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PROGRAMMABLE QUANTUM PHOTONIC PROCESSOR USING SILICON PHOTONICS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APRIL 2017

FINAL TECHNICAL REPORT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Photons play a central role in many areas of quantum information processing and quantum sensing, ranging from linear optics quantum computing and quantum simulation to quantum communications. A central problem in many of these applications is the need to control many spatial and temporal modes with high efficiency and precision. Photonic integrated circuits can contain closely-spaced and extremely phase-stable components that enable precision control of many spatial and temporal modes in dielectric waveguides. This program developed photonic integrated circuits (PICs) based on the silicon-on-insulator platform. We developed large-scale PICs with cascaded Mach-Zehnder interferometers (MZI) with precision electro-optic modulators. These PICs have very low internal losses (<0.1 dB/MZI) and achieve exceptionally high contrast interference (> 80 dB) over tens of spatial modes. These fully programmable mode transformers have driven experimental and theoretical advances in quantum simulation, cluster-state quantum computing, all-optical quantum repeaters, neuromorphic computing, and other applications. In addition, we developed new schemes for ballistic quantum computation, new methods for high-efficiency single photon sources, a new approach for 3-photon cluster state generation that forms the essential ingredient for percolation-based generation of scalable cluster states, and quantum logic gates based on weak optical nonlinearities.

15. SUBJECT TERMS

Photonic Integrated Circuits, Mach-Zehnder Interferometers, quantum computation, quantum computing, quantum processing, cluster state quantum computing, quantum logic gates

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1. Summary

This program developed photonic integrated circuits (PICs) based on the silicon-on-insulator platform. We developed large-scale PICs with cascaded Mach-Zehnder interferometers (MZI) with precision electro-optic modulators. These PICs have very low internal losses (<0.1 dB/MZI) and achieve exceptionally high contrast interference (> 80 dB) over tens of spatial modes. These fully programmable mode transformers have driven experimental and theoretical advances in quantum simulation, cluster-state quantum computing, all-optical quantum repeaters, neuromorphic computing, and other applications. In addition, we developed new schemes for ballistic quantum computation, new methods for high-efficiency single photon sources, a new approach for 3-photon cluster state generation that forms the essential ingredient for percolation-based generation of scalable cluster states, and quantum logic gates based on weak optical nonlinearities.

2. Introduction

Photons play a central role in many areas of quantum information processing and quantum sensing, ranging from linear optics quantum computing and quantum simulation to quantum communications. A central problem in many of these applications is the need to control many spatial and temporal modes with high efficiency and precision. Photonic integrated circuits can contain closely-spaced and extremely phase-stable components that enable precision control of many spatial and temporal modes in dielectric waveguides.

3. Methods, Assumptions and Procedures

3.1 Demonstration of high-fidelity linear-optics mode transformations

Realizing scalable, high-fidelity interferometric networks is a central challenge to be addressed on the path towards linear optical quantum computation as well as for mediating optical interactions between nonlinear, matter-based qubits. We demonstrated a programmable nanophotonic processor composed of 88 ultra-high contrast Mach-Zehnder interferometers each exhibiting a record extinction ratio exceeding 80 dB, as shown in the figure below.

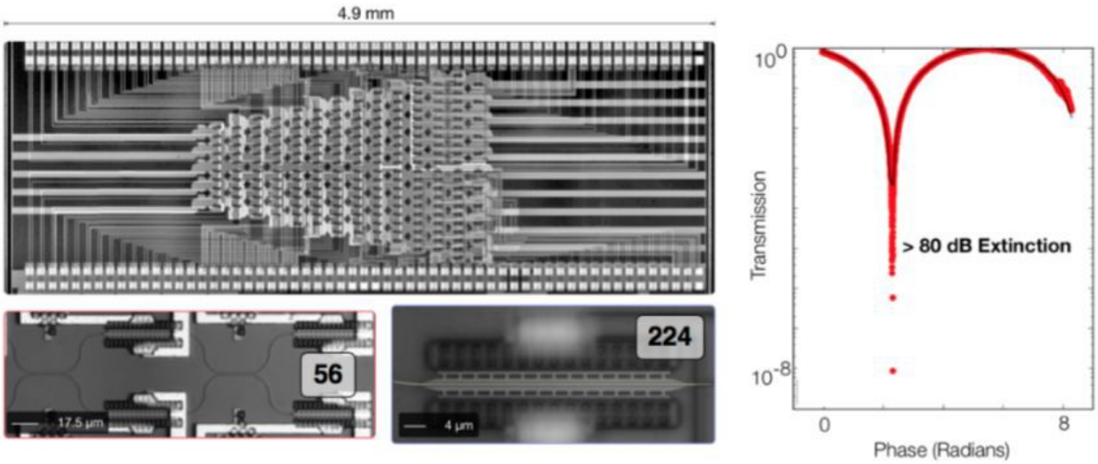

Figure 1: Photonic integrated circuit. Left: programmable PIC. Right: Transmission at one of the output modes, as one of the internal MZI's phase shifters is modulated.

3.2 Entangled pair sources

Working with collaborators, we developed a chip-integrated source of entangled photon pairs by nonlinear four-wave mixing in silicon-on-oxide ring resonators. Unlike previous demonstrations, we leveraged an advanced silicon photonics foundry process (OPSIS) to integrate spectral stabilization and filtering of the pump field by more than 95 dB on a single silicon chip using electrically tunable ring resonators and passive Bragg reflectors. By leveraging PICs that are produced in a CMOS-compatible way paves the way toward large-scale quantum photonic circuits with quantum light sources.

3.3 Near-perfect post-fabrication-tunable linear optic transformations

Through numerical simulations based on experimentally measured imperfections of fabricated circuits, we showed that it is possible to mitigate any PIC imperfections nearly perfectly (except for photon loss). Specifically, we showed that optical circuits for basic operations, such as heralded CNOT gates, are sufficiently good to reach near-perfect fidelity (>99.99%) -- they are not limited by imperfect mode overlap, but instead by imperfect detectors and photon sources.

3.4 Bosonic Quantum Walks with Fully Programmable Noise

We used the programmable PIC to simulate quantum walks with programmable dynamic and static noise. This allowed us to study the effect of environmental noise and disorder, which play a critical role in quantum particle and wave transport in complex media, including solid-state and biological systems. The PIC enabled us to fully map out the role of static and dynamic disorder in quantum transport using a low-loss, phase-stable mesh of 56 generalized beamsplitters programmable on microsecond timescales. Over 85,600 transport experiments, we observed several distinct transport regimes, including environment-enhanced transport in strong, statically disordered systems. Low loss and programmability make this nanophotonic processor a promising platform for many-boson quantum simulation experiments.

3.5 Coherent Optical Networks for Ultrafast, Ultralow Power Neuromorphic Computing

It quickly became clear that the fully programmable PIC developed in this program has many other applications outside the immediate area of quantum computing and quantum simulation. In one such spin-off application, we leveraged the PIC to demonstrate the first protocol for neuromorphic computing using optical encoding, in a collaboration with Prof. Marin Soljacic of the MIT Physics Department. The motivation for using optical rather than the typical electronic encoding is that today's computing hardware is inefficient at implementing neural networks, in large part because much of it was designed for von Neumann computing schemes. Vigorous research efforts are now seeking to develop electronic architectures tuned to implement artificial neural networks that improve upon both computational speed and energy efficiency.

3.6 All-Optical Quantum Repeaters for Long-Distance High-Speed Quantum Secure Communication

As one of the goals of this program, we analyzed how difficult it is to produce photonic cluster states of “useful size” -- i.e., sufficiently large to enable an application that can beat the state of the art. It is well known that 2D cluster states are sufficient for general-purpose quantum computation, but the size of the cluster depends on the type of application one is interested in. Instead of picking a problem of arbitrary difficulty, we instead analyzed how difficult it would be to produce a cluster state sufficiently large so that if it were maintained at repeater nodes, it would be possible to beat a repeaterless quantum communication link. This work was done in collaboration with Dr. Saikat Guha and Dr. Hari Krovi of BBN Technologies in Cambridge, MA.

3.7 Ballistic quantum computing with microclusters

The work on cluster state generation for quantum repeaters inspired us to look more closely into more efficient methods of cluster state production, and to expand the scope to cluster states that would also be universal for general-purpose one-way quantum computing. This work was also done in collaboration with Dr. Guha of BBN, and this time also with Dr. Don Towsley of the University of Massachusetts, Amherst, MA.

The interest in cluster states for general purpose quantum computing arises from the fact that any quantum algorithm can be implemented by an adaptive sequence of single node measurements on an entangled cluster of qubits in a square lattice topology. Photons are a promising candidate for encoding qubits but assembling a photonic entangled cluster with linear optical elements relies on probabilistic operations.

3.8 Review of atom-like solid-state on-demand single photon sources

Single photon sources represent an essential resource in the applications considered in this program. However, experimentally, we are still some ways from an 'ideal' on-demand single- photon emitter. A wide range of promising material systems have been developed, and several have transitioned from proof-of- concept to engineering efforts with steadily improving performance.

3.9 Proposal for on-demand single photon sources based on quantum feedback of a nonlinear dielectric cavity

As mentioned above, increased infidelity in the single photon states produced by sources sharply increases the resource overhead for quantum repeaters and ballistic quantum computing. Single photon sources based on atomic emitters have improved greatly over recent years -- for example, emission from InAs quantum dots can now achieve indistinguishability between consecutive photons in excess of 99% at an efficiency greater than 75% (Aharonovich, Englund, and Toth 2016) -- but their performance still does not reach the desired >99% or so(Pant et al. 2016). Moreover, single photon sources based on quantum emitters in solids typically have considerable inhomogenous distribution in emission. On the other hand, single photon sources based on heralded entangled pair generation can be very bright, operate at room temperature, and have excellent photon indistinguishability. Moreover, many heralded sources based on nanophotonic circuits can be tuned perfectly into resonance (Harris et al. 2014; Harris et al., n.d.). A heralded single photon source relies on the information obtained from measurements of the device to predict its quantum state. It is normally implemented using a photon pair (signal and idler) source and a single photon detector that performs measurements on, e.g. the idler Hilbert space. The success probability of single photon generation can be increased by creating photons in multiple modes and multiplexing them into a single output mode. All the degrees of freedom of photons may be used as modes and multiplexing both spatial, temporal, and frequency modes have been demonstrated. Spatial- and frequency multiplexing can produce modes in parallel from several individual sources or a frequency comb, respectively. Temporal multiplexing is a serial process where a single (a) source is triggered multiple times.

In our recent work, we considered temporal multiplexing, with the option to also use spectral multiplexing.

3.10 On-demand GHZ source based on QND and dynamic cavity control (manuscript in preparation)

As mentioned above, 3-photon GHZ states form a minimal resource for loss-tolerant production of cluster states for ballistic quantum computing. However, no efficient 3-photon GHZ state source exists today. To this end, we have extended the concept of the on-demand single photon source by cavity feedback to produce 3-photon GHZ states.

The central idea is to monitor the cavity photon population using quantum nondemolition measurements of the cavity modes, using cross-Kerr nonlinear interactions with the probe beam and homodyne detection, as shown in the figure below.

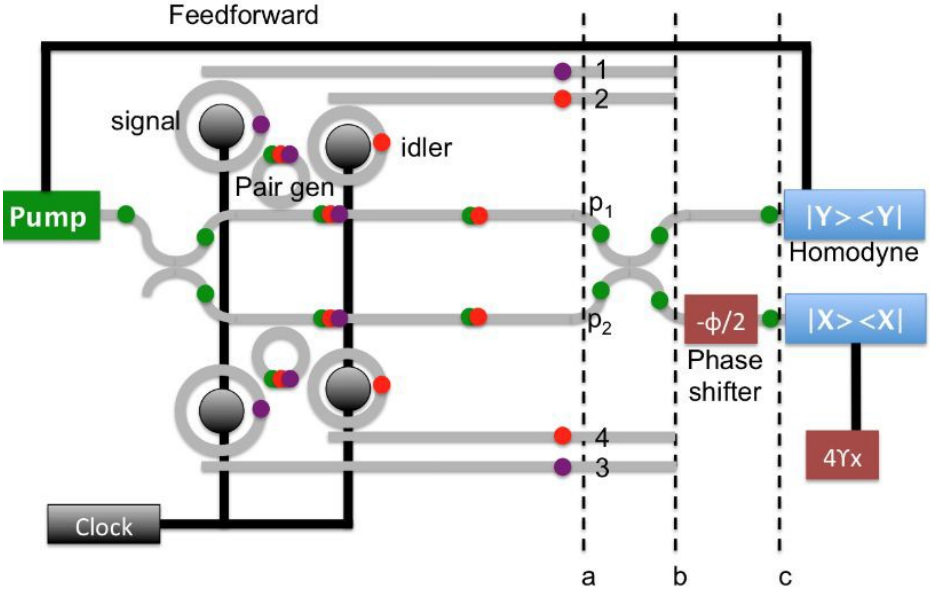

Figure 2: Proposal for on-demand GHZ state factory.

3.11 Limitations of two-level emitters as non-linearities in passive two-photon controlled phase gates

Two-level atomic systems in cavities are often cited as one possible mechanism for producing two-photon phase gates (or other two-photon logic gates). We investigated various architectures and found that it is not possible to reach unity fidelity for such gates for a time-invariant cavity.

Using a "dual Hong-Ou-Mandel" geometry shown in Fig. 3, we were able to ensure that the incoming and existing photon states are in the dual-rail logic representation.

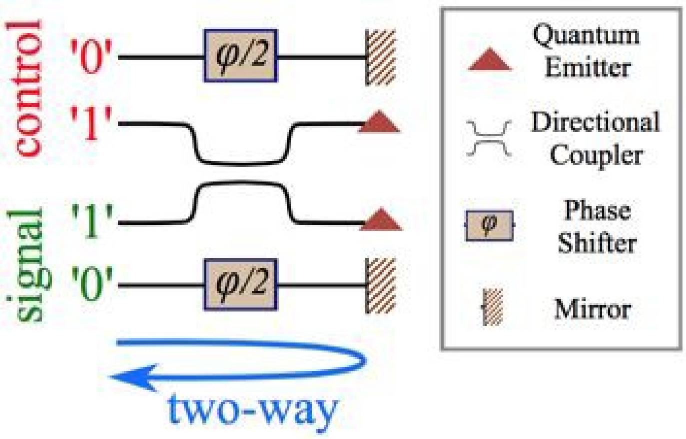

Figure 3: Schematic of two-photon phase gate.

We analyzed such gates under the action of finite-duration photon wave packets for signal and control photons.

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4. Results and Discussion

4.1 Demonstration of high-fidelity linear-optics mode transformations

We demonstrated a programmable nanophotonic processor composed of 88 ultra-high contrast Mach-Zehnder interferometers each exhibiting a record extinction ratio exceeding 80 dB. We benchmarked the performance of the processor on single-qubit rotations and showed the first experimental demonstration of a new, error-tolerant universal unitary encoding protocol by implementing 9-dimensional unitary transformations sampled from the Haar measure. We also showed how the fidelity of these transformations can be boosted using in-situ nonlinear optimization techniques. In addition, we introduce new methods for characterizing these large interferometric networks. A manuscript is in preparation with our collaborators at the Air Force Rome Laboratory.

4.2 Entangled pair sources

Working with collaborators, we developed a chip-integrated source of entangled photon pairs by nonlinear four-wave mixing in silicon-on-oxide ring resonators. Unlike previous demonstrations, we leveraged an advanced silicon photonics foundry process (OPSIS) to integrate spectral stabilization and filtering of the pump field by more than 95 dB on a single silicon chip using electrically tunable ring resonators and passive Bragg reflectors. By leveraging PICs that are produced in a CMOS-compatible way paves the way toward large-scale quantum photonic circuits with quantum light sources. For more detail, please refer to the publication (Harris et al. 2014).

4.3 Near-perfect post-fabrication-tunable linear optic transformations

Through numerical simulations based on experimentally measured imperfections of fabricated circuits, we showed that it is possible to mitigate any PIC imperfections nearly perfectly (except for photon loss). Specifically, we showed that optical circuits for basic operations, such as heralded CNOT gates, are sufficiently good to reach near-perfect fidelity (>99.99%) -- they are not limited by imperfect mode overlap, but instead by imperfect detectors and photon sources. For more detail, please refer to our publications on the subject (Harris et al., n.d.; Mower et al. 2015). See Fig. 4 for the circuit that shows record high visibility in the on-chip interferometers.

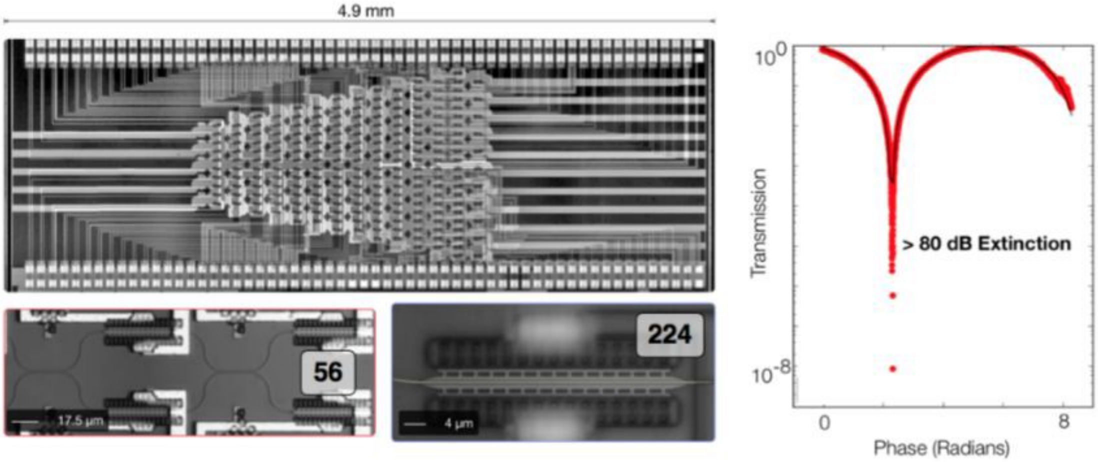

Figure 4.Photonic integrated circuit. Left: programmable PIC. Right: Transmission at one of the output modes, as one of the internal MZI's phase shifters is modulated.

4.4 Bosonic Quantum Walks with Fully Programmable Noise

Over 85,600 transport experiments, we observed several distinct transport regimes, including environment-enhanced transport in strong, statically disordered systems. Low loss and programmability make this nanophotonic processor a promising platform for many-boson quantum simulation experiments. A preliminary publication is on ArXiv (Harris et al. 2015). Using a larger PIC with 11 quantum walk steps and 26 output modes, it is now possible to observe, for the first time in a discrete-step quantum walk, environment-assisted quantum transport as theoretically predicted (Rebentrost et al. 2009).

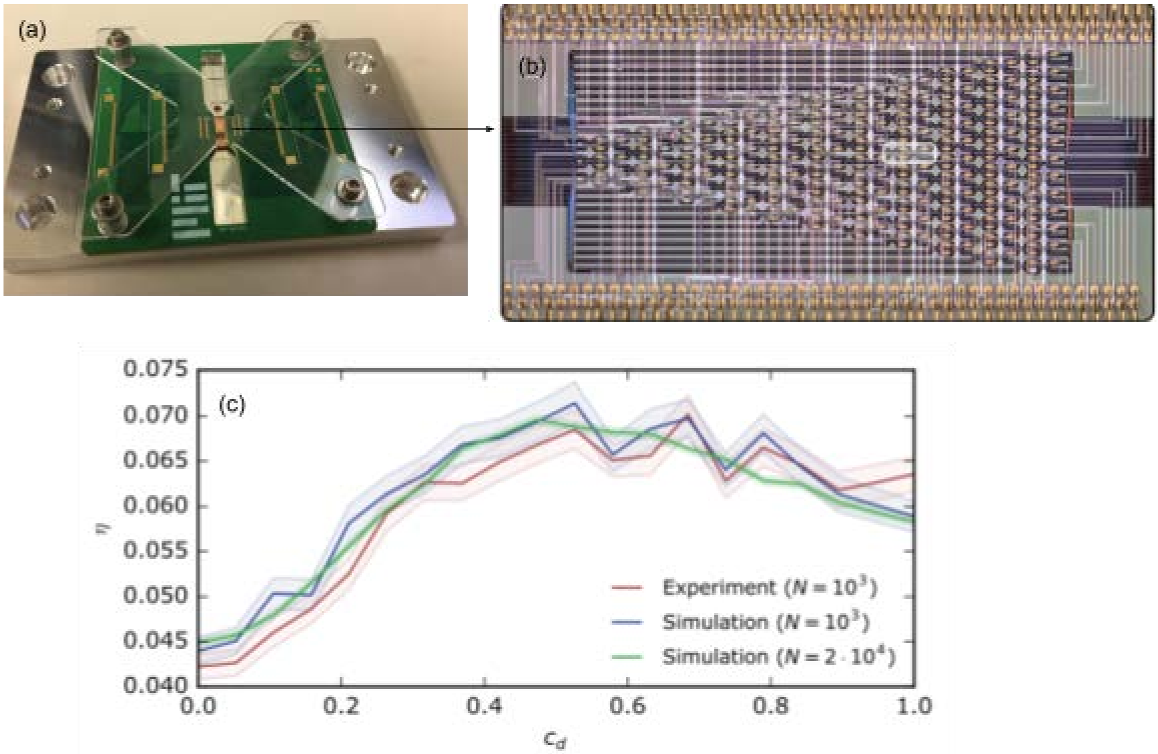

Figure 5: (a,b) Packaged programmable nanophotonic processor (c) Transport efficiency η vs dynamic noise parameter Cd.

Fig. 5 (a,b) shows this new PIC, a packaged programmable nanophotonic processor containing 176 individually tunable phase modulators and 88 in a chip area of 4.9 by 2.4 mm.. Fig.5 (c) shows the transport efficiency of photons to emerge from mode 18 when injected into mode 14, for a particular setting of static disorder. This shows that for a fixed disorder setting, there exists an optimal setting of dynamic disorder (time-dependent phase shifts) -- the “quantum Goldilocks” regime (Rebentrost et al. 2009).

4.5 Coherent Optical Networks for Ultrafast, Ultralow Power Neuromorphic Computing

Our fully-optical neural network exploits the unique advantages of optics -- including instantaneous matrix transformations and easy fan-in and fan-out. This optical approach promises a computational speed enhancement of at least two orders of magnitude over the state-of-the-art and three orders of magnitude in power efficiency for conventional learning tasks. The programmable PIC allowed us to experimentally demonstrate the essential component of this optical neuromorphic computing architecture (Shen et al. 2016). This work has engendered strong interest in such new computing architectures from established computing and data-driven companies, as well as venture capital.

4.6 All-Optical Quantum Repeaters for Long-Distance High-Speed Quantum Secure Communication

In our analysis, we developed a resource-performance tradeoff of an all-optical quantum repeater that uses photon sources, linear optics, photon detectors and classical feedforward at each repeater node, but no quantum memories. We were able to show that the quantum-secure key rate has the form $R(\eta) = D\eta s$ bits per mode, where η is the end-to-end channel's transmissivity, and the constants D and s are functions of various device inefficiencies and the resource constraint, such as the number of available photon sources at each repeater node. Even with lossy devices, we it was possible to beat repeaterless communication links.

Based on realistic assumptions of device performance of photonic routing circuits and detectors, we analyzed the resource cost to build a sufficiently large cluster state, which turned out to be of order 100 photons. We developed a suite of optimizations in the cluster state generation that allowed us to reduce the resource costs of the original all-optical repeater protocol by K. Azuma, A. Mizutani, and H.-K. Lo (Azuma, Tamaki, and Lo 2015) from $\sim 10^{11}$ to $\sim 10^{6}$ photon sources per repeater node. Please refer to our publication for more detail (Pant, Krovi, et al. 2017).

4.7 Ballistic quantum computing with microclusters

In our work, we showed that given a supply of n-photon-entangled microclusters, using a linear optical circuit and photon detectors, one can assemble a random entangled state of photons that can be subsequently "renormalized" into a logical cluster for universal quantum computing.

Remarkably, it was possible to prove that there is a fundamental tradeoff between n and the minimum success probability $\lambda(n)_c$ that each two-photon linear-optical fusion operation must have, to ensure that the resulting state can be renormalized: $\lambda(n)_c \geq 1/(n-1)$. We developed a new way of formulating this problem where $\lambda(n)_c$ is the bond percolation threshold of a logical graph and provide explicit constructions to produce a percolated cluster using n=3 photon microclusters (GHZ states) as the initial resource. We settled a heretofore open question by showing that a renormalizable cluster can be created with 3-photon microclusters over a 2D graph without feedforward, which makes the scheme extremely attractive for an integrated-photonic realization. We also provided lattice constructions, which show that $0.5 \leq \lambda(3)c \leq 0.5898$, improving on a recent result of $\lambda(3)c \leq 0.625$.

Finally, we discuss how losses affect the bounds on the threshold, using loss models inspired by a recently-proposed method to produce photonic microclusters using quantum dot or diamond nitrogen vacancy (NV) emitters. The work is now on ArXiv (Pant, Towsley, et al. 2017).

This work shows that even a relatively small number of atomic systems, such as quantum dots or NVs, could be used to produce large photonic cluster states that may be sufficient for general - purpose quantum computing. One on-going challenge that we are investigating is the use of photonic encoding schemes such as photon loss protection by parity codes.

This work has opened an entirely new research direction for us that is now inspiring us to develop improved loss-tolerant general-purpose quantum computing schemes using lossy quantum networks connecting atomic memories.

4.8 Review of atom-like solid-state on-demand single photon sources

We reviewed recent progress in the race towards the ideal single-photon emitter required for a range of quantum information processing applications. We focused on solid-state systems including quantum dots, defects in solids, two-dimensional hosts and carbon nanotubes, as these are well positioned to benefit from recent breakthroughs in nanofabrication and materials growth techniques.

The central performance metrics of single photon sources are: source purity (lack of multi-photon emissions); photon indistinguishability (every photon emitted has the same mode shape); and efficiency (product of internal quantum efficiency and collection efficiency into a desired electromagnetic mode). Our review of recent works showed major deficiencies in the reporting of these source qualities. Reporting was most rigorous for InAs/GaAs self-assembled quantum dots, which were also the most advanced technologically, indistinguishability ~ 99%, efficiency ~ 75%, and photon purity g(2)(0) < 1%.

A review article on these sources is published in Nature Photonics (Aharonovich, Englund, and Toth 2016).

4.9 Proposal for on-demand single photon sources based on quantum feedback of a nonlinear dielectric cavity

In our recent work, we considered temporal multiplexing, with the option to also use spectral multiplexing.

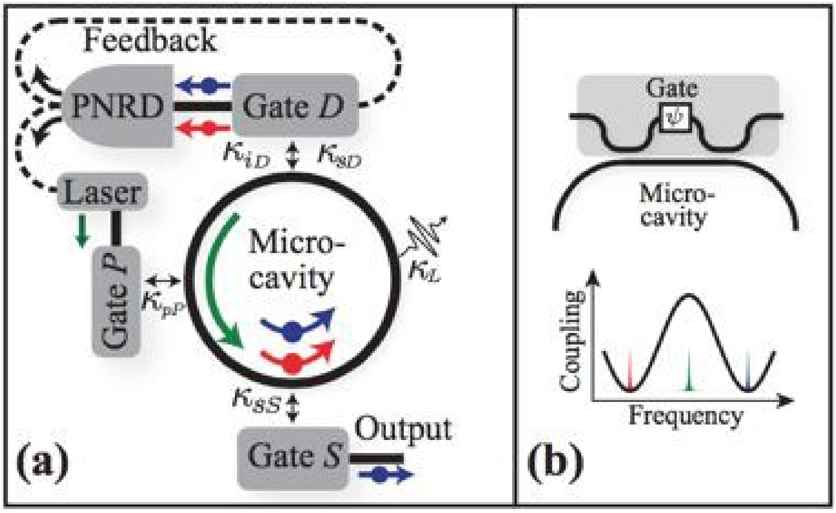

Figure 6: (a) Proposed on-demand single photon source based on dynamic cavity storage. (b) Example of a gate implementation

The proposed architecture of an on-demand single photon source based on dynamic cavity storage is shown in Fig. 6. It consists of an ultrahigh Q microcavity with a χ(3) nonlinearity that allows signal and idler photons to be generated in pairs. In Fig. 6(a), subscripts i, p, s refer to idler, pump, and signal wavelength. Solid lines are optical waveguides, while dashed lines represent electrical control signals. FP- NRD: Frequency- and photon number resolving detector. The resonator is coupled to a switchable driving laser, a frequency- and photon number resolving detector (FPNRD), and an output channel via frequency selective tunable gates that control the coupling rates to the resonator. As indicated in Fig. 6(b), an example of a gate implementation that has a large coupling for the pump frequency but is uncoupled for the signal and idler frequencies, the selective waveguide coupling of pump, signal, and idler fields is achieved by matching the arm length difference of the MZI to the free spectral range of the micro cavity.

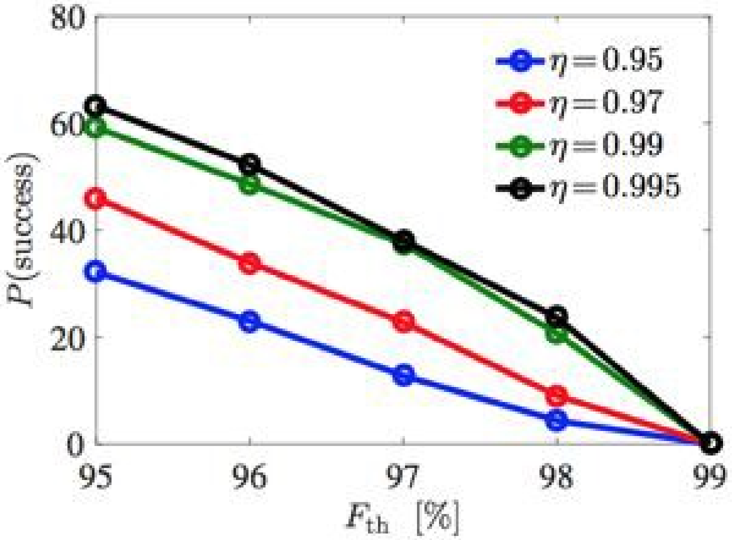

Figure 7: Fidelity vs heralding trade-off

Fig. 7 plots the single-photon fidelity F_{th} (%) against the probability of a heralding event in a given clock cycle, for a range of detector efficiencies η. This device uses temporal heralding in a single ring only. With a heralding probability of even just P(success) = 30% (corresponding to η = 0.99 and Fth = 0.98) , spectral multiplexing over 15 multiple sources increases the probability of heralding at least one event increases to $1-(1-0.3)^{15} > 99.5\%$. Thus, such a source could produce single photons of sufficient efficiency and fidelity.

4.10 On-demand GHZ source based on QND and dynamic cavity control (manuscript in preparation)

As mentioned above, 3-photon GHZ states form a minimal resource for loss-tolerant production of cluster states for ballistic quantum computing. However, no efficient 3-photon GHZ state source exists today. To this end, we have extended the concept of the on-demand single photon source by cavity feedback to produce 3-photon GHZ states. The central idea is to monitor the cavity photon population using quantum nondemolition measurements of the cavity modes, using cross-Kerr nonlinear interactions with the probe beam and homodyne detection, as shown in the figure below.

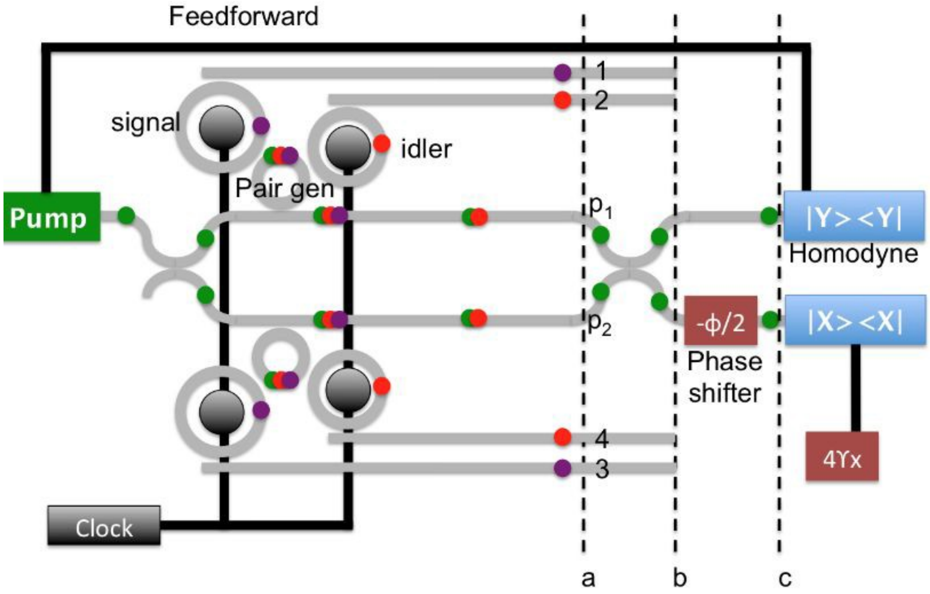

Figure 8: Proposal for on-demand GHZ state factory.

4.11 Limitations of two-level emitters as non-linearities in passive two-photon controlled phase gates

We investigated various architectures and found that it is not possible to reach unity fidelity for such gates for a time-invariant cavity.

We analyzed such gates under the action of finite-duration photon wave packets for signal and control photons. The two-photon gate fidelity is plotted in Figure 9, where v_g is the group velocity in the waveguides (for signal and control photons) and Γ the emitter decay rate into waveguide modes. This work is on ArXiv (Nysteen et al. 2016) and under review.

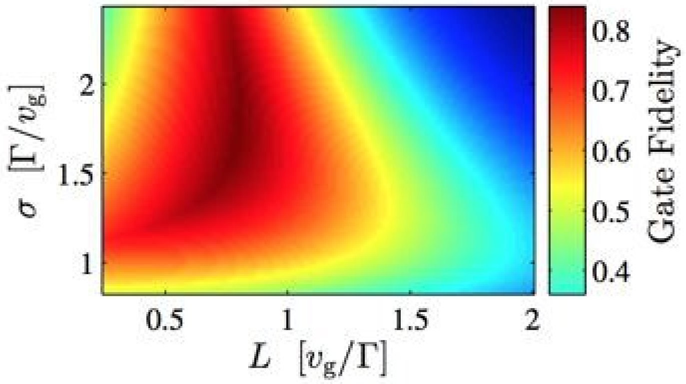

Figure 9: Gate fidelity simulation results.

We plan to expand this analysis to time-dependent waveguide-cavity coupling, which promises to actually allow near-unity gate fidelity.

5. Conclusions and Outlook

This program developed fully programmable photonic integrated circuits that are proving extremely useful for quantum information processing, including the largest programmable quantum walks that now show environment-assisted quantum transport(Harris et al. 2015), as well as for several unexpected applications such as ultrafast neuromorphic computing(Shen et al. 2016), optimal quantum receivers (Guha 2011), beam steering, and adaptive optics.

The program also contributed to the development of theoretical protocols that greatly lowered the resource requirements of linear optics quantum computing (Pant, Towsley, et al. 2017) and all-optical quantum repeaters (Pant, Krovi, et al. 2017). Such systems-level resource analysis identified key components that must be developed for practical implementations. To this end, this program contributed to new schemes for entangled photon sources (Harris et al. 2014) and multi-qubit photonic logic gates (Nysteen et al. 2016; Lahini et al. 2015).

This program contributed to the training of four PhD students and five undergraduate students who are pursuing careers in quantum information technologies.

6. References

Aharonovich, Igor, Dirk Englund, and Milos Toth. 2016. “Solid-State Single-Photon Emitters.” *Nature Photonics* 10 (10). Nature Research: 631–41.

Azuma, Koji, Kiyoshi Tamaki, and Hoi-Kwong Lo. 2015. “All-Photonic Quantum Repeaters.” *Nature Communications* 6 (April): 6787.

Guha, Saikat. 2011. “Structured Optical Receivers to Attain Superadditive Capacity and the Holevo Limit.” *Physical Review Letters* 106 (24): 240502.

Harris, Nicholas C., Darius Bunandar, Mihir Pant, Greg R. Steinbrecher, Jacob Mower, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, and Dirk Englund. n.d. “Large-Scale Quantum Photonic Circuits in Silicon.” *Nanophotonics* 5 (3). doi:10.1515/nanoph-2015-0146.

Harris, Nicholas C., Davide Grassani, Angelica Simbula, Mihir Pant, Matteo Galli, Tom Baehr-Jones, Michael Hochberg, Dirk Englund, Daniele Bajoni, and Christophe Galland. 2014. “Integrated Source of Spectrally Filtered Correlated Photons for Large-Scale Quantum Photonic Systems.” *Physical Review X* 4 (4). American Physical Society: 041047.

Harris, Nicholas C., Gregory R. Steinbrecher, Jacob Mower, Yoav Lahini, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, Seth Lloyd, and Dirk Englund. 2015. “Bosonic Transport Simulations in a Large-Scale Programmable Nanophotonic Processor.” *arXiv Preprint arXiv:1507. 03406*.

Lahini, Yoav, Gregory R. Steinbrecher, Adam D. Bookatz, and Dirk Englund. 2015. “High-Fidelity Quantum Logic Gates with Interacting Bosons on a 1D Lattice.” *arXiv Preprint arXiv:1501. 04349*.

Mower, Jacob, Nicholas C. Harris, Gregory R. Steinbrecher, Yoav Lahini, and Dirk Englund. 2015. “High-Fidelity Quantum State Evolution in Imperfect Photonic Integrated Circuits.” *Physical Review. A* 92 (3). APS: 032322.

Nysteen, Anders, Dara P. S. McCutcheon, Mikkel Heuck, Jesper Mørk, and Dirk R. Englund. 2016. “Limitations of Two-Level Emitters as Non-Linearities in Two-Photon Controlled Phase Gates.” *arXiv [quant-Ph]*. arXiv. http://arxiv.org/abs/1612.04803.

Pant, Mihir, Hari Krovi, Dirk Englund, and Saikat Guha. 2016. “Rate-Distance Tradeoff and Resource Costs for All-Optical Quantum Repeaters.” *arXiv [quant-Ph]*. arXiv. http://arxiv.org/abs/1603.01353.

———. 2017. “Rate-Distance Tradeoff and Resource Costs for All-Optical Quantum Repeaters.” *Physical Review. A* 95 (1). American Physical Society: 012304.

Pant, Mihir, Don Towsley, Dirk Englund, and Saikat Guha. 2017. “Percolation Thresholds for Photonic Quantum Computing.” *arXiv [quant-Ph]* http://arxiv.org/abs/1701.03775.

Shen, Yichen, Nicholas C. Harris, Scott Skirlo, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, Xin Sun, et al. 2016. “Deep Learning with Coherent Nanophotonic Circuits.” *arXiv [physics.optics]*. arXiv. http://arxiv.org/abs/1610.02365.

Appendix A - Program Journal Publications

- Nicholas C. Harris, Davide Grassani, Angelica Simbula, Mihir Pant, Matteo Galli, Tom Baehr-Jones, Michael Hochberg, Dirk Englund, Daniele Bajoni, Christophe Galland, "Integrated Source of Spectrally Filtered Correlated Photons for Large-Scale Quantum Photonic Systems," Phys. Rev. X (2014)
- Nicholas C. Harris, Darius Bunandar, Mihir Pant, Greg R. Steinbrecher, Jacob Mower, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, Dirk Englund,, "Large-scale quantum photonic circuits in silicon," Nanophotonics 42493 (2016)
- Nicholas C. Harris, Gregory R. Steinbrecher, Jacob Mower, Yoav Lahini, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, Seth Lloyd, Dirk Englund, "Bosonic transport simulations in a large-scale programmable nanophotonic processor," arXiv:1507.03406 (2015)
- Mihir Pant, Hari Krovi, Dirk Englund, Saikat Guha, "Rate-distance tradeoff and resource costs for all-optical quantum repeaters," Physical Review A 95, No.1 (2017) [PRA EDITORS' SUGGESTION]
- Yichen Shen, Nicholas C. Harris, Scott Skirlo, Mihika Prabhu, Tom Baehr-Jones, Michael Hochberg, Xin Sun, Shijie Zhao, Hugo Larochelle, Dirk Englund, and Marin Soliacic, "Deep Learning with Coherent Nanophotonic Circuits," under review arXiv:1610.02365 (2016)
- Anders Nysteen, Dara P. S. McCutcheon, Mikkel Heuck, Jesper Mørk, and Dirk R. Englund, "Limitations of two-level emitters as non-linearities in passive two-photon controlled phase gates," arXiv:1612.04803 (2016)
- Mikkel Heuck, Mihir Pant, and Dirk englund, "Temporally Multiplexed Single Photon Source using Photon Addition and Subtraction with Quantum Feedback Control," to be submitted (2017)
- Hyongrak Choi, Mikkel Heuck, and Dirk Englund, "Self-similar nanocavity design with arbitrarily small mode volume for single-photon nonlinearity," under review at Phys Rev Letters (2016)
- Mihir Pant, Don Towsley, Dirk Englund, and Saikat Guha, "Percolation thresholds for photonic quantum computing," under review arXiv:1701.03775v1 (2017)

Appendix B - Program Conference Presentations & Invited Talks

- D. Englund et al, "Semiconductor Quantum Technologies for Information Processing and Sensing,," Canadian Institute for Advanced Research - Quantum Information Science Program Meeting, Toronto, Canada. (6/5/2015)
- Ren-Jye Shiue, Yuanda Gao, Cheng Peng, Dmitri Efetov, James Hone, and Dirk Englund, "On-Chip Graphene Optoelectronic Devices for Optical Interconnects," , CLEO/Europe-EQEC 2015, Munich, Germany (6/21/2015)
- Jacob Mower, Nicholas C. Harris, Gregory R. Steinbrecher, Faraz Najafi, Yoav Lahini, Tom Baehr-Jones, Michael Hochberg, Karl K. Berggren, and Dirk Englund, "Quantum Information Processing Using Active Silicon Photonic Integrated Circuits," CLEO/Europe-EQEC 2015, Munich, Germany (6/22/2015)
- D. Englund et al, "Semiconductor Quantum Technologies for Information Processing and Sensing," , ICFO-Institute de Ciencies Fotoniques, Barcelona, Spain (6/30/2015)
- D. Englund et al, "Quantum Photonic Processors," , Majorca at MIT, MIT, Cambridge, MA (7/28/2015)
- D. Englund et al, "Progress Towards Scalable Entanglement of Spin Qubits in Photonic Integrated Circuits," , GeneExpression Systems & Appasani Research Conferences - Physical Sciences Symposia, Cambridge, MA (9/22/2015)
- D. Englund et al, "Quantum information processing with photons and spins on photonic integrated circuits," , NSF Quantum Information on a Chip Workshop - Padua, Italy (10/12/2015)
- D. Englund et al, "Quantum information processing using active silicon photonics integrated circuits," , RIEC-RLE Meeting, Tohoku University, Sendai, Japan (10/27/2015)
- D. Englund et al, "Towards Networked Quantum Memories on Photonic Integrated Circuits," , Physics Seminar, University of Lisbon (11/30/2015)
- Bayn*, I., Chen*, E., Trusheim, M., et al, "Nanoscale fabrication of diamond spin chains," Gordon Research Conference: Nanostructure Fabrication (2014)
- Chen*, E. H., Li*, L., Zheng, J., et al, "Efficient Photon Collection from a Nitrogen Vacancy Center in a Circular Bullseye Grating in Diamond," Division of Atomic, Molecular and Optical Physics (DAMOP) (2015)
- Zheng, J. Chen, E. H., Li, L., Dolde, F., Englund, D. R.;, "Optimized scalable circular grating with efficient photon extraction for Nitrogen Vacancy centers in a bulk diamond," Conference on Lasers & Electro-optics (2015)
- Mouradian*, S. L., Schroeder*, T., Poitras, C. B., et al, "Scalable Integration of Solid State Quantum Memories into a Photonic Network," Conference on Lasers & Electro-optics (2015)
- Patel, R., Schroder, T., Wan, N., et al., "Efficient Single Photon Generation

using a Fiber-integrated Diamond Micro-Waveguide,'' Conference on Lasers & Electro-optics (2015)

- Li*, L., Chen*, E.H., Zheng, J., et al., ''Efficient collection from a nitrogen-vacancy qubit in a circular grating,'' Conference on Lasers & Electro-optics (2015)
- Dirk Englund, ''Integrated Photonics for Quantum Information Processing ,'' Workshop on scalable information processing with quantum nano-photonics (2016)
- Dirk Englund, ''Computing, Communicating, and Sensing with Spins and Photons,'' Engineering Now: Insights from the Labs at MIT: 2016 National Academy of Engineering Symposium at MIT (2016)
- Dirk Englund, ''Quantum Information Processing with III-Nitride Photonics,'' MIT MTL-GaN Initiative (2016)
- Dirk Englund, ''Semiconductor Quantum Technologies for Information Processing and Sensing,'' US Naval Undersea Warfare Center Research Seminar Series (2016)
- Dirk Englund, ''Semiconductor Quantum Technologies for Quantum Networks,'' University of Washington Seminar (2016)
- Dirk Englund, ''Quantum Information Processing Using Programmable Silicon Photonic Integrated Circuits,'' Workshop on quantum stochastic differential equations for the quantum simulation of physical systems, Army Research Laboratory, Adelphi, MD (2016)
- Dirk Englund, ''Towards High-Speed Quantum Communications,'' Future Directions of Quantum Information Processing Workshop (2016)
- Dirk Englund, ''Photonic Integrated Circuits for Quantum Communications,'' QCrypt 2016 (2016)
- Dirk Englund, ''Large-Scale Programmable Photonic Circuits and Applications in Quantum Information Processing,'' Stanford Photonics Research Center (SPRC) (2016)
- Dirk Englund, ''Quantum Information Processing Using Programmable Silicon Photonic Integrated Circuits,'' FIO 2016, Rochester, NY (2016)
- Mihir Pant, Hari Krovi, Dirk Englund and Saikat Guha, ''Rate-distance tradeoff and resource costs for all-optical quantum repeaters,'' QCrypt 2016 (2016)
- E. Bersin, N. Harris, C. Lee, D. Bunandar, S.L. Mouradian, M. Walsh, T. Schroeder and D. Englund, ''Photonic Integrated Circuits for Quantum Communications,'' IEEE Photonics Conference (2016)
- Jordan Goldstein, Hongtao Lin, Amir Atabaki, Juejun Hu, Rajeev Ram, Dirk Englund, ''Waveguide-Integrated Graphene Photodetectors on a Foundry CMOS Platform and for Mid-IR Detection,'' MRS Fall meeting 2016 (2016)
- Dirk Englund, ''Photonic Integrated Circuits for Quantum Communications,'' U. of Stuttgart Physik Kolloqium (2017)
- Dirk Englund, ''Semiconductor Quantum Technologies for Communications and Computing,'' Niels Bohr Institute Colloquium (2017)
- Dirk Englund, ''2D Materials Optoelectronic Devices for Quantum Information Processing and Sensing,'' Graphena (2017)
- "Dirk Englund, ''Networking Quantum Memories on Photonic Integrated

Circuits,'' Physikalisches Kolloquium, Department für Physik
- FAU Erlangen-Nürnberg (2017)"
- Dirk Englund, ''Semiconductor Quantum Technologies for Communications and Computing,'' Center for Ultracold Atoms, MIT (2017)
- Dirk Englund, ''Quantum Information Processing with Spins and Photons in Semiconductor Circuits,'' Vienna Physics Colloquium (2017)

Appendix C - Patents

- 20160245639 METHODS, SYSTEMS, AND APPARATUS FOR PROGRAMMABLE QUANTUM PHOTONIC PROCESSING, International Class: G01B 9/02, Filing No. 15143450 (Publ. Date 25.08.2016)
- WO/2016/028363 METHODS, SYSTEMS, AND APPARATUS FOR PROGRAMMABLE QUANTUM PHOTONIC PROCESSING, International Class: G06N 99/00, Filing No. PCT/US2015/034500 (Publ. Date 25.02.2016)

List of Symbols, Abbreviations, and Acronyms

1D: 1 Dimensional

2D: 2 Dimensional

3D: 3 Dimensional

PIC: Photonic Integrated Circuit

Qubit: quantum bit

GHZ state: Greenberger–Horne–Zeilinger State