Integrated Photonic Wavelength Division Multiplexing for Scalable Trapped Ion Quantum Computing

Darren Ho[1], Daniel Klawson[2], Ming C. Wu[2]
[1] Foothill College; [2] UC Berkeley

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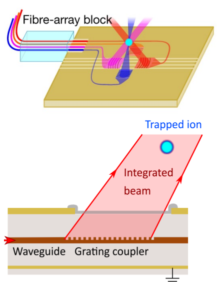
Background

Footprint Too Large – Control and measurement of trapped ions, require multiple lasers of different wavelengths. Current trapped ion quantum computing (QC) experiments typically rely on the use of free-space bulk optics, which poses major challenges for scaling towards higher-qubit architectures.

Enter Integrated Photonics – Leveraging components such as waveguides, couplers, and detectors, on the trap allows for light routing to precisely address individual ions with reduced crosstalk. A network of traps integrated with a wavelength division multiplexing (WDM) device enables multiple beams to be routed through a single waveguide, further improving the scalability and modularity of the system.

Motivation



Integrated trap set up by MIT LL

First demonstrations on the use of integrated photonics for QC utilized 4 separate grating couplers for light delivery to **$^{88}Sr^{+}$** ions [1]. The gratings are only single wavelength and can be prone to fabrication intolerance. Thus, we explore WDM to combine light on the integrated trap which allows for light delivery using shared optical components to improve QC scalability and performance.

Approach

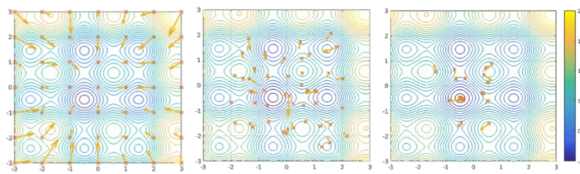
Numerical simulations solving for Maxwell's equations (FDTD) are employed on a single ring resonator model in conjunction with a PSO algorithm to extract coupling parameters. The result is paired alongside with theory to derive solutions to a system's geometry for low-loss multiplexing of 6 different wavelengths needed for qubit control and readout in **$^{133}Ba^{+}$** [2] .

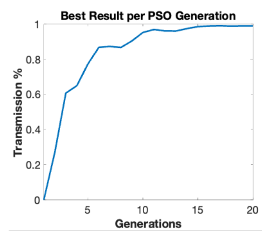
Figure Of Merit (Objective Function)

$$r^{*} = \underset{r\,\in\,[\alpha\,,\,\beta]}{\arg\max} \prod_{i=1}^{N} \left(Td_{\lambda_i} - \sum_{n\neq i}^{N} Td_{\lambda_n} \right) \qquad L = \frac{\lambda_{\text{res}}}{n_{\text{eff}}} m$$

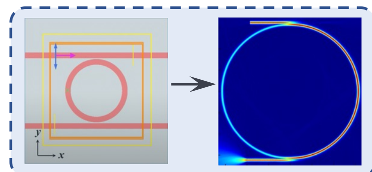
Particle Swarm Optimization Algorithm applied to single Ring Resonator

$$\begin{aligned} v_{t+1} &= w \cdot v_t + \eta_1 (p_t - x_t) + \eta_2 (g_t - x_t) \\ x_{t+1} &= x_t + v_{t+1} \end{aligned}$$





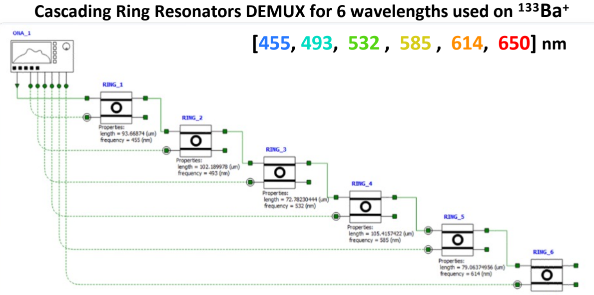
FDTD - Geometry Parameter Extraction



Converged solution simulated for 650 nm resonance

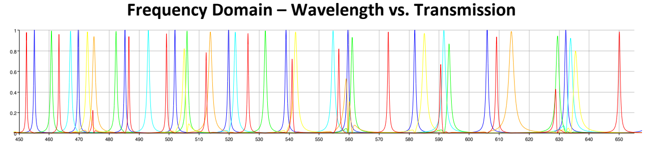
Cascading Ring Resonators DEMUX for 6 wavelengths used on $^{133}Ba^{+}$

[455, 493, 532 , 585 , 614, 650] nm



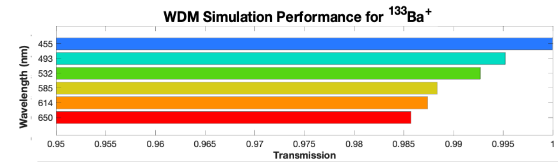
Solutions found based off Figure of Merit

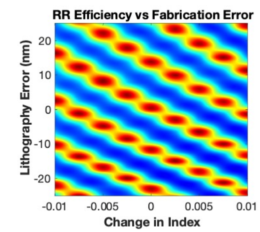
Frequency Domain – Wavelength vs. Transmission

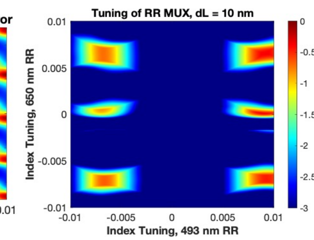


Experimental Results

Semi-analytical results yielded by our DEMUX PIC design in INTERCONNECT demonstrate all wavelengths to have over 0.985 transmission. Multi-dimensional parameter sweeps on variations in lithography and changes in effective index (from temperature or fabrication) for multi-ring (493 and 650 nm) systems show less than 3 dB loss in worst case scenarios.







Ongoing and Future Work

Initial results on low-loss performance of a ring resonator (RR) based WDM device show promise. However, a multi-ring FDTD simulation on our solutions need to be further verified. There exists concerns over RR sensitivity to process variation, which would incur additional experimental overhead such as heat tuning. As such, we look to explore AWGs as an alternative.

References

[1] *Niffenegger et al., "Integrated multi-wavelength control of an ion qubit," Nature.*
[2] *Christensen, J.E.,. et al. High-fidelity manipulation of a qubit enabled by a manufactured nucleus. npj Quantum Inf.*

Acknowledgements

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