## 1. Welcome

8:00  Opening remarks

8:05  Exhibitor previews: Micro Photon Devices; Hamamatsu; idQuantique; SmartQuantum

### 2. Single-Photon Avalanche Detectors I (session chair: S. Cova)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:25</td>
<td>Mark Itzler</td>
<td>Invited InP avalanche diode-based single photon detectors: current status and future prospects</td>
</tr>
<tr>
<td>8:50</td>
<td>Richard Harris</td>
<td>Degradation of InP-Based Geiger-Mode Avalanche Photodiodes Due to Proton Irradiation</td>
</tr>
<tr>
<td>9:05</td>
<td>Angelo Gulinatti</td>
<td>A physically based model for evaluating the Photon Detection Efficiency and the Temporal Response of SPAD detectors</td>
</tr>
<tr>
<td>9:20</td>
<td>Michael Krainak</td>
<td>Photon-counting detectors on ICESat 1 and candidates for ICESat</td>
</tr>
<tr>
<td>9:35</td>
<td>Andrew Huntington</td>
<td>High-Rate Photon Counting with a Multi-Stage Sub-Geiger InGaAs APD</td>
</tr>
<tr>
<td>9:50</td>
<td></td>
<td>Break</td>
</tr>
</tbody>
</table>

### 3. Single-Photon Avalanche Detectors II (session chair: M. Itzler)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:05</td>
<td>Joe Campbell</td>
<td>Invited Single Photon Avalanche Detectors: Quenching Circuits for Reduced Afterpulsing</td>
</tr>
<tr>
<td>10:30</td>
<td>Sergio Cova</td>
<td>Ultra-fast time-gating of SPAD for wide dynamic range optical measurements</td>
</tr>
<tr>
<td>10:45</td>
<td>Krishna Linga</td>
<td>Very high gain, low excess noise self quenching near infrared single photon counting detectors and arrays</td>
</tr>
<tr>
<td>11:00</td>
<td>Ivan Rech</td>
<td>SPAD array detectors for parallel photon timing applications</td>
</tr>
<tr>
<td>11:30</td>
<td>Yuji Iwai</td>
<td>Hamamatsu will present an introduction to Hamamatsu's Multi Pixel Photon Counter (MPPC) technology and a review of our development and production efforts to date.</td>
</tr>
<tr>
<td>11:45</td>
<td>Fabrizio Guerrier</td>
<td>Single-Photon Imager with Number-Resolving Capability</td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td>Lunch</td>
</tr>
</tbody>
</table>

### 4. Applications of Single-Photon Detectors I (session chair: J. Campbell)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:30</td>
<td>Sergio Cova</td>
<td>Invited Silicon Single-Photon Avalanche Diodes: technology trends and application drive</td>
</tr>
<tr>
<td>13:55</td>
<td>Alessandro Restelli</td>
<td>Investigation of SPAD operation with high-speed sub nanosecond periodic gating</td>
</tr>
<tr>
<td>14:10</td>
<td>Lijun Ma</td>
<td>Single photon detector and spectrometer using up-conversion technology</td>
</tr>
</tbody>
</table>
14:40  Mary Rowe  Single-Photon Detection with Quantum Dot, Optically Gated, Field-Effect Transistors
14:55  break

5. Advanced Measurements with Single-Photon Detectors I (session chair: M. Krainak)

15:15  Hendrik Coldenstrodt-Ronge  Engineering photon sources and detectors for quantum technologies
15:40  Charles Bamber  Direct Measurement of the Photon Wavefunction
15:55  Jessica Cheung  Measurement standards and techniques for photon counting technologies
16:10  Saikat Guha  Enhanced standoff optical sensing resolution using quantum illumination
16:25  Jeff Lundeen  Bridging Particle and Wave Responsivity in a Phase-Sensitive Photon-Number Detector

Nov. 4, Wednesday

1. Advanced Single-Photon Detectors I (session chair: M. Fejer)

8:00  Invited  James Dynes  InGaAs photodetectors for high bit rate single photon applications
8:25  Jungsang Kim  Optimized Photon Detection with Visible Light Photon Counters and its Variations
8:40  Burm Baek  Measurement of single photon detection timing jitter in a visible light photon counter
8:55  Andrew Kerman  Progress in Superconducting Nanowire Single-Photon Detectors at MIT
9:20  Eric Dauler  High-Rate Quantum Key Distribution with Superconducting Nanowire Single Photon Detectors
9:45  break

2. Advanced Single-Photon Detectors II (session chair: A. Kerman)

10:00  Jeffrey Stern  Development of Superconducting Nanowire Single Photon Detector Arrays
10:15  S. B. McCracken  Optimization of States in a Lossy Metrology
10:30  Burm Baek  Superconducting nanowire single-photon detector in an optical cavity for front-side illumination
10:45  Zhizhong Yan  Single photon optoelectronic mixing in the NbN superconducting nanowires
11:00  Adriana Lita  Progress Report on Optimization of Transition-Edge Sensors for High-Efficiency Photon-Number Resolving Detectors
11:15  Olga Minaeva  Up-to-date performance of ultrafast superconducting NbN photon counter
11:30  Martin Fejer  Devices for Single-Photon Wavelength Conversion
3. Advanced Measurements with Single-Photon Detectors II (session chair: E Dauler)

13:30    Brice Calkins  Compact, Robust Sample Mount for Fiber-Coupled Cryogenic Detectors
13:45    Daniel Santavicca  Characterization of terahertz single-photon sensitive bolometric detectors
14:00    Erik Duerr  Photon-Counting Imaging Ladar System at 2-mm Wavelength
14:15    Tracy Clement  High resolution measurement of relative group delay with superconducting nanowire single-photon detectors
14:30    Josef Blazej  Correlation photon counting experiment under conditions of extreme photon fluxes
14:45    break

4. Applications of Single-Photon Detectors I (session chair: J. Dynes)

15:15    Thomas Jennewein  Experimental requirements for few-photon applications outside the coincidence basis
15:30    Thomas Gerrits  Joint spectral distribution of a periodically poled KTP source for quantum information applications
15:45    Xiao Tang  Photon Sources and Detectors for Quantum Communication
16:00    Alexander Ling  Observation of fringe compression with a photon-number resolving detector
16:15    Ryan Bennink  Simultaneous teleportation of multiple photonic degrees of freedom
16:30    R.J. Collins  Short Wavelength Quantum Key Distribution in Telecommunications Optical Fiber

Nov. 5, Thursday

1. Non-classical Sources (session chair: A. Ling)

8:00    Franco Wong  Generation of Single Spatiotemporal Mode Photons
8:25    Chris Chunnilall  A source of entangled photons for the 1550 nm telecommunications window
8:40    Andreas Muller  Towards cross-platform two-photon interference using an efficient single photon source based on a semiconductor quantum dot
9:05    Stefania Castelletto  Near infrared ultra-bright triggered single photon source from nano-diamonds
9:20    Prem Kumar  Ultrafast Switching of Photonic Entanglement
9:45    break

2. Single-Photon Technology I (session chair: P. Kumar)

10:00    Xiaolong Hu  Efficiently Coupling Light to Superconducting Nanowire Single-Photon Detectors
<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:25</td>
<td>Alex Clark</td>
<td>Creating intrinsically time bandwidth limited photon pairs</td>
</tr>
<tr>
<td>10:50</td>
<td>Kevin McCusker</td>
<td>A Pseudo-Deterministic Single-Photon Source</td>
</tr>
<tr>
<td>11:05</td>
<td>Petr Anisimov</td>
<td>Sub-Heisenberg limited phase measurement with two-mode squeezed light</td>
</tr>
<tr>
<td>11:20</td>
<td>Masahiro Takeoka</td>
<td>Photon detections for continuous variable quantum information processing and quantum receivers</td>
</tr>
<tr>
<td>11:45</td>
<td>Xingxing Xing</td>
<td>Towards fundamental tests and quantum information applications using novel photon sources from quantum dots and cavity-enhanced down-conversion</td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td>lunch</td>
</tr>
</tbody>
</table>

### 3. Single-Photon Technology II (session chair: S. Polyakov)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:30</td>
<td>Shellee Dyer</td>
<td>All-Fiber Polarization-Entangled Photon Pair Source: CW Pumping for High Photon Pair Rates</td>
</tr>
<tr>
<td>13:45</td>
<td>Ryan S. Bennink</td>
<td>Optimal Gaussian Beams for Collinear Spontaneous Parametric Down-Conversion</td>
</tr>
<tr>
<td>14:00</td>
<td>M.G. Tanner</td>
<td>Enhanced telecom wavelength sensitivity in NbTiN superconducting nanowire single-photon detectors fabricated on oxidized silicon substrates</td>
</tr>
<tr>
<td>14:15</td>
<td>Martin Stevens</td>
<td>Multi-Element Superconducting Nanowire Single-Photon Detectors for High-Order Coherence Measurements</td>
</tr>
<tr>
<td>14:30</td>
<td>Daniel Lum</td>
<td>The Quantum Tripwire: Analysis in the Presence of Photon Loss</td>
</tr>
<tr>
<td>14:45</td>
<td>Paul Lett</td>
<td>A four-wave mixing source for multi-spatial-mode entanglement</td>
</tr>
<tr>
<td>15:00</td>
<td></td>
<td>break</td>
</tr>
</tbody>
</table>

### 4. Poster Session (15:15-17:00) (Posters should be up from Tuesday to Friday)

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:15</td>
<td>Daniela Bagliani</td>
<td>Study of the thermal coupling in suspended IrAu transition edge sensors operated as single photon detectors</td>
</tr>
<tr>
<td>15:15</td>
<td>Stefan Kuck</td>
<td>Radiometric calibration of single-photon counting detectors</td>
</tr>
<tr>
<td>15:15</td>
<td>Josef Blazej</td>
<td>SPAD detector package for laser time transfer in space</td>
</tr>
<tr>
<td>15:15</td>
<td>N. J. Krichel</td>
<td>Three-Dimensional Profiling of Low-Signature Targets Using Time-Correlated Single-Photon Counting</td>
</tr>
<tr>
<td>15:15</td>
<td>Chris Chunnilall</td>
<td>The measurement of photon indistinguishability to a quantifiable uncertainty using a Hong-Ou-Mandel interferometer</td>
</tr>
<tr>
<td>15:15</td>
<td>Ivo Degiovanni</td>
<td>Suppressing deadtimes for high rate telecom-band photon counting exploiting multiplexed detector array systems</td>
</tr>
<tr>
<td>15:15</td>
<td>Jun Chen</td>
<td>Photon pairs from a PPKTP waveguide: a spectral study</td>
</tr>
<tr>
<td>15:15</td>
<td>Saikat Guha</td>
<td>Approaching Helstrom limits to optical pulse-position demodulation using SPD and optical feedback</td>
</tr>
</tbody>
</table>
5. Summary Session (17:00-18:00) (ringmasters: P. Kwiat & F. Wong)

17:00 Single Photon Technology Summary and Prospects Discussion

Conference Dinner (18:30-21:00)

20:00 Joseph Abeles Photon-Counting Photomultipliers: Technology and Provenance, 1934- present

Nov. 6, Friday

1. Entanglement I (session chair: P. Grangier)

8:00 Plenary Jeff Kimble Quantum Networks with Single Atoms, Photons, and Phonons

9:00 Invited Harald Weinfurter Atom – Photon – Entanglement

9:25 Invited Philip Walther Quantum information processing beyond the state-of-the-art technology

9:50 break

2. Entanglement II (session chair: J. Kimble)

10:00 Invited Philippe Grangier Schrödinger's Kittens and Non-Gaussian States of the Light: New Tools for Quantum Communications

10:25 Invited David Moehring Multi-Photon Entanglement from a Single Trapped Atom

10:50 Invited Wolfgang Tittel Measuring entanglement with universal time-bin qubit analyzers

11:15 Alexander Sergienko Dispersion Cancellation in Quantum Interferometry and Quantum Imaging

11:30 Radhika Rangarajan Engineering Polarization-Entangled Photons

11:45 Alexander Sergienko Photon-counting optical coherence tomography using superconducting single-photon detectors

12:00 lunch

3. Entanglement III (session chair: H. Weinfurter)

13:30 Invited Christian Kurtsiefer Substantial scattering of Photons by a Single Atom

13:55 Invited Warren Grice The Role of Spectral and Spatial Entanglement in Down-Conversion Experiments

14:20 Invited Robert Thew Novel Photon Pair Sources and Threshold Detectors
4. Entanglement IV (session chair: W. Tittel)

15:15 Invited
Allessandro Fedrizzi
Applications and experimental limitations of photonic quantum computing

15:40
Tian Zhong
High Quality Photonic Polarization Entanglement Distribution at 1.3-μm Telecom Wavelength

15:55
Oliver Slattery
Two techniques for high-speed entangled photon pair generation using periodically poled potassium titanyl phosphate waveguides

16:10 Invited
Ivo Degiovanni
Experimental estimation of entanglement at the quantum limit

16:35
Alexios Beveratos
Towards a deterministic entangled and single photon source at telecom wavelength using InAsP/InP quantum dots

16:50
adjourn
InP avalanche diode-based single photon detectors: current status and future prospects

Mark A. Itzler
Princeton Lightwave Inc., 2555 US Route 130 South, Cranbury, NJ 08512 USA

Single photon detectors based on avalanche diode structures are frequently the best choice for applications requiring not only high performance but also high reliability, ease of implementation, and scalability. In the past several years, significant progress has been achieved for certain properties of InP-based single photon avalanche diodes (SPADs), but important limitations remain. Two strategies that have been adopted recently to circumvent some of these present limitations will be reviewed: specifically, the extraction of enhanced device performance using improved hybrid back-end electronic circuitry, and new monolithic chip-level concepts for obtaining improved performance through avalanche self-quenching. To further assess the future prospects for InP SPAD performance, a comparison with Si-based SPADs is instructive.

We have made significant improvement in the fundamental tradeoff between photon detection efficiency (PDE) and dark count rate (DCR) for InP/InGaAs SPADs designed for 1.55 µm photon detection. For PDE ~ 20%, devices routinely exhibit DCR values of a few kHz, and "hero" devices demonstrate that it is possible to achieve sub-kHz DCR performance at temperatures readily accessible using thermoelectric coolers. High precision timing jitter has also been demonstrated for these detectors, with 100 ps jitter found for typical operating conditions, and 50 ps or less obtained for sufficiently high excess bias.

More constraining performance limitations have generally been found with respect to maximum count rate. Although intrinsic SPAD response is fast, with avalanche build-up occurring in less than 1 ns, afterpulsing effects have often limited counting rates to the range of 1 to 10 MHz. Given the materials challenges inherent in reducing defects that give rise to the carrier trapping and de-trapping events that cause afterpulsing, a more prevalent strategy has been to reduce the potential number of carriers that can be trapped by limiting the charge flow per avalanche event. Promising results have been shown through novel electronics circuitry such as a self-differencing architecture for which GHz-range gating frequencies have been attained with 5 to 10% afterpulsing. Additionally, recent low-parasitic hybrid integration implementations of a passive quenching/active reset circuit have shown 100 MHz free-running counting with afterpulsing limited to 1%.

As another path towards reducing avalanche charge flow, there has been considerable progress in implementing rapid self-quenching using monolithic chip-level solutions. These designs are essentially based on passive quenching but with very low parasitic effects. We have pursued self-quenching solutions with integrated resistive feedback and distributed feedback mechanisms. It is interesting to note that while the goal of achieving photon counting with high-gain linear mode APDs is often considered to be quite distinct from Geiger mode operation, these recent attempts to achieve controlled Geiger-mode avalanches through self-quenching may signal a convergence of Geiger-mode and linear-mode approaches.

Finally, a comparison of InP SPAD results with those of state-of-the-art Si avalanche diodes suggests what may be possible if InP materials engineering can be brought to the level of Si. InP-based detectors will always be at a disadvantage relative to Si given the smaller bandgap of the InGaAs(P) absorbers, but this comparison is nevertheless instructive for assessing where improvements in InP avalanche diode devices may be most feasible.

Degradation of InP-Based Geiger-Mode Avalanche Photodiodes Due to Proton Irradiation

Richard D. Harris, William H. Farr, and Heidi N. Becker
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

Degradation of InGaAs/InP Geiger-mode avalanche photodiodes caused by proton irradiation has been studied for the first time. These devices are being explored at JPL for potential communication applications for future NASA missions. Devices for this study were acquired from Princeton Lightwave, Inc. Irradiation was performed using 50-Mev protons at UC Davis to fluences of $2.7 \times 10^9$, $7.5 \times 10^9$, and $8.1 \times 10^{10}$ protons/cm$^2$. Substantial changes in the dark I-V characteristics as well as increases in the dark count rate are observed after even the lowest fluence explored.

Count rates are determined in an ungated mode. The time between the application of an over bias reverse voltage pulse and device breakdown is determined and the times are binned in 1 ns increments into a histogram of counts in each bin vs. time. These interarrival time histograms were collected for a variety of conditions, including dark and illuminated, and for different irradiation fluences.

Analysis of the interarrival time histograms provides dark counts rates, photon count rates, and after pulse count rates. A substantial change in the dark count rate is observed at even the lowest proton fluence. No systematic changes in photon count rate are observed nor in the amount of after-pulsing. The devices are rendered non-operational following the highest fluence employed. These observations indicate that the device changes due to the radiation are primarily due to damage in the absorber region.
A physically based model for evaluating the Photon Detection Efficiency and the Temporal Response of SPAD detectors

A. Gulinatti¹, I. Rech¹, M. Assanelli¹, M. Ghioni¹,², S. Cova¹,²

¹ Politecnico di Milano, Dipartimento di Elettronica e Informazione, Milano, Italy
² MPD Micro-Photon-Devices, via Stradivari 4 – 39100 Bolzano, Italy

We present a physically-based model aimed at calculating the Photon Detection Efficiency (PDE) and the temporal response of a Single-Photon Avalanche Diode (SPAD) with a given structure. A comparison between simulation and experimental results is also reported in order to confirm the model accuracy.

In the last few years, Silicon Single Photon Avalanche Diodes (SPADs) gained wide acceptance as an alternative to Photomultiplier Tubes (PMTs) in many photon counting and photon timing applications thanks to their remarkable performance. In particular, their Photon Detection Efficiency (PDE) is higher than the one usually achievable with PMTs. Nevertheless, many demanding applications would greatly benefit of a further improvement of the PDE, especially at the longer wavelengths (800nm < λ < 1000nm). Similarly, some special applications, such as quantum key distribution, would equally benefit of a reduction in the slow component of the device temporal response. Both the targets can be attained by suitable modifications of the detector structure; however, the complexity of the problem requires the development of models that can help device designers in the optimization task.

In this paper we present a physically-based model aimed at calculating the PDE and the temporal response (TR) of a SPAD with a given structure. In order to calculate these quantities, it necessary to evaluate both the probability and the delay with which a photon impinging on the detector area triggers an avalanche. Three tasks are sequentially performed: as a first step, the electron-hole generation profile along the device is calculated according to the silicon absorption coefficient at the considered wavelength; successively, the temporal evolution of the carriers distribution along the device is calculated by solving drift diffusion equations; finally, the avalanche triggering probability is calculated as a function of the photon absorption point.

Validation of the model has been carried out by comparing simulation and experimental results of a few generations of detectors previously realized in our laboratory. Doping profile, needed for the calculation of the electric field, has been obtained by using Secondary Ions Mass Spectroscopy (SIMS). Photon detection efficiency has been measured and calculated for wavelengths ranging from 400nm to 1000nm and for excess bias voltages ranging from 2 to 8V. Similarly, temporal response has been investigated at two different wavelengths (520 and 780nm).

Two example of comparison between simulation and experimental results are reported in Figure 1 and Figure 2. The former represents the PDE, as a function of the wavelength, for a 50µm diameter device belonging to production lot S62. The latter reports the TR of a detector belonging to production lot S44 evaluated at a wavelength of 780nm. In both cases, both the measurement and the simulation have been carried out at an overvoltage of 5V. However, similar results have obtained at the other overvoltages.

A remarkable agreement between experimental and simulation results has been obtained in the entire characterization domain simply introducing the measured doping profile into the model. A key point is that the model does not include any fitting parameters and therefore it should be able to predict the performance of other SPAD. In conclusion, we think that the model we developed will be a valuable tool for the design of detectors with improved performances. In particular, our aim is to use this model to design devices with either a higher PDE, a faster diffusion tail or a better temporal response at the short wavelengths (<450nm).

![Figure 1. PDE of a SPAD belonging to lot S62. Both simulation and measurement have been carried out at 5V of overvoltage.](image)

![Figure 2. Temporal response of a SPAD belonging to lot S44. Both simulation and measurement have been carried out at wavelength of 780nm.](image)
Photon-counting detectors on ICESat 1 and candidates for ICESat 2

Michael A. Krainak, Guangning Yang and Xiaoli Sun

NASA Goddard Space Flight Center
Greenbelt, MD 20771

Si avalanche photodiode (APD) single photon counting modules (SPCMs) are used in the Geoscience Laser Altimeter System (GLAS) on Ice, Cloud, and land Elevation Satellite (ICESat 1), currently in orbit measuring Earth surface elevation and atmosphere backscattering. These SPCMs are used to measure cloud and aerosol backscattering to the GLAS laser light at 532-nm wavelength, with quantum efficiencies of 60 to 70% and maximum count rates greater than 13 millions/s. The performance of the SPCMs has been monitored since ICESat launch on January 12, 2003. There has been no measurable change in the quantum efficiency, linearity or afterpulsing. The detector dark counts rates monitored while the spacecraft was in the dark side of the Earth have increased linearly at about 55.5 counts/s per day due to space radiation damage. As the ICESat 1 mission nears completion, we have proposed ground-to-space optical and quantum communication experiments to utilize the on-orbit 1-meter optical receiver with multiple SPCMs in the focal plane. For ICESat 2, major candidate photon counting detectors under evaluation include 532 nm and 1064 nm wavelength-sensitive photomultiplier tubes and Geiger-mode avalanche photodiode arrays. Key specifications are high maximum count rate, detection efficiency, photon number resolution, radiation tolerance, power consumption, operating temperature and reliability.
High-Rate Photon Counting with a Multi-Stage Sub-Geiger InGaAs APD

Andrew S. Huntington, Voxtel, Inc., 12725 SW Millikan Way, Suite 230, Beaverton, OR 97005

Abstract: Afterpulsing imposes a dead time following single photon detection which limits the maximum count rate at which a Geiger avalanche photodiode (APD) can be operated. One strategy to minimize afterpulsing is to reduce the amount of current which flows when a photon-counting APD fires, because this limits the population of traps which are filled during the detection event. Sub-Geiger photon-counting APDs are operated at sufficiently high avalanche gain to develop a detectible signal in response to generation of a single primary photoelectron, yet below the breakdown voltage of the diode junction, such that current flow is minimized. Calculations based upon the pulse height distribution of linear-mode APDs shows that the photon detection efficiency of a high-gain linear-mode APD will be highest for APDs with the lowest excess multiplication noise. We describe a multi-gain-stage InGaAs APD structure that operates with very low excess multiplication noise at high linear gain, and its characterization as a sub-Geiger photon counter.

This work was funded by NIST under SBIR contracts:
Phase I: SB-1341-08-SE-0665
Phase II: SB-1341-09-CN-0079
Single Photon Avalanche Detectors: Quenching Circuits for Reduced Afterpulsing

Joe C. Campbell and Chong Hu
University of Virginia, 351 McCormick Road, 22904 Charlottesville, USA

Much of the research on single photon avalanche diodes that operate in the short wave infrared (SWIR) spectral regime has focused on increasing the photon detection efficiency while reducing the dark count rate, which has resulted in performance that is adequate for several “single photon” applications. On the other hand, afterpulsing continues, in many cases, to severely restrict performance owing to the requirement for long hold off times to permit the emission of trapped carriers. One technique to reducing afterpulsing is to decrease the total charge flow in each avalanche event. Using this approach, we report a quenching circuit, passive quenching with active reset, that has permitted > 500x reduction in the hold-off time.

SWIR SPADs utilize a reach-through structure in which most of the incident light is absorbed in a low-field region. The photogenerated carriers are then injected into a high field multiplication region. The relative field strengths are determined, to a great extent, by a charge layer between the multiplication and absorbing layers. The single photon detection efficiency is the product of the external quantum efficiency in the absorber, the transport efficiency from the absorber to the multiplication layer, and the probability that an injected carrier will initiate a self-sustaining avalanche breakdown. By utilizing sufficiently thick absorption layers and good anti-reflection coatings, external quantum efficiencies greater than 90% are easily attained. The transport efficiency is usually ~ 100%. Hence, the single photon detection efficiency is primarily determined by the avalanche breakdown probability, which increases with higher excess bias voltage. The dark counts, which are false positives in the digital sense, arise from the dark current. The dark current is primarily due to trap-assisted generation in the absorbing region and, in some cases, tunneling tunneling in the multiplication layer. While higher photon detection efficiency can be achieved by increasing the excess voltage above breakdown, this also results in higher dark current and, thus, an increase in the dark count rate.

InP/InGaAsP [1,2,3,4,5] and InP/InGaAs [3,6,7,8,9] SACM SPADs have been studied widely as single-photon counters for operation at 1.06 μm and ~1.55 μm, respectively. While room temperature operation has been achieved, in most cases cooling is required in order to achieve acceptable dark count rates. At 1.06 μm Itzler et al. have achieved 40% single photon detection efficiency and dark count rates of 2 kHz at an operating temperature of 248 K [2]. Room temperature operation with 50% detection efficiency and dark count rates < 20 kHz was reported by Verghese et al. [3]. SPADs that operate at 1.55 μm, typically require more cooling because the lower bandgap of InGaAs results in higher dark current. Liu et al. [10] have reported high single-photon detection efficiency (~40%) and low dark count rate (< 10^7/s) at 220K. S. Verghese, et al., reported SPADs with InGaAs absorbers optimized for 1.55 μm wavelength; at 240 K these SPADs achieved dark count rates <20 kHz with photon detection efficiency as high as 45% [3]. Recently a dark count rate as low as 1 kHz and 20% detection efficiency have been achieved at 243 K [11]. Even higher efficiencies can be achieved but at the cost of higher error probabilities. Figure 1 shows the photon detection efficiency of a planar 25 μm-diameter InP/InGaAs SPAD at 1550 nm versus excess bias normalized to the breakdown voltage for temperatures of 200K, 240K, and 280K. At 280K the detection efficiency is as high as 65%, however, the error probability is 9%.

Figure 1. Photon detection efficiency versus excess bias normalized to the breakdown voltage at 200K, 240K, and 280K. The error probability for each curve is indicated with an error.
reducing the total charge flow through the multiplication region for an avalanche event. At higher operating temperature, the traps have higher emission rates; consequently, the hold off time is reduced resulting in the potential for higher transmission rates. Higher temperature operation can be achieved by (1) decreasing the electric field in the absorber and (2) improving the material quality to reduce the number of trap states. Alternatively, fewer carriers will be captured in the multiplication region by limiting the total charge flow during an avalanche event to the minimum value required to achieve accurate counts or by developing materials technologies to significantly reduce the number of trap centers.

Recently, we have developed a new quenching circuit, passive quenching with active reset (PQAR) [12]. A schematic diagram of the PQAR circuit is shown in Fig. 2 [13]. The transistor connected in series with the SPAD is normally on. Since the current is limited to a high degree by the large “on-state” resistance, an avalanche current will quickly discharge the device to lower its bias, and therefore effect rapid quenching shortly after the avalanche has been triggered. Owing to the large quenching resistance the excess voltage will remain very low. This is the passive quenching aspect of the PQAR circuit. As the avalanche is initiated, the negative voltage pulse at the cathode of the SPAD is coupled into the input of an amplifier through a 10 nF capacitor and the amplified signal pulse registers on the counter. Simultaneously, the counter triggers the following pulse generator, which after a specified delay (hold-off), sends another pulse to turn off the transistor for a short time. Recharge now occurs through the 50 Ω resistor and the “off-state” resistance, which is very fast. The net result is the excess bias on the SPAD is very low to allow the trapped carriers to escape and then the voltage is quickly reset to the detection state. This quenching approach has achieved the same single photon detection efficiencies and dark count probabilities as gated quenching. The hybrid gated mode PQAR circuit included an InP/InGaAs planar SPAD and two GaAs FETs on a sapphire/ceramic submount. The photon detection efficiency (PDE) and dark count probability (DCP) were measured at a gate repetition rate of 1 MHz owing to the maximum operating frequency of the pulsed laser driver. To measure the afterpulsing probability, a two-pulse measurement technique was utilized. The light intensity in the first pulse was sufficient to guarantee 100% avalanche probability. Afterpulsing probability was measured in the second pulse. The afterpulsing probability was measured for various delays between the two pulses. At 280K, 1% afterpulsing probability for 10 ns delay was achieved with 12% PDE and 3×10^{-3} DCP. At 230K and 10 ns delay, 30% PDE and 1×10^{-5} DCP was achieved with 6% afterpulsing probability.

In conclusion, the performance of single photon avalanche diodes is rapidly improving, which is enabling several emerging application for low-light-level detection. While there is always room for improvement, the single photon detection efficiencies and dark count rates that have been achieved are acceptable for many applications. However, higher operating temperature, particularly for 1.55 μm operation, will continue to be a research thrust. Reduced afterpulsing in order to achieve higher frequencies remains a critical issue for high transmission applications, such as quantum communications.

This work was supported by DARPA through the Photon Counting Arrays Program.

References


Ultra-fast time-gating of SPAD for wide dynamic range optical measurements

Alberto Tosi, Alberto Dalla Mora, Franco Zappa, Sergio Cova
IIT, Politecnico di Milano - Dipartimento di Elettronica e Informazione
Davide Contini, Antonio Pifferi, Lorenzo Spinelli, Alessandro Torricelli, and Rinaldo Cubeddu
IIT, ULTRAS-INFM-CNR and IFN-CNR, Politecnico di Milano - Dipartimento di Fisica
alberto.tosi@polimi.it

In applications like time-resolved NIR spectroscopy (functional brain imaging [1], optical mammography [2], optical molecular imaging [3], etc.), a large amount of photons either precedes or follows the useful signal. In order to cut away such strong stray light, it is useful to employ detection systems based on a single-photon detector that can be gated on and off very quickly [5]. The photodetector must be fired only by the useful signal photons and has to be tough enough not to be damaged by the excitation laser pulse.

We present a novel technology based on Single-Photon Avalanche Diode (SPAD) [6] able to gate-on the detector in less than 200 ps and to guarantee a clean response (with no ringings, distortions, etc.) right after the rising-edge of the enabling waveform. The SPAD can be operated at a repetition frequency up to 50 MHz, with gate duration selectable from 500ps to hundreds of ns. Our differential avalanche-signal read-out circuit allows to achieve a timing resolution of about 50ps (Full-Width at Half Maximum), thus guaranteeing a sharp temporal reconstruction of the signal waveform, i.e. high signal bandwidth.

The silicon SPAD, developed at Politecnico di Milano [7] and employed in commercial modules by Micro Photon Devices Srl, has a 200-µm active area diameter and a breakdown voltage of about 30V. We developed our own fast pulse generator to gate on and off the detector with clean and sharp transitions down to 50 ps. It is triggered by the optical excitation pulse, after a well-defined time delay, which is selectable by means of a programmable delayer (with minimum time steps of 25 ps). Unwanted photons are avoided by simply delaying the gate pulse with respect to the optical excitation.

In particular, we used our technology in time-resolved reflectance spectroscopy. When the source-detector separation is decreased to improve performances [5], standard detection electronics certainly saturates because of the huge amount of “early” photons, diffused by superficial layers. Instead, our setup rejects those photons and detects only “late” photons (coming from deep layers of the tissue under investigation). Thanks to this feature, it is even possible to increase the injected excitation power, in order to increase dynamic range and signal-to-noise ratio. We acquired diffusive curves of two phantoms with 95-ps time resolution and 10⁷ dynamic range, with a strong improvement of three orders of magnitude in measurement time. This approach allows to overreach the limits of TCSPC technique, where the optical excitation power at small interfiber distances must be limited to avoid saturation of the detection electronics.

“The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7 2007-2013) under grant agreement n°. HEALTH-F5-2008-201076.”

References
Very high gain, low excess noise self quenching near infrared single photon counting detectors and arrays

Krishna Linga

Amplification Technologies Inc
1400 Coney Island Ave
New York NY 11230
linga@amplificationtechnologies.com

We have designed and developed a new family of photodetectors with internal discrete amplification mechanism for the realization of very high gain, low excess noise self quenching single photon counting detectors and detector arrays in the visible and near infrared spectral regions. Potential benefits of this technology over conventional avalanche photodetectors include ultra low excess noise factor, very high gain and lower reset time with no dead time. In the photon counting mode, the devices can be operated in the non-gated mode under a constant dc bias. Because of its unique characteristics of self-quenching and self-recovery, no external quenching circuit is needed.

We present the discrete amplification design approach used for the development of self quenching single photon counting detectors and detector arrays in the near infrared wavelength region. We present the simulation results as well as the measured performance results. The demonstrated device performance far exceeds any available solid state single photon counting photodetectors in the near infrared wavelength range. The measured devices have the following performance characteristics: gain > 2X10^5, excess noise factor < 1.05, rise time < 350ps, fall time < 500ps, dark current < 2X10^6 cps, operating Voltage < 60V. These devices are ideal for researchers in the field of free space optical communication, spectroscopy, industrial and scientific instrumentation, Ladar, quantum cryptography, night vision and other military, defence and aerospace applications.

About the Author:

Dr. Linga has more than 18 years experience in the p-i-n and APD based photodetectors, detector arrays, optical receivers, light emitting devices, lasers and other opto-electronic components. He has more than 25 publications, five US patents issued and several pending. Dr. Linga earned his Ph.D., and M.S. degree in Electrical Engineering from New Jersey Institute of Technology. His Ph.D. work was focused on using a technology to develop novel photodetector designs.
SPAD array detectors for parallel photon timing applications

I. Rech¹, C. Cammi¹, A. Gulinatti¹, P. Maccagnani², M. Ghioni¹, S. Cova¹

¹ Politecnico di Milano, Dipartimento di Elettronica e Informazione, Milano, Italy
² IMM-CNR, Bologna, Italy

Over the past few years there has been a growing interest in monolithic arrays of single photon avalanche diodes (SPAD) for spatially resolved detection of faint ultrafast optical signals. SPADs implemented in CMOS-compatible planar technologies offer the typical advantages of microelectronic devices (small size, ruggedness, low voltage, low power, etc.). Furthermore, they have inherently higher photon detection efficiency than PMTs and are able to provide, beside sensitivities down to single-photons, very high acquisition speeds. In order to make SPAD array more and more competitive in time-resolved application it is necessary to face problems like electrical crosstalk between adjacent pixels.

Time Correlated Single Photon Counting (TCSPC) has reached a considerable importance and a great deal of techniques have been developed based on it, such as Fluorescence Lifetime Imaging (FLIM), optical tomography and time-resolved laser scanning microscopy. Recently, new improvements in the TCSPC technique allowed its application to multidimensional measurements; this consequently required the development of new arrays of detectors with high photon detection efficiency, low dark counting rate and afterpulsing, low optical and electrical crosstalk and high timing performances. TCSPC was developed relying on photomultiplier tubes (PMTs) but, in recent years, Single Photon Avalanche Diodes (SPADs) have emerged as a solid state alternative, in particular for the production of arrays, since they present remarkable advantages such as: low cost, high integrability, low power dissipation and higher quantum efficiency. We have already shown [1] that it is possible to fabricate good detectors with diameters of 50, 100 and 200 µm, and we are currently developing SPAD detectors with diameters up to 500 µm. We also proved that it is possible to obtain time resolutions down to 30-35 ps FWHM not only using the smaller detectors, but even with diameters as large as 200 µm.

To obtain better timing performances, the rising edge of the current flowing into the SPAD detector has to be sensed during the initial part of its rise, where the multiplication region is still confined within a small area and the contribution to the temporal jitter due to the avalanche propagation can be considered negligible. For this reason, the sensing of the avalanche onset is made by a fast comparator at very low threshold, in the order of 5-10 mV [2]. This approach is not suitable for the realization of a parallel system because of the presence of electrical couplings between adjacent channels due to the use of multiple AQCs.

The key idea of this work is to integrate the front-end electronics close to the device in order to reduce the parasitic capacitances and, with them, the couplings between adjacent channels. Besides, we know that it is important to avoid any filtering of the current flowing into the device in order to obtain a good temporal resolution. Therefore, it is expected that integrating the timing circuitry directly close to the device could reduce the jitter or, more likely, could give the same timing performance, with a more relaxed electronics. This solution does not affect only the timing performances of the detector, but could also improve afterpulsing and optical crosstalk [3], which are proportional to the number of carriers flowing into the device during the avalanche, and thus to the capacitance connected to the quenching node.

In order to achieve high performances, SPADs are fabricated in a custom technology which gives a complete control on the structure of the detector. To allow the integration of MOS transistors, the process flow has been modified paying attention to retain the structure and the performances of the SPAD. The architectural solution adopted for the front-end electronics allows us to use only few transistors and their performances are adequate to our purposes. The passive quenching circuit is obtained using a nMOS, sized to limit the current flowing through the device near breakdown to 50 µA. The performances of the circuit have been investigated, obtaining a temporal resolution of about 37 ps. The results underline that the adopted approach is suitable for the development of a monolithic array with high timing performances.


Crosstalk Analysis of Integrated Geiger-mode Avalanche Photodiode Focal Plane Arrays

MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA USA 02420

ABSTRACT

Large arrays of photon-counting Geiger-mode avalanche photodiodes (APDs) sensitive to 1.06 and 1.55 μm wavelengths as large as 256 x 64 elements and down to 50 μm pitch have been fabricated for defense applications. As array size, density and performance increase, optical crosstalk becomes an increasingly limiting source of spurious counts. We characterize the crosstalk by measurement of emitted light, and by extracting the spatial and temporal focal plane array (FPA) response to the light from FPA dark count statistics. From this crosstalk response, we discuss the physical and geometrical causes of FPA crosstalk, suggest metrics useful to system designers, then present measured crosstalk metrics for large FPAs as a function of their operating parameters. We then present FPA designs that suppress crosstalk effects and show a greater than 100 times reduction in crosstalk.

This work was sponsored by the Defense Advanced Research Projects Agency under Air Force contract number FA8721-05-0C-002. The opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
Hamamatsu will present an introduction to Hamamatsu's Multi Pixel Photon Counter (MPPC) technology and a review of our development and production efforts to date

Yuji Iwai and Earl Hergert, Hamamatsu Corporation

Hamamatsu will present an introduction to our MPPC (SiPM) technology. The discussion will start with the performance of MPPCs as well as efforts to improve their performance. Then we will discuss the trade off involved when selecting one of these devices for a particular application. We will then introduce some developments and custom work we have done. We will end with a summary of our current state of MPPC production.
Single-Photon Imager with Number-Resolving Capability

F. Guerrieri\textsuperscript{1,3}, S. Tisa\textsuperscript{2}, F. Zappa\textsuperscript{1}, F.N.C. Wong\textsuperscript{3}

\textsuperscript{1} Politecnico di Milano, Dip. Elettronica e Informazione, Milano, 20133, Italy
\textsuperscript{2} Micro Photon Devices, Bolzano, 39100, Italy
\textsuperscript{3} Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139

email: guerrieri@elet.polimi.it

Summary

Two-dimensional monolithic imagers are essential in many applications that require both very high sensitivity (possibly at the single-photon level) and very high acquisition speed (i.e., either high frame rates or very short integration time slots). Notwithstanding several imagers already exist, very few of them fulfill both requirements. CCDs and similar imagers lack in speed because their readout process is based on a slow charge-transfer mechanism. On the other hand, CMOS active pixel sensors (APSs) are not able to detect very faint optical signals due to poor sensitivity and noisy electronics.

We propose and demonstrate an imager in which every pixel comprises not only a 20 \textmu m-diameter Single-Photon Avalanche Diode (SPAD), but also a front-end electronics and a processing circuitry for counting photons. Therefore each pixel is a completely independent photon-counting channel. The chips are fabricated in a standard high-voltage 0.35-\textmu m CMOS technology and have dimensions of 3.5 mm x 3.5 mm. Measured Photo Detection Efficiency (PDE) tops 43\% at 5V excess-bias, while Dark-Counting Rate (DCR) is below 4kcps (counts per second) at room temperature. The maximum frame rate depends on the system clock; with a convenient 100 MHz clock, free-running speed from the whole 1024 pixels tops at 100 kframe/s. The on-chip global electronics improves imager flexibility by allowing the user to arbitrarily select any desired sub-area of the overall array, thus increasing its maximum operating speed. Moreover, for applications exploiting synchronous excitation, we equip the imager with a gating input pin to quickly gate on/off the integration (sub-nanosecond transitions). The gating mechanism makes it possible to accumulate photon counts in different gating periods for the same frame window.

In addition to the standard operating mode, pixels can be grouped so that the imager becomes suitable for Photon-Number-Resolved acquisitions. A single SPAD detects only one photon per dead time because the detection event prevents any other photons to be detected during the dead-time period. The saturating maximum count rate is the inverse of the dead time. On the contrary, if N SPADs are considered as belonging to a bigger super-pixel, that super-pixel saturates at a count rate that is N-times higher, and will be able to detect up to N photons simultaneously. We have characterized the imager as a multi-photon detector and found that the results of super-pixels composed of one single pixel, a quadrant of the imager (i.e., an array of 16x16 SPADs) and the whole imager are in good agreement with theory.

Our array is a general-purpose variable-area imager for single-photon, high-speed applications with Photon-Number-Resolving capability working in both free-running and gated-mode acquisitions. It can operate as a stand-alone chip (with 1 kpixels) or used as the building block of much larger arrays (e.g. 1 Mpixels), by simply placing chips side by side (e.g. 10 x 10 self standing chips) and delivering data from different chips through a single time-multiplexed bus.
The progress in planar device fabrication technology has led Silicon single-photon avalanche diodes (SPAD) to emerge from the laboratory research phase and be commercially available from various manufactures. Planar Si-SPADs with remarkable performance can nowadays be developed also by fab-less laboratories, relying on industrial microelectronic fabrication services of Silicon foundries that offer advanced High-Voltage CMOS technologies. As the applications of planar Si-SPADs progressively expand in various fields, challenges are met that generate driving forces for further technological development of the Si-SPAD technologies. The prospect of widespread use in free-space systems for Quantum Key Distribution (QKD) calls for improvement of the single Si-SPAD detector, with key requirements concerning larger diameter of the sensitive area and improved photon detection efficiency (PDE) in the red and near infrared spectral range. High-performance and high-rate QKD systems require also photon-timing with low jitter and shorter diffusion tail and a low dark-count rate (DCR). Applications in life sciences (Bio-Analytical instrumentation up to Single Molecule detection) require not only high-performance single detectors, but also array detectors. Depending on the various applications, requests may concern different kind of arrays (linear arrays or matrix arrays) and put forward different ranking of the various features and performance parameters involved. In cases where high frame-rate imaging is a primary goal, the requests concern primarily high number of pixels and monolithically integrated systems, which include detector and electronic circuitry for detector operation and data pre-processing. In other cases (e.g. Fluorescence Lifetime Imaging Microscopy FLIM; Fluorescence Correlation Spectroscopy FCS) the accent is more on pixels with size and performance similar to that requested for single Si-SPAD detectors. The current state of the art of the Si-SPAD detector technology will be briefly reviewed, taking into account the issues concerning both the planar Si-SPAD device and the associated circuitry for detector operation. The situation will be analyzed in the light of the requests coming from applications of current interest. The main issues met will be discussed and work being carried out in our lab will be reported. An outlook on the prospect of progress will be proposed.
Investigation of SPAD operation with high-speed sub-nanosecond periodic gating

Alessandro Restelli, Joshua Bienfang.
National Institute of Standards and Technology
Gaithersburg, MD 20899

Gated operation of InGaAs/InP single-photon avalanche diodes (SPADs) enables the use of detectors whose high dark count and afterpulse probabilities would otherwise limit their utility. Recent experimental work has shown that minimizing the avalanche current, by reducing the gate duration and over voltage, can allow SPADs to operate at high repetition rates, albeit with lower detection efficiency. Several electronic schemes for the discrimination of weak avalanche signals from the capacitively coupled gating pulse have been proposed and analyzed in the literature. We investigate discrimination techniques with a single InGaAs/InP SPAD, and present results for detection efficiency, afterpulse probability, and dark count probability. We are specifically interested in how these characteristics change with gate amplitude and temporal width at various operating temperatures.
Single photon detector and spectrometer using up-conversion technology

Lijun Ma, Oliver Slattery and Xiao Tang,

Information Technology Laboratory, National Institute of Standards and Technology
100 Bureau Dr., Gaithersburg, MD 20899 USA

We developed a low-noise up-conversion single photon detector for 1310 nm based on a 5-cm long periodically-poled LiNbO₃ (PPLN) waveguide. Signal photons at 1310 nm are up-converted to 710 nm in the PPLN waveguide with a pump of synchronized optical pulses at 1550 nm and then detected by a silicon avalanche photodiode (Si-APD). The low-noise feature of the detector is achieved mainly by using highly efficient waveguide and a synchronized pulse pumping arrangement with the pump at a wavelength longer than the signal wavelength.

We further use a 1550-nm tunable laser as a pump seed laser in the detector and develop related counting system to implement an up-conversion spectrometer at 1310-nm band. The up-conversion spectrometer traces the 1310-nm band spectrum by scanning the pump laser wavelength, instead of dispersive elements, such as tunable filter or grating, therefore reducing the transmission loss. With the unique property and high detection efficiency, the sensitivity of the spectrometer reach to -126dBm, this is at least three-orders-magnitude higher than that of any commercial optical spectrometer.

In this talk, we will present the up-conversion detector and spectrometer and its experiment results.
Jitter Characterization of Near-Infrared Sensitive Single Photon Detectors

William Farr, David Aveline and Kevin Birnbaum
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

High detection efficiency and low dark count rate are always important performance goals for single photon detector technologies. However, for many applications high timing precision for single photon arrival events is also a critical performance metric.

At the Jet Propulsion Laboratory we have pursued characterization and development of single photon detectors for interplanetary optical communications in the near infrared spectral region from 1 to 1.6 microns, where DC to optical power efficient laser sources are available. Photon efficient communications at data rates exceeding hundreds of megabits per second then demand single photon sensitive detectors with sub-nanosecond detection event timing resolution. Furthermore, these interplanetary optical communications systems can also be excellent platforms for testing relativistic gravity and probing physics beyond the Standard Model, and those experiments can have even more stringent requirements on timing precision.

To these ends we have characterized and present measurement results of single photon timing jitter for numerous near-infrared detector technologies, including silicon Geiger mode avalanche photodiodes, InGaAs and InGaAsP phototubes, InGaAs and InGaAsP Geiger-mode and self-resetting negative avalanche feedback photodiodes, cryogenic Si:As linear mode photon counters, and Nb(Ti)N superconducting nanowire arrays. Finally, we shall also show use of single photon detector arrays to improve timing precision beyond the bandwidth and jitter limits of a single detector element.
Single-Photon Detection with Quantum Dot, Optically Gated, Field-Effect Transistors

M. A. Rowe, G. M. Salley, E. J. Gansen*, S. M. Etzel, S. W. Nam and R. P. Mirin
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305 USA
mrowe@boulder.nist.gov

*University of Wisconsin-La Crosse, 1725 State Street, La Crosse, WI 54601 USA

We will describe an innovative approach to single-photon detection, where a non-perturbing gain mechanism is utilized. The quantum dot, optically gated, field-effect transistor (QDOGFET) traps photoexcited charge in quantum dots embedded in its heterostructure. This trapped charge is amplified when it produces a persistent change in the transistor's channel current, which can be measured for an extended time, allowing sensitivity to single photons. By using quantum dots as charge traps, which can be controllably positioned within an engineered heterostructure, we have tailored our high electron mobility transistor device for photon detection with high internal quantum efficiency and signal uniformity. Because photoconductive gain is applied independently and uniformly to each photon we have seen well-resolved signals from different photon numbers. In addition, this device offers the potential to preserve the incident photon's polarization information and possibly even re-emit a photon with the original photon's polarization state. With these unique device capabilities quantum information applications such as quantum memories or repeaters may be enabled. We will expand on the QDOGFET's mechanics as well as the advantages and challenges of this emerging technology.
Engineering photon sources and detectors for quantum technologies
Brian J. Smith$^{1,2}$, O. Cohen$^2$, N. Thomas-Peter$^2$, H. Coldenstrodt-Ronge$^2$, P. Mahou$^2$, J. S. Lundeen$^3$, G. Puentes$^2$, and I. A. Walmsley$^2$

$^1$Centre for Quantum Technologies, National University of Singapore
3 Science Drive 2, 117543 Singapore, Singapore
$^2$University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom
$^3$Institute for National Measurement Standards, National Research Council
1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada

Abstract: The ability to create and efficiently measure quantum states of light is of great importance to emerging quantum technologies and tests of quantum theory itself. Nonlinear optical approaches such as spontaneous parametric downconversion and four-wave mixing allow creation of a wide range of useful states – from highly-entangled to completely separable photon pairs as well as squeezed states of light. Here we present techniques for controlling the spatial-temporal mode structure of the light produced by nonlinear processes. In particular, we show that it is possible to create heralded single photons in pure quantum states by engineering the mode structure into which spontaneous scattering can take place. Further, guided wave structures enable efficient nonlinear conversion. Optical detection methods, such as photon counting or homodyne detection, are useful in both preparing and characterizing the quantum state of such non-classical sources. We have developed a phase-sensitive photon-counting detector based upon weak-field homodyne detection coupled with photon-counting detectors in order to characterize few-photon states produced by such sources. This detector bridges the particle-like aspects of a photon-counting detector and the wave-like aspects of a standard homodyne detector. To determine the operation of quantum detectors, characterized by their positive operator-value measure (POVM), an approach similar to quantum state tomography can be used. As an example, we present detector tomography of two optical detectors often used in photon-counting experiments – an avalanche photodiode and a mode-multiplexed photon-counting detector.
Direct Measurement of the Photon Wavefunction

C. Bamber\textsuperscript{1}, Jeff S. Lundeen\textsuperscript{1}, Rick Gerson\textsuperscript{1}, Aabid Patel\textsuperscript{2}, Corey Stewart\textsuperscript{2}

1: Institute for National Measurement Standards, National Research Council, Ottawa, Canada
2: University of Waterloo, Canada

Many methods exist to computationally reconstruct the wavefunction from a series of measurements on an identically prepared ensemble. In contrast, here we experimentally demonstrate that the quantum wavefunction can be measured directly, in that it appears as a reading on our measurement apparatus. We make a weak measurement (i.e. minimally disturbing) of the transverse position of a photon. The average result of this measurement, in the subset of photons found to subsequently have zero transverse momentum, is directly proportional to the photon's transverse position wavefunction, including the phase. We present results using photons from a single-photon source.
Measurement standards and techniques for photon counting technologies

Andrew R. Beaumont1, Jessica Y. Cheung1, Christopher J. Chunnilall1, Geiland Porrovecchio2, Marek Smid2, Evangelos Theocharous1, Peter J. Thomas1,3, Jonathan M. Williams1

1National Physical Laboratory, Teddington TW11 0LW, UK
2Czech Metrology Institute, LFM, V. Botanice 4, Praha 5, Czech Republic
3School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, UK

This paper provides an overview of the current research activities at NPL to develop a metrological infrastructure for quantum optical technologies. We discuss progress in developing a technique for calibrating photon-counting detectors – using both conventional and correlated photon techniques, as well as the measurement of the uniformity, linearity and jitter of (VIS/NIR) photon counting detectors.

Measurement of detector quantum efficiency

NPL has been developing a technique which can provide an absolute calibration of detector quantum efficiency (q.e.) in the photon counting regime, using correlated photons produced via spontaneous parametric down conversion (SPDC) in non-linear media1. The uncertainty with which the technique is currently realized is better than 1% 2,3. An independent measurement is required to cross-validate the correlated photon technique. To this end, NPL has collaborated with the Czech Metrology Institute (CMI) to measure the detection efficiency of a photon counting detector using a conventional trap detector and a CMI/NPL–developed switched integration amplifier (SIA)4. When used with a trap detector, the SIA offers high gain and low noise performance compared with the more commonly used TIA (transimpedance amplifier). The trap detector has been calibrated against the current primary standard for optical radiation, the cryogenic radiometer. The results of the conventional calibration, and further characterisation of the SIAs, will be reported.

Measurement of detector uniformity, linearity and jitter

The spatial non-uniformity is a critical aspect of the cross validation as we cannot be sure that we are irradiating the same area of the detector in the two techniques. The NPL spatial uniformity and linearity facility has recently been upgraded to allow operation in current mode and photon-counting mode. Results, and interpretation, will be presented on the spatial uniformity, linearity and jitter measurements carried out on various photon-counting detectors in the visible and infrared wavelength regions.

References

Acknowledgements

This work has been supported by the Department for Business, Innovation & Skills, the Engineering and Physical Sciences Research Council, and the European Community’s Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257
Enhanced standoff optical sensing resolution using quantum illumination

Jeffrey H. Shapiro (jhs@mit.edu) and Saikat Guha (sguha@bbn.com)
(Dated: September 8, 2009)

It has been shown in recent work that even though loss and noise can quickly destroy entanglement, entangled sources of light, when paired with appropriate quantum-limited optical detection can reap substantial benefits over comparable classical sources for far-field point-target detection using a line-of-sight free-space optical transmitter, in the presence of propagation loss and a strong thermal background [Llo08, Tan08, Guh09]. In this talk, we show that the benefits of quantum illumination can be extended to enhancing spatial resolution of standoff remote sensing using an entangled optical transmitter to discriminate between one on-axis specular point target versus two off-axis specular point targets placed at angles ±θ from the on-axis direction.

The transmitter uses a continuous-wave spontaneous parametric downconversion (SPDC) source, transmitting the signal beam (N_S photons per mode) towards the target region while retaining without loss the idler beam – which is maximally entangled – for subsequent joint measurement with the reflected target return. Each T-sec-long transmission comprises K = WT >> 1 signal-idler mode pairs, where W is the source’s phase-matching bandwidth. The return field is incident on a length-D hard-aperture pupil, and λ is the center wavelength of the transmitter. The round-trip transmissivity is κ, and N_B is the mean thermal-noise photons per mode. We show by numerically evaluating the quantum Chernoff bound, that the entangled-state transmitter in conjunction with optimum quantum measurement can get a 6 dB error-exponent gain over the optimum-measurement coherent-state sensor in the highly lossy, noisy, and weak-transmitter (κ<<1, N_B>>1, N_S<<1) regime. We further show analytically that using a structured phase-conjugate receiver, which we recently proposed [GE09], the entangled-state transmitter can perform 3 dB better in the error-exponent than the optimum-measurement coherent-state sensor in the above regime (see Fig. 1). We also evaluate numerically the SNR vs. resolution scaling (measured in minimum angular separation between the two point targets that is resolvable with a given probability-of-error threshold as a function of the received signal-to-noise) of our system with both the optimum quantum measurement (whose structured implementation is not yet known) and the structured phase-conjugate receiver (see Fig. 2).

Bridging Particle and Wave Responsivity in a Phase-Sensitive Photon-Number Detector

Jeff S. Lundeen\textsuperscript{1,2}, Graciana Puentes\textsuperscript{2}, Matthijs P. A. Branderhorst\textsuperscript{2}, Hendrik B. Coldenstrodt-Ronge\textsuperscript{2}, Brian J. Smith\textsuperscript{2}, and Ian A. Walmsley\textsuperscript{2}
1: Institute for National Measurement Standards, National Research Council, Ottawa, Canada
2: Clarendon Laboratory, University of Oxford, Oxford, UK

The detection of optical fields plays a central role in both fundamental and applied physics. Consequently, adding to the fundamental types of quantum optical detectors available promises to open avenues of research and enable novel applied technology. We describe and demonstrate a device that is based on a combination of weak-field homodyne techniques and photon-number-resolving detection. The resulting detector can be adjusted by varying different system parameters such as local oscillator coupling, amplitude, and phase. In this way, it can be tuned between measuring Fock-state projectors to a variety of phase-dependent quantum-state measurements, such as squeezed states and Schrodinger Kittens. Experimental tomographic reconstructions of classical benchmark states are presented as a demonstration of the detector capabilities.
InGaAs photodetectors for high bit rate single photon applications


Toshiba Research Europe Limited
208 Milton Road
Cambridge
CB4 0GZ
United Kingdom

InGaAs avalanche photodiodes (APDs) have been used by the quantum information community as a convenient single photon detector in the near infrared for more than a decade. Particularly for quantum key distribution (QKD), they are the natural choice, due to their compactness and cryogenic-free operation. However, afterpulse noise in these devices has severely limited the bit rate in practical QKD systems to a few kbps. Recently, a simple and low cost self-differencing (SD) circuit has leased a new life to InGaAs APDs for high bit rate applications. Here we show SD-APDs single photon detection at gigahertz clocked rates, and their subsequent applications in high speed QKD, long distance entanglement distribution and photon number resolving.
Optimized Photon Detection with Visible Light Photon Counters and its Variations

Jungsang Kim, 1* Kyle S. McKay, 1 Henry H. Hogue, 2 and Maryn G. Stapelbroek 3
1 Fitzpatrick Institute for Photonics, Electrical and Computer Engineering Department, Duke University, Durham, NC 27708, USA
2 DRS Sensors & Targeting Systems, Inc, 10600 Valley View St, Cypress, CA 90630, USA
3 College of Optical Sciences, University of Arizona, Tuscon AZ 85721, USA

Visible light photon counters (VLPCs) are solid-state devices providing high quantum efficiency (QE) photon detection with photon number resolving capability. Experiments have demonstrated single photon detection QE of 88% [1], multi-photon detection with low bit-error-rate [2], and timing resolution of 250 ps in the visible wavelength range [3]. Despite these demonstrations, the VLPC device was developed for high energy particle tracking applications [4], and many device features can be improved for target applications. In this paper, we will discuss the optical and electrical operating principles of VLPCs, and propose a range of device optimization paths that improves various aspects of VLPC for advanced quantum optics and quantum information processing experiments.

VLPC features high QE in the 400-1,000 nm wavelength range, as the main photon absorption mechanism is provided by electron-hole pair generation across the silicon bandgap. The QE in the UV is reduced since the photon is predominantly absorbed in the top contact layer, where the photo-generated carrier does not propagate into the gain layer to trigger an avalanche. We reduced the thickness of the top contact layer and dramatically increased the QE of the VLPC in the 300-400 nm range [5]. Further optimization of the top contact layer using highly doped thin epitaxial layers should enable ultraviolet photon counters (UVPCs) with high QE (over 50%) below 400 nm, which is crucial for ion trap quantum computing applications.

The QE of VLPC drops dramatically for photons with wavelengths above 1 μm due to lack of photon absorption across the silicon bandgap. However, the direct photo-ionization of arsenic impurities used in the gain region of VLPCs allows single photon detection for photons with wavelengths up to 28 μm, but the absorption coefficient of this photo-ionization process is low in the 1-2μm range [6]. We describe a strategy for engineering an infrared photon counter (IRPC) that features high QE photon detection (potentially over 90%) in the telecom wavelength range using novel illumination geometry.

Relatively high dark count rate (~20,000 counts per second at high QE operating conditions) is considered to be a drawback of the VLPC device, but re-design of the layer structures, optimization of doping levels and reduction of the device area can lead to devices with dark count rates reduced by several orders of magnitude. Such re-design can also reduce the timing jitter in VLPCs to below the measured value of 250 ps.

Measurement of single photon detection timing jitter in a visible light photon counter

Burm Baek,1 Kyle S. McKay,2 Martin J. Stevens,1 Jungsang Kim,2 Henry H. Hogue,3 and Sae Woo Nam1

1National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
2Fitzpatrick Institute for Photonics, Electrical and Computer Engineering Department, Duke University, Durham, NC 27708, USA
3DRS Sensors & Targeting Systems, Inc, 10600 Valley View St, Cypress, CA 90630, USA
*Corresponding author: burm.baek@nist.gov

Visible light photon counters (VLPCs) offer many attractive features as photon detectors, such as high quantum efficiency and photon number resolution. The single-photon detection timing jitter is a critical performance factor in a time-correlated photon-counting measurement, but has not been studied in detail for VLPCs. We report measurements of the single-photon timing jitter in a VLPC, which is fiber-coupled and mounted in a closed-cycle cryocooler. The measured timing jitter varies from 250 ps to 270 ps at a wavelength of 633 nm with dark count rates ranging from 6.9-25 kHz. We measure how the timing jitter depends on the wavelength of light and on the voltage bias and temperature of the VLPC.

Figure 1. Plots of the measured detection timing jitter in FWHM (a) with wavelength variation and (b) bias voltage variation.
We describe recent work in which we have developed and validated an electrothermal model for the behavior of SNSPDs after the initial formation of the photon-induced non-superconducting region [1]. This model describes quantitatively the behavior that results from interaction between the nanowire and its resistive load during the photoresponse. In particular, our model explains the phenomenon of “latching” which occurs when the reset time of the detector is made too fast. We discuss possible approaches and work towards mitigating this effect, and the detector speeds that can be achieved.

We also report on work in which we have developed a NbN- film growth and SNSPD fabrication process on oxidized Silicon substrates, which allows us to use the high-quality oxide under the NbN as an optical layer. With the addition of a second SiO$_2$ layer and gold mirror fabricated on top of the device, we can reach nearly 100% optical absorption at 1550nm with back illumination, and single-photon detection efficiencies as high as 87%. This is also the first step towards integration of these devices with CMOS electronics and high-NA micro-optics.

Finally, we describe a multichannel detector system being developed for high-data-rate optical communications and quantum key distribution applications.

This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

High-Rate Quantum Key Distribution with Superconducting Nanowire Single Photon Detectors


A 1.7 Mbit/s secure key rate was achieved over 101 km of fiber using the differential phase shift quantum key distribution (DPS-QKD) protocol [1-2] and superconducting nanowire single-photon detectors (SNSPDs) [3-4]. The generated key would be secure against photon-number-splitting attacks [5], general collective attacks on individual photons [5] and sequential USD attacks [6], except for the use of pseudo-random bit sequences as opposed to true random number generators to set the photon states. This secure key rate is $\sim 100 \times$ higher than the fastest secure QKD rate previously reported at a >100 km distance [2], which was also demonstrated using a DPS-QKD system with SNSPD detectors. The achieved improvement in speed is primarily the result of the 32% system detection efficiency of the SNSPDs and the low-loss and high-extinction-ratio of the all-fiber interferometer used in this work. Furthermore, the lower, <40 ps, timing jitter of these SNSPDs permitted the use of a 10.7 GHz clock frequency with a relatively small penalty from the selected time window and residual error rate. Although further improvements in the detector performance will continue to increase demonstrated secure key rates, the high efficiency and high speed of these detectors rule out an additional $100 \times$ increase in secure key rate at these distances due to detector performance improvements alone. Substantially higher secure key rates over long distances will instead require multiplexing QKD systems (wavelength, polarization, etc.), using lower-loss fiber or developing more loss-tolerant key distribution protocols. However, even the demonstrated 1.7 Mbit/s secure key rate is sufficient for provably secure one-time-pad encryption for many applications.

This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

Single Photon Detection and Quantum Photo Detector

V. Saveliev

National Research Nuclear University, Russia

The main limitations of the detection of the single photon in present time especially at room temperature are very low level of the energy carrier by the photons and electronic noise of the measurement system. This leads to search the way to provide the high intrinsic amplification gain inside the detector structure.

Single photon detection performance at room temperature is one of the fascination characteristic of the Quantum Photo Detector, shows the Quantum Photo Detector as an ultimate instrument for study of nature of elementary quant of radiation in detail and useful element in many applications.

The detection principle in a Quantum Photo Detector is based on the quantum nature of the electromagnetic radiation. In particular using the distributions of the radiation quanta in space and detection of the quant flux by submicron space distributed semiconductor micro-cells, sensitive to the single electromagnetic radiation quanta.

The quantum photo detector structure is based on the matrix of optically isolated submicron semiconductor micro-cells with a density of a few thousands per mm², working in breakdown mode with integrated quenching elements and common electrode. All micro-cells are identical and independent provided internal gain of amplification of order $10^5 – 10^6$ and allow detection up to single photon at room temperature. The common electrode structure gives these devices the possibility to acts as a proportional detector for measurement at ultra low intensity photon flux levels. The output signal is defined as the sum of the elementary uniform signals of independent micro-cells triggered by initial flux of photons.

An important challenge in the practical realization of such quantum photo detectors is prevention of optical crosstalk between the microcells during avalanche detection process. Here we report a novel technique based on the precise manufacture of a trench structure to prevent such optical cross-talk. The reducing of the optics crosstalk more then of order of magnitude is achieved with technology, without reducing the fill factor (geometrical efficiency) of the quantum photo detectors in comparison to traditional silicon photomultipliers.

The quantum photo detector has a broad range of applications. Examples include experimental high energy physics, medical imaging systems and homeland security systems, military applications.
Superconducting Nanowire Single Photon Detectors (SNSPDs) have demonstrated near ideal properties for both quantum optics and low-flux optical communication, including high detector efficiencies (≤70%), low jitter (< 50 psec), low dark counts (<100 Hz at >40% DE) and no after-pulsing. However, these detectors are limited by a relatively long (~10 nsec) reset time, small detector areas (typically 10x10 μm²) and the inability to resolve photon number. All of these limitations can be mitigated by using arrays of SNSPDs: For sufficiently large arrays in a low flux measurement, the probability of a second photon striking an individual pixel during the reset time can be made low. The collecting area of the detector scales linearly with the pixel count for fixed area detectors. And for a large array of high DE detectors we can get a statistical estimate of photon number. While there are no physical limitations in fabricating SNSPD arrays, there are a number of engineering challenges. We will describe on efforts in building a multi-pixel SNSPD array. The primary engineering challenges are detector yield and the cabling and amplification of the output signal lines. Our initial arrays will be 48 pixels, but we are working on a design that will scale well up to several hundred pixels.
Generic Two-Qubit Photonic Gates Implemented by Number-Resolving Photodetection

Dmitry B. Uskov
Tulane University, New Orleans, Louisiana 70118

Existing theoretical results on measurement-induced two-qubit photonic gates with number-resolving photodetection [1] are limited to only the controlled-NOT (controlled-Sign) gate. It was found that this gate can be implemented with maximal success probability of $2/27$ [2, 3] using two ancilla photons. However, according to the Gottesman-Knill theorem, a quantum algorithm based on this gate alone can be efficiently simulated by a classical computer and to exploit the full power of quantum computation one must incorporate quantum transformations beyond the Clifford Group.

We use numerical optimization techniques [3, 4] to find optimal schemes implementing arbitrary two-qubit entangling gates, represented by generic points in the Weyl chamber of Cartan KAK’ decomposition of the SU(4) group [5]. We find that while any two-qubit controlled-U gate, including CNOT and CS, can be implemented using two ancilla photons with success probability $0.05 < S \leq 2/27$, a generic SU(4) operation requires three unentangled ancilla photons. Our study indicates that direct implementation of a generic SU(4) gate using an integrated optical circuit [6] offers an order of magnitude increase in the success probability and two-fold reduction in overhead ancilla resources compared to standard triple-CNOT and double-B gate decompositions [7]. We find that the B gate, which is the most efficient deterministic gate for decomposing an arbitrary SU(4) transformation, has success probability close to 0.0072. In the context of probabilistic KLM-type transformations, this makes the B gate less efficient than the CNOT gate as a building block for generic SU(4) transformations. Our results are consistent with previous work on the optimization of the Deutsch-Toffoli gate, where direct implementation of this three-qubit operation was shown to be four orders of magnitude more efficient than six-fold decomposition into CNOT gates [3, 8].

References


Superconducting nanowire single-photon detector in an optical cavity for front-side illumination

Burm Baek, Jeffrey A. Stern, and Sae Woo Nam

1 National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
2 Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
Corresponding author: burm.baek@nist.gov

We have integrated superconducting nanowire single-photon detectors (SNSPDs) with an optical cavity design for front-side illumination. Our optical cavity design increases the coupling efficiency of light to the nanowire detector and enables straightforward proximity fiber-coupling for a multichannel detector system. Using a confocal optical scanning technique, we measured a significantly enhanced optical absorptance of 73 % in comparison with 20 % in a typical bare nanowire device at 1550 nm and 3 K. Our method of fabrication of these devices on a silicon wafer and the local optical absorptance measurement are important steps towards developing next-generation SNSPD technology.

Figure 1. (a) Modeled spectral absorptance. Inset: optical cavity SNSPD layer structure. (b) Optical micrograph of a fabricated round-shape device of 15 μm diameter. AA: active area. (c) Measured spatial distribution of local reflected photon count rate in Hz. (d) Measured local detection efficiency distribution. (b)-(d) are presented in the same spatial scale.
Single photon optoelectronic mixing in the NbN superconducting nanowires

Zhizhong Yan $^{1,2}$ and A. Hamed Majedi $^{1,2}$

$^1$ Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada
$^2$ Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

We report an optoelectronic mixing in NbN superconducting nanowire that is sensitive to the average input photon flux on the single photon level for the first time. This mixer has the same geometrical structure and material as that of the typical Superconducting Nanowire Single Photon Detector (SNSPD). The mixer is driven by an electrical RF power as its local oscillator (LO) signal designated by LO frequency, $\omega_{LO}$; and by highly attenuated repetitive laser pulses or time harmonic continuous laser signal at $\omega_m$. The output signal is the intermodulated frequency products at $m\omega_m \pm n\omega_{LO}$, which are here treated as intermediate frequency (IF) products. The measurements confirm that both the single photon repetition rate and the time harmonic frequency are located at the expected frequency point when the LO frequency is considered. However, the single photon information is manifested by the IF power level that correlates to the input average photon flux in the frequency domain. Furthermore, we exploit the kinetic inductance nonlinearity in superconducting nanowire by means of bias current and absorbed mean photon number. The superconducting kinetic inductance in the nanowire can be sensitive enough to reflect the photon field strength proportional to the voltage amplitude it generates. Thus, the IF power level correlates to the average photon number in the photon flux. The proposed mixer can be continuously operated in several hundreds of MHz of the photon repetition rate after-pulse free without any complex electronics to perform recovery time control. We will discuss some of the current and future works and applications of the proposed mixer in quantum optical experiments and quantum communication.
Single-photon detectors operating at visible and near-infrared wavelengths with high quantum efficiency, photon-number-resolving capabilities and very low dark-count rate are mandatory to enable a number of applications in the field of quantum information. Superconducting transition-edge sensors (TESs) are microcalorimeters that have photon-number resolution with negligible dark counts. Detection of visible and near-infrared light at the single-photon level and discrimination between one- and two-photon absorption events place stringent requirements on TES design in terms of heat capacity, thermometry, and optical detection efficiency.

The devices described in this paper can be optimized for high quantum efficiency at particular wavelengths from near-ultraviolet to near-infrared (Figure 1), by designing multilayer device structures that include integrated thin-film layers that enhance the absorption of light into the active device material. Accurate measurements of optical constants for all materials and fine control over layers thicknesses in the optical stack can increase the detector efficiency at values higher than 99%.

We describe our progress on the fabrication and evaluation of our fiber coupled high-efficiency photon-number-resolving detectors.
Up-to-date performance of ultrafast superconducting NbN photon counter.

O. Minaeva\textsuperscript{1,*}, A. Korneev\textsuperscript{1}, A. Divochiy\textsuperscript{1}, M. Tarkhov\textsuperscript{1}, G. Chulkova\textsuperscript{1}, V. Seleznev\textsuperscript{1}, N. Kaurova\textsuperscript{1}, Yu. Korneeva\textsuperscript{1}, B. Voronov\textsuperscript{1}, I. Florya\textsuperscript{1}, M. Elezov\textsuperscript{1} and G. Goltsman\textsuperscript{1}

\textsuperscript{1}Moscow State Pedagogical University, Moscow, 119991, Russia

*Present address: Boston University, Boston MA, 02215 USA

Nanowire NbN superconducting single-photon detectors (SSPDs) are nanodevices patterned from 4-nm-thick NbN films as meander-shaped 500-\textmu m-long and 100-nm-wide stripes. The SSPDs exhibit excellent performance parameters in the visible-light to middle-infrared radiation wavelengths: quantum efficiency (QE) of the best devices approaches a saturation level of \~30\% at 1.3 \textmu m wavelength and 2 K operation temperature and is limited by the NbN film optical absorption. SSPDs exhibit quantum efficiency of about 0.5 \% at 5 \textmu m wavelength. The dark count rate can be reduced as low as 2 \times 10^{-4} s\textsuperscript{-1}.

The advanced NbN SSPDs which features subnanosecond response time due to low kinetic inductance and photon number resolving capability consist of several meander-shaped nanowires connected in parallel and covering 10um\times10um active area. Such SSPDs exhibit 200 ps response time with 16 ps timing jitter and capability to resolve the number of absorbed photons which can be distinguished by the photoresponse magnitude.

Efficient fiber coupling enables the implementation of a two channel receiver system operated in a standard liquid He transport dewar. Finally, successful coupling of the SSPD with a single mode optical fiber makes SSPD a device of choice for wide range of applications including study of single-photon sources, telecom systems, quantum key distribution systems and quantum computing. Because of the favourable characteristics and the possibility of installation into closed cycle refrigerator system many applications of the SSPD have already been reported. The most impressive one is the report on the quantum key distribution (QKD) over 200 km distance. Among other applications are non-quantum optical communications, research into emission of single-photon sources, e.g. quantum dots or quantum wells, by time-correlated single-photon counting methods, and experiments on quantum information processing with SSPD.
Devices for Single-Photon Wavelength Conversion

M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, CA, USA

The interoperability of single-photon sources, detectors, transmission media, and other quantum devices can be significantly enhanced with devices for single-photon wavelength conversion. It is well established that three-wave mixing processes in $\chi^{(2)}$ media can be used for up- and down-conversion of single photons. With the efficiency enhancement available in suitable waveguide configurations in quasi-phasematched media such as periodically-poled lithium niobate (PPLN), typical internal efficiencies exceeding 99% are possible with CW pump powers of tens of milliwatts. Key remaining issues are minimizing noise from spontaneous processes and minimizing propagation and coupling losses. Progress in understanding and controlling these phenomena will be discussed, and examples of recent devices, including upconversion detectors with ~200 noise counts per second, presented along with general strategies for reducing noise in up- and down-conversion devices. As time allows, building blocks such as adiabatic waveguide mode convertors and quasi-group-velocity matching structures, for more complex waveguide devices, will also be described.
Compact, Robust Sample Mount for Fiber-Coupled Cryogenic Detectors

B. Calkins¹, A. Miller², A. Lita¹, A. Migdall³, S. Nam¹

¹National Institute of Standards and Technology, Boulder, CO, 80305, USA
²Albion College, Albion, MI 49224, USA
³National Institute of Standards and Technology, Gaithersburg, MD, 20899, USA and Joint Quantum Institute, Univ. of Maryland, College Park, MD 20742, USA

Cryogenic single-photon detectors coupled to optical fiber have become an extremely valuable tool in quantum optics. For any such detector, the cold optical coupling of fiber to detector can be a major source of repeatability problems and optical losses, not to mention assembly labor. In addition, existing fiber-coupling schemes can make it difficult to mount more than just a few detectors onto the cold stage in a single refrigerator, which can make the setup of limited use to the single-photon experimentalist. To address these issues we have developed a high coupling efficiency fiber-coupling technique that is compact and repeatable, and have created a low-profile device mount capable of holding 16 such detectors.

The new mount utilizes a fiber self-alignment technique in which the 300 µm silicon substrate of a device is cut by deep reactive ion-etch to fit precisely inside a zirconia fiber-sleeve, which allows both repeatable alignment and compact size. We have applied this technique to high-efficiency tungsten optical transition edge sensor (TES) microcalorimeters, but it can in principle be used for other types of single-photon detectors fabricated on a silicon substrate. Due to the high intrinsic quantum efficiency of the TES detectors, we demonstrate repeatable high coupling efficiencies directly from measurements of system detection efficiency, which are 90-95% at 1550 nm. Here we describe the design and performance of this new mount and the alignment scheme, as well as the high-efficiency TES detectors themselves.
Characterization of terahertz single-photon sensitive bolometric detectors

D. F. Santavicca¹, B. Reuler², B. S. Karasik³, S. V. Pereverzev³, D. Olaya⁴, M. E. Gershenson⁴, L. Frunzio¹, and D. E. Prober¹

1 Department of Applied Physics, Yale University, New Haven, CT
2 Laboratoire de Physique des Solids, Université Paris-Sud, Orsay
3 Jet Propulsion Lab, Pasadena, CA
4 Department of Physics, Rutgers University, Piscataway, NJ

We describe a new technique for characterizing bolometric detectors that have sufficient sensitivity to count single terahertz photons. The device is isolated from infrared blackbody radiation and a photon of arbitrary energy is simulated by a fast microwave pulse. The pulse duration is much shorter than the detector time constant, and the absorbed energy of the pulse is equal to the energy of a single higher-frequency photon. The frequency of the simulated photon can be easily adjusted by changing the amplitude of the microwave source. We have employed this technique to characterize bolometers consisting of a superconducting titanium nanobridge ($T_c = 0.3$ K) with niobium contacts ($T_c = 8$ K). The large superconducting energy gap in the niobium creates Andreev barriers that confine excitations in the titanium nanobridge, and the thermal relaxation time is set by electron-phonon coupling in the titanium. Present devices are of intermediate size and have a measured intrinsic energy resolution of approximately 6 terahertz, near the value predicted for intrinsic thermal fluctuation noise, with a count rate approaching 100 kHz. Future smaller devices are expected to achieve an intrinsic energy resolution approaching 1 THz.
Photon-Counting Imaging Ladar System at 2-μm Wavelength


Lincoln Laboratory, Massachusetts Institute of Technology, 244 Wood Street, Lexington, MA 02420-9108

A photon-counting laser radar system has been developed at MIT Lincoln Laboratory operating at 2-μm wavelength. The compact source uses optical parametric generation to produce 1.5-μm to 3.5-μm-wavelength pulses from a periodically-poled lithium niobate (PPLN) crystal pumped by a 1.064-μm-wavelength, Q-switched microchip Nd:YAG laser. The ~200-ps-long pulses contain at least 3 μJ per pulse over the entire wavelength range and can be produced at up to 10-kHz repetition rate. The detector array is a 1024-element array of GaSb-based Geiger-mode avalanche photodiodes (APDs) with a cutoff wavelength of approximately 2-μm. The detector array is indium-bump-bonded to a CMOS readout circuit that records frames of firing times of each pixel with 2-ns timing resolution. The focal plane array is housed in a compact dewar cooled by a miniature, cryogen-free, Stirling-cycle cooler. Three-dimensional images acquired with this source and detector will be presented.
High resolution measurement of relative group delay with superconducting nanowire single-photon detectors

Tracy S. Clement, Thomas Gerrits, Shellee D. Dyer, Burm Baek, Sae Woo Nam
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80305

We have developed a new technique for measuring relative group delay that is based on time-of-flight measurements using a superconducting nanowire single-photon detector (SNSPD). Our system is capable of determining relative group delay over a very broad spectral range with a temporal resolution better than 1 ps. We launch tunable pulses of light into the device under test and measure the arrival time of the photons as a function of wavelength using the SNSPD and timing electronics. The SNSPD detection system has very low jitter (~65 ps) and low dark count rates [1], and by using time-correlated single-photon counting, we can resolve the mean of the photon arrival time distribution with better than 1 ps resolution. In addition, the broadband spectral response of the SSPD makes it well suited for relative group delay measurements at a wide range of wavelengths.

Previous methods of measuring relative group delay with high resolution, such as low coherence interferometry [2] and the modulation phase shift method [3], are limited to either relatively short total delays or narrow wavelength ranges. With our technique we have measured group delay in fibers as short as 1 meter and as long as several tens of kilometers and over a broad wavelength range in the infrared.

We have measured relative group delay in single-mode fiber, dispersion-shifted fiber, and non-zero dispersion shifted fiber, with lengths ranging from 1 meter to several kilometers, over a wavelength range from 1100 – 1750 nm. We are currently using the relative group delay measurements to predict the phase-matching conditions required to generate photon pairs using spontaneous four-wave mixing. In addition, we are using these relative group delay measurements to calibrate a time-of-flight fiber spectrometer that is currently being used to measure the joint spectral distribution of squeezed light and photon pair sources.

Correlation photon counting experiment under conditions of extreme photon fluxes

I. Prochazka, J. Blazej
Czech Technical University in Prague, Brehova 7, 115 19 Prague 1, Czech Republic
phone +420 774139637, fax +420 224922822, blazej@fjfi.cvut.cz

The standard way to realize single photon counting experiment under conditions of extreme photon flux – order of $10^9$ photons per second – is to minimize the detector dead time. In case of some correlation experiments when the goal is not to detect each photon but to measure photon statistics (like second order correlation function) some another approaches can be applied. We are presenting the one of them – synchronously gated detectors. The numerical estimations based on experimental data will be presented for several values of detector dead time and gate width. And it will be compared with using of non-gated single photon detectors from point of view of amount of data to process, data yield, and probability to detect correlation.
Experimental requirements for few-photon applications outside the coincidence basis

Thomas Jennewein

University of Waterloo, RAC 2111
200 University Avenue West
Waterloo, ON N2L 3G1

Photons are good candidates for quantum information processing, and they have been widely used in implementations of quantum communication and quantum information processing. I will outline recent experimental results on quantum computing with entangled photon. Furthermore, I will present the results of numerical studies on the actual requirements for photon sources and detectors in order to perform photonic quantum computing outside the coincidence basis, and a possible approach to a single photon source using switched SPDC.
Joint spectral distribution of a periodically poled KTP source for quantum information applications

Thomas Gerrits\textsuperscript{1}, Burm Baek\textsuperscript{1}, Martin J. Stevens\textsuperscript{1}, Tracy S. Clement\textsuperscript{1}, Sae Woo Nam\textsuperscript{1}, Robert H. Hadfield\textsuperscript{2}, Ryan S. Bennink\textsuperscript{3}, Warren P. Grice\textsuperscript{3}, Sander Dorenbos\textsuperscript{4}, Val Zwiller\textsuperscript{4}, Tony Zijlstra\textsuperscript{4}, Teun Klapwijk\textsuperscript{4}

\textsuperscript{1}National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
\textsuperscript{2}Heriot-Watt University, Edinburgh, EH14 4AS, UK
\textsuperscript{3}Center for Quantum Information Science, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA
\textsuperscript{4}Kavli Institute for Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CE Delft, The Netherlands

We present our efforts towards developing a periodically poled KTP (pp-KTP) crystal suited to produce a pure squeezed vacuum state. A pure squeezed vacuum is one of the building blocks towards high fidelity optical cat state generation via photon subtraction \cite{1}. A pure squeezed vacuum, i.e. without excess noise, can in theory be achieved by engineering a down-conversion source in which spatial and spectral output modes are exactly tailored to the local oscillator modes of the homodyne detection measuring the squeezed vacuum. These theoretical calculations are similar to those for pure photon pair sources that can be used in quantum information experiments without the necessity of spectral filtering \cite{2}. The tailoring of the source implies the engineering of a source output mode that has the same spectral and spatial decomposition as the local oscillator. The spectral decomposition can be determined by measuring the joint spectral distribution of the signal and idler modes. We focus on how we determined the spectral output state of our pp-KTP source using a dispersion-based fiber spectrometer. Earlier approaches of this kind of fiber spectrometer use single photon detectors with fairly high jitter and required gated operation \cite{3}. The gate’s timing had to be scanned which reduced the ability to measure the complete spectrum at once. In our study we use superconducting nanowire single photon detectors (SNSPD) \cite{4}. These detectors do not require gating, as the dark count rate is \textasciitilde500 Hz. Therefore, we are able to acquire the full joint spectral distribution in one single measurement in less than 1 hour. The SNSPD and readout electronics combined have a timing jitter of 65 ps FWHM. Such low jitter results in accurate arrival time determination and therefore high certainty in wavelength determination. In addition to the joint spectral distribution of our source shown in Fig.2, we will show that higher order spatial modes overlap with the first order Gaussian mode and therefore create excess noise in the squeezed vacuum. The power of this method is the short measurement time, which allows for rapid scans of parameter sets, such as the crystal temperature and pump fluence.

![Figure 1: Experimental Setup](image1)

![Figure 2: joint spectral distribution of pp-KTP source](image2)

References:

\cite{3} M. Avenhaus et al., arXiv:0902.3364v2 (2009)
We have developed a number of complete fiber-based high-speed quantum communication systems that includes an 850 nm Quantum Key Distribution (QKD) system for a local area network (LAN), a 1310 nm QKD system for a metropolitan area network (MAN), and a 3-node quantum network controlled by a network manager. We will briefly introduce the key techniques used to implement these systems, especially a low noise frequency up-conversion detector based on a periodically polled lithium nitrate (PPLN) waveguide. Using our quantum network, a QKD secured video surveillance application has been demonstrated.

There is no suitable quantum communication technology for wide area networks (WANs). One potential solution for QKD over long distances, other than linking multiple QKD systems together and requiring that the intermediate nodes all be trusted, is a quantum repeater with an entangled-photon-pair source. An entangled photon pair source at 1310 nm and 895 nm has been developed in our lab to achieve greater distances on the 1310 nm side while benefiting from low cost on the 895 nm side. More importantly, 895 nm matches the D1 transition line of Cs atoms that can be used to implement quantum memories, which are necessary for a quantum repeater.
We present two experimental studies of fringe compression using a coherent light source and a photon-number resolving detector. In the first experiment, we show that the width of the fringe produced by the diffraction of a coherent light beam on a single slit decreases for a detected higher photon-number state. In the second experiment, we show that when two coherent light-illuminated Airy-disks are separated by the conventional Rayleigh limit, photon-number resolving measurements can provide high visibility, much greater than the classical visibility of 15%. These features may be useful in imaging and metrology applications.
Simultaneous teleportation of multiple photonic degrees of freedom

Travis S. Humble*, Ryan S. Bennink, and Warren P. Grice
Center for Quantum Information Science, Oak Ridge National Laboratory

We report how quantum information encoded into multiple photonic degrees of freedom may be simultaneously teleported using a single, common physical platform. While teleportation has been previously demonstrated using information encoded into a single degree of freedom, e.g., polarization, the formalism suggests that the teleportation of the complete quantum state of a single photon is also possible. Simultaneously teleporting quantum information encoded into multiple degrees of freedom would provide a means to utilizing a greater portion of the photonic Hilbert space. Moreover, as each degree of freedom naturally partitions the complete photon Hilbert space into distinct subspaces, these encoded qubits could be individually addressed; whence, it would become possible to teleport multiple, potentially entangled, qubits physically encoded into a single photon.

We present a physical platform for implementing simultaneous teleportation of multiple photonic degrees of freedom. Our proposal is based on up-conversion of a biphoton state in order to implement simultaneous teleportation of the spectral, transverse-spatial, and polarization degrees of freedom in a single-photon state. The first significant contribution of this work is a novel proposal for spectral teleportation, in which teleportation of a single-photon spectral amplitude is mediated by a pair of spectrally entangled biphotons and initiated by frequency up-conversion. We analyze in depth the dependence of the spectral teleportation fidelity on the degree of spectral entanglement (quantified in terms of the Schmidt number) for several different physical scenarios, and we estimate that near-unit fidelity is achievable using currently available sources of spectrally entangled biphoton with Schmidt numbers on the order of 5-20 or higher.

In addition to spectral teleportation, we review existing proposals for teleportation of the transverse-spatial and polarization degrees of freedom. We note that all three physical variants of teleportation can be implemented using distinct forms of up conversion (based on matching frequency, momentum, or polarization), and we present a common physical platform by which the necessary up-conversion and subsequent measurement processes can be realized. Furthermore, we derive the fidelity for the teleportation of a complete single-photon state when mediated by a hyper-entangled state that is entangled in all three degrees of freedom. As expected, when the different degrees of freedom are separable, i.e., when a single photon encodes three individual qubits, then the composite fidelity is the product of the individual fidelities. However, when the photonic degrees of freedom are inseparable, e.g., cross-correlated and/or entangled, then the resulting fidelity is no longer separable but rather depends on the composite entanglement carried by the pair of hyper-entangled photons. We present these results, as well as a proposed experimental setup capable of implementing this idea, alongside estimates for the composite fidelity achievable using current hyper-entanglement sources.

* humblets@ornl.gov
Short Wavelength Quantum Key Distribution in Telecommunications Optical Fiber


1School of Engineering and Physical Sciences, David Brewster Building, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom
2Department of Physics and Astronomy, Hicks Building, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, United Kingdom
3Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom
4Present address: Instituto de Física Aplicada, Consejo Superior de Investigaciones Científicas (CSIC), Serrano 144, 28006 Madrid, España

*Corresponding author: R.J.Collins@hw.ac.uk
**Corresponding author: G.S.Buller@hw.ac.uk

Abstract: We present recent results on two innovative fiber based short wavelength quantum key distribution (QKD) systems. Short wavelengths offer the advantage that they are widely spectrally separated from the classical communications already present in the existing telecommunications infrastructure. The higher losses incurred in telecommunications fiber mean that transmission distances are limited to those consistent with the <20 km distances permitted in access network links.

We have applied single-photon sources based on quantum dot microcavities to polarization basis set QKD at a wavelength of 895 nm. Transmission distances of up to 2 km of standard telecommunications fiber at a clock rate of 40 MHz have been demonstrated and will be presented. Quantum bit error rates (QBER) as low as 1.22% have been observed.

We have also developed a novel phase system which is robust to changes in environmental conditions. This system uses 850 nm wavelength photons to achieve gigahertz clock rates over standard telecommunications optical fiber. Experimental results for this system will be presented.
Generation of Single Spatiotemporal Mode Photons

Franco N. C. Wong
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
franco@ncw2.mit.edu

Abstract: Single photons in a single transform-limited spatiotemporal mode are essential resources for implementing measurement-based quantum logical gates in linear optics quantum computing. Generation of single-mode photons have been experimentally demonstrated via ultrafast parametric downconversion in a PPKTP bulk crystal under extended phase matching and characterized using two-photon joint temporal density measurements.

In linear optics quantum computing (LOQC), probabilistic measurement-based quantum logic gates are implemented via two-photon quantum interference. For efficient implementation of a LOQC quantum gate the two typically independent photons should arrive at the gate at the same time and their spatial and spectral modes should be identical to maximize their interference signal. An efficient source of identical single photons in a single spatiotemporal mode is therefore a key LOQC resource. In this talk I will examine the use of spectral engineering in ultrafast spontaneous parametric downconversion (SPDC) to achieve the generation of factorizable two-photon states [1, 2] that can be used to herald single photons in a single spatiotemporal mode.

Two-photon states generated by SPDC are controlled by the pump spectrum and the phase matching function. One spectral engineering technique that has been utilized to realize a single-mode two-photon state is to apply ultrafast pumping with an appropriate pump bandwidth and extended phase matching in a type-II phase-matched periodically poled KTiOPO_4 (PPKTP) nonlinear crystal [3]. The ideal pure-state SPDC output is a separable two-photon state that is spectrally unentangled, and from it a single-mode photon can be heralded upon the detection of the conjugate photon. Characterization of spectrally engineered two-photon states can be accomplished in a number of ways such as two-photon joint spectral density [4] and joint temporal density [2] measurements, and Schmidt decomposition is a valuable tool to quantify the degree of spectral entanglement of a two-photon state. Results of the generation and characterization of spectrally unentangled two-photon states in bulk PPKTP will be presented and the prospect of more efficient generation in a PPKTP waveguide will be discussed.

References
Most of the research activity using correlated and entangled photons has been carried out in the visible/near-infrared spectral region because of the availability of high performance silicon photodiode avalanche detectors. Improvements in photon counting detector technology for the telecom region are making work in this region more tractable, and the availability of fibre and other waveguide structures makes this region extremely interesting for research using distributed waveguide networks. We describe a new source of entangled photons which operates in the region of the 1550 nm telecom window.

A source of correlated photons has been built using periodically-poled potassium titanyl phosphate (ppKTP) as the downconversion medium. Pump photons at 792 nm are downconverted into degenerate, orthogonally polarized photon pairs at 1584 nm. These wavelengths have been selected to enable extended spectral phase-matching, thereby permitting both CW and pulsed excitation. The 792 nm photons are produced by a Ti:sapphire laser pumped at 532 nm by a frequency doubled YAG laser, and the pump field is enhanced by using an optical resonator cavity. The downconverted pairs are coupled into a single spatial mode in optical fibre at a rate estimated to be \(\sim 6.2 \times 10^4 \text{ s}^{-1} \text{ mW}^{-1}\) pump power, giving an order of magnitude improvement on the generation efficiency relative to the non pump-enhanced setup. Hong-Ou-Mandel interferometry\(^1\) was used to characterize the indistinguishability of the resulting photon pairs. The design and characterisation of the source will be further described, as well as modifications to enable the generation of polarisation entangled photons.

References

Acknowledgements
This work has been supported by the Department for Business, Innovation & Skills, the Engineering and Physical Sciences Research Council, and the European Community’s Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257
Towards cross-platform two-photon interference using an efficient single photon source based on a semiconductor quantum dot

A. Muller,¹ S. V. Polyakov,¹ N. Rutter,² A. Ling,¹ E. B. Flagg,¹ E. Van Keuren,² A. L. Migdall,¹ and G. S. Solomon¹

¹Joint Quantum Institute, NIST and University of Maryland, Gaithersburg, Maryland
²Georgetown University, Washington, District of Columbia

Due to its atom-like electronic properties, a semiconductor quantum dot (QD) constitutes a stable chip-based source of single photons. We first report our progress towards making such a source deterministic, so as to yield exactly one photon per trigger pulse. For this purpose, an external-mirror microcavity system was developed, consisting of a concave micromirror built at the tip of a single mode fiber, and semiconductor QDs on top of a distributed Bragg reflector (DBR). This stable microcavity solves several outstanding problems of existing QD/microcavity systems such as spectral and spatial tuning, and allows to increase photon collection efficiency by several orders of magnitude compared to conventional planar optical microcavities, with a high yield directly into the fiber. Because its underlying DBR structure supports waveguide modes, this system is compatible with orthogonal excitation and detection to eliminate background laser scattering and initialize the QD state resonantly with a pi-pulse. We further describe our efforts towards two-photon interference experiments aiming at realizing a quantum interface between a single QD and a second, entirely separate system. We examine various scenarios in which this second system is either classical, i.e. a laser source, or a quantum light source such as provided by entangled photon pairs from parametric down-conversion. To make the sources compatible their spectral and temporal characteristics must be matched. A stabilized, tunable Fabry-Perot interferometer is introduced for such matching and two-photon indistinguishability between the two systems investigated by Hong-Ou-Mandel measurements.
Near infrared ultra-bright triggered single photon source from nano-diamonds

S. Castelletto, I. Aharonovich, D. A. Simpson, A. Greentree and S. Prawer

School of Physics, The University of Melbourne, 3010 Victoria, Australia
Email: sacas@unimelb.edu.au

Quantum communication and quantum metrology established a demand for an accessible solid state systems which can generate a stream of single photons on demand [1]. Although single photon emission has been demonstrated from quantum dots (QD)[1,2], single molecules [3] and nanowires [4], their practical operation is limited by the temperature or photostability. Diamond crystals, however, are the most promising platform for generation of robust, photo-stable, single photons at room temperature [5,6]. Nevertheless, out of more than 500 existing optical centers in diamond only three known centers demonstrated a clear single photon emission: the nitrogen-vacancy complex [6,7], the silicon-vacancy complex [8] and the nickel-nitrogen complex [9,10].

Recent progress in materials science and fabrication techniques of diamond color centers unveiled novel quantum emitters with photo-physical properties surpassing the current mainstream [11,12,13]. Consequently, the versatility of the diamond lattice to host various impurities which give luminescence signals lead to a dramatic discovery of ultra bright single photon emitters operating in the MHz regime [14]. These new centers, comparable with QD in terms of brightness [1], but have the tremendous advantage of their room temperature operation and photo-stability. Furthermore, it opened a new avenue to investigate essentially an unknown group of single photon emitters.

A brief description of the fabrication methods and a detailed quantum optical characterization of this class of diamond emitters is the subject of this presentation. In particular we will present the photo-physical properties of a novel family of single photon emitters, most likely originated from Cr impurities within the chemical vapor deposition grown nano-diamond crystals. We concentrate on the typical emission lines in the range of 740 - 790 nm, which exhibit single photon emission with count rate in the range of 0.8-3.2 10^6 counts/s at the limit of infinite optical excitation power, and life time as short as 1 ns. Even more, some of the emitters exhibit a photon statistics without any photon bunching, indicating a two-level system with unitary quantum efficiency.

We will also show preliminary results of a resonant excitation at 4 K. We will highlight future directions to optimize these sources and avenues to investigate the fundamental properties of these centers.

References
Ultrafast Switching of Photonic Entanglement

Prem Kumar
Northwestern University, Evanston, IL
Efficiently Coupling Light to Superconducting Nanowire Single-Photon Detectors

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Oral preference

We developed a superconducting nanowire single-photon detector (SNSPD) system in a close-cycled cryocooler with system detection efficiency of 24.4% and 21.7% at the wavelengths of 1550 nm and 1315 nm, respectively, and a dark count rate of ~ 1000 counts/sec, as shown in Figure 1. In the past, we successfully developed a robust process for fabrication of SNSPDs and demonstrated device detection efficiency above 50% at near-infrared wavelengths [1]. However, a major technical challenge is how to efficiently couple light into SNSPDs because of the small active area of the SNSPD and its low operating temperature. Past work has addressed this challenge by integrating multi-elements into a single “macro-pixel” detector [2]. However, such an approach results in increased complexity of the device packaging and system integration. To achieve efficient coupling in a simpler package in a cryocooler, we fabricated a device with a relatively large area, and, at the same time, a good device detection. The detector was circular, with a diameter of 9 μm [Figure 2 (a)] integrated with a microcavity [Figure (b)]. We were able to obtain device efficiency of ~ 31% excluding coupling at 1550 nm wavelength. In the chip package [Figure 2 (c)], a fiber-focuser was used to shrink the spot-size of the light from a single-mode fiber down to 5 μm, and the nanopositioners were used to accurately adjust the position of the light spot in-situ three-dimensionally. The detector was directly connected with an SMA connector through wire bonding. The temperature of the chip was cooled down to 2.7 K in the cryocooler.

Using this cryogen-free SNSPD system[Figure 2 (d)], we were able to measure the quantum interference of polarization-entangled photons at 1316 nm generated in a periodically poled potassium titanyl phosphate (PPKTP) waveguide using this system[3]. We measured 4.5 pairs of polarization-entangled photons per second at a pump power of 45 μW and an average two-photon quantum-interference visibility of 92.9% without subtraction of accidentals.

We also designed and fabricated SNSPDs with plasmonic nano-antennae to facilitate light-coupling and thus reduce the length of the nanowire needed for coupling [4]. The reduction of the length of the nanowire sped up the detector. We define the speed of the detector as 1/τ, in which τ is the 90%-efficiency recovering time for the detector after pulsing [5]. In our design, we increased the pitch of the meander, and added gold plasmonic structure to ensure that the incident light was dominantly absorbed by NbN nanowire. We experimentally demonstrated 47% device efficiency for a 9 μm-by-9 μm, 600-nm pitch SNSPD. The total length of the nanowire was 145 μm. Compared with a traditional 200-nm pitch SNSPD with the same area, the length of the nanowire was reduced to 1/3, and therefore the speed was expected to be increased by a factor of 3.

This work was supported by IARPA.

Reference
Figure 1: System detection efficiency and dark count rate of a single-photon detector inside a close-cycled cryocooler. The efficiency was measured at the wavelengths of 1315 nm and 1550 nm.

Figure 2: (a) A scanning-electron microscope image of a circular nanowire single-photon detector with a diameter of 9 µm; (b) A top view, optical microscope image of the detector with cavity-integration [1]. (c) The chip package. Note that it is back-illumination, and the chip, aligned with the fiber-focuser, is sitting on the other side of the chip plate. (d) The SNSPD system in a close-cycled cryocooler.
Creating intrinsically time bandwidth limited photon pairs

M. Halder\textsuperscript{1}, J. Fulconis\textsuperscript{2}, A. Clark\textsuperscript{1}, A. McMillan\textsuperscript{3}, C. Xiong\textsuperscript{4}, W.J. Wadsworth\textsuperscript{2}, J.G. Rarity\textsuperscript{1}

\textsuperscript{1}Centre for Communications Research, Department of Electrical and Electronic Engineering, University of Bristol, Bristol, BS8 1TR, UK
\textsuperscript{2}Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, Bath, BA2 7AY, UK

Single photons are at the heart of optical quantum technologies such as quantum cryptography, quantum computing and quantum metrology. To achieve high visibility two-photon interferences, the photons need to be in a pure state which usually is achieved by narrow band filtering. This reduces the overall efficiency of detection ($\mu$) and hence limits current experiments to a photon number in the order of 4-6. To achieve significant count rates for higher order multi-photon experiments (e.g. cascaded CNOT or Cluster states) an improvement in $\mu$ to over 20% is essential.

Here we report on the creation of photon pairs via four-wave-mixing (FWM) in birefringent Photonic Crystal Fibres (PCF) [1]. It has recently been suggested that by carefully engineering the phase matching conditions in birefringent PCF, photon pairs can be created in an intrinsically pure state and narrow band [2-4]. This can be achieved for cross-polarized phase matching, where two pump photons in the slow axis are converted into a pair of photons, polarized in the orthogonal fast axis. The aim is to produce such intrinsically pure and narrow-band photons and hence to achieve high non-classical interference visibility without any requirement for spectral filtering. A direct consequence is an increase in the collection efficiencies $\mu$.

Pairs of signal (s) and idler (i) photons are created in an uncorrelated spectral state with a factorable joint amplitude: $f(a_s, a_i) = f_s(a_s) \otimes f_i(a_i)$. In this case detecting one photon of the pair can be used to herald the other one in a pure quantum state. In order to experimentally test the purity of our single photons, we perform a Hong-Ou-Mandel experiment using two heralded signal photons generated in two separate PCF sources. A pulsed laser (Ti:Sa, 705 nm, 80 MHz, 1ps) pumps two PCFs and photon pairs are created with intrinsic bandwidths of $\Delta \lambda_s=0.13$nm (see Fig.1b) and $\Delta \lambda_i=0$nm, respectively and split up by dichroic mirrors. Wide bandpass filters block the residual pump light in each arm and Raman background is suppressed by spatial and polarization filtering. The photons are launched into fibres and the signal photons are combined in a single-mode 50:50 coupler. All four outputs are connected to Silicon photon detectors linked to four-fold coincidence electronics [4]. When the two signal photons arrive simultaneously on the beam splitter ($\delta=0$) a 78% reduction in the 4-fold coincidence count rate can be observed (Fig.1a) with efficiencies $\mu_s \sim 0.21$ and $\mu_i \sim 0.18$.

![Fig.1](image)

\textbf{Fig.1.} a) 4-fold coincidence rate as a function of temporal overlap $\delta t$. b) Signal emission spectrum. c) Schematic of the entanglement experiment.

In a further setup, we are using one piece of PCF in a Sagnac loop configuration (Fig.1c), in order to create pairs of entangled photons. Pump pulses with diagonal polarization are sent on a PBS, propagating along the PCF in both directions and giving rise to photon pairs. By twisting the optical axis of the fibre through 90$^\circ$ (as depicted), the pairs always exit through the same output port (opposite to the pump), but with orthogonal polarizations. They are in a superposition of horizontal and vertical polarization $|H\rangle \pm \epsilon |V\rangle$ and hence entangled. A full state tomography gives a fidelity of 86% with the entangled state. These sources of heralded and entangled photons now allow us to build multi-photon setups such as cluster states and teleportation gates. We will report on progress towards on these experiments at the conference.

A Pseudo-Deterministic Single-Photon Source

Kevin T. McCusker and Paul G. Kwiat

University of Illinois at Urbana-Champaign

Spontaneous parametric downconversion can be used as an excellent source of heralded single photons, but the maximum probability of producing a single photon is limited to less than 37%. By multiplexing the output of several consecutive outputs from one source, it is possible to create a pseudo-deterministic source of single photons. In particular, we have shown that with existing components, it should be possible to achieve a single-photon probability exceeding 50%, with a two-or-more-photon probability less than 20%; this would then be the best single-photon source to date. We discuss our implementation, current progress, experimental limitations, and future prospects.
Sub-Heisenberg limited phase measurement with two-mode squeezed light

Petr M. Anisimov, Gretchen M. Raterman, Aravind Chiruvelli, Sean D. Huver, Hwang Lee and Jonathan P. Dowling

Hearne Institute for Theoretical Physics and Department of Physics and Astronomy
Louisiana State University, Baton Rouge, LA 70803

Different physical mechanisms result in phase accumulation, and thus, phase measurements provide measurements of the underlying physical processes that take place. High sensitivity phase estimation is critical for basic research as well as practical applications.

A Mach-Zehnder interferometer (MZI) is the simplest device for optical phase estimation. MZI with a coherent state input and intensity difference measurement at the output is the benchmark that optical interferometry is compared against. This benchmark provides shot-noise limited sensitivity of phase measurement. Namely, uncertainty of the measured phase cannot be better than $1/\sqrt{\bar{n}}$, where $\bar{n}$ is the average number of photons detected.

In 1981, Caves pointed out that coherent light together with squeezed vacuum provides sub-shot-noise sensitivity [1]. It was shown in Ref. [2] that input state entanglement is important in order to achieve better than sub-shot-noise limited sensitivity in a linear interferometer. In particular, the so-called N00N states of Boto, et al., are entangled and allow for a phase estimation limited by $1/N$ [3], which is the so-called Heisenberg limited sensitivity.

We study the sensitivity and resolution of phase measurement in MZI by exploiting a two-mode squeezed vacuum (TMSV) input with $\bar{n}$ photons on average. TMSV provides entangled states of light with high flux of photons $\bar{n} \gg 1$ in contrast to the low-flux, high-N00N state approach ($N \gg 1$), the latter of which are experimentally challenging to obtain, as N00N state generation involves typically post-selection or feed-forward techniques. We show that super-resolution and “sub-Heisenberg” sensitivity is obtained with a TMSV combined with a parity detection. Parity detection can be carried out, for example, using the NIST photon number resolving detectors. In particular, in our setup dependence of the signal on the phase evolves $\bar{n}$ times faster than in traditional schemes, and uncertainty in the phase estimation is better than $1/\bar{n}$.


Photon detections for continuous variable quantum information processing and quantum receivers

M. Takeoka1, J. Neergaard-Nielsen1, M. Takeuchi1, H. Takahashi1, K. Hayasaka1, K. Tsujino1, D. Fukuda2, G. Fujii3, S. Inoue3, and M. Sasaki1

1 National Institute of Information and Communications Technology, 4-2-1 Nukui-kitamachi, Konganei, Tokyo 184-8795, Japan
2 National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
3 Institute of Quantum Science, Nihon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8303, Japan

Single-photon detectors or photon-number-resolving detectors with high efficiency and low noise are important devices in photonic-qubit based quantum information processing (QIP) as well as continuous-variable (CV) QIP. So far, in many of CV QIP experiments, quantum states are well manipulated and detected by Gaussian quantum operations, including linear optics, squeezing, and homodyne measurements. However, recent theoretical studies revealed that some important QIP protocols do not work with only Gaussian operations, for example, entanglement distillation of Gaussian states or quantum computing speed-up. Photon detection, precisely the projection onto photon number states, is the most realistic candidate as an efficient non-Gaussian operation at present technology.

In this contribution, we discuss our recent experimental results on non-Gaussian quantum operations using photon detectors. One is the technique to subtract photons from squeezed states by photon detectors, which enables us to distill Gaussian entangled states [1] and generate or manipulate Schrödinger’s cat-like states, i.e. the quantum superposition of coherent states [2, 3]. Another topic is an implementation of quantum receivers for optical communications with extremely weak coherent signals. The best signal modulation and detection scenario in the conventional technology is known as coherent communication in which the shot-noise limited detection is achieved by homodyne receivers in ideal. Here we discuss how to go beyond the shot-noise limit by quantum mechanically well designed measurements. We also propose a simple and realistic quantum receiver and show our experimental results in which a superconducting transition-edge sensor is installed as a high-efficiency photon detector [4].

Towards fundamental tests and quantum information applications using novel photon sources from quantum dots and cavity-enhanced down-conversion

X. Xing$^1$, Y. Soudagar$^2$, S. Ravets$^1$, S. Kocsis$^1$, L. K. Shalm$^1$, F. Wolfgramm$^3$, M. W. Mitchell$^3$, M. J. Stevens$^4$, R. P. Mirin$^4$ and A. M. Steinberg$^1$

1 Centre for Quantum Information & Quantum Control, Department of Physics, University of Toronto, ON M5S 1A7, Canada
2 Laboratoire des fibres optiques, Centre optique, photonique et laser, Dep. de génie physique, École Polytechnique de Montréal, QC H3C 3A7, Canada
3 Institut de Cincies Fotniques, 08860 Castelldefels, (Barcelona), Spain
4 National Institute of Standards and Technology, Boulder, CO 80305, USA

E-mail: xingxing@physics.utoronto.ca

In this talk, we will present work using two novel sources of nonclassical light – photon pairs from a far-below-threshold OPO [1, 2] built in collaboration with ysvOx and single photons from a quantum dot source fabricated at NIST – in tests of fundamental quantum mechanics and in pursuit of quantum information goals.

In the first project, we have developed a narrow-band source [3] of down-converted photons with a brightness of 46 pairs/MHz/mW/s as well as high two-photon coherence. I will discuss our long-term project of using this source in conjunction with Bose-condensed atoms for quantum light-matter interfaces, and our present work on demonstrating a novel 4-qubit entangled state known as a “loop cluster” [4, 5], which may prove a valuable resource for quantum computation.

In the second project, we have used single photons from a self-assembled quantum dot in a micropillar cavity to implement a variant of Wiseman’s proposal [6] to measure the Bohmian trajectories. I will show experimentally reconstructed single-photon trajectories, confirming that weak measurement of momentum conditioned on position does indeed yield the predicted Bohmian trajectories of single photons in a double-slit experiment.

We demonstrate a CW-pumped all-fiber polarization-entangled photon pair source with pair generation in the important telecom C-band. Fiber-based sources of correlated and entangled photon pairs are attractive because the pairs are generated directly within single-mode fiber, which eliminates the mode-matching losses that can occur when coupling from free-space sources to single-mode fibers. Additionally, sources with photon pair generation in the telecom C-band are compatible with existing fiber-optic telecom networks for low-loss, single-mode, long-distance transport of the photons in applications such as quantum key distribution (QKD). However, fiber-based generation of photon pairs is limited by accidental coincidences created by the spontaneous Raman scattering that occurs in fiber. Raman-generated photons are a particular problem for telecom C-band pairs in which the detuning between the pump and the photon pairs is small; for these detunings, the Raman generation is quite strong. This strong Raman contribution makes it difficult to simultaneously achieve both low-noise and high-photon-rate operation. Pulsed pumping has typically been used to achieve high pump intensities as well as to reduce the rate of accidental coincidences by reducing the effective time delay window over which coincidences are measured to the narrow time duration of each pulse, but CW pumping is desirable in order to increase the rate of pair generation.

Here we demonstrate a significant increase in the photon-pair generation rate through CW-pumped spontaneous four-wave mixing in 300 m of dispersion-shifted fiber. The result is the brightest and lowest-noise sources demonstrated to date in the C-band, with a generation rate of more than $10^7$ photon pairs per second in a 1 nm filter bandwidth and a coincidence-to-accidental ratio (CAR) of more than 100. We achieve the high CAR by cooling the fiber to 4 K to suppress the Raman generation. Also critical for the high CAR result is the low jitter and low dark counts of our superconducting nanowire single-photon detectors (SNSPDs). The dark count rate of our SNSPDs is approximately 100 Hz, significantly lower than other types of single photon detectors. The timing jitter of the single-photon detectors determines the time delay over which the CW-pumped photon pair coincidences are spread; a small jitter such as the 80 ps of our SNSPDs creates a narrow coincidence peak with fewer accidental coincidences occurring within that narrow time window.

We create polarization-entangled photon pairs through a counter-propagating scheme, in which the pump is split into two orthogonal polarization states and these two pump signals are counter-propagated in the nonlinear fiber. Achieving an all-fiber polarization entangled source is complicated by the polarization state modifications induced by bends and twists in the fiber. We perform photonic state tomography measurements to show that we have generated a state of $|\Psi\rangle = |HH\rangle + e^{i\phi}|VV\rangle$ with fidelity greater than 90%. This is the first demonstration of a CW-pumped all-fiber entangled photon pair source with photon pairs in the telecom C-band.
Spontaneous parametric down-conversion (SPDC) is a process widely used to produce both entangled photon pairs and heralded single photons. In the most common situation, a bulk nonlinear optical crystal is pumped by a focused laser beam and the emitted light is focused into a pair of optical fibers. Although the question of how best to focus the pump and/or fiber modes in such situations has been addressed several times in recent years[1], and brighter SPDC sources have since been obtained, important questions remain. For example, previous studies have not elucidated the scaling laws governing optimized SPDC, nor addressed how focusing impacts the spectral purity of the collected photons. To address such questions, I have undertaken a new study of the properties of SPDC with Gaussian spatial modes for the pump and photons, and obtained a number of new and different results.

The pump, signal, and idler fields are each expressed in terms of a Laguerre-Gauss family of modes characterized by a frequency $\omega$, waist size $w$, and linear polarization. The amplitude of SPDC involving the fundamental modes is $G(\omega_s, \omega_i) \propto \sqrt{N_p s(\omega_p)}$ where $N_p$ is the number of pump photons, $s(\omega_p)$ is the normalized pump spectral amplitude, and $\mathcal{O}(\omega_s, \omega_i) \equiv \int \chi^{(2)} : E^*_\omega_s E^{\ast} \omega_i E^{\ast} \omega_j d\mathbf{r}$ is the mode overlap which generalizes the usual phase matching function. $E_{\omega_j}(\mathbf{r})$ is the Gaussian mode. In the typical case $\Delta k \ll k_p, k_s, k_i$, $G(\omega_s, \omega_i)$ peaks when $\xi_s = \xi_i = \xi_p = 2.84$, where $\xi_j = L/k_j w_j^2$ is the dimensionless focal parameter of field $j$. This is the same condition which has long been known to maximize sum-frequency generation.

Integrating $|G(\omega_s, \omega_i)|^2$ over signal and idler frequencies yields the total joint collection probability

$$P_{ii} = \frac{8\pi hc}{\varepsilon_0} \left| \frac{N_{\text{eff}}}{\lambda^2 \lambda_t^2} \right|^2 \frac{n_i n_i}{n_p (n'_s - n'_i)} \frac{1}{AB} \arctan \left( \frac{B}{A} \xi_p \right)$$

where $n'_s, n'_i$ are the group indexes and $A, B$ are dimensionless parameters depending only on $\xi_s/\xi_p$ and $\xi_i/\xi_p$. Eq. (1) reveals that the source efficiency (i) depends on focusing only through the dimensionless ratios $L/k_j w_j^2$, (ii) has an upper bound independent of crystal length, and (iii) cannot be maximized with finite focal parameters. Furthermore, one finds that tight focusing ($\xi_j \gtrsim 10$) broadens the emission bandwidth beyond the expected $1/L$ dependence. Similar expressions are obtained for the single-photon collection probabilities $P_s, P_i$. The left figure shows the best trade-off of brightness $P_i$ and coupling efficiency $P_i/\sqrt{P_s P_i}$ for the nominally degenerate case. Notably, high coupling efficiencies ($\geq 0.95$) come at the cost of an order-of-magnitude drop in brightness.

The dependence of the spectral purity $\rho = \sum_j \sigma_j^2$ on the beam parameters was also studied, where $\sigma_1, \sigma_2, \ldots$ are the coefficients of the Schmidt decomposition of $G(\omega_s, \omega_i)$. The right figure shows that high spectral purities ($\rho \geq 0.94$) can be obtained in regimes of high brightness as long as the joint dispersion angle $\arctan \frac{[(2n_p - n'_s - n'_i)/(n'_s - n'_i)]}{\xi_p}$ is $45^\circ$ or smaller.
Enhanced telecom wavelength sensitivity in NbTiN superconducting nanowire single-photon detectors fabricated on oxidized silicon substrates

M.G. Tanner1, C. M. Natarajan1, V. K. Pottapenjara1, J. A. O'Connor1, R. J. Warburton1, R. H. Hadfield1, B. Baek2, S. Nam2, S. Dorenbos3, T. Zijlstra2, T. Klapwijk3, V. Zwiller3

1Heriot-Watt University, Edinburgh, EH14 4AS, UK
2National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
3Kavli Institute for Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

Current work on Superconducting Nanowire Single Photon Detectors (SNSPDs) is focused towards improving Quantum Efficiency (QE) at telecommunications wavelengths, whilst exploiting low dark count rates and picosecond timing resolution [1,2]. Devices fabricated in a new material, NbTiN, offer improved signal to noise characteristics [3]. In this work we present high efficiency measurements of practically fibre coupled NbTiN SNSPDs at telecoms wavelengths. Efficiency is significantly enhanced as the SNSPDs have been fabricated on silicon substrates with a 225nm thermally grown SiO₂ layer directly underneath the active device layer. The reflection at the SiO₂ – Si interface increases absorption in the NbTiN layer yielding practical efficiencies in excess of 20% at 1310 nm and 7% at 1510 nm, at dark count rates ~1 kHz. The efficiency drop off at lower bias current is slight, yielding 10% efficiency with only 20Hz dark counts at 1310nm.

Absorption in the superconducting layer has a significant effect on device efficiency. Simple plane wave Fresnel equation simulations of the NbTiN device with inclusion of the underlying reflector layers enables estimation of the absorption as a function of incident photon wavelength. Inclusion of a probability of hotspot formation dependent on the photon energy and additional cavity oscillations from the fibre to device separation yields a simulation closely matching measured QE vs wavelength data as shown in the figure below. These insights will enable us to optimise devices for high efficiency at 1550 nm wavelength. This methodology will also be used to examine the relationship between absorption and device efficiency as a function of wavelength. There is much interest in enhancing coupling through use of cavities [4]. Further simulations suggest more complex optical reflectors will significantly increase efficiency, whilst allowing convenient front side fibre coupling to devices. Thus devices of this type promise to provide a practical solution to the demand for high efficiency single photon detection at telecom wavelengths.

References
Multi-Element Superconducting Nanowire Single-Photon Detectors for High-Order Coherence Measurements

Martin J. Stevens¹, Burm Baek¹, Eric A. Dauler²,³, Andrew J. Kerman³, Richard J. Molnar³, Scott A. Hamilton³, Karl K. Berggren², Richard P. Mirin¹ and Sae Woo Nam¹

¹National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305 USA; marty@boulder.nist.gov
²Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02420, USA

We demonstrate a new approach to measuring high-order temporal coherences that uses a four-element superconducting nanowire single-photon detector (SNSPD). The four independent, interleaved single-photon-sensitive elements (Fig. 1a) parse a single spatial mode of an optical beam over dimensions smaller than the minimum diffraction-limited spot size, offering an alternative to conventional setups with multiple beamsplitters and discrete detectors that each sample a replica of the entire mode. We measure \( n \)-th order coherences, \( g^{(n)}(\tau_1, \tau_2, ..., \tau_{n-1}) \), by computing \( n \)-th order temporal correlations among photon arrival times at each of the four elements for \( n = 2, 3, 4 \).

Third-order coherence data from a chaotic source (a CW diode laser scattered off a rotating ground glass disk, coupled into optical fiber and directed to the detector) are shown in Fig. 1b. At the origin, \( g^{(3)}(0,0) = 5.87 \pm 0.17 \), close to the value of \( 3! = 6 \) expected for a chaotic source. Figure 2 plots an illustrative subset of the fourth-order coherence data for two fixed values of \( \tau_3 \). Here, \( g^{(4)} \) reaches a value of \( 23.1 \pm 1.8 \) at the origin (all four elements fire at the same time), in good agreement with the theoretical prediction of \( 4! = 24 \). As a control, we have repeated all these measurements for a coherent source (laser coupled directly into the fiber), and measured \( g^{(3)} = 1.006 \pm 0.002 \) and \( g^{(4)} = 1.011 \pm 0.005 \), independent of delays (not shown). This last result indicates there is little or no crosstalk between any of the elements. The combined timing jitter of the SNSPD and electronics is \( \sim 50 \) ps, making it useful for characterizing processes with much faster temporal evolution than the chaotic source studied here.

---

This is a work of the U.S. government and is not subject to U.S. copyright. This work was sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States government.
The Quantum Tripwire: Analysis in the Presence of Photon Loss

Daniel J. Lum, S. Blane McCracken, Petr M. Anisimov, Jonathan P. Dowling

Hearne Institute for Theoretical Physics
Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803

Abstract: A quantum tripwire is a quantum interrogation technique based on single photon interference in a Mach-Zehnder interferometer (MZI). This interference is destroyed if one arm of the interferometer is blocked, tripping an alarm. The original approach proposed by Elitzur and Vaidman demonstrated the probability of a photon arriving at the dark port of the interferometer if an object was present, yielding an interaction free detection at 50% maximal efficiency [1]. Kwiat and collaborators improved scheme incorporated a quantum Zeno effect (ZE) that promised to be 100% efficient under ideal conditions at the limit of infinite photon cycles through the MZI [2]. More importantly, the probability-based detection becomes known only in the limit of an infinite number of photons. Our analysis assumes a limited number of photons, and the presence or absence of an object is determined based on the outcomes. Symmetric hypothesis testing and the Chernoff bound were used to estimate the error of a wrong declaration in one trial. Finally, the Chernoff information was calculated to provide error estimation after N trials to optimize the system. This work introduced the need for a partial quantum ZE. We deliberately introduce a controlled loss in the detection arm such that ZE takes place only partially and results in high photon loss. If the path is blocked then full ZE is achieved leading to low photon loss. System optimization has shown that detection error after N trials can be exponentially small without the single photon being lost to the object.

References:


A four-wave mixing source for multi-spatial-mode entanglement

Paul D. Lett
Atomic Physics Division, NIST and Joint Quantum Institute, NIST/U. Maryland

Recent experiments with four-wave mixing (4WM) in an atomic vapor have shown that it can be made into an effective source of non-classical light. The source can be narrowband and is close to an atomic resonance, so that it is well-suited to use in atomic quantum memory applications. The source is also high-gain, and can operate in a single-pass gain configuration. Thus it does not require a build-up cavity, which often leads to the coupling of acoustic noise into the system. In addition, a cavity will filter the spatial modes that it will pass, thus restricting its use in imaging and other multi-spatial-mode applications.

An off-resonant double-lambda system in hot Rb vapor is used to generate “twin beams” of light that are entangled in both their intensity and phase. Using this source we have generated images entangled at a level that displays the Einstein-Podolsky-Rosen paradox. The images can be bright fields that display position-dependent quantum noise reduction in their intensity difference, or vacuum twin beams that are strongly entangled when projected onto a large range of different spatial modes. The high degree of spatial entanglement demonstrates that the system is an ideal source for parallel continuous-variable quantum information protocols.

The twin beams that are generated by the 4WM source can also be used for detector calibrations in much the same way as correlated photon pairs can be used to calibrate photon counting detectors. The perfect pairing of the photons in two beams from spontaneous parametric downconversion allows one to gate one detector for a measurement based on the detection of a photon at the other detector. If detector A has measured the presence of a photon, then certainly a photon is present at detector B. The measured probability that a photon is actually detected under such circumstances gives the absolute quantum efficiency of detector B. The 4WM twin-beam source is essentially a bright source of paired photons, analogous to the parametric down conversion source. The rapid flux of photons does not allow the same sort of triggering as with single photons, but an analogous procedure based on intensity correlations coupled with a precision gain measurement of the source has been proposed and can be implemented.

Finally, a narrowband source of correlated and entangled photons is important for use in an photon/atom interface. That is, if one wants to take entanglement generated in an optical source and store it in a quantum memory device, the photons need to be narrowband for any of the atom-based memory schemes that are presently envisioned. The 4WM source described here is necessarily near-resonant with a strong atomic transition in an alkali-vapor. It can be seeded by a laser, and is thus narrowband. The multi-spatial-mode nature of the source would allow us to generate entangled images (multiple, parallel qubits) that could be stored in a similar atomic vapor. While storage in a hot vapor will limit the storage times available, storage using cold atoms held on an optical lattice holds promise for extended storage times.
In our laboratories transition edge sensors are made of IrAu bilayers deposited by laser ablation and e-gun evaporation on a Si substrate or SiN membrane. The energy conversion process of photons in heat absorbed by the Ir electrons and phonons systems, is now under study in order to optimize the detectors efficiency. In this work we present a preliminary comparison relative to the collection energy capability of two detectors built on a suspended SiN substrate and on a bulk silicon respectively.
Radiometric calibration of single-photon counting detectors

Waldemar Schmunk, Helmuth Hofer, Silke Peters, Mark Rodenberger, and Stefan Kück

A radiometric calibration technique typically applied in the field of fiber coupled detectors [1] is used to determine quantum efficiencies of single-photon counting Si-avalanche diodes (APD). For this purpose single photon sources are realized based on laser-induced fluorescence of nitrogen vacancies (NV-centers) in nano crystalline diamonds. The diamonds are distributed on a Si-wafer and localized as well as excited by a probe scanning confocal microscope setup. The fluorescence light, selected by a narrow band filter (FWHM ~1-3 nm) at 694 nm, is split into two fibers (fiber A and fiber B) and recorded by two fiber coupled APD’s, used as standard and device under test (DUT) detector. The count rates measured for each of two fibers are proportional to the incoming photon flux and the detector responsivities. With known responsivity of the standard, the efficiency of the DUT detector is determined from the experimental data. The present work will discuss the measurement results and analyze the uncertainty of the DUT detector, the photon counter and the coupling ratio as well as the measurement reproducibility and the influence of residual multiphoton processes.

(Acknowledgement to B. Sauer and C. Becher, Saarland University, for probe preparation, the ERA-NET Plus program, under Grant Agreement No.217257, International Graduate of Metrology, Joint Optical Metrology Center, and the German Federal Ministry of Education and Research, under Grant No.01BL0900)

SPAD detector package
for laser time transfer in space

I. Prochazka, J. Kodet, J. Blazej
Czech Technical University in Prague, Brehova 7, 115 19 Prague 1, Czech Republic
phone +420 224358659, fax +420 224922822, prochazk@cesnet.cz

G. Kirchner, F. Koidl
Observatory Graz-Lustbühel, Lustbühelstraße 46, A-8042 Graz, Austria

To realize the time transfer via single photon optical link between ground station and orbital module the flying detector package have to fulfill many specific requirements. The one of them is the long-term temporal stability in wide temperature range affecting detector control circuit and signal cables. We are presenting the principles of SPAD package with control circuit based on CMOS components with self-calibration capabilities. Detector is repetitively (with selectable repetition rate) switching between two operation modes. The first one is a standard single photon detection and the second one is a calibration mode. The calibration pulse is applied to the common load that is triggered from the beginning of the range gate pulse or another reference event. The produced data set allows applied post-processing algorithms to enhance final long-term stability of a range signal. The experimental results showing several days campaign at Graz observatory will be presented. The resulting long-term stability has been improved from 5 ps to 2 ps.
Advanced Architectures for Low-Noise Frequency Conversion of Quantum States Using Lithium Niobate Waveguides

Jason Pelc, Carsten Langrock, M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, CA, USA

It is well known that frequency conversion in $\chi^{(2)}$ media can translate the wavelength of a quantum state of light without altering its photon statistics or coherence properties. However, the generation of noise photons due to spontaneous scattering processes of the strong classical pump diminishes the fidelity of quantum state preservation. We analyze the contributions of random duty-cycle errors in periodically poled nonlinear structures on noise generation by parametric processes, and derive fabrication tolerances for efficient and low-noise operation. We also propose a novel architecture intended to minimize the effect of spontaneous scattering processes on device performance: to achieve low-noise operation a pump frequency $\omega_p$ should always be chosen to be lower than both the quantum state frequencies $\omega_1$ and $\omega_2$, where $\omega_1 + \omega_p = \omega_2$. For quantum state frequencies greater than an octave, e.g. $\omega_2 > 2\omega_1$, low-noise conversion can be achieved if one uses a device with multiple conversion steps. We discuss implementations of this scheme for both more efficient upconversion-assisted single-photon detectors, and devices for low-noise frequency down-conversion of single photons in the visible to the telecom band.
Three-Dimensional Profiling of Low-Signature Targets Using Time-Correlated Single-Photon Counting

N. J. Krichel, A. McCarthy, R. J. Collins, A. M. Wallace, and G. S. Buller

School of Engineering and Physical Sciences, David Brewster Building, Heriot-Watt University, Edinburgh, United Kingdom, EH14 4AS

Abstract: We present recent progress in the development of a scanning three-dimensional depth profiler employing photon time-of-flight measurements based on time-correlated single-photon counting (TCSPC). Using pulsed illumination of single points at the target with eye safe average and peak power levels, the system is capable of acquiring spatially resolved depth information on non-cooperative target surfaces at distances between a few tens of meters and several km. Illumination pulses are at a wavelength of 842 nm and are typically of tens of picoseconds duration repeated at clock rates from a few kHz to tens of MHz. Galvanometer mirrors are used to scan the output laser pulses across the target while simultaneously routing returned photons into a single, optimized single-photon avalanche diode (SPAD). Results from our system will be presented, including depth images from a variety of targets under various environmental conditions. The figure shows a depth profile scan of a human head after a spatial cubic-spline interpolation, enhancing and restoring the rounded and organic nature of the target. The insert shows the original depth profile data.

The performance of a first-generation system is analyzed in terms of parametric enhancement of quantities such as device attenuation, spatial filtering and target return analysis, and compared with later refinements. Theoretical modeling is used to show how the system’s target resolving capabilities may be improved in future generations of the device. The existing trade-offs between acquisition time, maximum range and excitation laser power levels will be discussed and projections made for this and future depth imaging systems using this approach for typical target materials. Work is in progress to operate the sensor at laser frequencies of ~ 100 MHz. The introduction of a non-periodic pulse pattern to avoid range ambiguity between closely spaced optical pulses means that such high repetition rates will not compromise the range accuracy or the maximum unambiguous depth of field possible in a depth image. We will discuss preliminary results based on an implementation of this technique.

State-of-the-art TCSPC hardware solutions facilitate the rapid transfer and storage of large quantities of raw data. This renders real-time analysis possible with speed-optimised algorithms such as fast Fourier transform-supported cross-correlation methods, as well as gathering additional information about the scene in post-processing steps based on approaches such as reversible-jump Markov-chain Monte Carlo (RJMCMC). This algorithm dynamically adapts the number of degrees of freedom of a range measurement, resulting in multi-surface resolution and the possible identification of targets obscured by objects such as foliage without a priori knowledge about the scene. We will compare current results obtained with a number of employed algorithms.

Scan of a human head at a distance of 325 m. The system is completely eye safe at all operating distances. Simple post-processing can assist with recognition of the target. (Inserts: upper right: photo, right: raw data).
The measurement of photon indistinguishability to a quantifiable uncertainty using a Hong-Ou-Mandel interferometer

Peter J. Thomas¹,², Jessica Y. Cheung¹, Christopher J. Chunnilall¹, Malcolm H. Dunn²

¹National Physical Laboratory, Teddington TW11 0LW, UK
²School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, UK

Despite the wide range of experiments and applications with the Hong-Ou-Mandel (HOM) interference effect¹ at their focus, little attention has been paid to the accuracy aspects to such experiments. Invariably, the HOM experiments involve the measurement of the HOM ‘dip’ visibility, but the accuracy of the measurement is rarely stated. Measurements have been largely restricted to the research laboratory but with many quantum technologies approaching commercial realisation, measurement uncertainty will become more important.

A measurement equation is presented for the measurement of photon indistinguishability to a quantifiable uncertainty using the Hong-Ou-Mandel technique. The origin of each term in the equation is explained, together with procedures for its experimental evaluation and uncertainty estimation. Additional experimental measurements that were required to quantify the uncertainties associated with the terms in the measurement equation are given. The results are presented in the uncertainty budget for the system, from which the nominal value and overall uncertainty of the indistinguishability measurement is given. Measurements made from a HOM interferometer sourced by twin photons from a parametric downconversion process² are described. The measured photon indistinguishability was found to be 0.965 ± 0.027 using the prescribed method. The measurement equation can be modified to give insight into other experiments requiring Hong-Ou-Mandel dip visibility measurements.

References
2. Thomas, P.J. et al., Review of Scientific Instruments, 80, 036101(3) (2009)

Acknowledgements
This work has been supported by the Department for Business, Innovation & Skills, the Engineering and Physical Sciences Research Council, and the European Community’s Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257
Suppressing deadtimes for high rate telecom-band photon counting exploiting multiplexed detector array systems

I. P. Degiovanni, G. Brida, F. Piacentini, V. Schettini
Istituto Nazionale di Ricerca Metrologica, Turin, Italy
S. V. Polyakov, A. Migdall
Optical Technology Division, National Institute of Standards and Technology, Gaithersburg, MD 20899-8441 and
Joint Quantum Institute, Univ. of Maryland, College Park, MD 20742

ABSTRACT

Single-photon technology is of growing importance as interest in quantum communication (in particular quantum key distribution) and computation intensifies [1,2, 3]. Because of growing demands for higher-rate secret key distribution, the single-photon detector (SPD) developer community is focused on improving relevant properties of detectors. Among these are detection efficiency, detector timing jitter, and detector deadtime. Unfortunately, one cannot focus on optimizing one property alone, because SPD properties can be interrelated. Therefore, our goal is to present a detector arrangement that reduces deadtime while other important characteristics are kept constant (or improved). We proposed to use active multiplexing as the way to significantly improve single-photon detection [4]. Our firsts proof of principle assessment proved that active multiplexing algorithms compares favorably to all passive detector arrangements [5-7]. The method proposed is becoming more practical as progress to integrate many single-photon detectors in microchip arrays continues [8,9].

Deadtime, i.e. the “recovery” time after photon detection when a detector cannot process next photon detection, is a feature common to most SPDs. Deadtime is the major factor impeding higher photon-counting rates. As we will see, this effect is especially severe at telecom wavelengths. There are various physical properties that lead to deadtime. For infrared avalanche SPDs (SPADs), a combination of effects contribute to deadtime: most important of these are (i) detector deadtime due to carrier trapping in the active avalanche region that requires longer times before the detector can be reactivated and (ii) electronics processing deadtime that requires recovery before processing another event. We have characterized the deadtime performance of commercially available infrared SPADs and find that both of the deadtime mechanisms play a significant role. We use this better understanding of infrared SPADs and the idea of multiplexed detectors array to create a photon-counting arrangement that improves single-photon detection rates for infrared detectors. In our last implementation [7] we report a 5x increase in detection rates as compared to a conventional InGaAs SPAD, while keeping deadtime effects at the exact same level, and a 2.1x increase over the multiplexed detector array of our previous work [5,6], where the switching algorithm did not address the properties of the infrared SPADs as completely.

REFERENCES


1 e-mail: i.degiovanni@inrim.it
We present a systematic study of a correlated photon-pair source based on a periodically-poled KTiOPO$_4$ (PPKTP) waveguide with the goal of developing a simply engineered, compact, highly efficient, low photon-loss, and cost-effective waveguide source of correlated photon pairs that is promising for future chip-scale quantum information processing applications. The waveguide was fabricated on a KTiOPO$_4$ crystal supporting type-II parametric down-conversion with periodic poling applied along the waveguide to quasi-phase-match the type-0 down-conversion process. The design pump wavelength is 532 nm, and the wavelengths of the down-converted, correlated photons are around 900 nm and 1300 nm. We examine the two-photon coincidence spectra and single photon spectra at a variety of temperature and power settings for both type-0 and type II down-conversion processes. We also map out relative contributions of two-photon to one-photon fluorescence. Our theoretical simulations match with experimental data very well, and explain how non-uniformity of the poling period affects the phase-matching bandwidths differently for type-0 and type-II phase matching. Our study shows that the waveguide source has a number of advantages compared to its bulk-crystal counterpart, including higher spectral brightness, narrower emission bandwidth and nearly single spatial-mode output.
Approaching Helstrom limits to optical pulse-position demodulation using SPD and optical feedback

Saikat Guha (sguha@bbn.com) and Jonathan L. Habif (jhabif@bbn.com)
(Dated: October 8, 2009)

Pulse-position modulation (PPM) is one of the most commonly used intensity modulation schemes for optical communication systems. It encodes $\log_2M$ bits of data by positioning a narrow optical pulse in one of $M$ successive time slots in each PPM frame. Demodulation is conventionally done using a direct-detection (DD) receiver, which declares the slot producing the maximum photon counts as the data-bearing slot. PPM is particularly popular in deep-space communications. High-order PPM modulation in conjunction with a state-of-the-art superconducting single-photon detector (SSPD) technology [Yan06] is being actively investigated by the MIT Lincoln Laboratories for their Lunar Laser Com Demonstration (LLCD) program. In the absence of detector dark noise and background, direct-detection demodulation does not require photon-number resolving power, and a single photon detector (SPD) suffices to achieve the direct-detection error probability $P_{e,\text{DD}} = (M - 1)\exp(-\eta N)/M$ where $N$ is the mean photon number per received pulse and $\eta$ is the quantum efficiency of the SPD, assuming $M$ equally like PPM symbols. Helstrom’s minimum probability of error (MPE) quantum limit [Hel76] to the PPM demodulation symbol error rate is given by $P_{e,\text{min}} = \left( (M - 1)/M \right) \left[ \sqrt{1 + (M - 1)e^{-\eta N}} - \sqrt{1 - e^{-\eta N}} \right]$, which has a $3\,\text{dB}$ higher error exponent than that of the DD receiver in the limit $Me^{-\eta N} << 1$ (see Fig. 1). A structured receiver design that achieves this quantum-limited minimum symbol error rate is not yet known.

One of the very few structured optical receivers that achieves its quantum-limited error rate is the binary-hypothesis Dolinar receiver [Dol76], which discriminates between two arbitrary coherent-state pulses at the MPE limit using continuous photo-detection assisted by optimized optical intensity feedback through the pulse duration [Ger07]. Based on an idea originally proposed in [Dol76], we show that a conditional-pulse-nulling (CPN) receiver (see Fig. 2) that progressively nulls PPM time-slots (by applying perfectly phase-matched inverted pulses) followed by single-photon detection assisted by classical feedback of the measurement results through the successive pulses can achieve the optimal MPE error exponent in the $Me^{-\eta N} << 1$ regime (see green line in Fig. 1). We show that even in the presence of typical dark-current floors of an SSPD, an extension of the CPN receiver, with perfectly phase-matched pulse-nulling can obtain a more than 10x reduction in symbol error rates as compared to direct detection, for operating parameters commensurate with those of the LLCD program. We show relative advantages of the CPN receiver in the presence of SPD dark currents, background and imperfect pulse nulling. We consider a broad category of practical optical demodulation schemes, and present recent results on receivers that approach quantum limits to demodulation error rates, and modulation sets and unconventional feedback-based receivers that approach quantum limits to optical channel capacity.

Quantum communication has spawned much interest in recent years, however, long-distance quantum communication requires quantum memories that store local qubits in matter-based internal states and utilize shared entanglement to overcome the exponential loss in photonic channels. We use Pr$^{3+}$:$\text{Y}_2\text{SiO}_5$ to generate single photons and implement the quantum repeater protocol of Duan et al. (DLCZ protocol) [1]. Pr$^{3+}$:$\text{Y}_2\text{SiO}_5$ is a promising candidate for quantum memory due to its seconds-scale coherence time [2]. The DLCZ protocol involves scattering a single photon from a specific ground state, so we use spectral hole burning to create a narrow absorbing feature in a particular ground state and ensure that no ions elsewhere in the spectral profile are resonant with the optical transitions of our selected ions. We use a three-step scheme like that described by Nilsson et al. [3] in which the first step pumps all ions in undesired frequency classes to dark states, the second step pumps all ions in the selected frequency class into a single ground state, and the third step creates an anti-hole in one of empty ground states. We also use spectral hole burning techniques to generate narrow spectral filters to separate fields which are detuned by a few MHz.

We have modeled the spectral hole burning process in our system and optimized the parameters for step one of our state preparation scheme. We model spectral hole burning as an incoherent process using standard population rate equations and find both time-evolved and steady-state solutions. To optimize the process we minimize the remaining population in undesired frequency classes that is resonant with any of the three hole burning fields (see Fig. 1).

![Figure 1](image)

**Fig. 1.** Figure of merit which we are minimizing vs. intensity in one of the hole burning fields. Shown are time evolved solutions for five different total sequence times and the steady state solution. Intensities in the other two fields are optimized at each point. Minima are noted for each curve.

We find that the steady-state solution in the limit of zero field intensity (and thus zero power broadening) provides a lower limit on how well we can pump away unwanted ions. We find that even for relatively short total sequence times we can achieve a figure of merit within an order of magnitude of this limit. We also present experimental progress in using spectral hole burning techniques for state preparation and spectral filtering.

†M.D. Eisaman is currently with Xerox PARC.


Novel very high transmittance narrow-band spectral interference filter

Jan Bogdanski, Ariel Danan, Scott Jobling, Kevin McCusker, Stephan Quint, Alexander Z. Smith, and Paul Kwiat

University of Illinois at Champaign-Urbana, Dept. of Physics

School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Israel

Johannes Gutenberg University, Mainz, Germany

A single-photon source is an important component in many quantum information processing applications. One of the most widely used single-photon generation schemes utilizes parametric down-conversion (PDC) with random emission of correlated photon pairs—detecting one of the photons of a pair heralds the presence of the second one. One of the essential parts of such a heralded single-photon source is a narrow-band spectral interference filter used for spectral-mode definition. The heralding efficiency of such a single-photon source is defined as the probability that the heralded photon is present in its single-mode fiber (used to define the spatial mode). This probability depends, among other parameters, on the transmission efficiency of the interference filter, usually in the range 60-65%. We present a novel scheme to improve the effective transmission of a standard interference filter, and demonstrate a near 100% transmission in the filter’s passband. The heralding efficiency should be similarly improved, which can be beneficial in many quantum information applications.
TERAEYE: a matrix of Q-Dots with THz single photon detection capability for application to fully passive and spectroscopic THz camera.

F.Gatti (University of Genoa)

The development of a fully passive and spectroscopic detection system in the THz band in the framework of the TERAEYE project is presented. The system which is based on nanofabricated detectors to identify harmful materials for homeland security that will provide both spectral analysis and imaging. The detector is based on Quantum Dots coupled with a single-electron-transistors (SET) or Quantum Point Contat (QPC). This device works at few Kelvin and is able to convert a single THz photon into electrical signal with a gain of about $10^7$ electron/photon. 8 Q-dot detectors are arranged in single pixel in order to provide spectral response from 0.2 to 2 THz. A prototype of THz camera with cryo-cooler, readout electronics and optics is under construction. We present the detectors performance and THz system overview.
Extraction of correlated 2-photons with high efficiency

Alexander Ling, Jun Chen, Jingyun Fan, and Alan Migdall
Optical Technology Division, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899-8441
and Joint Quantum Institute, University of Maryland, College Park, MD 20742
alexander.ling@nist.gov, jfan@nist.gov

Abstract: We demonstrate the extraction of high purity correlated 2-photons $(g^{(2)}(0) = 0.0055)$ from a microstructure-fiber source with near unit efficiency. Such a source may help many quantum information applications including loop-hole free Bell-type tests.

Despite rapid progress in increasing the brightness of 2-photon sources, the efficiency of extracting correlated 2-photons remains at 50% or less [1]. Here we report a significant improvement on this parameter. We demonstrate the extraction of high purity correlated 2-photons $(g^{(2)}(0) = 0.0055)$ with near unit efficiency.

Solid-core microstructure fibers have a greatly reduced mode area, allowing a relatively weak light pulse to induce significant nonlinear optical interaction over a short passage inside the fiber. The combination of low average pump power and a short optical path leads to low single-photon noise (from both the pump and pump-induced Raman scattering) while achieving a high 2-photon gain. While such fibers have made it easy to generate 2-photon entanglement, the extraction efficiency of 2-photons remains low. In addition, the system stability is sensitive to environmental perturbations due to the small fiber core size $(d \sim 1 \mu m)$, which requires high numerical aperture (NA) lenses to couple light into and out of the fiber [1]. As a result, any spatial drift of the tiny fiber tip is magnified over the optical path. This causes degradation in the two-photon visibility and collection efficiencies affecting many quantum information applications. Tapering the core at the fiber end up to $d \sim 10 \mu m$ greatly ameliorates the problem. It allows the use of anti-reflection-coated lenses of smaller NA for free-space-to-fiber coupling, allowing us to achieve a single-photon extraction efficiency of $\eta_f = 96\%$. The introduction of a pair of volume holographic gratings for selecting any wavelength of interest (see Fig.1 (a)) increased our spectral transmittance for that wavelength to $\eta_g = (98\%)^2$. Thus we have achieved a near unit efficiency in extracting a single photon from the fiber source: $\eta = \eta_f \eta_g = 92.2\%$. The overall 2-photon detection efficiency of 10% includes the efficiencies of single-photon detection modules (estimated at 70% each) and single-mode fiber collection (~ 50% per channel) which can be improved in the future by using various mode-matching techniques.

Fig. 1: (a) Schematic of the experimental setup. $\lambda_{\text{pump}} = 741.7$ nm, $\lambda_{\text{signal}} = 690.4$ nm, $\lambda_{\text{idler}} = 801.2$ nm, $\Delta \lambda = 0.15$ nm ;
(b) measurement of 2-photon coincidence and coincidence-to-accidental ratio; (c) measurement of second-order correlation.

At an average pump power of $P = 50 \mu W$ and a laser repetition rate of $R = 76$ MHz, we detected 50 photon pairs per sec with $g^{(2)}(0) = 0.0055$ (second-order correlation, $g^{(2)}(0) = 0$ for zero or one pair per pulse), and obtained a coincidence-to-accidental ratio $C/A = 900$ ($C/A \to \infty$ for no background accidentals). At $P = 500 \mu W$, we measured 3,800 pairs per sec with $g^{(2)}(0) = 0.03$ and $C/A = 100$. It is possible to achieve higher pair rates at the same $g^{(2)}$ level by increasing $R$, making this type of source practical for many quantum information applications. With better photon detection [2], the near unit extraction efficiencies may also help to enable fundamental physics tests including the loop-hole free Bell-type tests. This work has been supported in part by the Intelligence Advanced Research Projects Activity (IARPA) entangled photon source program.

Photon-Counting Photomultipliers: Technology and Provenance, 1934 - Present


The photomultiplier, developed by Iams & Salzberg, and by Zworykin, Morton, & Malter at RCA in the 1930s, is one of several vacuum devices still used 100 years after DeForest, Fleming, et al. and 60 years after Shockley, Brattain, & Bardeen. Multiple stage amplification was first achieved by Kubetsky in the Soviet Union. The enormous asymmetry between electrons and ion ejection to vacuum enables “noiseless” amplification. Thermionic vacuum tubes, radio/television, and photomultiplier technologies are intimately intertwined. Less well-known, thin-film technologies developed originally for photomultipliers and television cameras, such as the image orthicon, later enabled the solid-state electronics, ICs, and optoelectronics revolutions. For photon counting, the introduction of negative electron affinity III-V surfaces at RCA in the 1950s enhanced the secondary electron yield, and therefore the gain per stage. By mitigating the statistics of shot noise, pulse heights representing discrete numbers of incident photons could now be distinguished and photon counting was born. The solid state analog, e.g., the asymmetry of ionization energy and mobility for electrons and holes in avalanche photodiodes, is less perfect. These devices, known variously as silicon photomultipliers, single photon avalanche detectors, Geiger-mode APDs, etc., only in recent years have resolved photon number by analogy. A challenge for the newest approaches today is to improve the quantum efficiency of single-photon detection, which both for vacuum and solid-state photon-counting devices remains well under 100%.

1 - Sarnoff Corporation, Princeton, NJ 08540
2 - Sarnoff Corporation (Retired)
3 - David Sarnoff Library, Princeton, NJ 08540
4 - Princeton Lightwave, Cranbury, NJ 08512
Quantum Networks with Single Atoms, Photons, and Phonons

H. Jeff Kimble

Norman Bridge Laboratory of Physics, MC 12-33
California Institute of Technology, Pasadena, CA 91125

Quantum networks offer a unifying set of opportunities and challenges across exciting intellectual and technical frontiers, including for quantum computation, communication, and metrology, as well as for explorations of quantum many-body physics and associated quantum phase transitions [1]. The realization of quantum networks composed of many nodes and channels requires new scientific capabilities for the underlying physical processes used to generate, store, and distribute quantum states, as well as for the characterization and verification of quantum coherence and entanglement. Fundamental to this endeavor are quantum interconnects that convert quantum states from one physical system to those of another in a reversible fashion. Quantum connectivity also provides a means for physical interactions among nodes and thereby for the construction component by component of quantum many-body systems.

My presentation will describe recent progress to implement functional quantum optical networks by way of strong interactions between single atoms, photons, and phonons. Strong interactions can be harnessed for the implementation of quantum logic, for the realization of global quantum-optical interconnects, and for the reliable transport of quantum states across networks. These capabilities provide the basic primitives for the realization of complex quantum networks and thereby of qualitatively new phenomena in Quantum Information Science.

Atom – Photon – Entanglement

Wenjamin Rosenfeld, Markus Weber, Florian Henkel, Julian Hofmann, Michael Krug, Norbert Ortegl, Harald Weinfurter
Ludwig-Maximilians-University of Munich, Germany
Max-Planck-Institute for Quantum Optics, Germany

The emission of a single photon from another quantum system like an atom, ion, quantum dot etc., is a key ingredient for secure quantum key distribution. Yet, provided that there exist more than only one decay channel and that coherence between them can be established, the photon naturally becomes entangled with the emitter.

Here we exemplarily show how this principle can be applied for the generation of entangled photon-atom couples. The additional entanglement not only enables more sophisticated quantum cryptography protocols. Rather, a series of essential applications in quantum information becomes possible, for the first time with a system consisting of different species of quantum systems, where one of them is well suited for communication of quantum information, while the other is ideally applicable for storage and processing of quantum information. We describe the general principle and the experimental techniques to achieve remote state preparation as well as long storage times.

The internal state of a single $^{87}\text{Rb}$-atom becomes entangled with the polarization of the emitted photon.

W. Rosenfeld, et al., PRL 98, 50504 (2007)
Quantum information processing beyond the state-of-the-art technology

R. Ursin\textsuperscript{1}, S. Ramelow\textsuperscript{1}, P. Walther\textsuperscript{1} and A. Zeilinger\textsuperscript{1,2}

\textsuperscript{1} IQOQI - Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences
rupert.ursin@univie.ac.at
\textsuperscript{2} Faculty of Physics, University of Vienna

Single photon detectors are described by a wide variety of parameters like quantum efficiency, timing jitter, dark counts, dead time, after pulsing and others. Not all of these can be put to the extreme in a single device. Fortunately, depending on the scientific questions one would like to address in fundamental physics or an application and also depending on the photon source technology in use, only some of the parameters need to be optimized. In this talk we present what exciting experiments would be possible with the different combinations of various detector and source technologies. E.g. photon-number resolving detectors would allow to surpass the limitations of the spontaneous emission of down-conversion source; thus multi-photon states of more than 10 qubits might be feasible with present source technologies. We will also present an entangled photon source currently in its space qualification process for the use onboard the International Space Station in the framework of Space-QUEST.
Schrödinger's Kittens and Non-Gaussian States of the Light: New Tools for Quantum Communications

Philippe Grangier

Laboratoire Charles Fabry de l'Institut d'Optique, 91127 Palaiseau, France

We describe recent experiments [1, 2, 3] manipulating the quantum state of femtosecond light pulses, in order to generate Fock states (with \( n = 1 \) or \( 2 \) photons), quantum superpositions of coherent states (Schrödinger's cats and kittens), and non-gaussian entangled states. We also discuss possible applications of these states for quantum communications.

Multi-Photon Entanglement from a Single Trapped Atom


Max-Planck-Institut für Quantenoptik,
Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

Abstract

We report on the implementation of a deterministic protocol where a single rubidium atom trapped within a high-finesse optical cavity is entangled with an emitted photon [B. Weber et al., Phys. Rev. Lett. 102, 030501 (2009)]. After a chosen time, the atomic state is mapped onto a second photon, thus generating an entangled photon pair. Compared to previous experiments with falling atoms [T. Wilk et al., Science 317, 488 (2007)], the long trapping times of exactly one atom in the mode of the cavity allow for $10^5$ times more entangled photons per atom and also for a measurement of the coherence time of the atomic qubit. The entanglement is verified by a Bell inequality measurement and via quantum state tomography, both showing a clear violation of classical physics. Furthermore, we show also how this scheme may be used to create n-photon entanglement.
We experimentally investigate non-locality between time-bin entangled qubits using a novel Universal Time-Bin Analyzer (UTBA), which, for the first time, allows analyzing time-bin qubits in any basis. We reveal the nonlocal nature of our source by violating the Clauser-Horne-Shimony-Holt Bell inequality with measurement bases exploring all dimensions of the Bloch sphere. Moreover, we conduct experiments where one qubit is transmitted over a 12.4 km underground fiber link, demonstrating the practicality of our scheme in a real-world setting. The resulting source can also be interpreted as creating hybrid entanglement between different types of degrees of freedom of two physical systems, namely polarization and time, which could prove useful in large scale, heterogeneous quantum networks. Our work opens new possibilities for testing nonlocality [1] and for implementing new quantum communication protocols [2] with time-bin entanglement.

Dispersion Cancellation in Quantum Interferometry and Quantum Imaging

A. V. Sergienko1,2, D. S. Simon1, O. Minaeva1,3, B. E.A. Saleh1, and C. Bonato1,4

1Department of Electrical & Computer Engineering, Boston University, Boston, MA 02215, USA
2Department of Physics, Boston University, Boston, Massachusetts 02215
3Department of Physics, Moscow State Pedagogical University, 119992 Moscow (Russia)
4CNR-INFM LUXOR, Department of Information Engineering, University of Padova, 35131 Padova (Italy)
e-mail: alexserg@bu.edu

Abstract: We demonstrate simultaneous even- and odd-order spectral dispersion cancellation in a single experiment. We also present a spatial counterpart of the dispersion cancellation effect that leads to the removal of all sample-induced aberrations in the quantum “ghost-imaging” configuration.

We describe theoretical and experimental results demonstrating new approach to manipulating dispersion in quantum interferometry and in quantum imaging using spectral and spatial properties of optical entanglement.

Even-order dispersion cancellation that is based on frequency-anticorrelated entangled photons has been known for many years in quantum optics [1,2]. It has been used in several quantum measurement applications. This effect has been exploited for precise evaluation of a photon transit-time through a material [3]. The same effect has also provided superior accuracy in quantum optical coherence tomography [4] by reducing broadening of the coincidence interference pattern for the light passed through layers of dispersive material.

We designed a new type of a quantum coincidence interferometer that illustrates odd-order and even-order dispersion cancellation in one single experiment [5]. This effect is based on manipulation of quantum probability amplitudes of entangled-photon pairs produced in the nonlinear optical process of spontaneous parametric down conversion (SPDC). Selection of specific parameters of our coincidence interferometer enables us to separate the detection of two non-classical dispersion cancellation effects in one experimental setup. The interference pattern in the central section depends only on the even-order dispersion coefficients and it depends only on the odd-order terms for outside peaks.

This effect represents a generalization of the even-order quantum dispersion cancellation and opens new venues in quantum measurement. The possibility of accessing even-order terms independently from odd-order dispersion terms finds applications in the field of quantum metrology and high-resolution polarization mode dispersion evaluation in modern telecommunication components.

We also present results demonstrating a spatial counterpart of the dispersion cancellation effect that is based on the wave-vector entanglement of the biphoton states produced in parametric downconversion [6]. In particular, we engineer specific photon wave-vector distribution by means of an adaptive optical system with deformable mirror and we show that even-order aberrations (such as astigmatism and defocus) do not degrade the quality of the coincidence interference pattern.

At the last stage we extend our results to introduce a full cancellation of object-induced aberrations in the quantum "ghost imaging" configuration. This could lead to enhancements in the field of biological microscopy.

References

Engineering Polarization-Entangled Photons

Radhika Rangarajan1*, Alfred U’Ren2 and Paul G. Kwiat1
1University of Illinois at Urbana-Champaign, 1110 W Green St, Urbana, IL, USA 61801
2Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70–543, 04510 DF, Mexico City, Mexico
*rangaraj@illinois.edu

Abstract: We report on our progress in engineering high-rate spatio-spectrally unentangled polarization-entangled photons, a key technology for optical quantum information processing. As part of characterizing our unentangled source, we present the first reported experimental verification of the increasing dependence of downconversion polarization with emission angle, and techniques to counteract this effect. Moreover, we discuss our ultra-high fidelity ultrafast-pulsed polarization-entanglement source and propose a novel scheme to test the spatio-spectral unentanglement of the engineered photons.

Indistinguishable photon-pair sources — photons uncorrelated in spatial-mode and frequency — significantly improve several optical quantum information (QI) protocols. Interference, a required resource resulting in the quantum advantage, manifests ubiquitously in linear optical quantum computing and quantum communication in the form of the Hong-Ou-Mandel (HOM) interferometer1. For most QI applications, including teleportation, a HOM measurement has to be performed between photons originating from different sources. Such an “event-ready” HOM consists of two independent sources, each of which generates two photons; one photon from each source is then combined at a beam splitter. Here, mere indistinguishability between the two interfering photons does not suffice; any “which-process” information carried by the non-interfering partner photons essentially makes the interfering processes distinguishable. Currently, nearly all experiments solve this problem by incorporating extremely narrow-band spatial and spectral filters to reduce any distinguishing information. However, filtering also drastically reduces the incident photon flux, thereby greatly lowering the overall efficiency. A better solution is to use unentangled photons2-6, i.e., photons with no spatio-spectral correlations. Such truly indistinguishable photons would provide high visibility interference without filtering. However, for useful QI processing we still need usable entanglement, another fundamental resource for QI, in at least one degree of freedom, e.g., polarization. Here, we describe our progress in engineering the ideal indistinguishable photon-pair source for optical QI — polarization-entangled photons with spatio-spectral unentanglement. We expect such a source to successfully enable many QI protocols with high fidelity and high efficiency.

We engineer type-I polarization-entangled photons generated using the two-crystal geometry7 by first imposing simultaneous group velocity matching8 and then optimizing phase-matching parameters, such as pump bandwidth, pump beam focus, and crystal length. The integration of the spatio-spectral unentanglement technology with the two-crystal scheme for producing polarization entanglement leads to at least two challenges: spectral-temporal decoherence and emission-angle dependence of downconversion polarization.

The first challenge, spectral-temporal decoherence, occurs in pulsed two-crystal type-I sources, unlike cw-sources: due to dispersion each frequency component of the broadband pump pulse sees a different effective length of the crystal; averaging over the associated phases leads to effective decoherence and reduced entanglement. Using temporal precompensation9 and spatial compensation techniques10, we have achieved the highest fidelity (>99%) ultrafast polarization entanglement source11 (Fig. 1). The second challenge arises because simultaneous group-velocity and phase-velocity matching in the engineered source leads to a large emission angle of 16°. As shown by Migdall12, the polarizations of the downconverted photons vary with the emission angles, with the effect becoming quite pronounced for a 16° downconversion cone. This occurs because the ordinary downconversion polarization must be perpendicular to the propagation direction and the crystal optic axis. Here we show the first reported experimental verification of this effect (Fig. 2) and also discuss ways to overcome it by collecting at nontraditional azimuthal angles.

Finally, we discuss our progress on the engineered source by integrating all our solutions to the various challenges mentioned above. Additionally, we propose a novel 4-photon scheme to test the intrinsic indistinguishability
of the photons. The scheme is essentially an extension of the two-crystal scheme typically used to generate polarization entanglement. Two engineered crystals are pumped to emit HH and VV pairs. The signal photons act as the trigger to a polarization-based HOM experiment on the two idler photons. A dip in the coincidence rate indicates that the two photons are truly indistinguishable, without any innate which-source information. The main advantage in this scheme is that because the interfering photons are all collinear with one another, the HOM interferometer is inherently very stable and easy to align. Also, note that polarization entanglement is not a prerequisite between the two pairs.

![Experimental setup](image)

**Fig. 1.** Experimental setup for a pulsed two-crystal Type-I phase-matched polarization-entangled source. 810-nm light from a Ti-Saph laser is frequency doubled by a BBO crystal. A half-wave plate (HWP) sets the pump polarization, while a quartz crystal is used for temporal precompensation. A φ-plate is used to adjust the relative phase. The tomography system is used to reconstruct the density matrix of the produced state\(^2\), using quarter-wave plates (QWP), polarizers (P) and interference filters (IF) centered at 810 nm.

**Fig. 2.** Experimental data (triangles) and theoretical predictions (solid lines) of the Migdall effect, showing the expected downconversion polarization vs. the azimuthal collection angle for the 3°-(blue) and 16°-(red) cone opening half-angle. Polarization of the downconversion photons is measured relative to the pump polarization (0° in the lab frame).

### References

For about two decades physicists try to understand how to use a quantum description of physical systems to process or describe classical information. The connection of two quantum systems with different strengths, namely photons (with degrees of freedom like polarization to write information into) and atoms (with internal electronic or nuclear states) was so far discussed in the context of cavity quantum electrodynamics, where a strong coupling between atoms and photons can be achieved due to field enhancement in a cavity.

In this talk, I present an alternative method to enhance the electrical field of a photon simply by strong focusing. In our experiments, we observed already a substantial scattering of near-resonant photons by a single atom with an extinction about 10%, and a phase shift on a light beam of about 1 degree. This method could simplify atom-photon interfaces significantly and thus open new avenues to quantum information processing.
Photon-counting optical coherence tomography using superconducting single-photon detectors

N. Mohan¹, A. V. Sergienko², O. Minaeva², G. N. Gol’tsman³, M. B. Nasr², B. E. A. Saleh², and M. C. Teich¹

¹Department of Biomedical Engineering, Boston University, Boston, MA 02215
²Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215
³Department of Physics, Moscow State Pedagogical University, Moscow 119992, Russia
⁴Department of Physics, Boston University, Boston, MA 02215

Abstract: We experimentally demonstrate the possibility of using superconducting single-photon detectors (SSPDs) for optical coherence tomography (OCT) application in biophotonics. These detectors are sensitive over the full spectral range that is useful for carrying out such imaging in biological samples. With counting rates as high as 100 MHz, SSPDs also offer a high rate of data acquisition if the light flux is sufficient.

Over the past decade, optical coherence-domain techniques such as optical coherence-domain reflectometry (OCDF) and optical coherence tomography (OCT) have come into their own for use in biological imaging [1-3]. These techniques operate on interferometric principles and use heterodyne detection to achieve high detection sensitivity. In scattering tissue, they typically provide axial resolution of a few micrometers and imaging at depths of 2–3 millimeters. In order to provide maximum penetration into scattering tissue, OCDF and OCT imaging is primarily performed in the wavelength range 700-1500 nm [4]. Resolution in OCT measurements is dependent on the product of the spectral response of the imaging system and the optical detector, as well as the source spectrum. Improvement in resolution is attained by making use of a broadband source along with a detector that has high sensitivity over a broad spectral range. We carry out low-light-level coherence-domain imaging using superconducting single-photon detectors (SSPDs).

We report the development of a photon-counting optical coherence-domain imaging system that makes use of superconducting single-photon detectors (SSPDs) [5]. Such detectors are sensitive over a broad wavelength band, including the region of interest for biological imaging, thus allowing for flexibility in the choice of operating wavelength [6,7]. At the same time, they operate in a single-photon counting mode, which offers low detector noise and thereby provides high sensitivity even at low source powers.

The operational principle of the superconducting single-photon detector relies on the utilization of a resistive region that appears in a thin and narrow superconducting stripe after the absorption of a photon [5]. We make use of 10 x 10 μm² meandering 4-nm-thick NbN detector. These devices have continuous sensitivity over a broad spectral range from ultraviolet to infrared and have been shown to have pulse-counting rates that can exceed 100 MHz.

Fig. 1. Photon-counting OCT experimental arrangement using a Michelson interferometer comprising a beam-splitter (BS) and two mirrors. Mirror 1 is translated to change the length of the reference arm. Collinear spontaneous parametric downconversion generated in a 1.5-mm-thick BBO nonlinear-optical crystal (NLC), cut for type-I phase matching, serves as the optical source. D1 and D2 are dichroic components that direct the 532-nm output of the doubled Nd:YVO₄ pump laser to the NLC. Dichroic D3 and Glan–Taylor polarizers P1 and P2 are used to remove unwanted wavelengths. Experiments were performed using both SPADs and SSPDs as photon-counting detectors.
In our experiment we demonstrate the utility of SSPDs in performing coherence-domain imaging near an optical wavelength of 1 μm. We generate broadband infrared light centered at 1064 nm by the process of spontaneous parametric downconversion (SPDC) in a nonlinear optical crystal (see Fig. 1). The broadband light from the crystal enters a Michelson interferometer. The mirror in one of the arms of the interferometer is placed on a nanomotion-controlled stage. The interferogram is measured by translating the mirror in one of the arms. This measurement has been carried out using both an APD (Perkin Elmer SPCM-AQR-15-FC) and a SSPD, enabling the results to be compared. A reduction in the full-width at half maximum (FWHM), corresponding to an improvement in axial resolution, is observed with the SSPD. This is a result of its broader spectral sensitivity.

We have demonstrated the use of superconducting single-photon detectors (SSPDs) in coherence-domain imaging system. These detectors are sensitive over the entire spectral range useful for OCT in biological samples. Neither Si nor InGaAs detectors have comparable sensitivity over the entire spectrum of interest. In addition, SSPDs can also provide high-acquisition-rate imaging, with counting rates as high as 100 MHz, if a sufficient flux of light is available.

References

The Role of Spectral and Spatial Entanglement in Down-Conversion Experiments

W. Grice, R. Bennink, P. Evans, T. Humble
Center for Quantum Information Science, Oak Ridge National Laboratory
gricew@ornl.gov

Spontaneous parametric down-conversion (SPDC) has proven to be a very reliable source of entangled photon pairs for fundamental studies of quantum mechanics, as well as for specific quantum information applications. In addition, SPDC can serve as a heralded single-photon source, whereby the detection of one photon signals the presence of the other. In many cases, quantum information is encoded either into polarization or into photon number (0 or 1). However, photons exist in a richer space, and a more complete description should also include the spectral and spatial degrees of freedom. In general, these auxiliary degrees of freedom are entangled in the sense that the properties of one photon are not independent of those of the other. For many experiments, in fact, the joint spectral and spatial properties are more important than the individual photonic properties. We review here the role of spectral and spatial entanglement in SPDC photon pairs.

The most general expression for the two-photon SPDC state is

$$\psi = \int d\omega_1 d\omega_2 d\mathbf{q}_1 d\mathbf{q}_2 f(\omega_1, \omega_2, \mathbf{q}_1, \mathbf{q}_2) a^\dagger_{\mu_1}(\omega_1, \mathbf{q}_1) a^\dagger_{\mu_2}(\omega_2, \mathbf{q}_2) \text{vac},$$

where the $\mu_j$ ($j = 1, 2$) indicate the polarizations of the two photons and where $\omega_j$ and $\mathbf{q}_j$ describe their frequencies and transverse wave vectors, respectively. The spectral and spatial properties of the photon pair are described by the joint amplitude $f(\omega_1, \omega_2, \mathbf{q}_1, \mathbf{q}_2)$, which is determined by a number of factors, including the spectral content of the pump, the dispersive properties of the nonlinear medium, and the geometry of the interaction. In general, the joint amplitude cannot be factored, and so the spectral and spatial properties are not independent. With some reasonable assumptions, however, the spectral and spatial properties can be decoupled, thereby making it possible to study them independently.

The spectral behavior can be seen in a plot of the joint spectrum, which is simply the square modulus of the probability amplitude after tracing over the spatial variables. Some of the features of a typical joint spectrum can be seen in the example shown below, which was calculated for SPDC in BBO with an ultrafast pump. For example, there is some degree of spectral correlation in the photon energies, though it is not particularly strong. In addition, the distribution is not symmetric with respect to the two photons. By changing certain experimental parameters, it is possible to alter the shape of the joint spectrum and optimize it for a particular application. The ideal shape depends on the experiment: for two-photon polarization entanglement, a symmetric joint spectrum is preferred, although this constraint is relaxed in certain geometries; and for an experiment like entanglement swapping, it is more important to have a low degree of spectral entanglement.

The situation in the spatial domain is similar, although the pump focusing plays a more important role, as do the signal and idler collection optics. In addition, spatial entanglement plays a particularly important role in coupling efficiency when the photons are collected into single-mode systems. Specifically, coupling efficiency is optimized when spatial entanglement is eliminated.

![Fig. 1. Representative joint spectrum calculated for BBO with an ultrafast pump. The darker region represents the most probable pairs of signal and idler frequencies.](image-url)
Novel Photon Pair Sources and Threshold Detectors

R. T. Thew

Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland

We discuss our recent results for the generation and detection of novel quantum states of light. Specifically we report on a narrow-band (120MHz) integrated OPO photon pair source for the telecom regime. We also present preliminary results on threshold detectors - detects photon numbers above a certain level - replicating the behaviour of the human eye. This is based on a SiPM and in the first instance is combined with an up-conversion stage.

INTEGRATED CAVITY OPO W/G

In the push to extend the distances over which we can perform quantum communication, we are forced to consider quantum repeater protocols. This requires the use of quantum memories, which have natural bandwidths that are significantly narrower than the spontaneous parametric down conversion (SPDC) sources that we have mostly used in the past. Most solutions involve either strongly filtering the photon pair's spectrum [1] or using cavities around bulk nonlinear SPDC crystals. We have used periodically poled Lithium niobate (PPLN) waveguides (W/Gs) and placed dielectric mirrors on the end faces to create our cavity [2].

![Experimental set-up for a narrow band (120MHz) integrated waveguide OPO photon pair source.](image)

The waveguide cavity has a Finesse of 15 - a Free Spectral Range (FSR) of 1.8 GHz (14 pm) and a Full Width at Half Maximum (FWHM) of 117 MHz (0.91 pm). The source produces a large range of frequency modes, associated with those that are supported by the cavity and respect energy conservation, but only the entangled photon pairs, centred around the degeneracy point of 1560nm pass the 10 pm filters ensuring single mode operation. We present the characteristics of the source and discuss some of its novel features including continuous stabilisation.

THRESHOLD DETECTORS

Our motivation for studying threshold detectors are twofold: The limits of the Human eye as a photon detector are not so well defined in the low photon number regime and hence we are looking at better understanding this; from the perspective of quantum physics we are also interested in exploring the interface between micro- and macroscopic regimes - the human eye generally considered to be functioning on the macroscopic side.

![An experiment has been proposed that uses the human eye as a photon detector for detection quantum states of light.](image)

The micro - macro question has gained our attention and we have recently proposed the use of human eyes as detectors for quantum experiments [3]. This takes the concept of human-eye detectors to a regime capable of detecting quantum states of light - entanglement. The concept is illustrated in Figure 2 where a photon, possibly one of an entangled pair, is amplified, after which threshold detectors can be used to discriminate the desired signal.

Optimization of States in a Lossy Metrology

S B McCracken, Tae-Woo Lee, Sean D. Huver, Lev Kaplan, Hwang Lee, Changjun Min, Dmitry B. Uskov, Christoph F. Wildfeuer, Georgios Veronis and Jonathan P. Dowling

Physics and Astronomy
Hearne Institute for Theoretical Physics
Louisiana State University

We have utilized a genetic algorithm to determine the minimum possible phase sensitive in a lossy interferometer, and the corresponding states that yield this optimization. The setup involves an arbitrary source with a finite number of photons which is sent through the two arms of the interferometer. Both arms may contain an arbitrary loss and relative phase shift. The detection process passes the two arms through a beam splitter and measures the output with number resolving detectors. The probable number of photons incident on these detectors is used in calculating the Fisher information, which is then used to determine the minimum phase sensitivity of the sensor.

We implemented the optimization of the sensor’s input states via a genetic algorithm which utilized a forward calculation of the interferometer with fixed loss and photon number. The genetic algorithm consisted of 5 members in the population with 2% convergence requirement per generation, and was allowed to run for 100,000 total iterations. The optimization parameters consisted of relative phase shift between the arms of the interferometer in addition to input state amplitude and phase components.

It was found that maintaining no loss in the control arm of the interferometer increases phase sensitivity for all values of loss in the target arm. Not surprisingly, it was also determined that no single state is optimally phase sensitive over the entire regime of loss, but the optimum sensitivity as a function of loss for any number of photons has a nearly identical exponential dependence in the high loss regime.
Quantum computing promises computational power beyond that ever achievable with classical computers. It offers an exponential speedup for a number of important algorithms and will enable us to simulate quantum systems on a scale intractable with today’s methods. Among the physical architectures which have been explored for quantum computing so far, photonic quantum computing has been one of the most successful.

In this talk we will give a short overview of our recent demonstrations of quantum gates, quantum algorithms and quantum simulations with single photons. The challenge for our field in the next years will be to move from these early small-scale experiments to a future of robust, integrated many-photon devices. We will discuss the limitations of current technology which must be overcome for this to happen—those of photon sources, optical circuits and detectors. In particular, we will present results which show how noise terms in spontaneous parametric downconversion sources and imperfections in optical gates affect the performance of quantum circuits. Finally, we will present a simple experimental approach to reduce these noise terms.
High Quality Photonic Polarization Entanglement Distribution at 1.3-µm Telecom Wavelength

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
Tony D. Roberts and Philip Battle
AdvR, Inc., 2310 University Way, Building 81, Bozeman, MT 59715, USA
tzhong@mit.edu

Abstract: High quality polarization-entangled photons at 1.3 µm generated from a fiber-coupled PPKTP waveguide are distributed and analyzed using a remotely located high efficiency superconducting nanowire single-photon detector, yielding an average quantum-interference visibility of 92.9% and 4.5 detected pairs/s at 45 µW pump power.

High-flux waveguide photon-pair sources and superconducting nanowire single-photon detectors (SNSPDs) are promising technologies for realizing telecom entanglement distribution networks. Here we demonstrate efficient generation and distribution of high-quality polarization-entangled photons at 1.3 µm from a periodically poled KTiOPO4 (PPKTP) waveguide and detection with a single high system efficiency niobium nitride (NbN) SNSPD.

Figure 1 shows the schematic of our source and detector setup. The polarization entangled photon source and the detector were physically located in two separate buildings and linked by 200-m long SMF-28e single-mode fibers. The PPKTP waveguide had a pair generation rate of ~2.0×10^7 pairs/s/mW of pump, and an ultralow fluorescence noise of ~2% of the downconverted photons at 1316 nm within the type-II phase matching bandwidth of 1.1 nm. Spectral indistinguishability was ensured by using a reflecting volume Bragg grating (RBG) filter with a FWHM bandwidth of 0.7 nm. The postselected polarization-entangled photon pairs were distributed through separate fibers, polarization analyzed, and detected with a single SNSPD. The fiber-coupled NbN SNSPD system had a high system detection efficiency of ~21% and a low dark count rate <1100 counts/s. Using a fiber loop delay line and a time-multiplexed scheme of deploying only one SNSPD, we measured the two-photon quantum interference of our polarization-entangled photons, obtaining a visibility of 95.7% in the horizontal-vertical (H-V) basis and 90.1% in the antidiagonal-diagonal (A-D) basis without accidentals subtraction. Using our single SNSPD scheme, we measured a HOM visibility of 95.6% without accidentals subtraction at a pump power of 57 µW. Thanks to the high efficiency RBG filter, the coincidence rate per unit pump power has been improved by ~12x relative to our earlier implementation that utilized standard interference filters.

Tian Zhong and Xiaolong Hu contributed equally to this work. This work was sponsored by IARPA.

Fig. 1. Schematic of the experimental setup. PMF: polarization-maintaining fiber; SMF: single-mode fiber; RBG: reflecting volume Bragg grating; LPF: long-pass filter; PBS: polarizing beam splitter; HWP: half-wave plate; FPBC: fiber polarizing beam combiner; SNSPD: superconducting nanowire single-photon detector; TAC: time-amplitude converter.
Two techniques for high-speed entangled photon pair generation using periodically poled potassium titanyl phosphate waveguides.

Oliver Slattery, Lijun Ma and Xiao Tang,

Information Technology Laboratory, National Institute of Standards and Technology
100 Bureau Dr., Gaithersburg, MD 20899 USA

The generation of entangled photon pairs at the wavelengths 1310 nm and 895 nm is desirable for the implementation of a quantum repeater. Light at 1310 nm has low loss transmission in standard optical fiber and is compatible with the existing fiber infrastructure. On the other hand, light at 895 nm is resonant with the 6s-6p transition line of Cesium atoms, and is therefore suitable for use in quantum memory. These characteristics of long distance transmission and quantum memory are basic elements in a quantum repeater, making correlated photon pairs at these wavelengths strategically important.

We have experimentally implemented two alternative non-degenerate sequential time-bin entangled photon-pair sources using a periodically poled potassium titanyl phosphate waveguide at a clock rate of 1 GHz with the wavelengths of the signal and idler 895 nm and 1310 nm respectively.

Our first implementation of a non-degenerated coincidence/entanglement photon pair source at over a GHz repetition rate uses two separate periodically poled potassium titanyl phosphate (PPKTP) waveguides. In order to achieve the 1GHz rate, we used a 1064 nm light as the source since there was no high-speed modulator available for 532 nm. The 1064 nm light is modulated by a high-speed lithium niobate electro-optical modulator (EOM), and then amplified and frequency doubled to 532 nm by second harmonic generation (SHG) in the first waveguide. The non-degenerate photon pairs (895 nm and 1310 nm) are generated from the 532 nm light in the second waveguide by the spontaneous parametric down conversion (SPDC).

To simplify the experimental configuration, we used a single dual-element PPKTP waveguide to implement both the SHG and the SPDC and successfully generated time-bin entangled photon pairs at the same wavelength and repletion rate. The key innovation is the compact dual-element crystal waveguide that performs both the SHG of the 1064 nm input and the SPDC of the 532 nm photons into 895 nm and 1310 nm photons. This can simplify systems and reduce losses associated with multiple coupling of separate waveguides. However, placing both elements on a single structure required filtering and temperature optimization techniques that were not previously needed. For example, residual noise from the amplifier at wavelengths near the SPDC photons must be suppressed prior to entering the waveguide. Previously, with separated elements, this occurred when coupling to a single mode 532 nm fiber. Also, a single optimal temperature for both elements is needed whereas in separated elements, the temperature for each element may be optimized.
Experimental estimation of entanglement at the quantum limit

I. P. Degiovanni¹, G. Brida, A. Florio², M. Genovese, A. Meda, A. Shurupov³
Istituto Nazionale di Ricerca Metrologica, I-10135 Torino, Italy

P. Giorda, M. G. A. Paris⁴
ISI Foundation, I-10133 Torino, Italy

ABSTRACT

Entanglement is the central resource of quantum information processing and the precise characterization of entangled states is a crucial issue for the development of quantum technologies. In turn, quantification and detection of entanglement have been extensively investigated, see [1,2] for a review, and different approaches have been developed to extract the amount of entanglement of a state from a given set of measurement results. Of course, in order to evaluate the entanglement of a quantum state one may resort to full quantum state tomography which, however, becomes impractical in higher dimensions and may be affected by large uncertainty [3]. Other methods, requiring a reduced number of observables, are based on visibility measurements [4], Bell' tests [5], entanglement witnesses [6] or are related to Schmidt number [7].

Any quantitative measure of entanglement corresponds to a nonlinear function of the density operator and thus cannot be associated to a quantum observable. As a consequence, ultimate bounds to the precision of entanglement measurements cannot be inferred from uncertainty relations. Any procedure aimed to evaluate the amount of entanglement of a quantum state is ultimately a parameter estimation problem, where the value of entanglement is indirectly inferred from the measurement of one or more proper observables [8]. An optimization problem thus naturally arises, which may be properly addressed in the framework of quantum estimation theory [9,10], which provides analytical tools to find the optimal measurement and to derive ultimate bounds to the precision of entanglement estimation.

Here we present the results of an experiment where, for the first time, the amount of entanglement (negativity) of two-qubit photon states is estimated, by quantum correlations measurement, with the ultimate precision allowed by quantum mechanics [11]. This represents a substantial advance, paving the way for further progresses in quantum estimation.

REFERENCES

Towards a deterministic entangled and single photon source at telecom wavelength using InAsP/InP quantum dots.


Deterministic and efficient source of single and entangled photons are a basic component of quantum networks. In this paper we will present our theoretical work toward the production of a high quality entangled photon source, by coupling single quantum dots with photonic crystal cavity. By using the Purcell effect, it is possible to restore the entanglement. We will also present our experimental results on controlling the fine structure splitting of quantum dots with an P-I-N junction structure compatible with photonic crystal cavities. Finally, we will present experimental results on single photon emission from single InAsP/InP quantum dots at telecommunications wavelengths.

\[ g^{(2)}(\tau) \]

Time Interval between photon detections