Quantum Science and Engineering

Emitting and Absorbing a Directional Microwave Photon with Waveguide Quantum Electrodynamics

A. Almanakly, B. Yankelevich, B. Kannan, A. Di Paolo, A. Greene, B. M. Niedzielski, K. Serniak, M. E. Schwartz, J. L. Yoder, J. I.-J. Wang, T. P. Orlando, S. Gustavsson, J. A. Grover, W. D. Oliver
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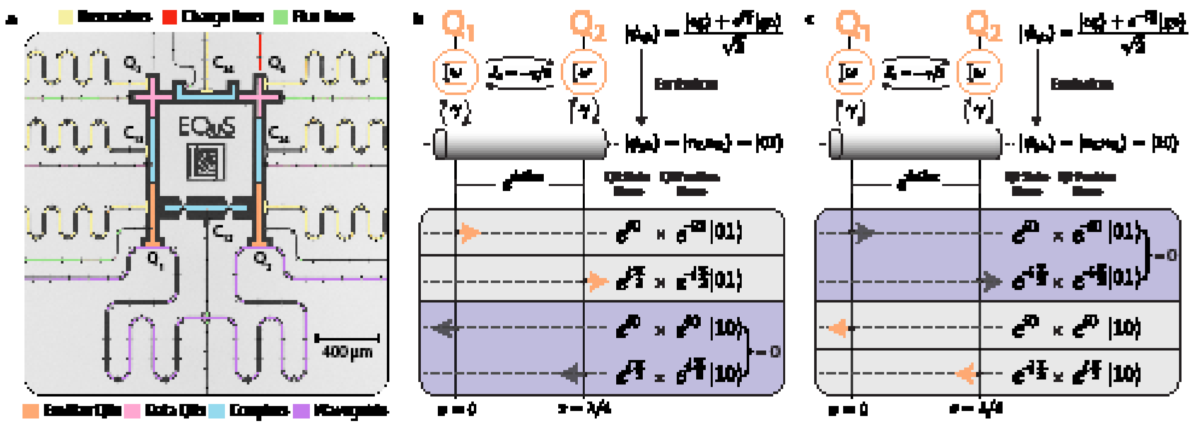
Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Propagating photons are efficient carriers of quantum information. In this work, we develop a quantum interconnect composed of an emitter, receiver, and propagation channel. We demonstrate high-fidelity directional microwave photon emission with quantum interference using an artificial molecule comprising two superconducting qubits strongly coupled to a bidirectional waveguide. By emitting time-symmetric photons from one module, we operate another identical module tiled along the waveguide as an absorber of photons, developing an interconnect capable of hosting remote entanglement for extensible quantum networks.



▲Figure 1: a) A false-colored optical micrograph of the device. b) Schematic outlining the quantum interference effect that enables the emission of a rightward-propagating photon in the waveguide. c) Same as b) but for a leftward-propagating photon.

Integrated Photonics for Advanced Cooling of Trapped-ion Quantum Systems

A. Hattori*, S. Corsetti*, T. Sneh, M. Notaros, R. Swint, P. T. Callahan, C. D. Bruzewicz, F. Knollmann, R. McConnell, J. Chiaverini, J. Notaros

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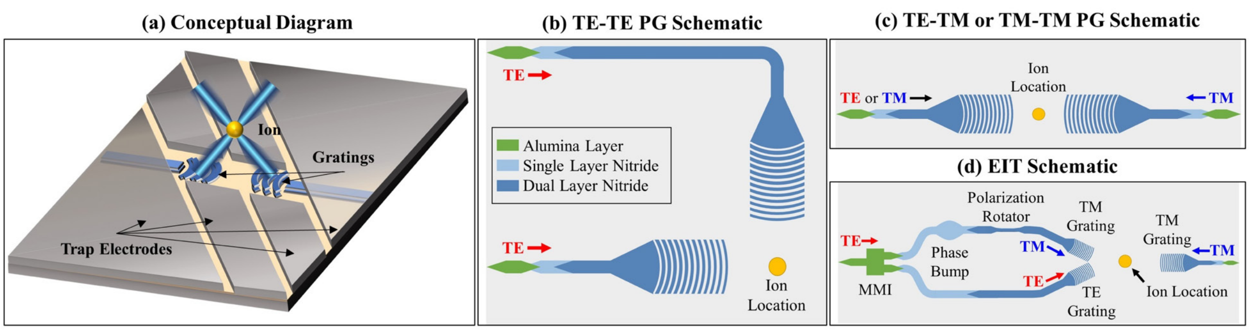
Trapped-ion systems are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates. However, most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibration and drift can limit fidelity and addressability of ion arrays, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges.

Motional state cooling is a key optical function in trapped-ion systems. However, to date, integrated-photonics-based demonstrations have been limited to Doppler and resolved-sideband cooling. In this work, we develop integrated-photonics-based system architectures and design key transverse-electric (TE) and transverse-magnetic (TM) integrated devices for two advanced cooling schemes, polarization gradient (PG) and electromagnetically-induced-transparency (EIT) (Figure 1). These systems improve cooling performance for trapped ions, enabling scalable quantum systems.



▲ 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).

FURTHER READING

- A. Hattori*, S. Corsetti*, T. Sneh, M. Notaros, R. Swint, P. T. Callahan, C. D. Bruzewicz, F. Knollmann, R. McConnell, J. Chiaverini, and J. Notaros, "Integrated-Photonics-Based Architectures for Polarization-Gradient and EIT Cooling of Trapped Ions," *Proc. Frontiers in Optics (FiO) (OSA)*, paper FM4B.3, 2022.
- T. Sneh*, A. Hattori*, M. Notaros, S. Corsetti, and J. Notaros, "Design of Integrated Visible-Light Polarization Rotators and Splitters," *Proc. Frontiers in Optics (FiO) (OSA)*, paper JTu5A.48, 2022.

Frequency Multiplexing of Cryogenic Sensors for the Ricochet Experiment

W. Van De Pontseele, J. Yang, P. Harrington, S. Weber, S. Henderson, W. D. Oliver, J. Formaggio
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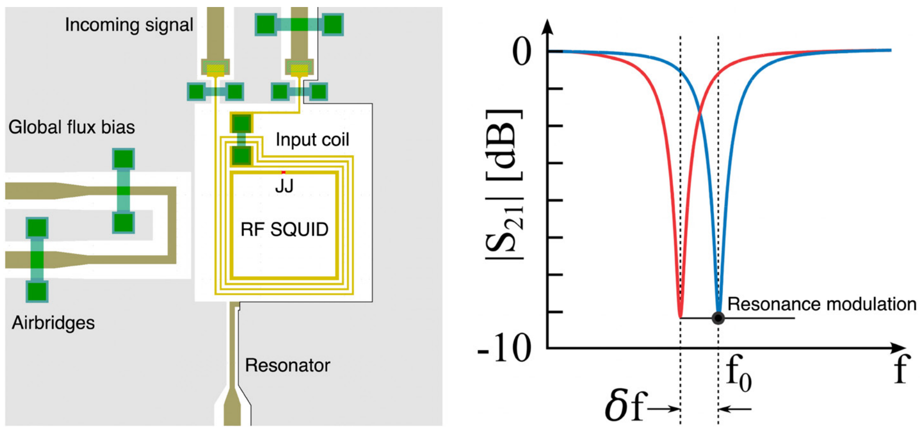
Readout of weak microwave signals over a wide bandwidth is increasingly important for fundamental science. The high frequency allows multiplexing detectors and reduces low-frequency noise for experiments such as Ricochet.

Ricochet aims to measure coherent neutrino scattering to search for new physics. It consists of superconducting crystals that function as bolometers and are read out using transition-edge sensors.

We designed and characterised devices for frequency multiplexing in 6 and 18-channel configurations with Lincoln Laboratory. The signals inductively couple into RF SQUIDS that modulate the resonant frequency of aluminium resonators. These high-Q resonators connect to a common RF feedline, reducing cabling and heat loads. The low-frequency signals are recovered using SLAC Microresonator Radio Frequency (SMuRF) electronics for read out of frequency-division-multiplexed cryogenic sensors.

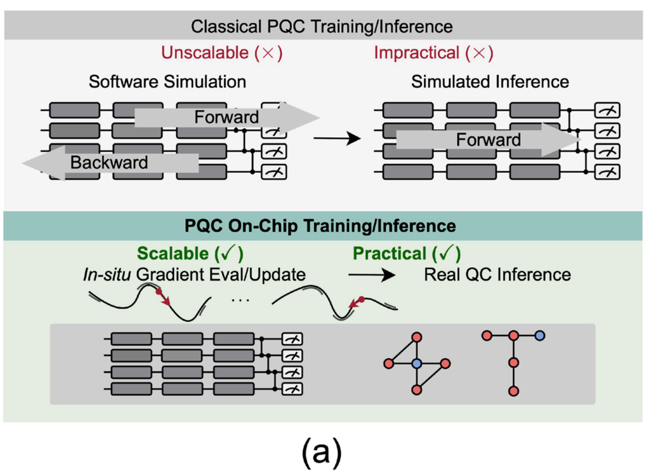


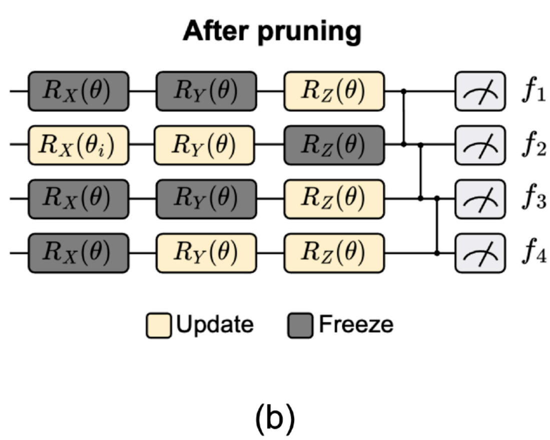
▲ Figure 1: (left) Schematic of a single RF SQUID of the 18-resonator chip. The scale of the inner SQUID loop is 60x60 micron. Fabricated at Lincoln Laboratories using Al-AlOx-Al trilayer process. (right) Effect of an incoming current on the resonant frequency.

QOC: Quantum On-chip Training with Parameter Shift and Gradient Pruning

H. Wang, Z. Li, J. Gu, Y. Ding, D. Z. Pan, S. Han
Sponsorship: MIT-IBM Watson AI Lab, NSF CAREER Award, Qualcomm Innovation Fellowship

Parameterized quantum circuits (PQC) are drawing increasing research interest thanks to their potential to achieve quantum advantages on near-term noisy intermediate scale quantum (NISQ) hardware. In order to achieve scalable PQC learning, the training process needs to be offloaded to real quantum machines instead of using exponential-cost classical simulators. One common approach to obtain PQC gradients is parameter shift, whose cost scales linearly with the number of qubits. We present QOC, the first experimental demonstration of practical on-chip PQC training with parameter shift. Nevertheless, we find that due to the significant quantum errors (noises) on real machines, gradients obtained from naive parameter shift have low fidelity and thus degrade the training accuracy. To this end, we further propose probabilistic gradient pruning to first identify gradients with potentially large errors and then remove them. Specifically, small gradients have larger relative errors than large ones, thus having a higher probability to be pruned. We perform extensive experiments with the quantum neural network (QNN) benchmarks on 5 classification tasks using 5 real quantum machines. The results demonstrate that our on-chip training achieves over 90% and 60% accuracy for 2-class and 4-class image classification tasks, respectively. The probabilistic gradient pruning brings up to 7% PQC accuracy improvements over no pruning. Overall, we successfully obtain similar on-chip training accuracy compared with noise-free simulation but have much better training scalability. The QOC code is available in the TorchQuantum library.





▲ Figure 1: (a) In QOC, PQC training and inference are both performed on real quantum machines, making the whole pipeline scalable and practical. (b) Gradients are probabilistically pruned with a ratio in the pruning window to mitigate noises and stabilize training.

FURTHER READING

- H. Wang, Z. Li, J. Gu, Y. Ding, D. Z. Pan, and S. Han, "QOC: Quantum On-chip Training with Parameter Shift and Gradient Pruning," *Proc. 59th ACM/IEEE Design Automation Conference*, pp. 655-660, 2022.
- H. Wang, J. Gu, Y. Ding, Z. Li, F. T. Chong, D. Z. Pan, and S. Han, "QuantumNAT: Quantum Noise-aware Training with Noise Injection, Quantization and Normalization," in *Proc. 59th ACM/IEEE Design Automation Conference*, pp. 1-6, Jul. 2022.
- H. Wang, Y. Ding, J. Gu, Y. Lin, D. Z. Pan, F. T. Chong, and S. Han, "QuantumNAS: Noise-adaptive Search for Robust Quantum Circuits," *2022 IEEE International Symposium on High-Performance Computer Architecture* (HPCA), pp. 692-708, 2022.