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RPPR Final Report

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Major Goals: Complex quantum communication protocols requiring many qubits are fundamentally limited by the transmission loss of photonic information. One way to overcome this obstacle is to encode many qubits onto a single photon. For example, by encoding ten qubits per photon into a two-photon, 20-qubit maximally entangled state the success probability of a quantum communication protocol can be increased by over five orders of magnitude when compared to a 20-photon, 20-qubit implementation. In order for this approach to be successful, however, novel methods for creating, manipulating, and measuring high-dimensional photonic quantum information must be developed.

Here we propose to modify a recently developed source of fiber-based entangled photon pairs and a novel ultrafast entangled-photon switching technology in order to create a practical source of telecommunications band photon pairs temporally encoded with a maximally entangled 20-qubit quantum state. Moreover, we propose to develop the advanced photonic switching tools required to reliably manipulate and measure the quantum information encoded onto the photon pairs generated by this new source. Although developed for quantum communications applications, the 20-qubit, two-photon state would be the largest entangled state ever measured, in any system

Accomplishments: As progress towards the goals, we made complete quantum state tomographies for dimensions up to $d=4$ ($d=2,3,4$). The tomographies make use of temporal bins with up to four time slots and receiver-side processing that allows the measurement of these high- d states to resemble that of multiple polarization entangled qubits. The quantum states are distributed over fiber and the associated fidelity degradation is characterized.

A key element of the project is the implementation of quantum fiber switches which allow for high speed selection of specific time-bins. These switches have been characterized and optimized for the given task. Methods to improve the switch performance, particularly in terms of reducing the generated background photon levels, have been identified and characterized. In particular, the wavelength of the pump plays an important part in the switch performance due to Raman photon generation. Issues related to scaling to yet higher d have been investigated.

As part of the project, we have developed models that allow us to simulate the performance of the tomography

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system including parameters from all the major components such as the entanglement generation block, the switches, and the detection block. This full system model allows us to predict the impact of changing any components in the system, such as the single photon detectors or the background photon generation rate in the switches.

Our early work had performance limited by the laser coherence time. We improved the measurement fidelity of our system by moving to a pump laser with a longer coherence time. This new pump pulse source has a coherence time of around 100 ns, which is much longer than the previous pulsed laser source used whose coherence time was 2.5 ns. New measurements of qubit ($d=2$), qutrit ($d=3$), and ququat ($d=4$) systems show marked improvement with accidental-count-subtracted fidelity to maximally entangled qubits, qutrits, and ququarts of $99.3 \pm 0.5\%$, $97 \pm 0.4\%$, and $93.7 \pm 0.4\%$, respectively. This can be compared with our prior results of $95.2 \pm 1.3\%$, $87.0 \pm 1.0\%$, and $72.1 \pm 0.7\%$, respectively.

Due to fairly high loss in the photon path, noise photons generated in the switches, and fairly low detection efficiencies some level of background count subtraction was needed to achieve a fidelity that violates Bell's inequalities. Subtracting background counts (as opposed to all accidental counts) did allow a fidelity that would violate Bell's inequalities. One main contributor to these background counts are background photons generated in the switch. We have found these are due to spontaneous Raman photon scattering and can be reduced by increasing the pump wavelength to the switch to longer wavelengths. For instance, we later reduced this noise by 50% by moving the mean cross phase modulation (XPM) pump wavelength from 1549 nm to 1562 nm. Of course we could also reduce the 1305 nm wavelength, but we do not have the appropriate filters to do so at this time.

We have also added a phase modulator to the system to allow different types of entangled states to be generated by modulating the time-bins appropriately. This shows the flexibility of the method and high fidelities to the expected states were observed. For instance, all the qutrit states had an accidental count subtracted fidelity $> 94\%$.

A main benefit of generating time-bin entanglement is that these states can be transmitted over long distances in optical fiber with minimal degradation of entanglement. We aimed to experimentally verify that these states can be transmitted over long distances using quantum state tomography. As we generate our states in the O-band, we can send the photons through a 25-km spool of SMF-28 where we expect little temporal broadening as the zero-dispersion wavelength is around 1310 nm. Here, we send only the signal photon (1306.5 nm) over 25-km. The time-bin separation was changed from 100 ps to 200 ps, and the photons are sent to their own optical switch instead of both being switched simultaneously with a cross-bar optical switch. Note that clock recovery is now necessary to generate a switching pump pulse at exactly the right time instant accounting for slow drifts in the distribution fiber.

A 1305 nm pump pulse is sent through the 25-km spool and photo-detected at the output. The generated electrical signal is used to carve the C-band pump pulse for the optical switch. This method ensures that the switch's pump is always temporally aligned with the incident signal photons despite the temporal drift in the 25-km of fiber. The 1305 nm pulse is also sent through a polarizer and a 10% tap is connected to a power meter. The fiber polarization controller (FPC) before the polarizer is used to adjust for polarization rotation. To clock the single photon detectors used for the 1306.5 nm photons, we also send a 50-MHz 1550 nm signal through the 25-km spool. This ensures the photons arrival at the detectors is synchronized with clock. Overall, there is additional 11 dB of loss in the signal photon path (10 dB from the spool, and 1 dB from the filters).

We were able to verify the transport of maximally entangled qubits and qutrits over this 25-km distance using the same quantum state tomographic techniques as before. The measured fidelity with accidental-subtracted coincidences were $97.8 \pm 0.6\%$ and $96.0 \pm 0.6\%$, for qubits and qutrits respectively. These fidelities are only marginally lower than obtained without sending one photon over 25-km.

The fiber distribution measurements quoted controlled Raman scattering to be $<10^{-4}$ photons/pulse by lengthening the pump wavelength to 1561 nm from 1547 nm (using a 1305 nm signal wavelength). However, we have since found that a good goal for long distance experiment is $<5E-6$ photons/pulse. We have performed a Raman scattering analysis of fiber (standard and non-zero dispersion shifted fibers) which fit the experimental data of scattering versus pump/signal wavelength separation to a multi-vibrational Raman mode fiber model. These measurements used single photon sensitive detectors and tunable lasers and filters to obtain the necessary sensitivity. We found that if the pump wavelength is extended to >1600 nm that the desired $<5E-6$ scattered photon/pulse metric is achievable. This is significant because this wavelength is in the technologically useful L-band where fiber amplifiers and lasers are readily available. This change combined with low noise detectors can

Creating and Manipulating High-Dimensional Photonic Entanglement

W911NF-13-C-0028

Figures to accompany report.

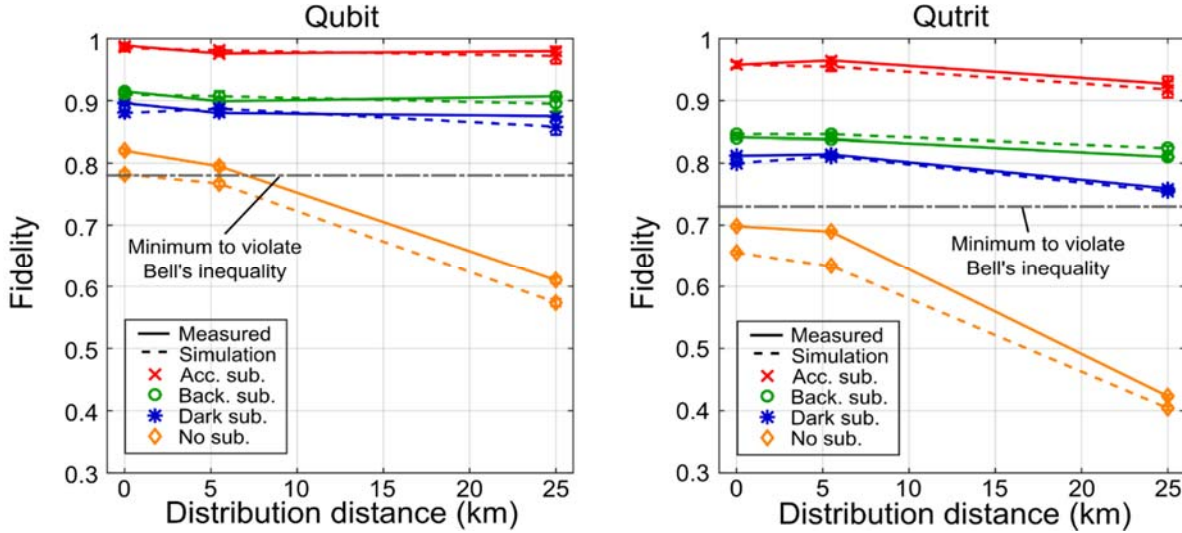


Fig. 1: Fidelity of the measured and simulated system with various noise-subtraction techniques (see legend) as a function of distribution distance. (Left) Qubits. (Right) Qutrits. The simulations and experiment match reasonably well for all cases. Here the switch noise and dark count probability are $3 \cdot 10^{-5}$ /pulse and 10^{-4} /pulse, respectively, and the detection efficiency is 15%.

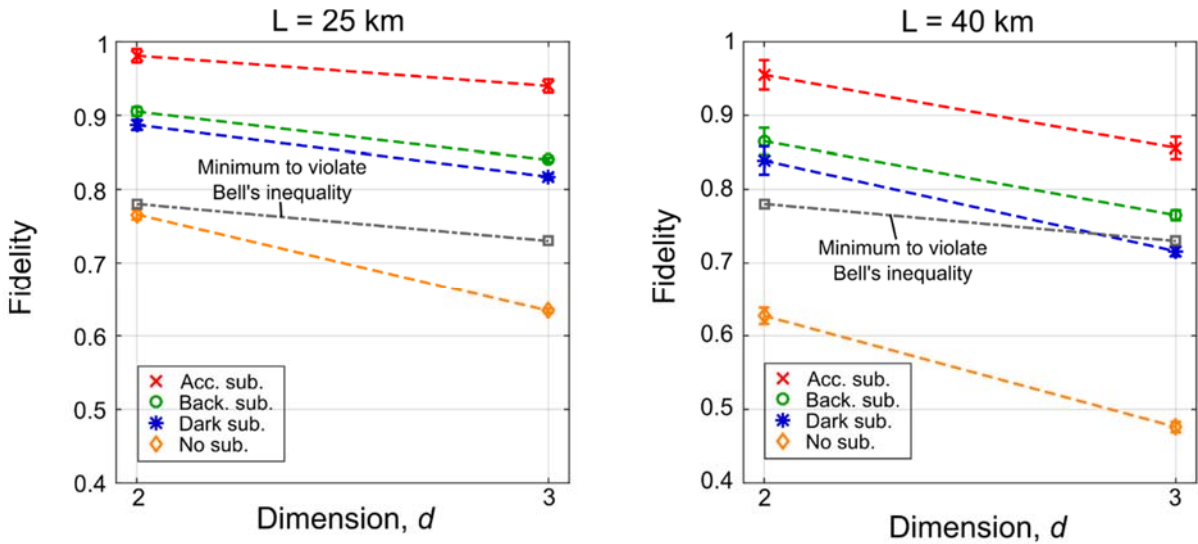


Fig. 2: Fidelity of a simulated system with various noise-subtraction techniques (see legend) as a function of dimension (d) for (Left) 25 km and (Right) 40 km distances. Here the switch noise and dark count probability are 10^{-5} /pulse and $5 \cdot 10^{-5}$ /pulse, respectively, and the detection efficiency is increased to 75%.

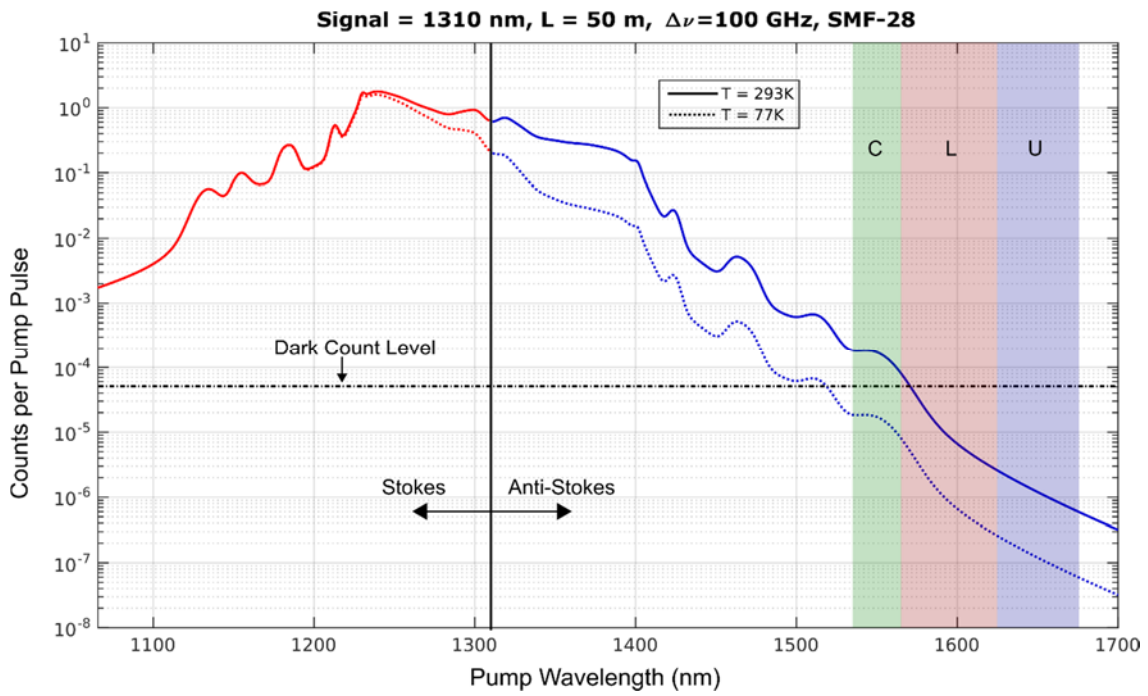


Fig. 3: Estimated switch background noise levels for a 1310 nm signal as a function of pump wavelength at full switching.

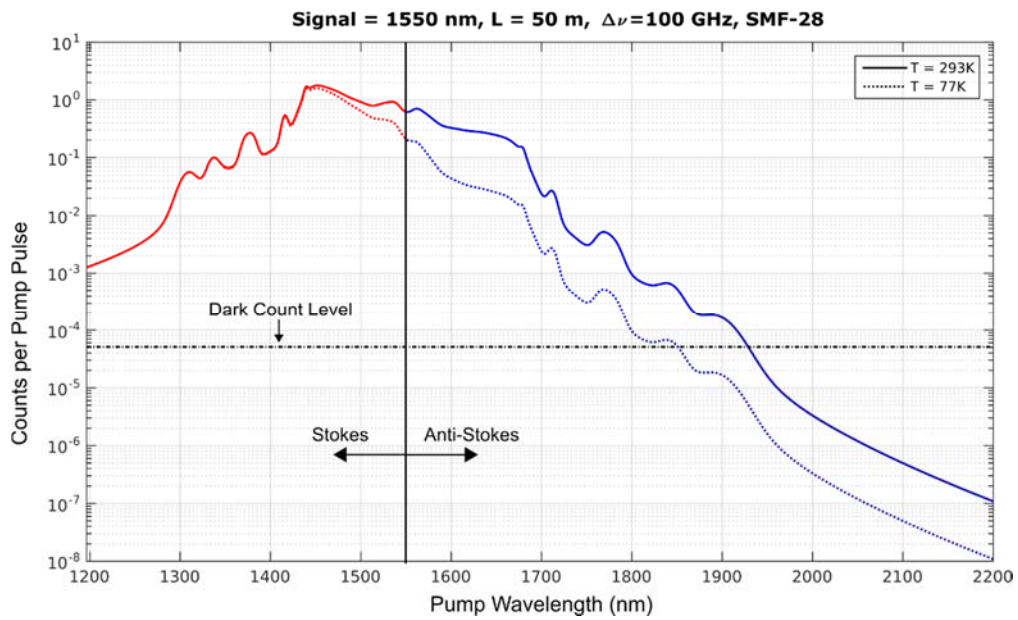


Fig. 4: Estimated switch background noise levels for a 1550 nm signal as a function of pump wavelength.