Photonics for Quantum Workshop

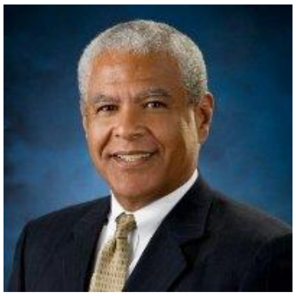
January 23-25, 2019

Program Book

Contents

Wednesday, January 23

Session 1



The National Quantum Initiative

Ed White

AIM Photonics; Test Assembly & Packaging, Rochester NY
National Photonics Initiative; Chair

With the recent passage of the National Quantum Initiative (NQI) into law, increased levels of Quantum research and workforce development will be enabled. Undoubtedly, this work will accelerate breakthroughs in many Quantum Information Science and Technology areas. In this talk, I will briefly describe the National Photonics Initiative (NPI) and it's linkage to the National Quantum Initiative. Further, I will describe the background of the NQI and discuss the roles, as defined in the legislation, for the Office of Science and Technology Policy (OSTP), NIST, NSF and the DOE. Finally, I will describe the next steps planned to address funding "appropriation" process associated with the $1.275B that has been allocated to the work described in the legislation.

Powering the 21st Century with Integrated Photonics

Michael Liehr[1,2]

[1]AIM Photonics and [2]SUNY Polytechnic Institute

AIM Photonics seeks to advance integrated photonic circuit manufacturing technology development while simultaneously providing access to state-of-the-art fabrication, packaging, and testing capabilities for small-to-medium enterprises, academia, and the government; create an adaptive integrated photonic circuit workforce capable of meeting industry needs and thus further increasing domestic competitiveness; and meet participating commercial, defense, and civilian agency needs in this burgeoning technology area. The talk describes the status of AIM technology, current applications and potential development for photonic quantum systems.

Session 2

Quantum Nonlinear Optics: New Materials and Interactions

Robert Boyd[1,2]

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[2]Institute of Optics and Department of Physics, University of Rochester, Rochester USA 14627
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In this talk, I describe new results on three research topics within my research group. We first describe some of the unusual optical properties of materials, known as epsilon-near-zero (ENZ) materials, for which the dielectric permittivity is very small. We describe some of the unusual geometrical optical properties of such materials and present theoretical predictions of how fundamental radiative properties are modified under such conditions. We also describe how these materials can display extremely large nonlinear optical effects under ENZ conditions [1,2]. The second topic of study is the filamentation of intense laser beams as they propagate through nonlinear optical materials. Our recent work has demonstrated that the threshold for filamentation can be raised by properly controlling the polarization properties of the transverse structure of the beam [3]. The third topic is quantum radiometry. Historically, black body radiation has been taken to constitute a calibration standard for optical instruments. However, the zero-point fluctuations of the electromagnetic field constitute another fundamental calibration standard. We have devised a means for calibrating the response of a spectrophotometer by utilizing these vacuum fluctuations to seed the process of spontaneous parametric down conversion [4].

[1] M. Z. Alam, I. De Leon, R. W. Boyd, Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region, Science 352, 795 (2016).
[2] M. Z. Alam, S. A. Schulz, J. Upham, I. De Leon and R. W. Boyd, Large optical nonlinearity of nanoantennas coupled to an epsilon-near-zero material, Nature Photonics, Vol. 12 (2018).
[3] F. Bouchard, H. Larocque, A.M. Yao, C. Travis, I. De Leon, A. Rubano, E. Karimi, G.-L. Oppo, and R.W. Boyd, Polarization Shaping for Control of Nonlinear Propagation, Phys. Rev. Lett 117, 233903 (2016).
[4] S. Lemieux, E. Giese, R.Fickler, M.V. Chekhova, and R.W. Boyd, A Primary Radiation Standard Based on Quantum Nonlinear, in review.

Electro-optic Quantum Transduction between Superconducting Microwave Qubits and Optical Photons

Mo Soltani

Quantum Engineering & Computing Group,
Physical Sciences and Systems Department Raytheon BBN

Quantum frequency conversion between superconducting (SC) microwave qubits and telecom optical photons is critical for long distance communication of networked SC quantum processors. While SC qubits operate at cryogenic temperatures to sustain their quantum coherence, converting them to the optical domain enables transferring the quantum states to room temperature and over long distances. For such a quantum state transduction process, several schemes have been investigated, including optomechanics, magnons, piezomechanics, and Pockels electro-optics (EO). The EO conversion approach is particularly attractive since it is broadband, low noise, mechanically and thermally stable (i.e., does not rely on freestanding structures), scalable (largescale integration of EO devices with superconducting circuits is possible), and tunable (e.g., using bias voltages). In this presentation we review our progress in an electro-optic based quantum transduction and discuss the promises and challenges.

Session 3

Linear Optical Quantum Information Processing in Silicon Nanophotonics

Edwin Hach[1]

[1]School of Physics and Astronomy & [2]Future Photon Initiative, Rochester Institute of Technology

It would be difficult to overestimate the level of attention being paid worldwide to quantum information processing, and anticipated advantages it may offer to a wide variety of pursuits in engineering, technology, and basic science. Futurists muse on the wondrous possibilities and theorists formulate actual algorithms for advanced computing not possible with classical

computing machines, *if only* there were scalable quantum computers. Further, several groups have performed compelling experiments related to quantum teleportation and quantum key distribution – both essential pieces for quantum cryptography. Still, it is a very challenging hardware problem to design architectures that support, appropriately protect, route, and process qubits to function as universal logic gates. To date, most of the optical successes toward this goal have been in bulk media, which is not easily scalable to carry out the required degree quantum error correction. In this talk, I will discuss a couple of the proposals that my collaborators at the Air Force Research Laboratory, at the Rochester Institute of Technology, and I have made toward addressing the issue, among others, of scalability. Further, thanks to the inception of the AIM Photonics Initiative, I will talk briefly about experimental tests that we have started and others that we have planned for assessing in situ the effectiveness of the devices that we have analyzed theoretically.

Optical Tweezer Phonon Laser

R. Pettit[1,2], W. Ge3, P. Kumar[3], L. Neukirch[1,2], D. Luntz-Martin[1], J. Schulz[1,2], Mishkat Bhattacharya[2,3,4] and A. N. Vamivakas[1,2]

[1]Institute of Optics & [2]Center for Coherence and Quantum Optics, University of Rochester
[3]School of Physics and Astronomy & [4]Future Photon Initiative, Rochester Institute of Technology

Optically levitated nanoparticles have recently emerged as a versatile platform for enabling next-generation sensing applications as well as for exploring fundamental physics. They are also very useful as testbeds for eventual chip-based applications. Experiments are approaching the quantum ground state of nanoparticle oscillation, and have realized applications such as thermometry, while theoretical modeling has produced precise agreement with experiment. In addition to the available linear vibrational mechanical degrees of freedom, spin, charge, and rotation have been added in various realizations of levitated optomechanics. In this work we introduce an important capability to the field of levitated optomechanics. We propose and develop a phonon laser based on the center-of-mass oscillation of a silica nanosphere levitated in an optical tweezer under vacuum. Our phonon laser is implemented via external feedback, thus allowing for optical creation and tuning of both mechanical gain and nonlinearity. We observe dynamics analogous to those familiar from the behavior of an optical laser: we record a threshold in the steady state phonon number as a function of gain, and the laser linewidth is observed to narrow across the threshold. Far above threshold, we measure a high degree of coherence indicated by an observation of the equal-time autocorrelation function of the mechanical amplitude [g^2 (0) ~ 1], and super-Poissonian but subthermal phonon statistics. All experimental data shows excellent agreement with a theory that includes spontaneous as well as stimulated emission of phonons.

Very-Fast Photon Sources and Detectors

Shayan Mookherjea

University of California, San Diego

Most quantum experiments are based on repeated “trials”. We present a roadmap based on integrated photonics for “very fast” sources and detectors to achieve a large improvement in the speed at which such trials can be performed.

Session 4

High-fidelity Quantum and Classical Control in Microfabricated Surface Ion Traps

Daniel Lobser

Sandia National Laboratories

Trapped ions are among the top candidates for realizing high fidelity gate operations for quantum computation as well as other applications including quantum simulation and sensing [1]. However, scaling these systems up to the number of qubits required to solve interesting problems with conventional macroscopic traps quickly becomes intractable. To overcome the scalability challenge, advanced microfabrication techniques have been developed to support a variety of complex electrode layouts, allowing for precise and dynamic control of confining potentials.

Using Sandia's microfabricated surface ion traps, which feature low heating rates, high trap frequencies, and long trapping times, we demonstrate novel classical control techniques that employ parametric voltage solutions for elegant composition of shuttling operations and accurate control over the curvature of the confining potential. To demonstrate the viability of Sandia's microfabricated ion traps for quantum information processing, we've realized of high-fidelity single-qubit gates below a rigorous fault tolerance threshold for general noise [2,3] and two-qubit Mølmer-Sørensen gates with a process fidelity of 99.58(6)%.

[1] N.M. Linke et al. Proc. Natl. Acad. Sci. 114, 13 (2017)
[2] R. Blume-Kohout et al. arXiv:1606.07674
[3] P. Aliferis and J. Preskill, Phys. Rev. A 79, 012332 (2009)

Quantum Integrated Photonics

Stefan Preble[1,2,3]

[1]Microsystems Engineering, Rochester Institute of Technology
[2]Future Photon Initiative, Rochester Institute of Technology
[3]Electrical and Microelectronic Engineering, Rochester Institute of Technology

Integrated Photonic circuits provide a scalable and stable platform for realizing quantum information technologies. In this talk I will discuss integrated photonic chips for the production, manipulation and storage of quantum bits (qubits). I will present two platforms for quantum photonics: one based on Silicon which leverages the high density of Silicon Photonic technologies, and the other based on Aluminum Nitride (AlN) which operates at visible/UV wavelengths and is highly suited for the realization of hybrid quantum systems based on atoms and solid state emitters. Lastly, I will present our related work on integrated photonic packaging at AIM Photonics Test, Assembling and Packaging (TAP) facility. The packaging capabilities include die, laser and fiber attach – all of which enable the realization of complex quantum photonic circuits.

Ytterbium Based Lasers Sources And OPOs For Quantum Technologies: Latest Capabilities

Christopher Leburn

Chromacity Ltd.

In this talk we will review the latest developments in Ytterbium based fiber laser and OPO technologies and discuss their implementation in a range of quantum based experiments. This will include a route to the detection of quantum signatures at 690nm (using third harmonic generation); the generation and detection of down-converted photon pairs at 2.080 µm (as a potential source for free-space quantum communications) and; the use of our tuneable near-IR OPO source to interrogate SiN and AlN integrated waveguides with entangled photons.

Thursday, January 24

Session 5

Continuous Variable Quantum Photonics

Zachary Vernon

Xanadu

Integrated quantum photonics has for the past decade been nearly synonymous with single photons and photon pairs. Yet many promising near term use cases of photonic quantum simulation and computation are best implemented using continuous variable (CV) encodings, which typically require squeezed light rather than single photons. In this presentation I provide an overview of our work towards realizing scalable CV quantum simulation and computation, including the most recent progress in developing nanophotonic sources of squeezed light.

Quantum Photonics for Computer Security and other Applications

Philip Walther

Stanford University

The precise quantum control of single photons, together with the intrinsic advantage of being mobile make optical quantum system ideally suited for delegated quantum information tasks, reaching from well-established quantum cryptography to quantum clouds and quantum computer networks.

Here I present that the exploit of quantum photonics allows for a variety of quantum-enhanced data security for quantum and classical computers. The latter is based on feasible hybrid classical-quantum technology, which shows promising new applications of readily available quantum photonics technology for complex data processing. As outlook I will discuss technological challenges for the scale up of photonic quantum computers, and our group's current work for addressing some of those.

Session 6

Large-scale Quantum Photonic Processors: Photonics for AI and AI for Photonics

Jacques Carolan

Massachusetts Institute of Technology

Photons play a central role in many areas of quantum information science, either as qubit themselves or to mediate interactions between long-lived matter based qubits. Techniques for (1) high-fidelity generation, (2) precise manipulation and (3) ultra-efficient detection of quantum states of light are therefore a prerequisite for virtually all quantum technologies. A quantum photonics processor is the union of these three core technologies into a single system, and, bolstered by advances in integrated photonics, promises to be a versatile platform for quantum information science. In this talk we present recent progress towards large-scale quantum photonic processors, leveraging the platform of silicon photonics. We demonstrate how quantum photonic processors can accelerate both quantum and classical machine learning, and how optimization techniques can enhance large-scale quantum control.

Engineering Non-classical Light in Photonic Integrated Devices

Marco Liscidini

University of Pavia

Integrated micro- and nano-structures allows for the efficient generation of photon pairs via parametric fluorescence, thanks to the enhancement of the light-matter interaction associated with light confinement in small volumes. For instance, the efficiency of spontaneous four wave mixing in a silicon micro ring resonator can range up to 10 orders of magnitude larger than in bulk silicon. Yet the advantages of using integrated devices go well beyond the sole efficiency improvement, for micro structures grant an unprecedented control over the properties of generated non-classical light. For instance, in a single photonic integrated circuit, one can exploit the interferences of many optical elements to construct complex multipartite states in a compact, stable, and scalable system.

In this talk I will focus on the generation of photon pairs and show how their spectral properties can be engineered in an integrated device for use as building blocks in the construction of a whole variety of states, from heralded single-photons to multipartite states.

[1] F. Rouxinol, Y. Hao, F. Brito, A.O. Caldeira, E.K. Irish, M.D. LaHaye. Nanotechnology 27, 36 (2016).
[2] H. Wang, A.P. Zhuravel, S. Indrajeet, Bruno G. Taketani, M.D. Hutchings, Y. Hao, F. Rouxinol, F.K. Wilhelm, M. LaHaye, A.V. Ustinov, B.L.T. Plourde. arXiv:1812.02579 (Dec. 06, 2018).
[3] J. Lozada-Vera, A. Carrillo, O. P. de Sá Neto, J. Khatibi Moqadam, M. D. LaHaye, M. C. de Oliveira. EPJ Quantum Technology 3, 1 (2016).
[4] F. Tacchino, A. Chiesa, M. D. LaHaye, S. Carretta, and D. Gerace. Phys. Rev. B 97, 214302 (2018).

Session 7

Hybrid Quantum Systems Composed of Superconducting Qubits, Nanomechanics, and Transmission Line Metamaterials

Matthew Lahaye

Syracuse University

Hybrid quantum interconnects and processor components are likely to play an important role in future scalable quantum communication and computation networks. In this talk, I will outline several nascent ideas for a new type of hybrid system, composed of mechanical elements, superconducting metamaterials, and superconducting qubits, which could be applicable to quantum transduction and memory functions. Before introducing these new ideas, I will start with a summary of recent incipient work at Syracuse that has inspired them. My summary will include a brief overview of efforts in the LaHaye group to investigate interactions between a superconducting transmon qubit and UHF nanomechanical element[1]; as well, I will highlight work conducted concomitantly and independently by the Plourde group to study the mode structure[2] and cQED interactions of a superconducting metamaterial transmission line. The talk will then conclude with an overview of related ideas to utilize qubit-coupled nanoresonator architectures as platforms for quantum simulation[3,4].

[1] F. Rouxinol, Y. Hao, F. Brito, A.O. Caldeira, E.K. Irish, M.D. LaHaye. Nanotechnology 27, 36 (2016).
[2] H. Wang, A.P. Zhuravel, S. Indrajeet, Bruno G. Taketani, M.D. Hutchings, Y. Hao, F. Rouxinol, F.K. Wilhelm, M. LaHaye, A.V. Ustinov, B.L.T. Plourde. arXiv:1812.02579 (Dec. 06, 2018).
[3] J. Lozada-Vera, A. Carrillo, O. P. de Sá Neto, J. Khatibi Moqadam, M. D. LaHaye, M. C. de Oliveira. EPJ Quantum Technology 3, 1 (2016).
[4] F. Tacchino, A. Chiesa, M. D. LaHaye, S. Carretta, and D. Gerace. Phys. Rev. B 97, 214302 (2018).

Simulating Subatomic Physics on a Quantum Frequency Processor

Pavel Lougovski

Oak Ridge National Laboratory

Photonics is at the forefront of quantum computing and simulations. It enabled a host of pioneering demonstrations of the variational quantum eigensolver (VQE) algorithm, of molecular vibronic spectra and dynamics simulations, and of experimental Hamiltonian learning. It offers a versatile platform to process quantum information with low noise in a multitude of encodings, ranging from spatial or polarization degrees of freedom, to temporal modes. We discuss how frequency encoding, where qubits are represented by photons in narrow frequency bins, can be utilized for simulating complex many-body quantum phenomena in nuclear physics and quantum field theory. Using an all-optical quantum frequency processor, the ground-state energies of light nuclei including the triton, 3He, and the alpha particle are computed. Complementing these calculations and utilizing a 68-dimensional Hilbert space, our photonic simulator is used to perform sub-nucleon calculations of the two-body and three-body forces between heavy mesons in the Schwinger model. This work is a first step in simulating subatomic many-body physics on quantum frequency processors---augmenting classical computations that bridge scales from quarks to nuclei.

You Should not Use the Electric Field to Quantize in Nonlinear Optics

J.E. Sipe

Department of Physics, University of Toronto

We show that using the electric field as a quantization variable in nonlinear optics leads to incorrect expressions for the squeezing parameters in SPDC, the conversion rates in frequency conversion, and the wrong behavior of cross- and self-phase modulation. This observation is related to the fact that if the electric field is written as a linear combination of boson creation and annihilation operators one cannot satisfy Maxwell's equations in a nonlinear dielectric.

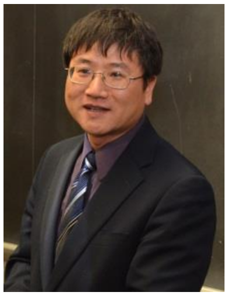
Session 8

Solid-state Quantum Photonics

Nick Vamivakas

The Institute of Optics, University of Rochester

Solid-state materials are providing new insights into quantum optics and offer unique opportunities for quantum information science. In this talk I will discuss how localized quantum emitters in solid-state materials can be leveraged to support the generation of quantum states of light as well as how these same objects can enable new approaches to metrology.



Integrated Photonic Devices for Controlling Quantum Properties of Light

Qiang Lin

University of Rochester

We will discuss our recent efforts in engineering various integrated photonics devices and platforms for manipulating the fundamental quantum properties of photons.

Quantum Photonics: How Far Can We Go?

Paul Kwiat

University of Illinois at Urbana-Champaign

Although existing experiments have implemented protocols employing up to 10 or even 12 photons, the inefficiencies of sources has resulted in exceedingly low rates of these high-photon events. Single and entangled-photon emitters both suffer from probabilistic operation, substantial losses, or both, so that extrapolating even to 20 photons is discouraging. However, recent experiments employing multiplexing techniques can trade overall rate (or component count) for increased probability, e.g., factors of 10-30 enhancement have been demonstrated. How far can such experiments be pushed? Using our best guesstimates on what system capabilities may be feasible, we discuss the near-term future for multi-photon quantum processing.

Quantum Caustics and Chaos in Continuously Measured Quantum Systems

Andrew Jordan

University of Rochester

Measured quantum systems exhibit their own form of dynamics that is stochastic and nonunitary. Of particular interest are the most likely paths in quantum space between two boundary conditions in a certain time. I will show how caustic structures can arise in these paths, and predict the occurrence of chaos. In the former case, comparison with experiments on superconducting quantum circuits will be given.

Photon Generation in Ultraviolet Integrated Photonic Circuits

Michael L. Fanto[1,2], Christopher C. Tison[1], A. Matthew Smith[1], Paul M. Alsing[1], Stefan Preble[2], Jeffrey Steidle[2], Zihao Wang[2], Paul Thomas[2], John Serafini[2], Gregory Howland[2], Dirk Englund[3], Tsung-Ju Lu[3], Hyeongrak Choi[3], Kent Averett[4], Matthew Hardy[5], Mohammad Soltani[6]

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[3]Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139
[4]Air Force Research Laboratory, Materials Directorate, Dayton, OH 45433
[5]Naval Research Laboratory, Washinton, DC, 20375
[6]Raytheon BBN Technologies, Cambridge, MA, 02138

Quantum information processing relies on the fundamental property of quantum interference, where the quality of the interference directly correlates to the indistinguishability of the interacting particles. The creation of these indistinguishable particles, photons in this case, has conventionally been accomplished with nonlinear crystals and optical filters to remove spectral distinguishability, albeit sacrificing the number of photons. This research describes the use of an integrated aluminum nitride microring resonator circuit to selectively generate photon pairs at the narrow cavity transmissions, thereby producing spectrally indistinguishable photons in the ultraviolet regime to interact with trapped ion quantum memories. The spectral characteristics of these photons must be carefully controlled for two reasons: (i) interference quality depends on the spectral indistinguishability, and (ii) the wavelength must be strictly controlled to interact with atomic transitions. The specific ion of interest for these trapped ion quantum memories is Ytterbium which has a transition at 369.5 nm with 12.5 GHz offset levels. Ytterbium ions serve as very long lived and stable quantum memories with storage times on the order of 10’s of minutes, compared with photonic quantum memories which are limited to 10^{-6} to 10^{-3} seconds. The combination of the long-lived atomic memory, integrated photonic circuitry, and the photonic quantum bits are necessary to produce the first quantum information processors. In this seminar, I will present results on ultraviolet wavelength operation, dispersion analysis, propagation loss in aluminum nitride waveguides, and the path forward to towards multiwavelength integration.

Friday, January 25

Session 9

Increasing atomic clock precision with and without entanglement

Christopher Gerry

Department of Physics and Astronomy, Lehman College, The City University of New York

The precision of an atomic clock based on the standard Ramsey spectroscopy, involving the measurement of the population of the atomic excited state, essentially a measurement of energy, is determined by the free evolution time T between successive $\pi/2$ pulses. The longer the time T, the narrower the Ramsey interference fringes and thus the greater the precision. The stability of an atomic clock is also increased with increased T. But there are practical limits to the degree to which T can be extended. The main approach so far has been through the introduction of the so-called atomic fountain clocks. In this talk we present alternative approach not based on extending T but based on collective atomic states where a non-classical observable, an observable having no classical counterpart, is to be measured. This is the collective atomic, or SU(2), parity for an ensemble of two-level atoms. We show that with this observable the corresponding Ramsey-like fringes can become remarkably narrower with an increasing number of atoms in the ensemble even when the atomics are not prepared in an entangled state. By preparing the atoms in an entangled state, such as a state known to be spin-squeezed, the precision can be further increased through atomic parity measurements. The issue of performing the required collective atomic parity measurements will be discussed.

Large-Scale Photonic Circuits for Quantum Information Processing

Dirk Englund

Research Laboratory of Electronics
Massachusetts Institute of Technology

Photonic integrated circuits (PICs) have become increasingly important in classical communications applications over the past decades, including as transmitters and receivers in long-haul, metro and datacenter interconnects. Many of the same attributes that make PICs attractive for these applications — compactness, high bandwidth, and the ability to control large numbers of optical modes with high phase stability — also make them appealing for quantum information processing. Here we review our recent progress in developing PICs for quantum information processing.

The first part of the talk will describe architectures for programmable PIC that can be programmed to implement arbitrary unitary linear-optics transformations. We recently applied these chips to applications ranging from deep neural networks1 to quantum transport simulations2, but this talk will focus on recent advances in entangled photon sources3 and proposals for on-demand single photon sources4, photon-photon nonlinear interactions, and neural neural network processors5.

The second part of the talk will consider new PIC platforms that can be integrated directly with atom-like quantum memories. In particular, we will discuss PICs based on the AlGaN-sapphire material system that are transparent in the UV-VIS spectrum, for applications in multiplexed quantum repeaters. This PIC platform now allows quality factors in excess of 20,000 for wavelengths as short as 369nm6 and the integration of diamond nitrogen vacancy color centers and superconducting single-photon resolving detectors7. Finally, we describe a blueprint for scalable cluster-state quantum computing that builds on large numbers of cavity-coupled diamond color centers networked by photonic switches and waveguides8.

1. Shen, Y. et al. Deep learning with coherent nanophotonic circuits. Nat. Photonics 11, 441–446 (2017).
2. Harris, N. C. et al. Quantum transport simulations in a programmable nanophotonic processor. Nat. Photonics 11, 447–452 (2017).
3. Carolan, J. et al. Scalable feedback control of single photon sources for photonic quantum technologies. arXiv [quant-ph] (2018).
4. Heuck, M., Pant, M. & Englund, D. R. Temporally and spectrally multiplexed single photon source using quantum feedback control for scalable photonic quantum technologies. New J. Phys. (2018).
5. Steinbrecher, G. R., Olson, J. P., Englund, D. & Carolan, J. Quantum optical neural networks. arXiv [quant-ph] (2018).
6. Lu, T.-J. et al. Aluminum nitride integrated photonics platform for the ultraviolet to visible spectrum. Opt. Express, OE 26, 11147–11160 (2018).
7. Zhu, D. et al. A scalable multi-photon coincidence detector based on superconducting nanowires. arXiv [physics.ins-det]; to appear in Nature Nanotechnology (2017).
8. Pant, M., Choi, H., Guha, S. & Englund, D. Percolation based architecture for cluster state quantum computation using photon-mediated entanglement between atomic memories. Preprint at https://arxiv. org/abs/1704. 07292 (2017).

Imaging with Single-photon Detector Array Technologies

Jonathan Leach

Heriot-Watt University

Single-photon detector array technologies have advanced significantly in recent years. Cameras now exist that are not only sensitive to single photons but the individual pixels in the sensor provide photon time-of-arrival information the picosecond regime. Such unprecedented sensitivity and temporal resolution opens up a number of exiting new applications, such as light-in-flight imaging, looking around corners with laser echoes, and seeing through dense scattering media. I will discuss the recent developments of the camera technology and discuss our latest results. I will give details of our latest field trials, where we have been using single-photon detector array sensors to see through fog and smoke, discuss the application to ultra-fast imaging in three dimensions, and give details of quantum imaging of high-dimensional entanglement.

Session 10

Optimized Quantum Photonics

Jelena Vuckovic

Stanford University

At the core of most quantum technologies, including quantum networks and quantum simulators, is the development of homogeneous, long lived qubits with excellent optical interfaces, and the development of high efficiency and robust optical interconnects for such qubits. To achieve this goal, we have been studying color centers in diamond (SiV, SnV) and silicon carbide (VSi in 4H SiC), in combination with novel fabrication techniques, and relying on the powerful and fast photonics inverse design approach that we have developed.

Our inverse design approach offers a powerful tool to implement classical and quantum photonic circuits with superior properties, including robustness to errors in fabrication and temperature, compact footprints, novel functionalities, and high efficiencies. We illustrate this with a number of demonstrated devices, including efficient quantum emitter-photon interfaces for color centers in diamond and in silicon carbide. We are also employing this approach to implement a quantum simulator based on color centers in semiconductors.

Superconducting Optoelectronic Networks for Quantum and Neuromorphic Computing

Alexander Tait

Princeton University

Efficient single-photon detectors have enabled new directions in experimental physics. Superconducting nanowire single-photon detectors (SNSPDs) are a vital component in loophole-free Bell inequality violation, metrology beyond the shot-noise limit, and nuclear clock transition sensing. We discuss recent progress in cryogenic silicon photonic platforms at the National Institute of Standards and Technology (NIST). These platforms co-integrate SNSPDs, silicon-on-insulator waveguides, superconducting amplifiers, and all-silicon light sources based on emissive crystal defect centers. Together, these elements lay a foundation for large-scale quantum information systems and extremely low-power neuromorphic architectures.

Neuromorphic photonics uses the complementary properties of optics and electronics to realize information processing capabilities far beyond what is possible with pure electronics. Its performance potentials are highly desired as neural network approaches have retaken the helm of machine learning. We present recent results in neuromorphic photonic architectures at NIST and Princeton: one signaling at single-photon levels, one signaling on sub-nanosecond timescales, both propelled by the emerging industrialization of silicon photonics. Neuromorphic and quantum processing approaches based on silicon photonics will overlap substantially in terms of technical challenges and enabling technologies.

Session 11

Progress Towards Enabling Quantum Engineering

Steve Olson, Chris Hobbs, Hyuncher Chong, Jakub Nalaskowski, Harlan Stamper, John Mucci, Brian Martinick, Karsten Beckmann, Ilyssa Wells, Corbet Johnson, Vidya Kaushik, T. Murray, Steve Novak, Steve Bennett, Martin Rodgers, Chris Borst, Michael Liehr, and Satyavolu Papa Rao (presenting author)

SUNY Polytechnic Institute

Ongoing research at SUNY Polytechnic Institute to enable large scale fabrication of quantum devices with tightly controlled performance characteristics will be presented. Josephson junctions and transmon qubits patterned with 193 nm lithography will be used to illustrate how advanced process tools can control critical dimensions of devices, necessary for building larger ensembles of qubits. Advances in the CMOS industry enable superior surface roughness and interface quality to be achieved across the entire 300mm wafer – some examples will be presented. The integration of photonic circuits (waveguides and on-chip cryogenic IR emitters) with superconducting Josephson junctions to enable large-scale neuromorphic computing structures in the near future will be discussed. Ongoing work on developing materials and processes for UV-transparent photonic circuits at 300mm will be presented – such chips could be useful as part of the interface to trapped ion qubits. The talk will wrap up with a discussion of the synergies in technology development, and functionality integration that can be achieved using an advanced fabrication facility.

Interfacing Superconducting Quantum Processors with Cryogenic Digital Circuitry

Britton Plourde

Syracuse University

Superconducting qubits based on Josephson junctions are one of the leading candidates for building a largescale quantum information processor. There have been significant advances in the performance of superconducting qubits over the past decade and there is currently rapid progress in the development of systems with up to tens of qubits. In order to build to yet larger systems, new techniques will need to be developed to address the overhead requirements for room-temperature electronics hardware and cryostat wiring for controlling and reading out large numbers of qubits. One approach to this challenge involves implementing more of the qubit control and readout in the low-temperature environment. I will describe our efforts on integrating superconducting classical digital circuitry with superconducting qubits for coherent control and readout.

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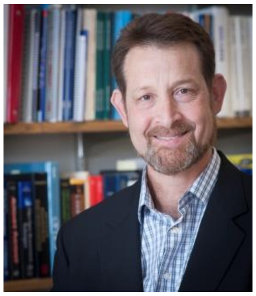

Frequency Bin Quantum Photonics

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Entanglement and encoding in discrete frequency bins – essentially a quantum analogue of wavelength-division multiplexing – represents a relatively new degree of freedom for quantum information with photons. In this talk I discuss biphoton frequency combs, generated either by spontaneous four-wave mixing (SFWM) from on-chip microring resonators or by spectral filtering of spontaneous parametric down conversion (SPDC) in second order nonlinear crystals. Potential advantages include generation of high dimensional units of quantum information (qudits), which can carry multiple qubits per photon, robust transmission over fiber, frequency parallelism and routing, and compatibility with on-chip implementations, as well as hyperentanglement with other photonic degrees, e.g., time-frequency hyperentanglement. Since the initial experiments less than two years ago, frequency bin quantum photonics has been advancing rapidly [1-8]. In this talk I will discuss a method using pulse shapers and phase modulators in order to mix different frequencies and perform two photon interference experiments for characterization of the frequency-bin entanglement. Similar components (pulse shapers and phase modulators) may be used to manipulate the frequency-encoded quantum states; this will be described in another talk by our collaborators at Oak Ridge National Labs. I will also discuss the use of time bins and frequency bins as independent degrees of freedom in a quantum encoding fashion to realize what we believe to be the first deterministic two qudit gates. Finally, I comment briefly on potential applications and on prospects for realization of integrated frequency bin quantum photonics.

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Efficiently Certifying Large Amounts of Entanglement in High-Dimensional Quantum Systems

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Abstract: Real-world platforms for enabling quantum information technologies are varied and imperfect; therefore, the quantum resources they provide must be characterized before they can be used. For some tasks, such as secure communication, resources like entanglement must be guaranteed, or certified. In large quantum systems, traditional approaches demand an intractable

number of measurements. We demonstrate a practical method for quantifying high-dimensional entanglement from extremely limited data that does not require numerical optimization techniques. Using only 6,456 measurements, we certify over 7 ebits of entanglement-of-formation shared by entangled photon pairs in a joint-measurement space exceeding 68 billion dimensions.

Frequency Bins for Quantum Information Processing

Joseph M. Lukens

Oak Ridge National Laboratory

Photons offer a myriad of bases for encoding quantum information, including such popular choices as polarization, spatial modes, and time bins. And due to frequency's inherent stability and compatibility with optical fiber, spectral modes provide a particularly attractive Hilbert space for quantum computation. Yet control and processing of such modes can prove quite challenging, typically requiring complicated operations and strong classical pump fields. In this talk, I will describe our paradigm for universal quantum computation based on frequency-bin qubits and standard lightwave technology: electro-optic phase modulators and Fourier-transform pulse shapers. Our approach offers excellent resource scaling, parallelizability, and compatibility with fiber-optic technology. I will discuss experiments so far, including frequency-bin Hadamard and tritter gates, both with ultrahigh fidelity and broad bandwidth; quantum interference and independent spectral control of two photons in the same optical fiber; and a frequency-bin controlled-NOT, the first of its kind. Such experiments are augmented by Bayesian machine learning techniques, allowing for more detailed gate analysis than possible with conventional approaches. Finally, I will conclude with an outlook on future work, highlighting opportunities to address current challenges and summarizing the potential for our technique, not only in quantum computation proper, but also quantum interconnects, frequency-multiplexed networks, and on-chip integration.

Chip-integrated visible-telecom entangled photon pair source for quantum communication

Xiyuan Lu

Maryland nanocenter, University of Maryland College Park, and Physical Measurement Laboratory, National Institute of Standards and Technology

Photon pair sources are fundamental building blocks for quantum entanglement and quantum communication. Recent studies in silicon photonics have documented promising characteristics for photon pair sources within the telecommunications band, including sub-milliwatt optical pump power, high spectral brightness, and high photon purity. However, most quantum systems suitable for local operation (e.g., storage/computation) support optical transitions in the visible or short nearinfrared bands. In comparison to telecommunications wavelengths, the significantly higher optical attenuation in silica at such wavelengths limits the length scale over which optical-fiber-based quantum communication between such local nodes can take place. One approach to connect such systems over fiber is through a photon pair source that can bridge the visible and telecom bands, but an appropriate source, which should produce narrow-band photon pairs with a high signal-to-noise ratio, has not yet been developed in an integrated platform. Here, we demonstrate a nanophotonic visible-telecom photon pair source for the first time, using high quality factor silicon nitride resonators to generate narrow-band photon pairs with unprecedented purity and brightness, with coincidence-toaccidental ratio (CAR) up to 3,780 ± 140 and detected photon-pair flux up to (18,400 ± 1,000) pairs/s. We further demonstrate visible-telecom time-energy entanglement and its distribution over a 20 km fiber, far exceeding the fiber length over which purely visible wavelength quantum light sources can be transmitted. Finally, we show how dispersion engineering of the microresonators enables the connections of different species of trapped atoms/ions, defect centers, and quantum dots to the telecommunications bands for future quantum communication systems.

Posters

Active Control of Multimode Interferometer

Matthew van Niekerk[1,*], Jeffrey A. Steidle[1], Gregory A. Howland[1], Michael L. Fanto[1,2], Nicholas Soures[3], Fatima Tuz Zohora[3], Dhireesha Kudithipudi[3], Stefan Preble[1]

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Unitary circuits are necessary for applications in quantum and neuromorphic computing. With Silicon Photonics, there is a formulation for creating any unitary circuit with two simple components: beam splitters and phase shifters. Even though this solution is on a scalable platform, there is a physical constraint for the cascaded network. We investigate an active multimode interferometer (MMI) to considerably reduce the floorplan of the circuit, while approximating the unitary circuit.

Atto-joule per bit Photonic Crystal Nanocavity Modulator

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With the exponential growth of bandwidth requirement of data centers and supercomputers, energy already limits our ability to process and communicate information. There is an urgent need to develop low-energy photonic devices and systems that can push the energy efficiency to attojoule per bit level. Traditional silicon photonic modulators rely on the plasma dispersion effect by free-carrier injection or depletion, which occupies a large footprint and consumes relatively high energy for optical interconnects. From the device perspective, existing micro-ring and micro-disk resonators cannot achieve atto-joule per bit energy efficiency due to the relatively large optical mode volume. Here we report an ultra-compact hybrid silicon-conductive oxide electro-optic modulator with total device footprint of 0.6×8 μm^2. The device was built by integrating voltage-switched transparent conductive oxide with one-dimensional silicon photonic crystal nanocavity. The active modulation volume is only 0.06 μm^3, which is less than 2% of the lambda-cubic volume. The device operates by exploiting the refractive index modulation from both the conductive oxide and the silicon waveguide induced by the applied gate voltage. Such a

metal-free, hybrid silicon-conductive oxide nanocavity modulator also demonstrates only 0.5 dB extra optical loss, a balanced Q-factor of 4,000, high E-O efficiency of 250 pm/V, low energy consumption of 3fJ/bit, and operation speed at gigahertz frequency. In addition, we discuss the strategy to further improve the energy efficiency below 1fJ/bit and to achieve high-speed modulation above 10Gbps. The holistic design presented a new generation E-O modulators that can be used for extreme scale optical interconnects and quantum communication.

Bowtie Plasmonic Nanoantennas with Nanocrystals: Photon Antibunching, Polarization Selectivity and Tunability

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From all photonic structures for room-temperature single-photon source applications plasmonic nanoantennas provide both the highest reported emission rate enhancements and the highest photon flux increase from emitters [1]. Bowtie nanoantennas were used for fluorescence enhancement from dye molecules [2] and color-centers in nanodiamonds [3]. These nanoantennas consist of two triangle tips separated by a nanometer-size gap.

Photon antibunching was observed within gold bowtie plasmonic nanoantennas from NV centers in 20-nm diameter nanodiamonds and CdSeTe nanocrystal quantum dots (Qdot 800 ITK organic). We also showed polarization selectivity of these nanoantennas. Numerical modeling was carried out both for air and for tunable anisotropic environment.

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Cavity optomechanics with an annular rotating Bose gas*

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The characterization of the circulation of a rotating annular Bose-Einstein condensate (BEC) is an open problem in atomic physics. In contrast to existing techniques, here we exploit the approach of cavity optomechanics which is not only minimally destructive but also works in situ and practically in real time. The system consists of an annular rotating BEC interacting with orbital angular momentum carrying light beams inside an optical resonator. First, we show that the angular momentum of the rotating BEC can be detected from the cavity transmission. Second, for realistic parameters, we present the bistable behavior, the linear and nonlinear responses of the system, the rotation sensitivity including its quantum limits and bi- and tri-partite entanglement. Our protocol can improve the rotation sensitivity of ring BECs by two orders of magnitude. Thus, the proposed technique provides a versatile platform for the sensing, manipulation of multiply-connected rotating degenerate gases and characterization of the atomic current.

Highly Parallel Detector for Photonic Studies

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Dimensional scaling is a significant challenge which must be overcome for quantum technologies to become practical. Single photon detectors (SPDs) are workhorses for sampling light-based quantum states, as they provide a binary train of photon arrival information required for coincidence measurements, lifetime measurements, state tomography, etc. Avalanche photodiodes and photomultiplier tubes (PMTs) are the two most prominent SPD technologies which, until recently, have been limited to single-channel sensors. We present characterization of a multi-anode PMT detector as a single-photon counting camera with 256 pixels. A pulsed laser is used in conjunction with several pixels to measure a time stamp resolution of 44 ps and timing performance of 96 ps. We also measure the pulse's photon content, and use two pixels independently in a coincidence measurement. As routine demonstrations of quantum optics, the detector's performance here shows it to be an enabling technology for scaling a photonic platform.

Keywords: photonics, detectors, single photon counting, PMT, multi-anode PMT.

How Photonics Enables Light-Driven Propulsion

Lucy Ying-Ju Chu, Prateek Srivastava, Dr. Grover Swartzlander

Center for Imaging Science, Rochester Institute of Technology

Sailcrafts make use of photon momentum -- harvesting radiation pressure from the sun. Diffractive sails may stand out from current reflective sails with both parallel and normal force component. We measured the radiation pressure owing to grating momentum, and also a beam rider structure. These measured forces may be useful for improving the efficiency and stability of sailing maneuvers.

Low Frequency Charge Noise in Si/SiGe Quantum Dots with Overlapping Gates

Elliot Connors, JJ Nelson, Haifeng Qiao, John Nichol

Spin qubits are an attractive platform for quantum computing as they offer extremely long coherence times, yielding the possibility for high fidelity gate operations. Currently, gate fidelities in silicon based spin qubits are limited by charge noise. Many techniques to improve gate fidelities rely on an understanding of device noise; however, a thorough characterization of the charge noise in these devices is lacking. Here, we measure the low frequency component of the charge noise on multiple Si/SiGe quantum dot devices and find the magnitude of the noise at 1 Hz to ranges from 0.2 to 1.9 $\mu\mathrm{eV}/\sqrt{\mathrm{Hz}}$ across devices. In an effort to characterize the noise source, we investigate the temperature dependence of the noise as well as the temporal correlation of the noise on two neighboring quantum dots.

Photonics Packaging

Mario Ciminelli, Thomas Palone, Peichuan Yin, Randy Kennard, John Serafini, Jeff Steidle, Mike Fanto, Stefan Preble and Martin Ansel

The rapid progress made in Silicon photonics over the past decade has advanced the fields of telecommunication, data communication, medical and sensing applications. Much of the success can be attributed to adopting standard CMOS fabrication techniques to create highly integrated photonic components without compromising device performance. The next stage in development is realizing a low-cost packaging system that is capable of efficiently moving off chip and interfacing with current technology. This includes bonding optical fibers to the photonic integrated circuit (PIC), but doing so with a scalable, cost effective manufacturing process. In this presentation, we demonstrate multiple approaches for realizing low-loss fiber attachment.

MicroNMR and Molecular Transport Sensing of Biomolecules on GaAs Chip

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Quantum 2.0 technologies offer opportunities to increase sensitivity and broaden the range of applications of existing nano- and bio-sensors, and to develop novel ones. We present the results that qualitatively extend established results from optical measurements within NMR family of techniques which can be reliably conducted on a chip for the NMR-based detection of native chip material species, such as isotopes of Ga and As, (or diamond and Si). Our approach relies on the diode-like sensor which optically detects dynamic nuclear polarization influenced electroluminescent signal, allowing, for the first time, for the detection of water protons on GaAs chip. We estimate that fewer than 10^4 protons could be detected in the few nanometers thick layer surrounding the sensor. This DNP-inspired microNMR signal is studied as a function of the temperature and magnetic field. In parallel with the microNMR approach, we show how methods of molecular and quantum transport could be used to correlate transport and spectroscopic data to identify molecular species adhering to or moving within the vicinity of the interface between nanoscale controlled etch of GaAs surface and probed bio-relevant molecules. Correlating molecular transport and FTIR, among other methods, allows us to identify Ga-O, Ga-H, As-O, and As-H, among other bonds with our approach. Various ions within PBS solutions of varied concentration are also detectable, as are representative amino acids of all categories. The results

open a perspective on quantum optical sensing of several ionic species of broad interest in the biophysics of interfaces between inorganic solids and organic liquids solutions.

Keywords: GaAs photonics, microNMR, quantum selection rules for zinc blende lattice, molecular quantum transport

Optimal Control for Robust Atomic Fountain Interferometry

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Atomic fountain interferometers [1] provide precision measurements of gravitational fields with unprecedented sensitivity. This provides a wealth of possible applications, from fundamental science such as testing the equivalence principle, to next-generation inertial navigation systems. Fundamentally, the atom interferometer is implemented by laser pulses driving Bragg-transitions between the momentum states of the atomic cloud. Signal contrast is limited by the ability to realize momentum-transfer atomic mirrors and beamsplitters with high fidelity and robustness with respect to laser amplitudes and initial velocity distribution of the atoms. Starting from a pulse scheme based on rapid adiabatic passage, we employ Krotov's method of numerical optimal control and ensemble optimization [2] to find laser pulses that improve both robustness and fidelity by at least an order of magnitude. We will demonstrate how the method can be extended to reach arbitrarily high momentum states.

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Over 100-THz Bandwidth Selective-Difference-Frequency Generation at LaAlO3/SrTiO3 Nano-junctions*

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The ability to combine continuously-tunable narrow-band terahertz (THz) generation that can

access both far-infrared and mid-infrared regimes, with nanometer-scale spatial resolution, holds great potential for uncovering the underlying light-matter interactions as well as realizing selective control of rotational or vibrational resonances in nanoscale objects. Here, we report selective difference frequency generation with over 100 THz bandwidth through femtosecond optical pulse shaping. The THz emission is generated at nanoscale junctions at the interface of LaAlO3/SrTiO3defined by conductive atomic force microscope lithography, with the potential to perform THz spectroscopy on individual nanoparticles or molecules. Numerical simulation of the time-domain signal helps to identify different contributing components for the THz generation. These results transform the LaAlO3/SrTiO3 interface into a promising platform for integrated lab-on-chip devices.

Quadruple Quantum Dots in GaAs/AlGaAs with Overlapping-Gate Architecture

Haifeng Qiao, Yadav P. Kandel, and John M. Nichol

Spin qubits in semiconductor quantum dots are considered promising candidates for quantum computation due to their long coherence times. In the past years, singlet-triplet qubits defined by double quantum dots in GaAs/AlGaAs heterostructure have been well studied, and have shown promising results in qubit control, readout, and coherence time. Most of the previous device designs adopted a stadium style architecture, where quantum dots are defined laterally by electrostatic gates. We instead fabricate quantum dots using an overlapping architecture, where electrons reside directly underneath the gates, which is expected to create tighter confinement of the dots as well as to provide more precise control over electrons in the dots. We have fabricated quadruple-dot arrays with two nearby charge sensors, and we have been able to tune up all four dots with crosstalk corrections. Tilt and symmetric Ramsey oscillations of singlet-triplet qubits have also been observed. Current experiments and results lay the foundation for future work on stabilization and manipulation of multi-spin states in quantum dot arrays.

Time-frequency two-qudit operation in a single photon

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Time-frequency entangled states have attracted a lot of attention in recent years due to their integrated generation and manipulation processes, as well as their high-dimensional nature. These states can be generated using on-chip microring resonators which make these processes highly scalable. The manipulation of these states can be done by interferometers and switches in the time domain, and using phase modulators and pulse shapers in the frequency domain, all of which can be implemented in on-chip platforms. The high-dimensionality of these states can result in these states to exist in relatively large Hilbert spaces, making them attractive for near-term optical quantum information processing. Recently, we have used on-chip silicon nitride microrings to generate such entangled photon pairs, and by heralding one of these photons, created a probabilistic single photon source [1]. This heralded single photon is capable of carrying two qudits, one in its time and one in its frequency degree freedom. Using dispersion modules, switches and interferometers, we have demonstrated a modulo SUM operation, which adds the frequency qudit to the time qudit. This SUM gate can be used in a qudit teleportation scheme [2], and its components can all be implemented in on-chip platforms. Qudit teleportation can show the power of high-dimensional quantum states for high-rate quantum communications [3].

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Training Quantum and Nanotechnology Workforce: 13 years of Quantum Optics, Quantum Information and Nano-Optics Teaching Laboratory Facility at the Institute of Optics, University of Rochester

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We have adapted to the main challenge (the lack of space in the curriculum) by developing series of modular 3-hour experiments and 20-min-demonstrations based on technical elective, 4-credit-hour laboratory course "Quantum Optics, Quantum Information and Nano-Optics Laboratory", that were incorporated into a number of required courses ranging from freshman to senior level. Rochester Monroe Community College (MCC) students also benefited from this facility that was supported by four NSF grants. Since 2006, total 566 students passed through the labs with lab reports submission (including 144 MCC students) and more than 250 students through lab demonstrations. Four teaching labs were prepared on generation and characterization of entangled and single (antibunched) photons: (1) entanglement and Bell's inequalities; (2) single-photon interference (Young's double slit experiment and Mach-Zehnder interferometer); (3) single-photon source 1: confocal microscope imaging of single emitter fluorescence; (4) single-photon source 2: Hanbury Brown and Twiss setup. Fluorescence antibunching from nanoemitters. Manuals, student reports, lab journals, presentations, lecture materials and quizzes, as well as some NSF grants' reports are placed on a website

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/. In 2011 University of Rochester hosted 6 professors from different US universities in three-days training of these experiments participating in the Immersion Program of the Advanced Laboratory Physics Association.

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rit photonics for quantum

Versatile quantum frequency processor on a silicon photonics platform

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Photonic quantum state preparation and information processing in the frequency degree of freedom have attracted interest in the last couple of years because of the ease with which high-dimensional states can be created and manipulated [1,2]. Using Fourier transform pulse shapers and electro-optic phase modulators, we have measured high-dimensional frequency-bin entanglement in biphoton frequency combs [2], carried out high visibility Hong-Ou-Mandel interference in the frequency domain [3], and implemented elementary quantum gates to carry out deterministic parallel single qubit rotations [3]. We recently designed photonic integrated circuits capable of implementing these functions on a silicon photonics platform. In the addition to reducing optical losses relative to our work with discrete components, our design makes it possible to increase the mode density in the frequency domain, thereby extending the accessible computational space and range of gate operations.

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Characterization of a Picosecond Gated Optical Intensifier

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We present test results on a picosecond gated optical intensifier (GOI) that was originally

developed for use in high temperature plasma diagnostics, yet which provides interesting opportunities to explore high-speed imaging of photonic devices, such as direct observation of slow light in photonic crystals or the propagation of surface plasmonpolaritons

(SPP). The GOI studied has low jitter (SD 4 ps), gate widths less than 100 ps, and an axial magnetic field for improved spatial resolution. We use a pulsed laser to test the gate profile and the spatial resolution performance of the intensifier at different points within the gate. A streak camera is used to verify the pulse shape of the laser, which has a FWHM of 29 ps. A slant edge technique is used to measure the modulation transfer function (MTF), and image uniformity is demonstrated with a Ronchi ruling. The methods detailed will be useful for other detector

characterization, while the results show that the picosecond GOI provides increased time resolution over previous devices, opening up new imaging possibilities.

Keywords: detectors, imaging, photonics, high-speed, microchannel plate, intensifier.

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Additionally, IDQ is a leading provider of optical instrumentation products, most notably photon counters and related electronics. The company's innovative photonic solutions are used in both commercial and research applications

Photon Spot

Photon Spot's detectors and cryogenic systems are used by top research groups around the world. Our superconducting nanowire single-photon detectors (SNSPD) exhibit ultralow dark counts, sub-100ps jitter, and >90% quantum efficiency near 1550nm. This unparalleled detector performance brings much-needed solutions to difficult problems in free-space optical communication, quantum optics experiments, linear optics quantum computing, and semiconductor diagnostics.

Our fully-automated closed-cycle cryostats deliver temperatures below 1K (-272ºC, -457ºF) without the consumption and running expense of liquid helium. Our cryostats are a cost-effective and straight-forward alternative to other technologies like ADRs or dilution fridges in situations where temperatures in the 0.8K - 1K range are desired for an experiment.

We provide a modular system architecture to enable mix-and-match pairing of SNSPDs and cryogenics, so you can build the detector system that meets your exact needs. And if we do not have what you need, we can build it for you.

Princeton Instruments

Princeton Instruments provides state-of-the-art CCD, sCMOS, ICCD, EMCCD, emICCD, X-Ray and InGaAs cameras; spectrometers; spectrographs; imaging systems; optics and coatings that are key to the success of your application. We take pride in partnering with our customers to solve their most challenging problems in unique, innovative ways.

Quantum Design

Quantum Design Inc. (QD) is the manufacturing arm of QDI. Located in San Diego, California, QD is the leading commercial source for automated materials characterization systems incorporating superconducting technology. QD instruments may be found in the world's leading research institutions, and have become the reference standard for a variety of magnetic and physical property measurements. Quantum Design Inc. instruments are cited in, and provide the data for, more scientific publications than any other instrument in the fields of magnetics and materials characterization. This means that each year, literally hundreds of scientific publications, advancing the science of materials, use data generated from QD instruments.

Recently, Quantum Design Inc. expanded its product line beyond material characterization, to include instruments such as: a compact IR Crystal Furnace for the creation of new material; a Superconducting High-Gradient Magnetic Separator (SHGMS) for the processing and improvement of Kaolin clay; and a full line of Advanced Technology Liquefiers (ATL) and Helium Recovery Systems for the conservation and recycling of helium (a vital and increasingly scarce resource essential for cryogenic research and instrumentation).

Quantum Opus

Supplier of Single Photon Counting detectors based on superconducting nanowires. Efficiency is >85% at target wavelengths between 1100nm and 1550nm, and at 600nm - 1100nm we achieve >90% detection efficiency. Low dark counts, fast timing resolution and 40Mcps count rates. Complete solutions with a compact closed cycle cryocooler that supports up to 32 detector channels. Our Nanowires are Silicide based and can operate continuously (no recharge required) for months at a time.

Single Quantum

Single Quantum pioneers the commercialization of superconducting single photon detection systems. Located in Delft, the Netherlands, Single Quantum manufactures closed-cycle superconducting single photon detection systems and single photon spectroscopy systems suitable for single photon spectroscopy and photon correlation measurement. The detectors combine high detection efficiency, high time resolution, low dark count rate, and short dead time. They can detect single photons with higher than 85% efficiency over a broad spectral range and an ultra-high timing resolution of less than 15 ps. The design features continuous operation for up to 10,000 hours and requires no liquid helium consumption, thus a turn-key solution for optical measurements. The systems is designed for demanding applications in quantum information technology, quantum communication and quantum cryptography, infrared time-resolved spectroscopy, laser ranging and remote sensing (LiDAR).

SPIE

SPIE, the international society for optics and photonics, was founded in 1955 to advance light-based technologies.

Serving more than 264,000 constituents from approximately 166 countries, the not-for-profit society advances emerging technologies through interdisciplinary information exchange, continuing education, publications, patent precedent, and career and professional growth.

SPIE annually organizes and sponsors approximately 25 major technical forums, exhibitions, and education programs in North America, Europe, Asia, and the South Pacific.

Thorlabs

Thorlabs, a vertically integrated photonics products manufacturer, was founded in 1989 to serve the laser and electro-optics market. Since then, Thorlabs has extended its core competencies in an effort to play an increasing role in serving the photonics industry, as well as the industrial, life science, medical, and defense segments. The organization's manufacturing assets include semiconductor fabrication of laser diodes, optical amplifiers, lithium niobate modulators, quantum cascade/interband cascade lasers, VCSEL lasers; fiber towers for drawing both silica and fluoride glass optical fibers; metal fabrication facilities; advanced thin film deposition capabilities; and optomechanical and optoelectronic shops.

TOPTICA

TOPTICA is the world leader in diode laser and ultrafast technology for industrial and scientific markets. We offer the widest range of single mode tunable light in the 190 to 4000nm and 0.1 2.7 THz spectral region with various accessories to measure, characterize, stabilize and analyze light. Our products are successfully used for scientific applications in fundamental quantum technology including quantum physics, atom optics, photonics and more. If the required laser is pulsed or cw, tunable or actively frequency stabilized, a frequency comb or complete solution combining many lasers/photonicals – TOPTICA is the ideal partner.