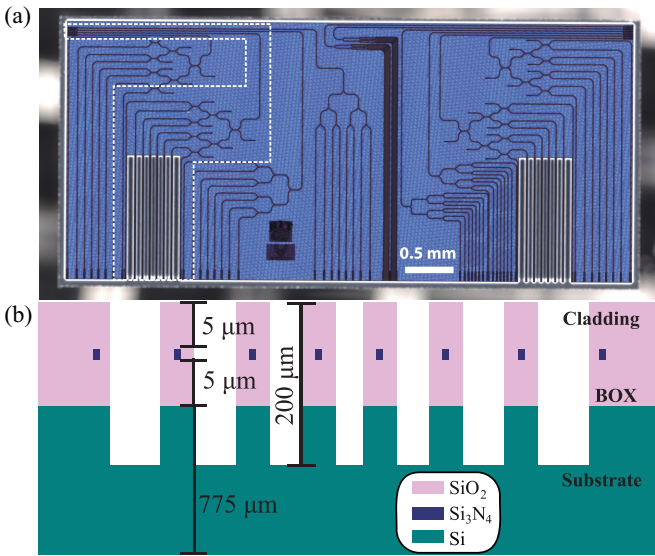


FIG. 2. The photonic chip platform design and simulation. (a) A microscope image of a photonic chip, including several device variants. The device outlined in dotted white (input on the top left) has multiple salient passive features for crosstalk mitigation, including trenches (bottom), output spot-size conversion, and waveguide output spacing. This device is the primary subject of discussion throughout the text. (b) The cross-section area of the waveguide output (not drawn to scale for clarity). The waveguide material (Si_3N_4 , dark blue) tightly confines the light. The surrounding cladding (SiO_2 , pink) surrounds the top and sides of the waveguide and is separated from the silicon substrate (Si, green) by a buried oxide layer (BOX, pink). The trenches extend fully through the cladding and BOX, and partially into the substrate, ensuring that no cladding is left to support a weakly guided slab mode.

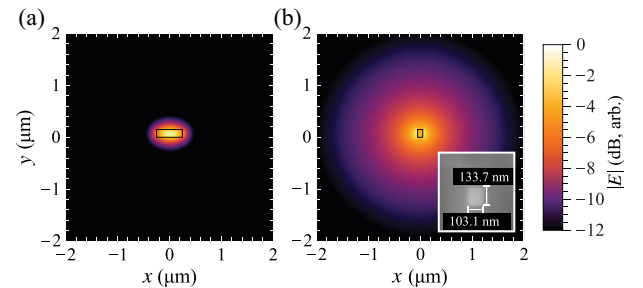


FIG. 3. (a) The simulated waveguide mode for the designed on-chip routing. The black box indicates the spatial extent of the 500 nm $\times$ 150 nm waveguide in the simulation ($\lambda = 650$ nm, TE mode). (b) The output edge coupler after the spot-size converter to taper the waveguide in (a) to a 100 nm $\times$ 150 nm waveguide, enlarging the output mode field diameter. The inset shows a scanning-electron-microscope (SEM) image of the output facet of the fabricated chip.

been simulated and optimized using the ANSYS LUMERICAL software package. The total end-to-end efficiency of the photonics chip is 31%, including fiber-coupling losses into the chip and waveguide loss through the chip. The output power variance, shown in Fig. 5, is 0.63 dB, with a maximum excursion of approximately 1.37 dB.

The fiber-chip and chip-free space interfaces use inverse tapered spot-size converters (SSCs) to expand the highly confined waveguide mode, so that focusing the mode through an objective produces diffraction-limited spots at the ion positions [44]. The 650-nm waveguide width is linearly tapered from 500 nm to 125 nm over a length of 100 μm such that the mode is adiabatically expanded without abrupt modal-mismatch interfaces. The resulting output mode simulated is shown in Fig. 3(b) with an inset scanning-electron-microscope (SEM) image of the Si_3N_4 SSC tip at the chip facet.

C. Photonic circuit architecture

Careful consideration of the chip architecture enables design choices that suppress unwanted output light, exemplified by the device characterized in this work, outlined in white dashes in Fig. 2(a). In addition to the intended in-waveguide propagation, weakly guided slab modes support transmission of undesired light through the device in the cladding. Of particular concern are areas in which light that does not couple into the waveguides is strongly concentrated, such as the input facet of the photonic chip, and at the splitter interfaces. Two sets of turns ensure that this slab mode does not contaminate the output light. First, a pair of 90° radial bends ensures that stray input light does not couple into the splitter-tree structure. Second, a 90° radial bend directs the output perpendicular to scattered light at both the input and splitter junction(s). To further extinguish slab modes, we have deep etched air trenches (extending into the substrate) between output waveguides to ensure that light in this region is not guided. Instead, the light diverges rapidly from the beginning of the trench for minimal coupling to the qubits.

This architecture allows control over the spacing of the waveguide output channels and the spot size at the output facet via SSCs. Combined with the effective refractive index of the waveguide, the spot size also sets the output numerical aperture (NA) of the chip. Meanwhile, the qubit array will have its own spacing, desired spot size, and target NA (for light collection). These parameters are not fully independent; the chip and qubit spacings are related by the imaging-system magnification, as are the corresponding spot sizes. In contrast, the NA is inversely proportional to the spot size [45]. Altogether, these form seven parameters (spot size, spacing, and NA at both the chip and the qubit, and the imaging-system magnification) and four constraining relationships, leaving three freely chosen parameters available during system design. The

qubit platform likely sets the qubit spacing but the other two may be chosen to enable experimental goals. For example, increasing the ratio of the spacing to the spot size allows for greater mode falloff with distance, potentially improving crosstalk, and choosing a large demagnification factor would scale down any errors in positioning the chip relative to the qubits. Alternatively, choosing a pair of NAs to enable efficient light collection without requiring an unwieldy imaging system may have a higher experimental priority.

For the device pictured in Fig. 2(a), the spacing between outputs correlates with the spacing between ions in an rf Paul trap [46] but scaled to 5–10 times larger than the spacing between ions in the trap. Specifically, the spacing between the outputs has been chosen such that the closest two outputs are 73.4 μm apart, to correlate with an ion spacing of approximately 10 μm . The taper size has also been chosen to produce a mode field approximately 2 μm in diameter at the output for 650-nm light. This allows for $<1\times$ magnification optics to reduce the size of the beam profile for efficient light delivery. The NA of the imaging system, 0.6, is limited by the solid angle afforded from the chamber and trap design.

III. DIRECT OPTICAL CHARACTERIZATION

To characterize the performance of the photonic chip, we have directly measured its output intensity using a microscope objective and a scanning slit in the image plane of the objective. This classical characterization technique can be used for any wavelength of laser light relevant to manipulating electronic transitions of trapped ions, and the dynamic range of this technique (5–6 orders of magnitude) is higher than typical fluorescence techniques from trapped ions [47].

This measurement technique includes residual crosstalk from the waveguide outputs and any residual stray light, such as slab modes, guided through the photonics chip. Incorporating this stray light into our crosstalk metric worsens the apparent performance from a true crosstalk-only measurement and encompasses stray light that can lead to loss of qubit fidelity. This more conservative crosstalk metric will be used throughout the paper. However, this technique does not incorporate errors from other needed components to individually address ions in a chain, such as imaging optics. In the next section, we show a qualitative proof-of-principle experiment in which ions in a chain are cooled using individual addressing from the optical chip at 650 nm.

Other methods of analyzing crosstalk with off-resonant light include those utilized in Ref. [30], which has used two methods of measuring crosstalk using a trapped ion qubit as a probe: measuring the ac Stark shift and measuring a bit-flip error induced by a Raman process. Both of these methods showcase the use of photonics chips by using

trapped ions as the probe while covering a large range of light intensity. However, these techniques are restricted to off-resonant light.

A. Characterization technique

Our measurements have utilized the configuration shown in Fig. 4. To isolate the signal from the laser from background light, a fiber acousto-optic modulator (AOM) modulates the amplitude of the input laser, and a signal analyzer connected to a high-gain photodiode measures the laser light at the modulation frequency. A 0.55-NA objective with a 200 mm tube lens forms a 50-times-magnified image. A 5- μm -width 3-mm-height slit moving along a linear positioning stage at 1- μm steps transmits a small slice of the image. The intensity of this section of light is detected by a variable-gain photodiode that travels in conjunction with the slit and from which the amplitude-modulated component is isolated using a signal analyzer. This method convolves the magnified image with the slit, so the original waveguide output profile is reconstructed using *Mathematica*'s built-in deconvolution algorithm [48] using a top-hat function as the kernel. Because slit size is much smaller than the image of the waveguide outputs and the kernel of a slit is simple, these deconvolutions accurately reflect the transversely integrated intensity profile.

Since the range of motion of the slit is limited to 10 mm, multiple scans have been combined. Furthermore, gradual fiber drifts during bench testing [49] over several hours impact splitting ratios and coupling, and taking shorter (approximately 30 min) scans allows frequent reoptimization of input couplings and equalization of the splitting

ratios, as evidenced by a maximum 1-dB peak height difference between temporally adjacent scans. To compensate for any residual output intensity drift, whether by polarization drift or decoupling, overlapping peaks have been normalized to each other during recombination. The above measurement can be limited by misalignment, scattering, and reflections from the optical imaging system.

A 2D distribution of light has been obtained by scanning a single-mode 4- μm mode field diameter optical fiber across the output face to directly couple light into the fiber, avoiding the use of optics. The deconvolution of the measured intensity distribution with the single-mode fiber kernel is complicated by unknown phase and edge-effect contributions to the transfer function of the fiber. Since the mode field diameter of the fiber is non-negligible in size in comparison to the chip output, this perturbation is expected to be significant, but is presented without deconvolution to avoid introducing large artifacts into the reported profile. In addition to providing a 2D intensity profile, the larger kernel increases the measurement dynamic range by collecting a larger portion of the output beam.

B. Characterization results

The full light distribution of the photonic chip output measured with the scanning slit is given in Fig. 5. Trenches have been etched in the regions between two waveguides, leaving the outer two with no trenches toward the outside. The impact of trenching is clearly evident, as the intensity of these outer edges falls off more slowly than the sharply decreasing intensity between the waveguides. This

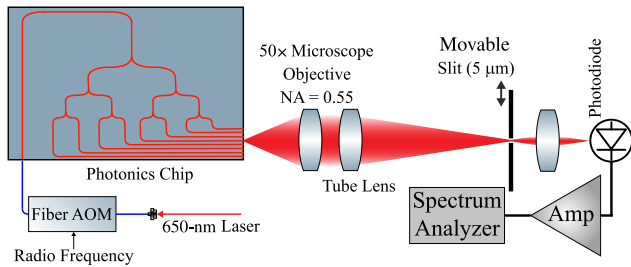


FIG. 4. The optical setup for characterizing the waveguide output and crosstalk. A fiber-coupled acousto-optic modulator (AOM) amplitude modulates a laser (tuned to 650 nm near the $D_{3/2} \leftrightarrow P_{1/2}$ transition in Ba^+ ions) at 28.1 kHz. The resultant fiber output couples directly into the photonic chip, which divides the light into eight outputs, the spacing of which matches a chain of eight trapped barium ions (up to a scale factor). The output of the chip is collimated using an NA = 0.55, 50 $\times$ objective and is imaged using a 200-mm tube lens. The light passes through a movable 5- μm -width slit attached to a high-gain photodiode. A spectrum analyzer extracts the signal component at the modulation frequency.

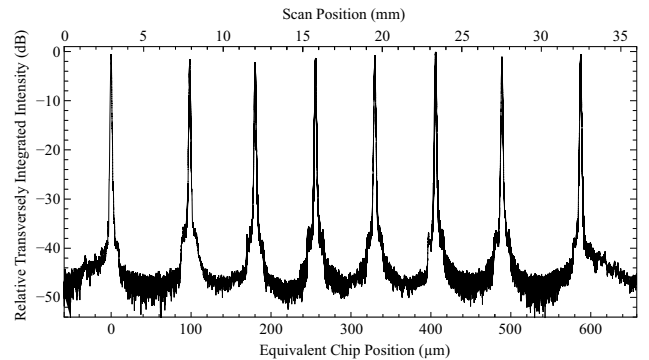


FIG. 5. The measured photonic chip output profile using the 50 $\times$ imaging system and apparatus shown in Fig. 4. The slit assembly samples the image plane at the indicated position (top axis). This corresponds to the equivalent chip position (bottom axis) inferred from comparing the output peak locations to the chip design specifications. Displayed is a composite profile across the chip, showing the relative transversely integrated intensity profile after deconvolution (see text for details). The markedly sharper falloff between waveguide channels is due to the trenches, which are not present on the outside edges.

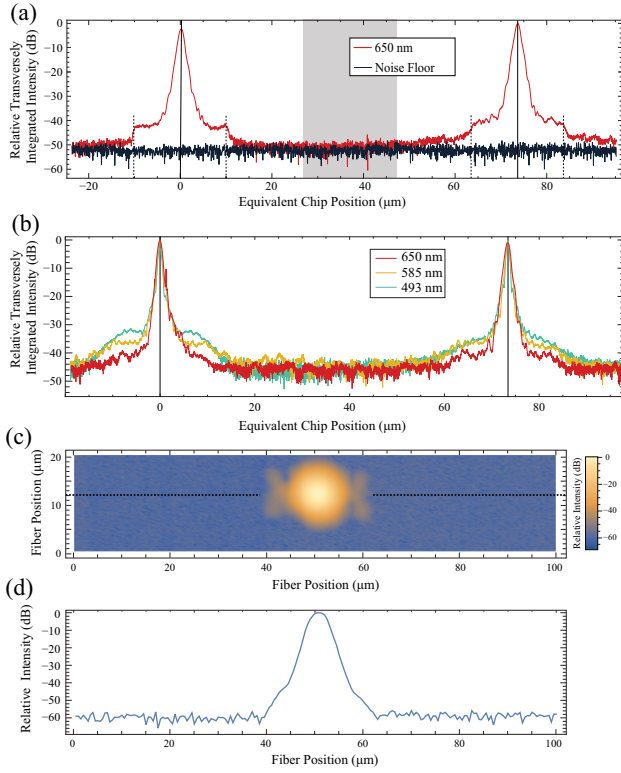


FIG. 6. Crosstalk measurements of waveguide outputs. (a) The relative transversely integrated intensity (red) across the two closest-spaced waveguides is compared to the detection-system noise floor (black), detected when the laser emission is off but all other electronics remain on. The vertical lines refer to the peak centers ($73.4\ \mu\text{m}$ apart). The measured crosstalk compares the central peak height to the mean of the points in the shaded region. The shaded region shows the extent of the cladding to scale, demonstrating that trenching produces a sharp falloff between outputs. (b) The relative transversely integrated intensity distributions for three separate devices designed for transmitting 493-, 585-, and 650-nm lasers (cyan, yellow, and red) show similar crosstalk performance. These devices do not have trenching and have a correspondingly less sharp falloff than their equivalents in (a), and do not reach the lower crosstalk values of trenching devices. (c) A direct fiber scan provides a 2D profile of a trenched waveguide output, with a cut-through at the height of the waveguide maximum, indicated by a dashed line (see Sec. III A). This isolates imaging aberration, scatter, and internal reflection effects from the intrinsic chip performance, and improves the measurement dynamic range in our system. (d) The relative intensity along the dashed line shown in c) highlights the measured crosstalk between the peak and the background, well away from the waveguide, as $-60.6(2.5)$ dB.

asymmetry provides a demonstration of the impact that trenching has on mitigating crosstalk.

Since there is no active control to directly measure the unintended power distribution at the output, the area in between peaks provides a measurable stand-in, and forms an upper bound because the waveguide mode is expected

to fall off with increasing distance. To find the most accurate measurement of crosstalk, excess scatter from light outside of the waveguide plane has been mitigated by reducing the height of the slit. The commercially available slit has been modified by painting over the top and bottom, which has reduced the height to $1.6\ \text{mm}$. This is much larger than the waveguide spot in the image plane, and the clipped light would not spatially overlap with a qubit in the envisioned use. The ratio between the peak maximum and the average of 1000 points between two peaks shown in the shaded region of Fig. 6(a) is $-50.8(1.3)$ dB. This has been extracted for the center and thus most tightly spaced waveguide pairs, which are expected to have the largest crosstalk. Similar glass-based waveguides [30,31] have demonstrated a crosstalk of -30 dB using the crosstalk metric in this paper (intermediate intensity between waveguide outputs).

A comparison of the waveguide across 493, 585, and 650 nm is shown in Fig. 6(b). Each trace shows similar crosstalk. Although the final architecture uses trenches between the waveguide outputs, the only configuration that was available and consistent for all of these wavelengths does not include trenching. We expect that the sharp cutoff that trenching provides will not depend on wavelength.

The 2D direct fiber scan in Fig. 6(c) shows a ratio of maximum intensity to the background away from the waveguide of . It is likely that the discrepancy between the crosstalk values measured from the scanning-slit method and direct coupling into a single-mode fiber is due to coupling and edge effects inherent to the fiber-scan method as discussed above.

IV. DEMONSTRATION: LASER COOLING OF TRAPPED IONS

The development of this photonic circuit was motivated by separate addressing of any ion or combination of ions within a single trapping region. A full individually addressed qubit control system would require active control of each of the splitter-tree outputs. However, the viability of the light-delivery portion of such a system is demonstrated using this fully passive device by providing repumping light to a chain of ions as part of a Doppler cooling cycle. The scattered cycling transition photons are detected by an electron-multiplying charge coupled device (EMCCD).

A. Ion-demonstration technique

The output of commercial lasers to address barium Doppler cooling transitions has been used to illuminate the ions via two separate beam paths, providing cooling along all principal trap axes. The laser wavelengths for 493 and 650 nm (607.42625 and 461.31185 THz, respectively) have been calibrated to the R(56) 32-0 iodine transition near 532 nm (563.25965 THz). One laser path

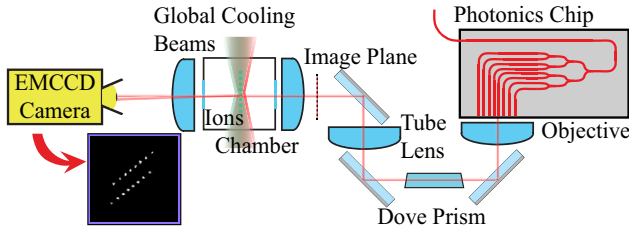


FIG. 7. A schematic of the trapped-ion and photonic chip setup. The photonic chip produces a closely and unequally spaced outputs matching an eight-ion barium chain after passing through an imaging system with net $0.19\times$ magnification. A Dove prism rotates the resultant image to align with the ion chain. The inset shows a fluorescence image at 650 nm of an eight-ion chain (lower grouping), illuminated by 493- and 650-nm global cooling beams. Simultaneously, the outputs of the decoupled photonic chip (upper grouping) are imaged on the camera at low output power. This illustrates the agreement of the waveguide spacing as fabricated and imaged to the spacing of the chain in our four-rod Paul trap. Aligning the chip output to the ions completes the laser cooling cycle, to produce the fluorescence image in Fig. 1 and described further in Sec. IV B.

has been aligned along the chain, while the other was at approximately 45° to the chain of ions. To account for the polarization dependency from the magnetic quantum numbers, an external magnetic field of a few gauss has been applied, providing magnetic field components along the parallel and perpendicular directions to the electric field polarization of the lasers.

A four-rod rf Paul trap (34-kHz axial secular frequency and 152-kHz lowest radial frequency) has been used to confine crystallized barium ions generated via a sample of BaCl_2 directly ionized by laser ablation. Light scattered from the ions is collected by a 0.6-NA (10% solid angle) lens and imaged onto an EMCCD camera.

A portion of the 650-nm laser, controlled by an AOM, has been fiber coupled into the photonic chip and fixed in place with epoxy. We have measured a combined waveguide output power of $3\ \mu\text{W}$, which has been directed to the ions using the scheme shown in Fig. 7. A net magnification $M = 0.19$ lens system projects an image of the outputs onto the trapped ions at a spacing matching the ions. The Dove prism allows for the photonic chip image to be rotated to match the tilt of the trapped ion chain. The image captured in the inset of Fig. 7 shows a simultaneous display of the ions and the purposefully offset chip light, illustrating the ability to match ion and waveguide spacing.

B. Ion-demonstration results

After crystallizing a chain of trapped ions using global 493-nm and 650-nm laser beams along with 650-nm light from the photonic integrated circuit (PIC), we have shut off the global 650-nm laser beam. If the PIC outputs are well

aligned to the chain, the ions remain crystallized as shown in Fig. 7. When translating the imaged waveguide outputs along the ion-chain axial direction, the ions encounter the low-intensity 650-nm laser regions between the waveguide outputs. This interrupts laser cooling and the ion chain heats up, resulting in a decreased fluorescence. The waveguide displacements required for this decrease were much smaller than the ion spacing, confirming that the 650-nm waveguide outputs individually address the ion chain. This demonstrates the viability of an intended application of the chip as a way to direct laser light to irregularly spaced trapped-ion targets. Although single trapped ions have been used to measure crosstalk in the -30 to -60 dB range [30], direct fluorescence imaging limits the signal-to-noise ratio [47] to much less than the light extinction measured in this work.

V. CONCLUSIONS

We have developed a CMOS-foundry-compatible low-crosstalk photonic waveguide array, where the fabrication process allows a precise irregular positioning of the laser outputs. The design has implemented stray-light reduction techniques including trenching between outputs and turning to shed weakly guided slab modes. These improvements are evident in the photonic chip measured crosstalk of using a scanning slit to evaluate low-intensity signals. This is an order of magnitude greater than the otherwise lowest crosstalk reported in the literature. A complementary 2D directly coupled fiber scan has shown a difference between the peak height and noise floor. A demonstration of one application of this device has allowed for direct cooling and crystallization of a chain of trapped Ba^+ ions in a single trapping region.

The envisioned use of this photonic chip to support quantum devices depends on integration into quantum systems while exhibiting low crosstalk between outputs. Primarily, this requires customizable photonics chip design with precise and accurate fabrication techniques to meet a wide range of applications. For example, the design presented in this paper has been fabricated as a device to interact with eight ions within a chain but the 300-mm wafer platform could also support many more outputs as well as customizable output spacings across the wafer. In addition, by providing parallel mode-matched interfaces between qubits and optical fibers, they may enable spatially multiplexed links between quantum network nodes. Overall, these characteristics make this a promising platform for interfacing with qubits.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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Correction: An equal contribution footnote was missing at publication and has been added. Values were missing from the third sentence of the abstract and the fifth sentence of the third-to-last paragraph of Sec. III and have been inserted.