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Integrated-Photonics-Based Architectures for Polarization-Gradient and EIT Cooling of Trapped Ions

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Abstract: We develop a framework for two advanced trapped-ion cooling schemes, polarization-gradient and electromagnetically-induced-transparency cooling, for $^{88}Sr^{+}$ ions using a visible-wavelength integrated-photonics platform and present the design of the key integrated devices.

1. Introduction

Systems of trapped ions are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates [1]. Most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibrations and drift can limit fidelity and addressability of ion arrays, hindering scaling to large numbers of qubits. Recent works based on integrated photonic devices offer a potential avenue to address many of these challenges [2,3].

Motional state cooling is a key optical function in trapped-ion systems. To date, integrated-photonics-based cooling demonstrations have been limited to Doppler and resolved-sideband cooling [2,3]. However, polarization-gradient (PG) and electromagnetically-induced-transparency (EIT) cooling can offer better cooling performance in multi-ion systems, where sub-Doppler temperatures in several non-degenerate modes are desirable. While free-space demonstrations of these cooling schemes have been shown [4,5], each having an advantage for differing applications, integrated versions of these systems have not yet been realized.

In this paper, we propose integrated-photonics-based system architectures and the design of key integrated photonic components for both PG and EIT cooling of trapped ions. Specifically, we design the systems for a wavelength of 422nm to target the $S_{1/2}$ to $P_{1/2}$ transition of $^{88}Sr^{+}$, a commonly used ion species for trapped-ion qubits.

2. System Architectures

We leverage a 200-mm wafer-scale visible-wavelength process developed at MIT Lincoln Laboratory to enable low-loss waveguide fabrication over a wavelength range relevant to commonly used ion species [6]. The platform consists of two bottom layers of 100-nm-thick silicon nitride (Si_3N_4) and an upper layer of 100-nm-thick alumina (Al_2O_3) separated by 90nm of silicon dioxide (SiO_2). A top metal layer is etched to create linear-ion-trap electrodes that confine ions 50 um above the trap surface via radiofrequency and DC voltages [1].

2.1 Polarization-Gradient Cooling

Trapped ions located in a suitable laser-polarization gradient can achieve sub-Doppler temperatures due to the preferential scattering of cooling photons in a spatially-varying, state-dependent energy potential [4]. Appropriate polarization gradients can be realized on-chip using different configurations of integrated grating couplers; for example, two TE gratings placed orthogonal to each other (TE-TE), a TE and TM grating placed opposite to each other (TE-TM), or two TM gratings placed opposite to each other (TM-TM) all suffice. Figures 1(e-f) show the simulated emission profiles for gratings specifically designed for TE and TM, respectively. Both gratings are designed to match intensity and focus near the ion at an angle of 45º, maximizing intensity at the ion location. In all three polarization configurations, light is routed to these gratings via two separate inverse-taper edge couplers and a combination of 650-nm-wide alumina waveguides, 300-nm-wide dual-layer silicon-nitride waveguides, and vertical transitions between layers. The final proposed architectures for PG cooling are shown in Fig. 1(b-c).

2.2 Electromagnetically Induced Transparency Cooling

EIT cooling enables near ground-state cooling over a wide frequency range by suppressing unwanted heating mechanisms otherwise incurred during laser cooling. Previous free-space demonstrations have relied on two appropriately-polarized laser sources (one circular and one linear) to create the desired laser absorption profile [5].

Fig. 1(d) depicts integrated realization of both the circular and linear sources. To generate the circularly polarized source, light is coupled on chip via an inverse-taper edge coupler to an alumina waveguide. Next, the light is split evenly into two arms using a 32.2-µm-long 1x2 alumina multimode interferometer (MMI); simulated efficiency as a

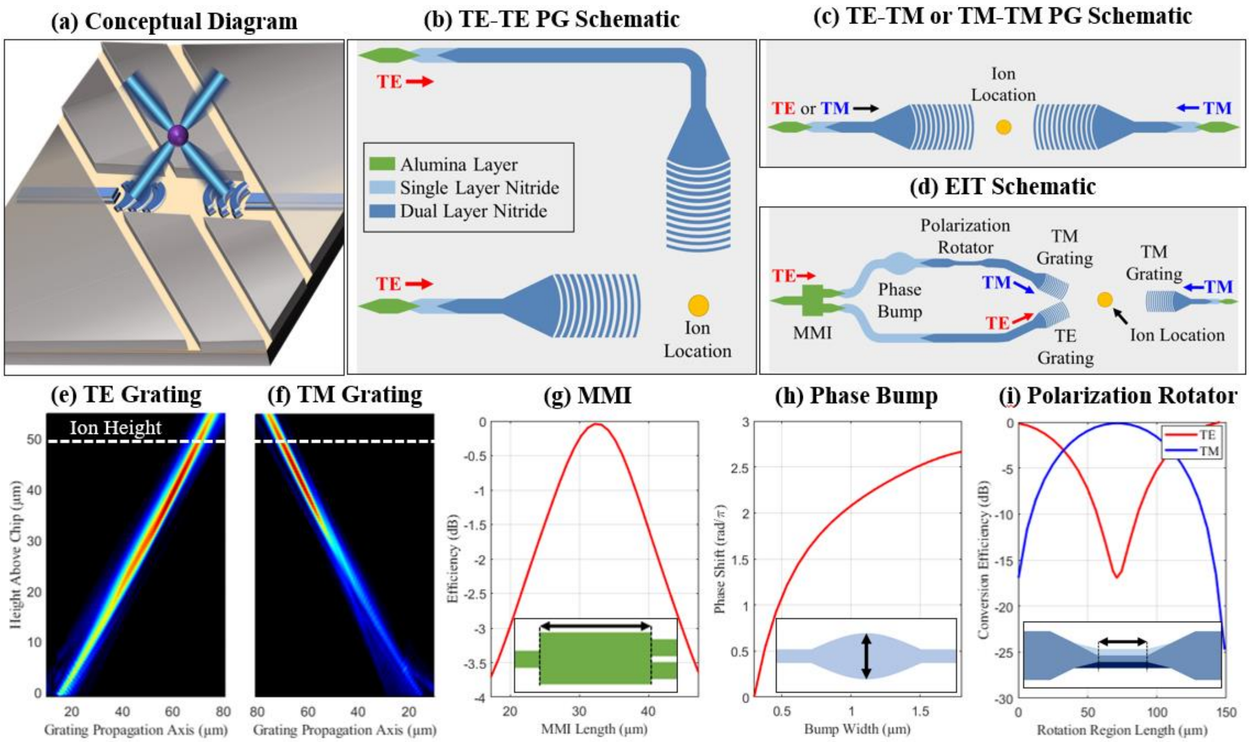

Figure 1. (a) Conceptual diagram of the integrated PG-cooling system. Simplified schematics showing the proposed integrated-photonics-based architectures for (b) TE-TE PG cooling, (c) TE-TM or TM-TM PG cooling, and (d) EIT cooling (not to scale). Simulated emission profiles for the (e) TE grating and (f) TM grating, showing focusing near the height of the ion. (g) Simulated MMI efficiency as a function of MMI length (inset shows device schematic). (h) Simulated phase delay as a function of phase bump width (inset shows device schematic). (i) Simulated conversion efficiency of the off-axis polarization rotator with TE in blue and TM in red (inset shows device schematic).

function of device length for the MMI is shown in Fig. 1(g). In the upper arm, the light is transitioned to single-layer silicon nitride. Then, the waveguide is adiabatically widened for a given length, forming a phase bump to impart a 90° phase shift; simulated phase as a function of bump width is shown in Fig. 1(h). After passing through the phase bump, the light is transitioned to dual-layer nitride. There, it goes through an off-axis polarization rotator, which rotates the incoming light from TE to TM; the conversion efficiency as a function of device length can be seen in Fig. 1(i), with a peak simulated conversion efficiency of 99.15% [7]. Finally, the TM light in the upper arm is emitted via a TM grating. In the lower arm from the MMI, the TE light is transitioned to dual-layer nitride and is emitted via a TE grating. The two gratings in each arm are angled so that the beams combine and form approximately circularly polarized light at the ion location. The linear TM input is coupled on-chip from an inverse-taper edge coupler into an alumina waveguide. Next, it is transitioned to dual-layer silicon nitride, where it emits from a focusing TM grating placed opposite to the circularly polarized source, thus enabling EIT cooling.

3. Conclusion and Acknowledgements

In this paper, we have developed a framework for two advanced trapped-ion cooling schemes, PG and EIT, using a visible-wavelength silicon-photonics platform at 422nm. We have also presented designs of key integrated-photonics components required to realize these architectures. This approach provides a scalable platform that promises more rapid cooling of multiple vibrational modes when compared to previously shown integrated approaches. Additionally, these approaches should be applicable to neutral-atom laser cooling when tailored to other wavelengths.

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4. References

[1] C.D. Bruzewicz et al., "Trapped-ion quantum computing: Progress and challenges," Appl. Phys. Rev. **6**, 021314 (2019).
[2] R. Niffenegger *et al.*, "Integrated multi-wavelength control of an ion qubit," Nature **586**, 538–542 (2020).
[3] K.K. Mehta *et al.*, "Integrated optical multi-ion quantum logic," Nature **586**, 533–537 (2020).
[4] M. Joshi *et al.*, "Polarization-gradient cooling of 1D and 2D ion Coulomb crystals," New J. Phys. **22** 103013 (2020).
[5] C. Roos "Experimental Demonstration of Ground State Laser Cooling with Electromagnetically…," Phys. Rev. Lett. **85**, 5547 (2000).
[6] C. Sorace-Agaskar *et al.*, "Versatile Silicon Nitride and Alumina Integrated…," IEEE J. Sel. Top. Quantum Electron. **25**(5), 1-15 (2019).
[7] T. Sneh *et al.*, "Design of Integrated Visible-Light Polarization Rotators and Splitters," under review.