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Kevin McCuster, YuPing Huang, Gregory Kanter

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Northwestern University Evanston Campus
Office for Sponsored Research (OSR)
1801 Maple Ave.
Evanston, IL 60201 -3149

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14. ABSTRACT
Single photons sources are desired for many potential quantum information applications. One common method to produce single photons is based on a “heralding” protocol, which involves generating a pair of photons in an optical nonlinear medium and then detecting one photon in the pair to announce the existence of the other photon of the pair. Compared to other schemes, such a method offers several significant advantages. A major challenge to overcome which is inherent to this method, however, is that the photon pairs are created stochastically in the optical nonlinear medium. Thus, in order to ensure high purity levels for the single photons generated via heralding

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Report Title

Final Report: High-Performance Single-Photon Sources via Spatial Multiplexing

ABSTRACT

Single photons sources are desired for many potential quantum information applications. One common method to produce single photons is based on a “heralding” protocol, which involves generating a pair of photons in an optical nonlinear medium and then detecting one photon in the pair to announce the existence of the other photon of the pair. Compared to other schemes, such a method offers several significant advantages. A major challenge to overcome which is inherent to this method, however, is that the photon pairs are created stochastically in the optical nonlinear medium. Thus, in order to ensure high purity levels for the single photons generated via heralding, sources of this type must be operated at low photon-pair production rates in order to keep the probability for simultaneous creation of multiple photon-pairs to an acceptably low level. A direct result of this restriction is a low heralding rate of single photons. A potential solution for achieving high-rate, high-purity, single-photon generation combines several heralding single-photon sources which are actively multiplexed to act as one source. The overall goal of this project is to develop methods to perform such multiplexing based on the use of a low loss high speed fiber optical switch.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

T. M. Rambo, K. T. McCusker, N. N. Oza, S. J. Nowierski, K. F. Lee, P. Kumar, G. S. Kanter, and Y.-P. Huang, "Implementing a high-rate single-photon source using ultra-low-loss all-optical switching," 12th International Conference on Quantum Communication, Measurement, and Computing, (2014).

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
03/23/201	1.00	Timothy M. Rambo, Kevin McCusker, Yu-Ping Huang, Prem Kumar. Low-loss all-optical quantum switching, 2013 IEEE Photonics Society Summer Topical Meeting Series. 07-JUL-13, Waikoloa, HI, USA. : ,
03/23/201	3.00	Timothy Rambo, Joseph B. Altepeter, Giacomo M. D'Ariano, Prem Kumar. Quantum Operator Permutation by Optical Means, Quantum Information and Measurement. 17-JUN-13, Rochester, New York. : ,

TOTAL: 2

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Samantha Jean Nowierski	0.02	
FTE Equivalent:	**0.02**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Kevin T. McCusker	0.65
FTE Equivalent:	**0.65**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
YuPing Huang	0.04	
Kim Fook Lee	0.28	
FTE Equivalent:	**0.32**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

"See Attachment"

Technology Transfer

Traveled to Jet Propulsion Laboratory to interface the switching system with superconducting detectors.

High-Performance Single-Photon Sources via Spatial Multiplexing

Final Report

(Reporting Period: 15 Aug 2012 – 31 Oct 2014)

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I: Title Page

Name of Grantee: Northwestern University,

633 Clark Street, Evanston, IL 60208

Principle Investigator: Gregory Kanter (in place of Prem Kumar),

Business Address: Center for Photonic Communication and computing
EECS Departments, Northwestern University
2145 Sheridan Road, Evanston, Illinois 60208-3118

Phone Number: 847-491-2726

Email Address: gregory.kanter@northwestern.edu

Date of Grant: 08/15/2012

Grant Expiration Date: 10/31/2014

II: Summary of Project

II. A. Introduction

Single photons, or more precisely, single-photon quantum states, constitute the basis for many potential applications, ranging from testing fundamental concepts of quantum mechanics to modern quantum techniques. Particularly in the rapidly growing field of quantum information processing, single photons are widely employed as the key ingredient for tasks such as quantum cryptography, quantum repeater, quantum teleportation, quantum computing, and truly-random number generation. Recently, it was also proposed that single-photon states can be used to approach the ultimate limit of communication efficiency, the so-called Holevo limit.

A generally-adopted method to produce single photons is based on a “heralding” protocol, which involves generating a pair of photons in an optical nonlinear medium and then detecting one photon in the pair to announce the existence of the other photon of the pair. Compared to other schemes, such a method offers several significant advantages in terms of device compactness and integrability, wavelength-versatility, and room-temperature operability. A major challenge to overcome which is inherent to this method, however, is that the photon pairs are created stochastically in the optical nonlinear medium. Thus, in order to ensure high purity levels for the single photons generated via heralding, sources of this type must be operated at quite low (~10% or less) photon-pair production rates in order to keep the probability for simultaneous creation of multiple photon-pairs to an acceptably low level. A direct result of this restriction is the low heralding rate of single photons.

To overcome this bottleneck, Migdall *et al*. have proposed a solution for achieving high-rate, high-purity, single-photon generation, wherein several heralding single-photon sources are spatially multiplexed to act as one source (hereafter referred to as the “Migdall scheme”). In their original proposal, the multiplexing is implemented by using *N* optical switches and an *N*-by-*1* optical combiner. In practice, however, such a setup will be subjected to high transmission losses for the heralded single photons. Consequently, the rate increase for single photon generation gained by spatial multiplexing is quickly lost. Furthermore, when the transmission loss is substantial, upon heralding the appearance of a single photon at the output port of the system becomes highly probabilistic, rendering such devices unsuitable for many applications where deterministic single photons are required.

II. B. Our approach

In this project, we aimed at overcoming the difficulty of transmission loss with the original Migdall scheme by exploiting two techniques developed in our lab. The first is a fiber-based source of photon pairs at telecommunication O-band (1.3 μm). This kind of sources has already been demonstrated to be operable at extremely high rates (10 GHz) and to produce entangled photon pairs with >99.5% fidelity to a maximally entangled state. In addition, because such photons are generated directly in single-mode fiber, the use of such sources obviates the need for potentially lossy mode matching for fiber transmission (or to ensure spatial-mode purity). The second is a state-of-the-art fiber-based all-optical switch capable of selectively coupling 10-ps time-bins to spatial or temporal modes at a 10-GHz repetition rate without introducing any measurable in-band noise. The same switch is capable of temporally serializing (multiplexing) and deserializing (demultiplexing) multiple spatial modes into a single spatial mode for decoherence-free transmission through either fiber or free-space. Thus far, several such switches in a Sagnac-loop configuration have been developed and experimentally characterized in our group, demonstrating very short switching windows (~ 30 ps) and low per-switch loss (1.3~1.7 dB). Furthermore, polarization-entangled photon pairs actively and passively transmitted through the switch were shown to experience negligible decoherence, maintaining >99.5% fidelity to a maximally entangled state.

We studied a high-rate, high-fidelity single-photon source by incorporating the fiber-based photon-pair generation and the fiber-based all-optical switching. Our source used the Migdall scheme, where multiple heralding single-photon sources are spatially multiplexed using a low-loss serializer built of fiber-based all-optical switches. As both the photon-pair generation and switching operation take place in the same single-mode fibers, the total collection efficiency of the heralded single photons should be able to approach unity. In order to maximize the single-photon production rate, we upgraded our existing fiber-based switches by substituting the Sagnac-loop configuration with a novel Mach-Zehnder-interferometer design. This upgrade significantly reduced the transmission loss of the switch by more than 70%, with down to as low as 0.16 dB per pass observed. This exceeds the goal of 0.3~0.5 dB per pass in our proposal. By using such ultralow-loss switches, single photons should be able to produced at high rate (approaching GHz or even higher) and with high fidelity (in excess of 95%). Indeed, by using GHz detectors acquired from NuCrypt, we successfully realized multiplexing of two single photon sources.

The overall goal of the experiment was to multiplex the output of four heralded single-photon sources using the low-loss switches at high rates. This was implemented, but the overall loss from filters as well as problems with the switching power led to an overall output that was not as high quality as desired.

II. C. Significance of our approach

Single photons are an indispensable resource for quantum optical information processing. Existing methods for producing single photons fall into the following three categories. The first is based on antibunched-emission of single photons in quantum systems that contain only a single emitter (such as single atoms, ions, molecules, and quantum-dots). Sources of this type usually require large-volume setup and cryogenic environment, and are thus inconvenient to implement in practice. The second kind is based on the "heralding" protocol, and has been well established in second-order nonlinear crystals/waveguides, optical fibers, Silicon-on-insulator (SOI) waveguides, and atomic ensembles. Single-photon sources of this kind are compact, scalable, and can be operated at room temperature. However, they are difficult to achieve simultaneously high production rate and high quantum-state purity, owing to the fact that the photon-generation in such systems is a probabilistic process. The third kind uses two-photon interference or two-photon absorption effect. Such sources, however, are overly restricted by some fundamental difficulties, including the requirement on phase stabilization and/or the lack of appropriate optical media.

In this project, we studied a high-rate, high-fidelity single-photon source adopting the Migdall scheme, where multiple heralding single-photon sources are spatially multiplexed using a low-loss serializer built of fiber-based all-optical switches. As both the photon-pair generation and the switching operations occur in single-mode fibers, the total collection efficiency can be very high, approaching 100%. In order to minimize the transmission loss, we developed an ultralow loss fiber-based switches suitable for quantum signals at a single-photon level. In addition, to test the maximal possible production rate in such fiber systems, we operated the overall system at 1 GHz clock rate, using custom-engineered, GHz-rate single-photon detectors. The above techniques will allow a high-performance single-photon source at high rate (in excess of 20 MHz and extendable to 1 GHz) and with high fidelity (with Fano factor less than 0.3). In addition, the developed ultralow loss technique for quantum switching can form the basis for networked quantum information processing.

III. Technical Details

III. A Fiber-based photon pair sources

The fiber pair source was based on a source of entangled photons previously developed in the Kumar lab [Ref: Matthew A. Hall, Joseph B. Altepeter, and Prem Kumar, Opt. Exp. **17**, 14558 (2009)]. This source uses a high-peak-power pump near the zero-dispersion point of fiber near 1305 nm, and produces pairs of photons through four-wave mixing in nearby wavelength bands. The bands used are about 0.5 nm wide, and only 1.5 nm detuned from the pump, which minimizes Raman noise. For this experiment, we created the pump by chopping a continuous-wave pump into 100 ps pulses. These pulses are then chirped using a phase modulator, and compressed by passing through several kilometers of dispersion-shifted fiber. This method allows us to produce short pulses (16 ps) at an arbitrary repetition rate up to several GHz.

III. B Fiber switches

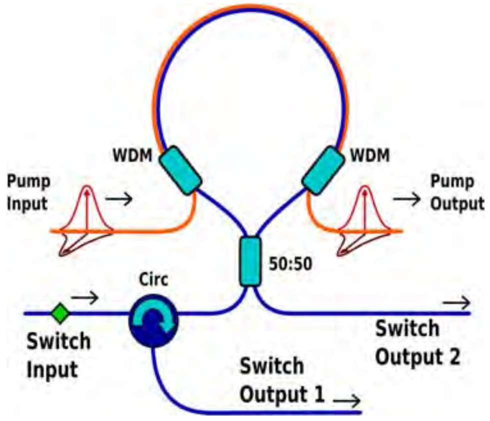

Figure 1. Switch with a Sagnac interferometer design. The use of a circulator caused a relatively high average loss of 1.7 dB.

The underlying all-optical ultrafast switching technology was previously developed in the Kumar lab [Ref : Matthew A. Hall, Joseph B. Altepeter, and Prem Kumar, Phys. Rev. Lett. **106**, 053901 (2011)]. This switch uses an interferometer, with the ability to modify the phase of one path of the interferometer using a strong optical pulse through cross-phase modulation. The switch can operate at up to 100 GHz and has very low in-band noise, including any contribution from Raman scattering. The original design relied on a Sagnac interferometer, which is inherently stable, but only has a total of two inputs and outputs, making it not suitable for a switch on its own (see Fig. 1). Adding a circulator allows this design to be used as a switch, but unfortunately the circulator increases to loss, leading to an average switching loss of 1.7 dB.

For this work, we needed to design a switch with a significantly lower loss. Rather than using a Sagnac interferometer, a Mach-Zehnder interferometer was used (see Fig. 3), in which case circulators were not necessary. This significantly reduced the loss of the switch, but also complicated the system, requiring active stabilization of the length of the two sides of the interferometer. This stabilization was done by using a separate laser at a different wavelength. The relative path length could be monitored using this laser, and drift in the path length could be compensated using a fiber stretcher. The monitor laser power was detected by a photodiode. The photodiode was measured using a microprocessor (Arduino Due), which also implemented a digital PID controller to control the fiber stretcher and compensate for path-length drift.

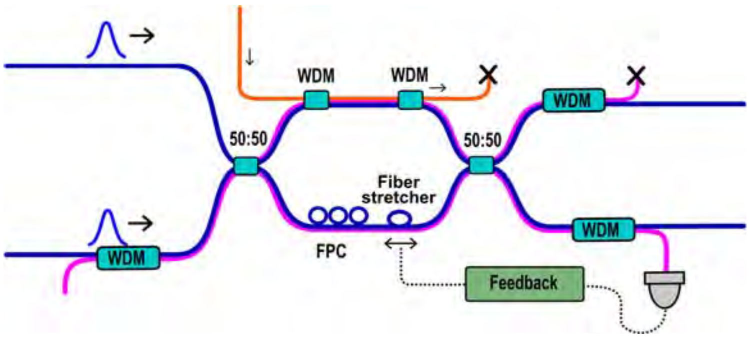

Figure 2. Switch with a Mach-Zehnder design. Removing the circulator lowered the loss to 0.2 dB, but necessitated the additional components to stabilize the interferometer.

With the above new design, the experimental loss was dramatically better than the stated goal, with an average of 0.2 dB loss per switch, compared to a goal of 0.5 dB loss per switch. This was achieved by selecting low-loss components. We also took advantage of the fact that the same filters that are required to filter out the pump in the pair source can also be used to couple in (and out) the monitor laser, which reduces the overall loss.

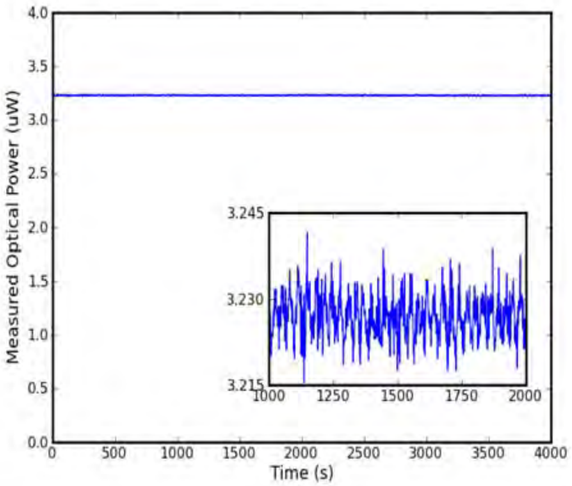

Figure 3. Output of one arm of the interferometer under active stabilization.

The interferometers we assembled had an excellent intrinsic visibility, measured to be over 99.9%. When actively stabilized, the contrast could be controlled to better than 99%, and could be stabilized for long periods of time, as shown in Fig. 3. Unfortunately, the contrast during the fast switching was limited due to an unknown effect to about 90% (see Fig. 4). We ran many tests to determine the cause for this, and determined that it was not due to polarization, pump pulse shape, pump pulse distortion due to self-phase modulation, fiber length, or Raman scattering effects. Ultimately, this was overcome by using a longer pulse (see Fig. 5), which increased the contrast to about 98%. This approach required more energy per pulse and decreased the switching speed, although it was still fast enough for our purposes.

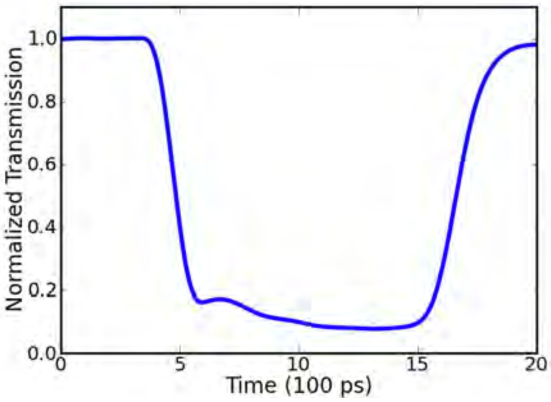

Figure 4. With a short pulse, we were unable to observe high contrast, regardless of the energy of the switching pulse.

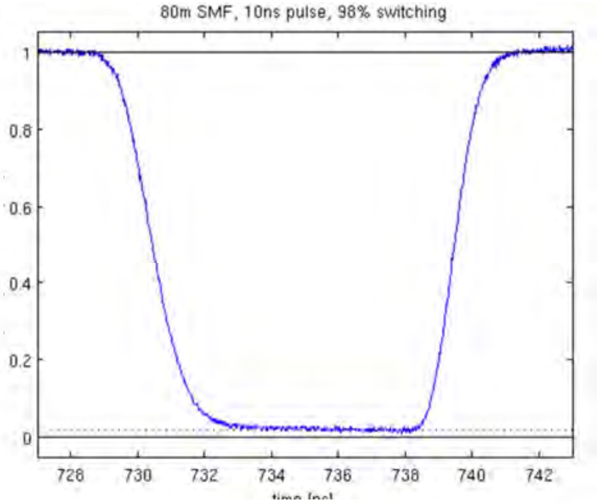

Figure 5. With a longer pulse, we were able to observe high-contrast switching.

Overall, after developing techniques to do so, assembling and stabilizing the switches was relatively straightforward. The biggest challenge in stabilizing the switches was in stabilizing the power for the monitor laser. Since the controller locked the output to a specific power, a fluctuation in the power led to a fluctuation in the path length. This was partially mitigated by locking the switch to a point where the power of the monitor laser was near a minimum, which reduces the effect of the fluctuations on the path length.

Another significant challenge was in controlling the energy in the optical pulses used to control the switch. As with any fiber amplifier, the gain of the amplifier we used (a 2-watt erbium-doped fiber amplifier) depended on the input power. Since we were switching at a very high rate compared to previous experiments, and with a higher energy, this was a more difficult task than in previous experiments. Furthermore, the pump pulses to control the three switches in the experiment used different wavelength channels on the same amplifier, which led to cross-talk between the switching rates on one channel with the pulse energy in another channel. Combined with the instability in the detector efficiency and dark counts, this led to an instability in the switching contrast of up to 70%, and ultimately to the performance of the overall experiment.

III. C: Photon Switching experiment

The overall goal of this experiment was to multiplex the output of four heralded single-photon sources to increase the rate of single photons without affecting the quality of them (i.e., Fano factor).

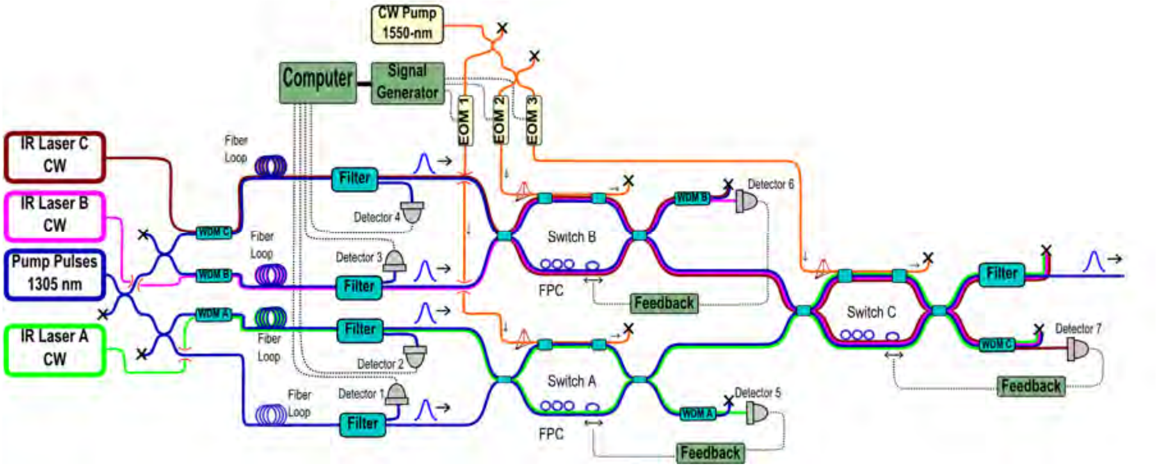

Figure 6. A full schematic of the four sources mutiplexed by three switches.

A schematic showing the overall experimental setup is in Fig. 6. Four sources fed into three switches. When a heralding photon from one of the first three sources was detected, the appropriate switches were fired (no switching was necessary for the fourth source).

The four sources were all pumped at a rate of 1.25 GHz, with an average heralding rate up to 8 MHz each, and a combined heralding rate of up to 32 MHz total. Multiplexing these four sources with feed-forward switching was successful (see Fig. 7), leading to a heralded single-photon source with a heralding rate of approximately 28 MHz, but unfortunately there was too much loss that limited the overall performance of the experiment, leading to a high Fano factor. The biggest source of loss was from the filters in the source, which were necessary to block out the pump as well as define the signal and idler bandwidths. In order to make the source near single mode, which minimizes the contribution from Raman photons, the filter bandwidths needed to be about the same as the pump bandwidth. Since the frequency correlation between the signal and idler photons maintains the same uncertainty as the pump photons, the bandwidth of the idler photons that are conjugate to the bandwidth defined by the signal filter are in significantly broader than bandwidth of the idler filter, and vice versa for the idler filter defining the bandwidth for the signal photons. This effect can be seen in the red dashed line in Fig. 8. All of this leads to a reduced heralding efficiency, which is defined as the probability of the signal photon

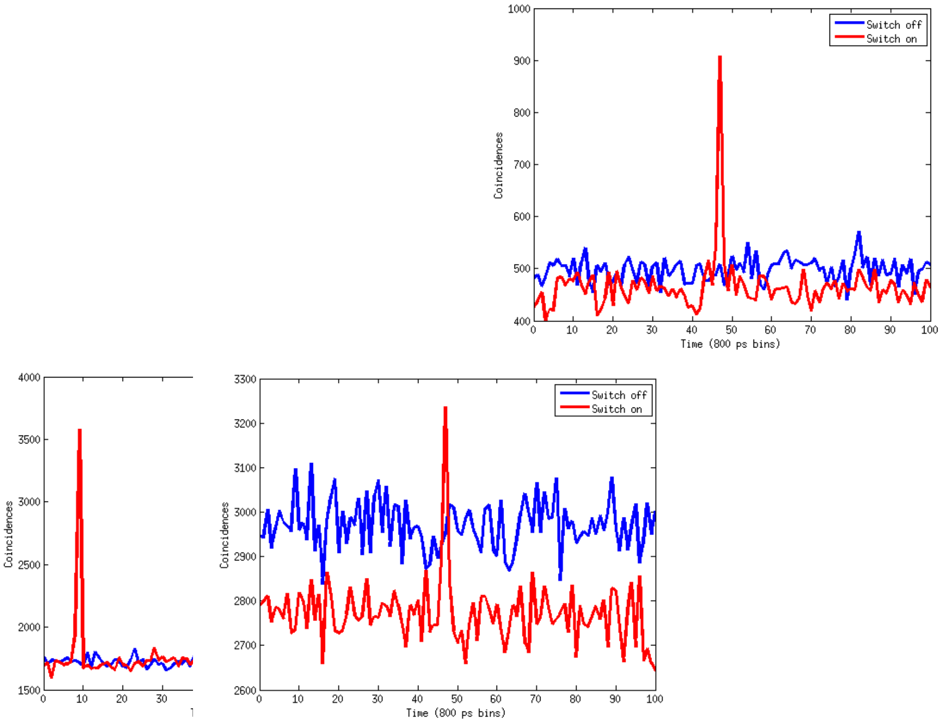

Figure 7. Coincidences between the output detector and three of the sources. Heralded counts were not measured in the fourth source since only four detectors were available. However, no switching was necessary for this source. Note that with the pump for the feed-forward switching is off (blue line), no coincidences beyond the accidentals were observed, but are seen when the pump is on (red). Data was taken simultaneously for all sources.

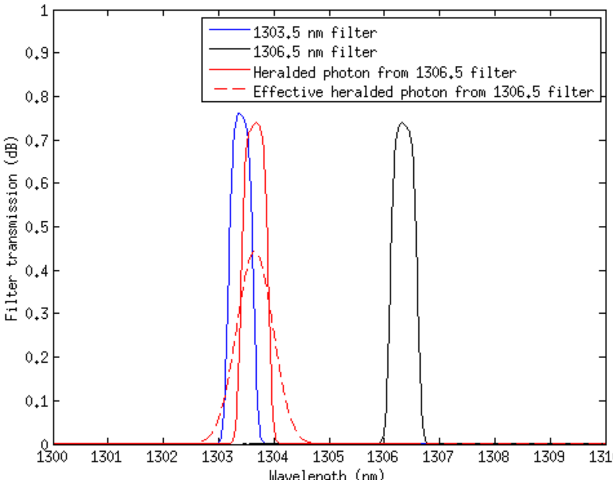

Figure 8. Spectra of two filter sets used in the experiment. Also shown in red is the spectra of the conjugate photon if a photon from a perfectly frequency-correlated pair source passes through the 1306.5 nm filter, as well as the spectra from a pair source that maintains the frequency uncertainty due to the finite bandwidth of the pump.

successfully passing through the signal filter, conditional on the idler photon from the pair passing through its filter. Overall, the heralding efficiency from the filters is about 0.3, which by itself would limit the Fano factor to 0.7. Raman contribution also significantly lowered the heralding efficiency, even operating near the single-mode regime. The contribution from Raman photons was about the same as the contribution from four-wave mixing photons, leading to a heralding efficiency of about 0.15, and Fano factor of

0.85. Significant additional loss came from the switching contrast, which was unstable at high rates, due to limitations in the amplifier for the switching laser. Further loss was from the final series of filters to remove all of the out-of-band light from the switch pump. Overall, the loss from where the photon was generated to the final detector was over 10 dB, which would correspond to a Fano factor of >0.9. If a source were used that had a high heralding efficiency (>75% is possible [B. G. Christensen *et al.*, Phys. Rev. Lett. **111**, 130406 (2013)) and the issue with switch contrast could be resolved, then the Fano factor could be as low as 0.3.

The biggest limitation for the experimental results was the necessary filtering and Raman noise intrinsic to the four-wave mixing source that was used. In order to achieve a higher-performance multiplexed source, a pair source with less noise such as a three-wave mixing source or a four-wave mixing source engineering to have only a specific bandwidth away from Raman noise would have to be used. In addition, the design for the switch pump laser should be modified to be more stable, and particularly less sensitive to fluctuations in the switching rate.

IV. List of Public Presentations

T. M. Rambo, K. T. McCusker, Y.-P. Huang, P. Kumar, "Low-loss all-optical quantum switching," Photonics Society Summer Topical Meeting Series, 2013 IEEE , vol. 179, no. 180, pp. 8-10 (2013).

Rambo, Timothy, et al. "Quantum Operator Permutation by Optical Means." *Quantum Information and Measurement*. Optical Society of America, 2013.

V. List of Poster Presentations

T. M. Rambo, K. T. McCusker, N. N. Oza, S. J. Nowierski, K. F. Lee, P. Kumar, G. S. Kanter, and Y.-P. Huang, "Implementing a high-rate single-photon source using ultra-low-loss all-optical switching," 12th International Conference on Quantum Communication, Measurement, and Computing, (2014).