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QUANTUM TELEPORTATION BETWEEN ION AND ATOMIC QUANTUM MEMORY NODES

STONY BROOK UNIVERSITY

MAY 2024

FINAL TECHNICAL REPORT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This effort was originally envisioned to be a three-year project but was reduced to only one year. Because of this, through the year of funding Stony Brook maintained the focus on Thrust I, developing all the technical aspects of a high-brightness cavity-enhanced entangled source, compatible with rubidium and telecom operation. Additionally, they use the newly developed source to perform quantum communication experiments using deployed fiber to communicate entangled photon-pairs.

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1.0 SUMMARY

Our proposal was originally envisioned to be a three-year project, aimed at exploring the interconnections between atomic and ion-based quantum network systems. The project included three research thrusts depicted in Figure 1. In Thrust I, we developed a first instance of a rubidium-tuned entanglement-pairs source (right and center of Figure 1). In Thrust II, we envisioned to develop frequency conversion systems allowing interconnections between rubidium and barium wavelengths. Lastly, in Thrust III, we envisioned developing the mechanism to interact entangled photons with rubidium and barium ions. For reasons independent of the principal investigator (PI), the proposal was reduced to only one year. Because of this, through the year of funding we maintained the focus on Thrust I, developing all the technical aspects of a high-brightness cavity-enhanced entangled source, compatible with rubidium and telecom operation. Additionally, we use the newly developed source to perform quantum communication experiments using deployed fiber to communicate entangled photon-pairs.

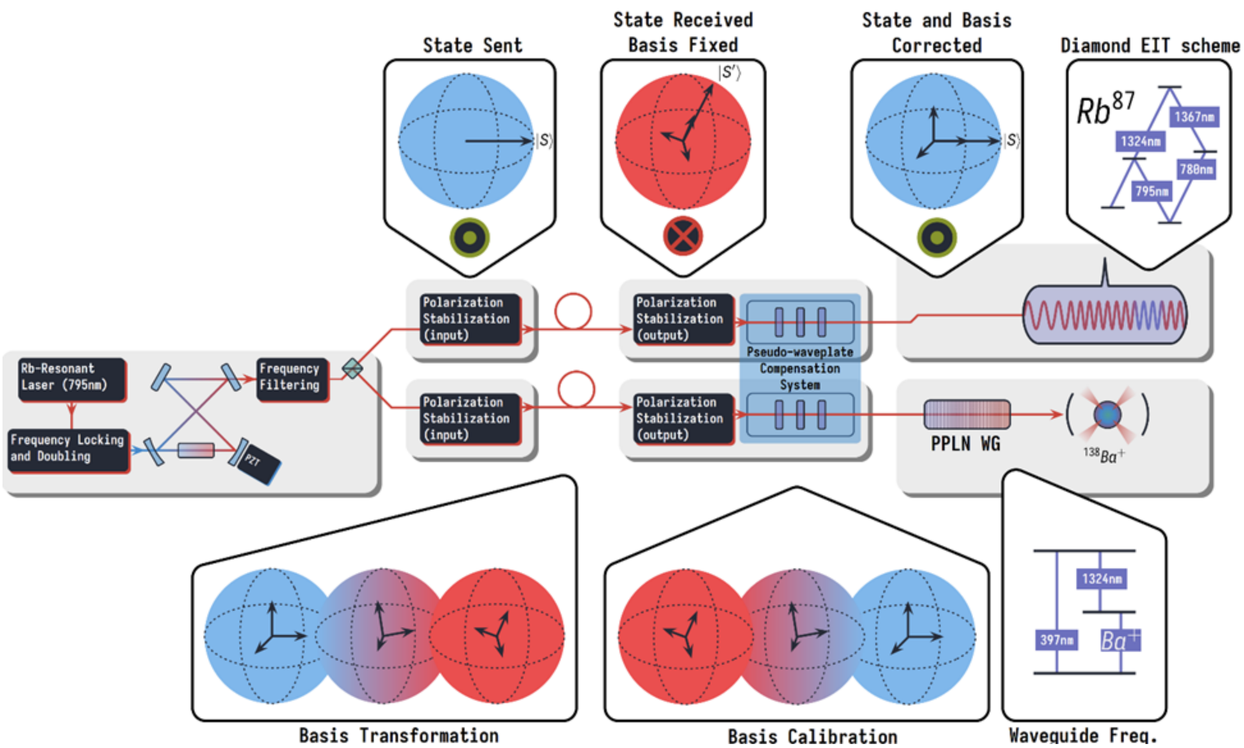

Figure 1. Overview of proposed ion/atom hybrid entanglement generation system

2.0 INTRODUCTION

Quantum information science and technology was identified as a key focus area in the National Defense Authorization Act. The ability to distribute entanglement across a network would enable ultra-secure communications, faster processing through distributed quantum computing, and provide new and unique ways to connect and distribute timing and sensing information. The key to quantum networking hinges on the ability to distribute quantum information across the network using entangled photons interfaced with memory-based qubits. This will allow the implementation of new protocols, such as quantum teleportation, to transmit and process information over a network in a fundamentally new, non-conventional manner. This ability to distribute entanglement and quantum information is currently a world-wide pursuit and the Air Force must ensure the US maintains a competitive strategic advantage in this area.

Our project involved the design and construction of fundamental technology needed to develop Quantum Local Area Networks (QLANs) which are hybrid in nature, connecting diverse physical systems (ion-based/atomic-based). We envisioned our hybrid quantum network project to become the blueprint to effectively connect disparate physical quantum systems in large quantum communication network settings. Our target was to build the infrastructure for a quantum entanglement distribution network, using ion-based and atomic-based light-matter quantum nodes, connected via distributed entanglement.

3.0 METHODS, ASSUMPTIONS AND PROCEDURES

3.1 High-precision Laser System tuned to Rubidium Telecom Wavelengths

We established a laser system consisting of four lasers: (i) a tunable tapered amplified diode laser operating at 1324 nm (used as the fundamental light, which will be locked to a telecom rubidium transition), (ii) a second harmonic generation system, based upon a bow-tie cavity, capable of converting the 1324 nm fundamental into 662 nm (used as the pump for the non-linear crystals), (iii) a second tunable tapered amplified diode laser operating at 1324 nm (used for alignment and stabilization of the OPA), and (iv) a tunable diode laser operating at 1367 nm (to be used in the two photon spectroscopy setup to lock the fundamental 1324 light to the corresponding rubidium transitions). The laser systems were customized to be deployable, which is one of the desired features of the future quantum communication systems. All the four lasers were built within a physical platform that allows for their compatibility with standard data-center-size racks.

3.2 Optical-Parametrical-Amplifier (OPA) system operating at 1324nm

Generation of bipartite entanglement at narrow linewidths, compatible with atom/ion systems, and operational at high repetition rates were key elements of our envisioned ion/atom hybrid entanglement generation system developed during this project. We worked on the design of a miniaturized Optical-Parametrical-Amplifier (OPA) system (Figure 2). Using the ABCD matrix method we determined the beam characteristics of the round trip of a bow-tie optical cavity (center of Figure 2) for a wavelength of 1324nm. We simulated the process where a single photon makes a full round trip through the cavity and returns to the point at which it began, with the constraint of having the same original spatial mode for two polarizations, thus allowing for polarization entanglement creation. Using these simulations, we derived expressions for the stability condition, beam waist radius, finesse, and free spectral range of the cavity. Additionally, we calculated spatial mode-matching conditions that will yield an optimal beam waist radius according to the Boyd-Kleinman theory, which is dependent on the length of the crystals and the confocal parameter of the beam. This procedure will ensure maximizing the twin-photon generation rate inside the cavity. This allowed us to produce a first version of the OPA design where custom optical elements were machined according to the drawing's specifications. Figure 2 below shows our implemented OPA design and the characterization devices forming our current experimental setup. We achieved a bow-tie cavity with a linewidth of approximately 400kHz and a Finesse of approx. 1000.

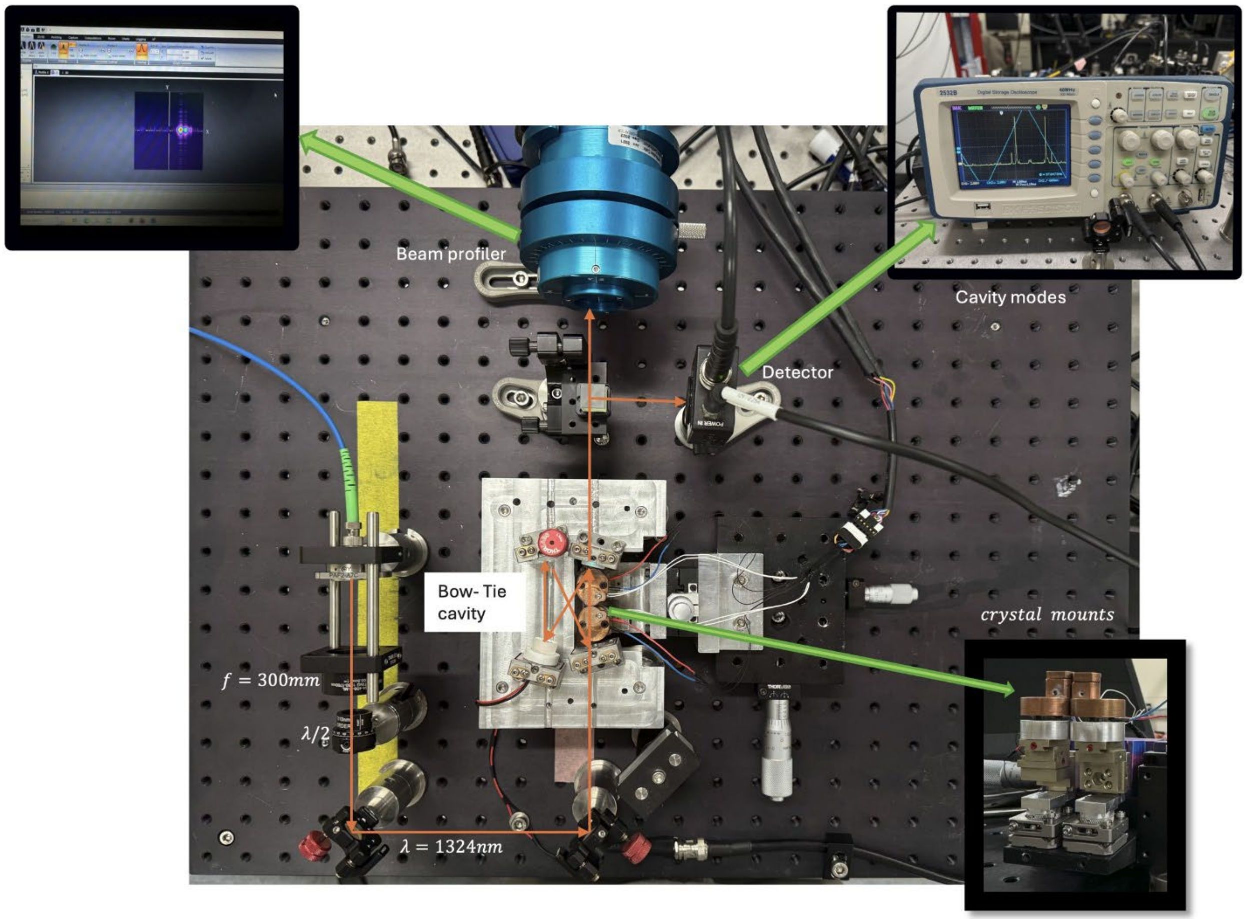

Figure 2. Current OPA experiment

3.3 Considerations for entanglement generation

An important consideration towards producing entangled photon pairs at telecom inside the OPA cavity, is to guarantee that the OPA cavity, including two non-linear crystals, will support two independent polarization modes within the linewidth of the cavity. Our design includes two periodically poled non-linear crystals with a specific poling period (16.975 um) customized to achieve quasi-phase matching for the 662 nm and 1324 nm wavelengths (see Fig. 2). The idea is to enhance the production of two independent polarization modes inside the OPA cavity by having two non-linear crystals in series with their optical axis rotated by 90 degrees. This configuration allows us to pump the crystals with diagonal polarization, and to create an entangled state of the form |HH>+|VV>. To guarantee that both polarization modes will undergo identical transformation inside of the cavity, which is the main condition to achieve double cavity resonance, one must allow independent alignment of the optical axes of the crystals. For our instrument, we designed technical elements that will allow us to achieve this condition, including: i) designing 5-axes customized opto-mechanics necessary to optimize the photon pair production in two crystals (and thus two polarization modes) simultaneously, and ii) designing compensation systems for temperature and alignment fluctuations (thus maximizing the photon-pair production of each crystal).

4.0 RESULTS AND DISCUSSIONS

4.1 Production of Photon Pairs at 1324 nm

Having the precision laser system operational and the OPA and non-linear crystals mounts and controllers available, allowed us to perform experiments aimed at characterizing the state generated by spontaneous parametric down conversion (SPDC) using both non-linear crystals simultaneously. In these experiments we pumped the two crystals with diagonally polarized light. As the two crystals are oriented perpendicularly, each of the polarization eigenmodes will produce photon pairs at orthogonal polarizations, ideally in the state:

$$|\phi+\rangle = |HH\rangle + e^{i\theta}|VV\rangle \quad (1)$$

To analyze the polarization state of the photon pairs generated in the crystal-crystal setup, we built a quantum state tomography setup consisting of rotating waveplates for polarization compensation, a beam splitter (BS), two polarization beam splitters (PBS) and four Nanowire Single Photon Counters. The idea is to verify coincidences among the detectors that can detect |H> (detector 1, located after the H port of the first PBS and detector 3, located after the H port of the second PBS), while simultaneously detecting coincidences among the detectors that can detect |V> (detector 2, located after the V port of the first PBS and detector 4, located after the V port of the second PBS).

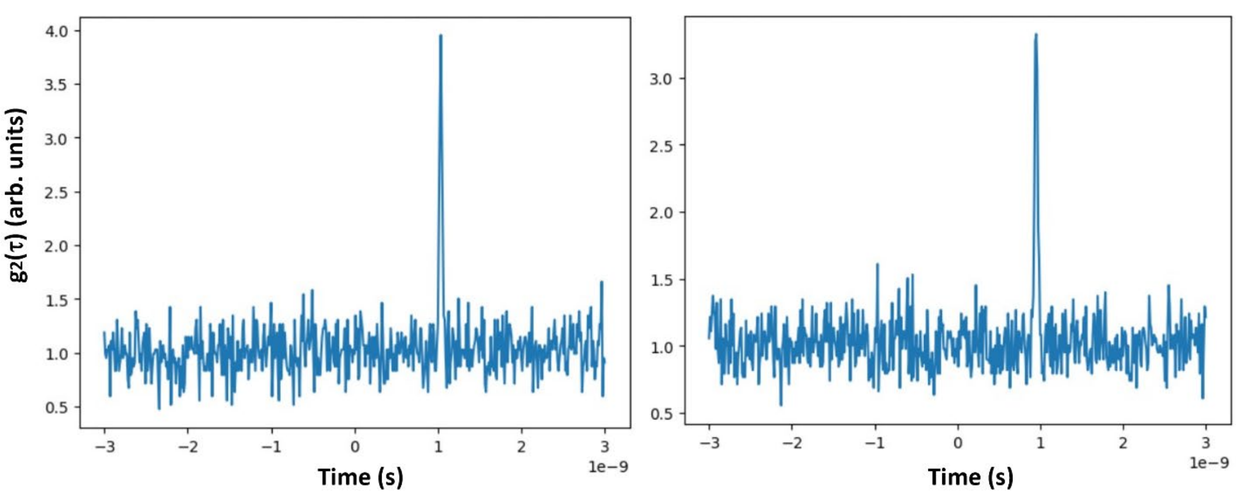

Figure 3. Correlation Function

Shown in Figure 3 are the measurements showing evidence of photon production in correlated pairs in the two polarization eigenstates HH and VV. By measuring the arrival times of 1324nm photons produced by the crystals and constructing second order correlation function for coincidences in the detectors 1 and 3 and 2 and 4, we have demonstrated the production of photon pairs within a temporal envelope integration region of approx. 200 ps. These measurements show the creation of the photon pairs in a polarization correlated state with an approx. 50,000 pairs/s rate.

4.2 Telecom entanglement distribution using deployed fiber.

In the later months of the proposal, we used our fiber network covering nodes across Long Island. This deployed fiber network includes multi-purpose quantum nodes at Brookhaven National Laboratory, Stony Brook University, and in the Commack (COM) data center. This three-node quantum network (see Fig. 4 below) is a first of its kind in the US and we used it to distribute entanglement over 140 km of commercial fiber.

We developed two operational Superconducting Nanowire Single Photon Detectors (SNSPD) systems. One of them comprises four channels sensitive at telecom wavelengths (~1300-1500nm) and four channels sensitive at near-IR (~800nm), and the second one (portable) has two telecom channels and two NIR channels. Additionally, we developed the classical control mechanisms needed for initialization, management, and online control of the entanglement distribution experiment. We developed classical communication systems including servers for data analysis and storage, optically connected switches forming the backbone of the control networks, wave-multiplexing systems to manage the traffic of classical and quantum information in the same fibers, and White Rabbit time synchronization systems for optical clock distribution among the network nodes.

For our combined network experiments, we deployed the OPA telecom entanglement source in BNL. We produced telecom photons in the BNL IO laboratory and distributed them (in a network-controlled fashion) to distant nodes using the aforementioned fiber infrastructure. We developed remotely controlled single photon detection systems and optical systems to analyze the distributed quantum states and to perform quantum tomography of the distributed estates. Figure 4 shows the three-node quantum network testbed, and the correlation function of the distributed 1324 nm photons after propagation over 140 km, obtaining usable entanglement at a rate as 200 pairs/s.

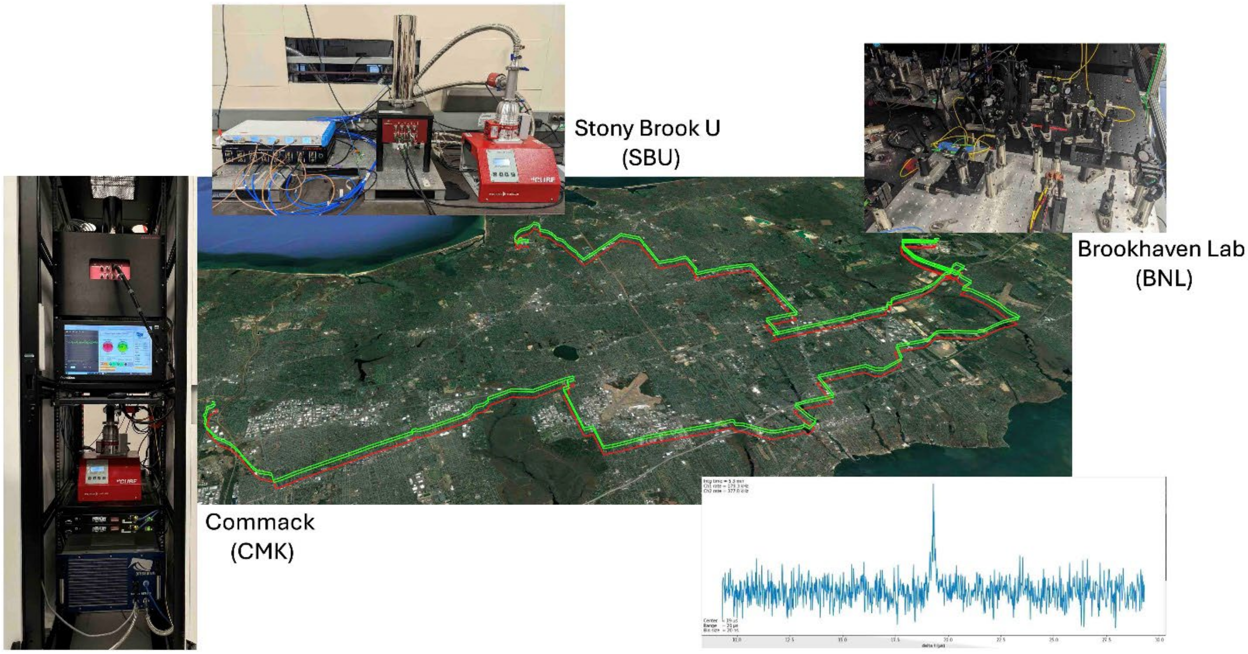

Figure 4. The entanglement distribution testbed

5.0 CONCLUSIONS

We have developed and tested a cavity-enhanced source of entangled photon pairs tuned to operate on-resonance with the telecom transition of rubidium atoms at 1324 nm. The source is capable of producing polarization entangled pairs with approx. 50,000 pairs/s rate with a bandwidth of approx. 400 kHz. The entanglement source has been tested using a deployed fiber scenario using two fibers with a total deployed length of 140 km, obtaining usable entanglement at a rate as 200 pairs/s.

6.0 LIST OF ACRONYMS

BNL – Brookhaven National Laboratory
BS – Beam Splitter
IR – infrared
kHz – kilohertz
NIR – near-infrared
nm – nanometer
OPA – Optical-Parametrical-Amplifier
PBS – Parametric Beam Splitter
PI – Principal Investigator
ps – picoseconds
QLAN – Quantum Local Area Network
SNSPD – Superconducting Nanowire Single Photon Detectors
SPDC – Spontaneous Parametric Down Conversion