The Quantum Communications and Networking Project at the Information Technology Laboratory of NIST

Oliver Slattery
ITL
NIST
Gaitherburg, MD. USA

Xiao Tang
ITL
NIST
Gaitherburg, MD. USA

Lijun Ma
ITL
NIST
Gaitherburg, MD. USA

Thomas Gerrits
ITL
NIST
Gaitherburg, MD. USA

Anouar Rahmouni
ITL
NIST
Gaitherburg, MD. USA

Sumit Bhushan
ITL
NIST
Gaitherburg, MD. USA

2021 IEEE Conference on Communications and Network Security (CNS) | 978-1-6654-4496-5 /21/$31.00 USG | DOI: 10.1109/CNS53000.2021.9705051

***Abstract*—Research in the Quantum Communications and Networking Project at the National Institute of Standards and Technology's (NIST) Information Technology Laboratory (ITL) focuses on developing quantum devices and studying them for use in quantum communications and quantum networking applications. In this paper, we review parts of our research on quantum communications devices and introduce the case for the development of metrology tools and testbeds for quantum network systems.**

Keywords—quantum communications, quantum repeater, quantum network metrology

I. Introduction

The goal of the Quantum Communication and Networking project is to bridge the gap between fundamental quantum mechanics and information theory and their practical applications in information technology. Our research covers two main areas: 1. The research on the creation, transmission, transduction/interfacing, storage, processing and measurement of optical qubits – the quantum states of single photons. The study of quantum devices, such as entangled-photon sources, single-photon detectors, optical quantum memory and quantum interfaces. 2. Together with multiple NIST laboratories, the implementation of a quantum network testbed to study the performance of quantum systems in a real-life network environment and the development of metrology tools to monitor photonic qubits as they transit the network. These tools will lead to the development of best-practices and protocols for quantum networks.

A principle goal of quantum communication and quantum networks is to share a quantum property called 'entanglement' among two or more qubits. Once entangled, these qubits can be used for quantum processes such as quantum key distribution (QKD), quantum teleportation, quantum sensing and distributed quantum computing. However, single photons of light - a primary carrier mechanism for entangled qubits - cannot travel beyond a few tens of kilometers even at optimal telecommunication frequencies due to absorption and decoherence losses in optical fiber. A fundamental provision of quantum mechanics, known as the 'no-cloning theorem', means that quantum signals cannot be copied or amplified in order to extend that distance as can be done in classical communications. A device called a quantum repeater has long been considered a viable solution to overcome this loss-limited transmission distance and while many protocols have been developed, a complete quantum repeater has yet to be physically realized. Most research groups, including ours, have focused on the development of individual components used in quantum repeaters such as sources, detectors, memories and interfaces.

As the development of these components in the laboratories continues, more attention is being paid to testing their implementation and performance in connected systems such as quantum networks. Characterization of photonic-based quantum components as well as validation and benchmarking their operation in a real-world setting is essential for new technologies to successfully integrate into quantum networks. Measuring and enhancing the performance of these quantum components, the quantum nodes and the wider quantum network therefore becomes a key motivation for our quantum network metrology efforts.

In section II, we will provide a review of some of our previous and ongoing research related to quantum communications and quantum repeater and quantum networking components. In section III, we describe how these components can be deployed in entanglement distribution schemes. In section IV, we outline the case for the metrology of quantum networks and quantum network components and list some of the key scientific challenges ahead.

II. Quantum Communication and Quantum Repeater Devices

A. *Quantum Cryptographic Systems and Testbeds*

The Quantum Communication and Networking project was established in the early 2000s in response to the growing interest in quantum technologies for information processing. Early research was coordinated around a NIST Quantum Communication Testbed (QCT) facility that focused on implementing high-speed quantum communications systems and providing a platform for testing and validating performances in its application, network and physical layers [1]. During this time, a high-speed Quantum Key Distribution

(QKD) protocol based on polarization encoded BB84 was implemented with the highest reported sifted key rates over both free-space and fiber [2-6]. This system included custom data handling circuit boards and optimized clock recovery techniques [7] to achieve the orders of magnitude improvement in sifted-key rates for line-of-sight free-space QKD. The rates were capped only by the dead-time of the single photon detectors available [8]. Both differential phase shift [9] and detection-time-bin-shift [10] QKD systems were implemented to overcome the detector dead-time rate cap to further increase data rates. Novel polarization drift recovery and auto-compensation schemes were developed to implement polarization encoded QKD protocols over optical fibers [11]. These high data rate QKD schemes paved the way for a practical one-time-pad encrypted surveillance video demonstration which included a specially designed QKD infrastructure protocol stack as well as a quantum network manager consisting of classical and quantum experimental control planes, which are essential for quantum networks [12]. The first known active multi-node QKD network (figure 1) using an optical switch to dynamically reconfigure the communication channels between a single 'Alice' node and a pair of 'Bob' nodes was implemented and used to study the performance of the optical switch as well as the polarization recovery and timing resynchronization schemes required after switching [12, 13].

Fig. 1. *An active QKD testbed consisting of one 'Alice' node (white rack in center) and two 'Bob' nodes (black racks on right and left).*

Early experiments in the QC project relied on commercial off the shelf silicon avalanche photodiode (Si-APD) single photon detectors due to their versatility, low cost and solid performance at visible wavelengths. However, Si-APDs are not suited for detecting telecom frequencies and thus the quantum channels in these experiments used single photons at 850 nm and were restricted to short distance optical fiber or free-space links. To overcome this, a high-speed superconducting nanowire single photon detector (SNSPD) – which was then an emerging technology – was used to detect 1550 nm (low loss transmission in optical fiber) polarization encoded single photons in long distance high speed QKD in optical fiber [14, 15]. Still, SNSPDs systems (at that time) were costly and bulky due to the need to be operated at cryogenic temperatures. In order to operate long distance QKD at room temperatures, the Quantum Communications Project pioneered a number of low-noise, low-cost and near room-temperature frequency up-conversion detection schemes in which a single photon signal at 1310 nm (also low loss transmission in optical fiber) was mixed with a strong pump at 1550 nm in a periodically-polled non-linear crystal to generate single visible photons at 710 nm in a process based on sum frequency generation (SFG) [16-19]. The generated visible photons can be efficiency detected at room temperature using a Si-APD. The longer wavelength of the pump compared to the signal ensured that Stokes noise, which hampered previous implementations of up-conversion detection, was reduced. This allowed a higher pump power in order to achieve near 100% conversion efficiency in the SFG crystal. The total detection efficiency of the up-conversion detector was greater than 32% for single photons at 1310 nm. Follow-on implementations further reduced detector noise [20-22]; enabled detection of multiple wavelengths or over multiple channels in a single device [23, 24]; and detected other wavelengths with low noise [21]. The frequency up-conversion detector was adapted for spectral characterization of single photon level telecom signals either directly [25] or by biphoton spectroscopy [26] and for the measurement of high-order temporal correlations [27-29].

B. *Quantum Repeater Components*

As quantum communication applications moved beyond QKD, more focus was given to developing protocols and components related to quantum repeaters. A quantum repeater uses the quantum phenomena of entanglement swapping to extend the separation between entangled pairs of qubits by 'swapping' the entanglement from multiple pairs of nearby qubits to ever more distant qubits. A particular protocol, called a quantum memory enhanced quantum repeater (figure 2) includes entangled photon pair sources, quantum memories, single photon detectors and quantum interfaces to implement the protocol.

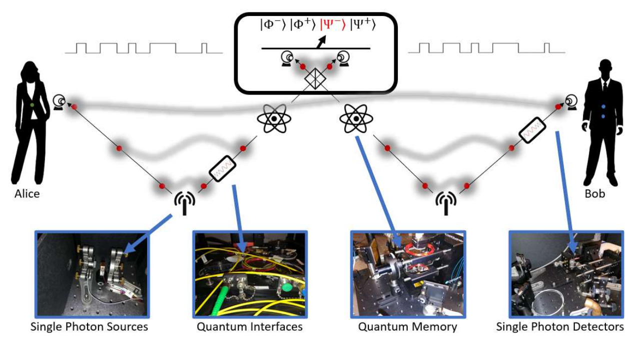

Fig. 2. *The purpose of a quantum repeater is to achieve entanglement between distant qubits at Alice and Bob. Initially, two sources generate two entangled pairs of photons with one photon from each pair sent to the distant locations and the other photon from each pair sent to a Bell State Measurement (BSM). In order to achieve a successful BSM, the photons are stored momentarily in quantum memory and released in a controlled way. The result of the BSM is classically communicated to Alice and Bob who will then know how to prepare their photons for the desired entanglement state of their photons.*

A common technique to generate single photon pairs is a process called Spontaneous Parametric Down-Conversion (SPDC) in periodically-poled non-linear crystals. In SPDC, a single high-energy pump photon is spontaneously destroyed and a pair of lower energy output photons (called the signal and idler photons) are simultaneously created. The periodic poling of the crystal enhances targeted output frequencies for the signal and idler while suppressing other frequencies. The most common entanglement schemes for quantum communications applications are polarization entanglement and time-bin entanglement. When optical fiber is used, time-bin entanglement has the advantage of being unaffected by the polarization drifts in the fiber. With fiber quantum communications in mind, we implemented a high-repetition rate sequential time-bin entangled photon pair source [30]. The source uses a GHz repetition rate pulsed pump at 532 nm to produce time-bin entangled pairs of photons at the greatly non-degenerate wavelengths specifically targeting atomic transitions (signal photon: 895 nm) for quantum memory and the low transmission loss telecommunication band (idler photon: 1310 nm) for long distance transmission. However, the intrinsic phase matching linewidth of a single pass SPDC process is typically several hundreds of GHz or THz for commonly used crystal lengths. Such sources cannot be efficiently coupled to the narrow bandwidth transitions in atomic systems and are therefore not optimal for quantum repeater applications. To achieve narrower linewidths, the SPDC crystal can be placed inside a resonating cavity such that the generation of the signal and idler photon pairs are restricted to and enhanced at the narrow spectral modes of the cavity [31]. Therefore, we implemented a non-degenerate single photon pair source based on SPDC in a short singly-resonant cavity that is locked to a Doppler-free transition of the cesium atom so as to ensure that the brightest central signal mode emitted from the cavity matches the targeted transition frequency. The cavity enhanced source generates bright correlated signal and idler pair modes with linewidths in the tens of MHz range - sufficiently narrow for coupling to certain atomic quantum memory schemes [32].

The function of a quantum memory is to convert a flying qubit into a stationary qubit, to store the quantum state for a period of time and to convert the stationary qubit back into a flying qubit at a desirable time [33]. A quantum memory enhanced quantum repeater protocol, for example, can use two quantum memories either side of a Bell State Measurement (BSM) to capture flying qubits from different sources; hold them as stationary qubits until both memories are prepared; and then release them in a controlled and synchronized way so as to enhance the performance of the protocol. Electromagnetically Induced Transparency (EIT) is an optical phenomenon in atoms that uses quantum interference to induce transparency into an otherwise resonant and opaque medium and can be used for slow light, light storage and quantum memory applications [34, 35]. EIT uses a strong optical ‘control’ light to activate or deactivate the quantum memory and in this way, the retrieval of the photon qubit is on-demand. However, in cesium-based EIT the retrieved signal photon and the strong control beam are spectrally very close (just 9.2 GHz spectral separation) and are emitted collinearly at the same time - resulting in a major source of noise that needs to be alleviated [36]. We implemented a cesium-based EIT quantum memory scheme that achieved several microseconds of storage followed by on-demand qubit release while directly addressing these noise issues. Using a series of specifically designed filters including polarization filters, etalons and atomic spectral filters [36], we achieved 125 dB reduction of the control beam induced noise while transmitting the single photon level signal at approximately 50%. We further adapted the EIT process for the spectral characterization of single photon sources with ultra-high resolution, accuracy, and sensitivity [37]. Currently, we are working to implement 2-dimensional magneto-optical-traps (MOT) with enhanced atom-photon interaction to capture flying qubit photons more efficiently than conventional 3-dimensional MOT schemes.

Since many processes in quantum communication systems are necessarily or optimally implemented at different specific frequencies - such as, for example, long-distance transmission (eg. telecom fiber frequencies), room temperature single photon detection (eg. semiconductor photodiode frequencies), quantum memories (atomic resonance frequencies) and quantum computing (UV or microwave frequencies) - quantum interfaces are needed to ensure whole-system operational compatibly. We have built a range of frequency converters to interface these different processes. The frequency up-conversion detector described earlier is an example of such an interface between the optical fiber compatible wavelength of 1310 nm and the silicon-based detector compatible wavelength of 710 nm. We have also implemented frequency conversion that interfaces three important wavelengths required for quantum processes in a cascade of two frequency converters based on SFG. Single photons at 895 nm (for example emitted from a cesium-based quantum memory) or at 1540 nm (for example emitted from a telecom fiber) can be selectively converted to 369 nm for ytterbium compatible quantum computing applications [38]. Current research on interfaces includes the implementation of low noise conversion between telecom wavelengths (1550 nm or 1310 nm) and quantum memory wavelengths (895 nm for cesium or 795 nm for rubidium).

III. Towards Entanglement Distribution

The essential requirement for quantum communications over a network is the distribution of entanglement between separated stationary qubits. By further developing the key components of a quantum communications system as described in the previous section, our project is currently in the process of developing a multi-node quantum entanglement distribution testbed. The nodes will include quantum memories based on atomic ensembles. A number of approaches for the distribution of entanglement are being considered including using a single source of entangled photons at the desired atomic wavelength and sending them via fiber over a short distance to atomic quantum memories. For longer distance distribution of entangled photons to stationary qubits, the entangled photon pair sources may be at telecom wavelengths and by using a quantum interface, as described earlier, convert these telecom wavelength photons to atomic compatible wavelengths before capturing them in the quantum memories.

A more complex scheme – essentially a long-distance elementary link of a quantum repeater – is also being investigated. In this scheme, two non-degenerate entangled photon pair sources can be implemented at distant locations.

Each pair must include a photon at the same telecom wavelength – such that they can be made indistinguishable – and the other photon can be compatible with various atomic quantum memories. The atomic quantum memory compatible photons can be captured by quantum memories corresponding to their respective wavelengths. The telecom photons from each source can be transmitted over fiber and interfered at a BSM, thereby swapping the entanglement to the more distance stationary qubits stored in the quantum memories. The implementation of such a scheme would require rigorous timing, phase and polarization management over long distances. In collaboration with other groups at NIST, we are implementing a quantum network testbed to design, develop and implement the type of synchronization required for such long-distance interference at the single photon level.

IV. Quantum Networking metrology

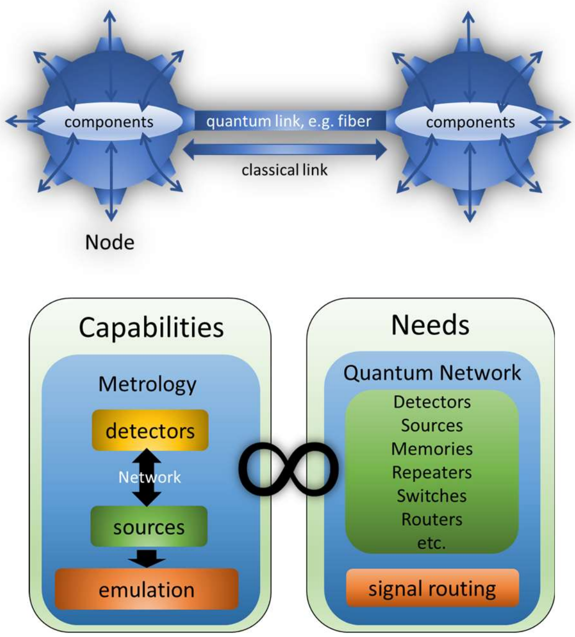

Fig. 3. *(Upper) A quantum network will consist of operational quantum nodes connected by fiber and will include a classical link. (Lower) High-performance and accurately calibrated single-photon sources and detectors will be essential tools to study the performances of quantum network components.*

As the fundamental development of quantum devices in laboratories continues, more attention is being paid to deploying these as functional components in connected systems such as quantum networks [39]. A future quantum network will consist of many hundreds or thousands of heterogeneous operational quantum nodes connected by optical fiber or free-space and consisting of a variety of photonic-based quantum components that are designed to create, receive, store, reroute, process and send quantum information. Just as network monitoring, link and device characterization and smart metrology-based routing protocols has enabled high-performance heterogeneous classical networks, understanding the operational and performance metrics of quantum systems and developing the required metrology tools will be essential for implementing and ultimately optimizing quantum networks. In particular, established methods for the characterization of quantum components as well as validation and benchmarking their operation in a real-world quantum network setting will be required for successful integration as the speed, size and complexity of quantum networks increases.

The challenge of building large-scale heterogeneous quantum networks is immense because the complexity grows exponentially with the number of connected components. To address this challenge, three essential scientific approaches will be needed: the development of a thorough theoretical foundation of the metrology of quantum states, quantum components and quantum networks; the implementation of quantum network testbeds to verify theoretical predictions and identify physical performance shortfalls; and the development of a complete range of robust field deployable devices and methods for in-situ quantum state, component and network characterization.

A. Theoretical Foundation

To ensure that this measurement problem remains tractable for networks of increasing complexity and size, it will be necessary to develop a thorough theoretical foundation related to the metrology of quantum components and quantum networks. Towards that end, it is necessary to identify the key performance metrics (such as noise, loss, data rates, error rates, latencies, etc.) both for individual quantum components and for quantum networks as a whole; to establish methods and procedures for determining these metrics; and to evaluate the required performance thresholds (such as timing precision, fidelity, loss/error tolerance, etc.) for various quantum network applications and tasks. This theoretical foundation will be necessary to understand how a quantum state changes as it travels though quantum components and networks. Understanding these performance metrics and the application performance thresholds will enable the type of emulation and simulation needed for network optimization. This emulation will be of crucial importance for the development of quantum network components and protocols. Such theoretical research will also construct optimized operational protocols for particular circumstances and applications; derive the network performance limits (such as quantum channel capacity or maximum quantum data rates); and enable the maximal benefits of quantum networking relative to high performing classical networks.

B. Quantum Network Testbeds

Metrology-focused quantum network testbeds and component testing suites will play a vital role in verifying theoretical performance predictions and identifying issues (such as component specific performance limits) early in the development and deployment phases. Testbeds will enable quantum state, quantum component and quantum network performance characterization using real fiber and free-space links for comparison to theoretical predictions and to precisely controlled laboratory conditions. Such a testbed will allow researchers to study, implement and improve control protocols using well characterized components and apply these results to more complex and less well understood quantum network configurations. Most experimental protocols will require a classical network infrastructure in conjunction with the quantum network. These testbeds will provide platforms for applying and testing schemes for integrating the quantum and classical infrastructure and explore the limits of coexistence of the classical and quantum network signals.

C. Deployable Metrology Tools

Efficient, well-defined entangled photon sources and single-photon detectors that are accurately calibrated using existing NIST calibration methods can serve as essential baseline measurement tools [40]. Once these source and detector metrology tools have been built, they can be used to study changes to the tomography of well characterized qubits transiting through components and systems such as fibers, switches, transducers, memories and quantum repeaters, networks and provide valuable information about the links themselves. These metrology-grade components can be engineered to be portable so as to allow them to be used both in the lab and in the field. It is our goal to build and deploy such tools into quantum network testbeds like that currently being established on the NIST Gaithersburg campus and connected to other Washington area agencies in a regional quantum network. From these results, we will be able to predict how a quantum state sent through a component is altered such that we can emulate these components on a larger-scale network.

V. Conclusion

A great amount of progress has been made in the study and development of quantum components over the last two decades. As these components emerge from the laboratory setting, the need exists for robust and deployable metrology tools and methods that are built on a solid theoretical foundation to ensure that they can be optimally integrated into functioning quantum networks.

Acknowledgment

The authors wish to acknowledge the many collaborators (as listed in the publications) over the years both inside and beyond NIST. We specifically acknowledge other project members past and present including P. Kuo, A. Mink, B. Hershman, Y-S. Kim, T. Chang, H. Yu, and K. Zong. We also wish to acknowledge our other colleagues (not already mentioned) working on the development of a quantum network testbed including: N. Zimmerman, A. Battou, S. Polyakov, J. Bienfang, K. Srinivasan, A. Migdall, Y. Li-Baboud, L. Sinclair, M. Knill, S. Glancy, and D. Anand. We especially appreciate the support from the NIST, ITL, PML (Physical Metrology Laboratory) and ACMD (Applied and Computational Mathematics Division) leadership for our research.

References

[1] C. J. Williams *et al.*, "High-speed quantum communication testbed," in *Free-Space Laser Communication and Laser Imaging II*, 2002, vol. 4821, pp. 421-426: International Society for Optics and Photonics.

[2] J. C. Bienfang *et al.*, "Quantum key distribution with 1.25 Gbps clock synchronization," *Optics Express,* vol. 12, no. 9, pp. 2011-2016, 2004.

[3] D. Rogers *et al.*, "Free-space quantum cryptography in the H-alpha Fraunhofer window," in *Free-Space Laser Communications VI*, 2006, vol. 6304, p. 630417: International Society for Optics and Photonics.

[4] X. Tang *et al.*, "High speed fiber-based quantum key distribution using polarization encoding," in *Quantum Communications and Quantum Imaging III*, 2005, vol. 5893, p. 58931A: International Society for Optics and Photonics.

[5] X. Tang *et al.*, "Quantum key distribution system operating at sifted-key rate over 4 Mbit/s," in *Quantum Information and Computation IV*, 2006, vol. 6244, p. 62440P: International Society for Optics and Photonics.

[6] X. Tang *et al.*, "Experimental study of high speed polarization-coding quantum key distribution with sifted-key rates over Mbit/s," *Optics Express,* vol. 14, no. 6, pp. 2062-2070, 2006.

[7] A. Mink *et al.*, "High-speed quantum key distribution system supports one-time pad encryption of real-time video," in *Quantum Information and Computation IV*, 2006, vol. 6244, p. 62440M: International Society for Optics and Photonics.

[8] H. Xu, L. Ma, J. C. Bienfang, and X. Tang, "Influence of avalanche-photodiode dead time on the security of high-speed quantum-key distribution systems," in *Quantum Electronics and Laser Science Conference*, 2006, p. JTuH3: Optical Society of America.

[9] L. Ma, H. Xu, T. Chang, O. Slattery, and X. Tang, "Experimental implementation of 1310-nm differential phase shift QKD system with up-conversion detectors," in *Quantum Electronics and Laser Science Conference*, 2008, p. JTuA105: Optical Society of America.

[10] L. Ma, T. Chang, A. Mink, O. Slattery, B. Hershman, and X. Tang, "Experimental demonstration of a detection-time-bin-shift polarization encoding quantum key distribution system," *IEEE Communications Letters,* vol. 12, no. 6, pp. 459-461, 2008.

[11] L. Ma, H. Xu, and X. Tang, "Active Polarization Auto-Compensation in Fiber-Based Quantum-Key Distribution Systems," in *CLEO/QELS Conference*, 2006.

[12] A. Mink *et al.*, "A quantum network manager that supports a one-time pad stream," in *Second International Conference on Quantum, Nano and Micro Technologies (ICQNM 2008)*, 2008, pp. 16-21: IEEE.

[13] X. Tang *et al.*, "Demonstration of an active quantum key distribution network," in *Quantum Communications and Quantum Imaging IV*, 2006, vol. 6305, p. 630506: International Society for Optics and Photonics.

[14] B. Baek, L. Ma, A. Mink, X. Tang, and S. W. Nam, "Detector performance in long-distance quantum key distribution using superconducting nanowire single-photon detectors," in *Advanced Photon Counting Techniques III*, 2009, vol. 7320, p. 73200D: International Society for Optics and Photonics.

[15] R. H. Hadfield, J. L. Habif, L. Ma, A. Mink, X. Tang, and S. W. Nam, "Quantum key distribution with high-speed superconducting single-photon detectors," in *Quantum Electronics and Laser Science Conference*, 2007, p. QML4: Optical Society of America.

[16] L. Ma *et al.*, "1310 nm differential-phase-shift QKD system using superconducting single-photon detectors," *New Journal of Physics,* vol. 11, no. 4, p. 045020, 2009.

[17] L. Ma, O. Slattery, and X. Tang, "Single photon frequency up-conversion and its applications," *Physics reports,* vol. 521, no. 2, pp. 69-94, 2012.

[18] H. Xu, L. Ma, A. Mink, B. Hershman, and X. Tang, "1310-nm quantum key distribution system with up-conversion pump wavelength at 1550 nm," *Optics Express,* vol. 15, no. 12, pp. 7247-7260, 2007.

[19] H. Xu, L. Ma, O. Slattery, and X. Tang, "Low-noise PPLN-based single-photon detector," in *Quantum Communications Realized*, 2007, vol. 6780, p. 67800U: International Society for Optics and Photonics.

[20] L. Ma, O. Slattery, and X. Tang, "Study on noise reduction in up-conversion single photon detectors," in *Quantum Communications and Quantum Imaging VIII*, 2010, vol. 7815, p. 781508: International Society for Optics and Photonics.

[21] J. S. Pelc *et al.*, "Long-wavelength-pumped upconversion single-photon detector at 1550 nm: performance and noise analysis," *Optics express,* vol. 19, no. 22, pp. 21445-21456, 2011.

[22] X. Tang, L. Ma, and O. Slattery, "Ultra low dark-count-rate up-conversion single photon detector," in *2010 23rd Annual Meeting of the IEEE Photonics Society*, 2010, pp. 112-113: IEEE.

[23] L. Ma, J. C. Bienfang, O. Slattery, and X. Tang, "Up-conversion single-photon detector using multi-wavelength sampling techniques," *Optics express,* vol. 19, no. 6, pp. 5470-5479, 2011.

[24] J. Pelc, P. Kuo, O. Slattery, L. Ma, X. Tang, and M. Fejer, "Dual-channel, single-photon upconversion detector at 1.3 μm," *Optics express,* vol. 20, no. 17, pp. 19075-19087, 2012.

[25] L. Ma, O. Slattery, and X. Tang, "Single photon level spectrum measurement at fiber communication band using frequency up-conversion technology," *Laser physics,* vol. 20, no. 7, pp. 1612-1617, 2010.

[26] O. Slattery, L. Ma, P. Kuo, Y.-S. Kim, and X. Tang, "Frequency correlated biphoton spectroscopy using tunable upconversion detector," *Laser Physics Letters,* vol. 10, no. 7, p. 075201, 2013.

[27] P. S. Kuo, J. S. Pelc, O. Slattery, M. M. Fejer, and X. Tang, "Photon Temporal Correlations Measured Using a Dual-Channel Upconversion Detector," in *Frontiers in Optics*, 2012, p. FTh4B. 1: Optical Society of America.

[28] L. Ma, M. T. Rakher, M. J. Stevens, O. Slattery, K. Srinivasan, and X. Tang, "Temporal correlation of photons following frequency up-conversion," *Optics express,* vol. 19, no. 11, pp. 10501-10510, 2011.

[29] M. T. Rakher, L. Ma, M. Davanço, O. Slattery, X. Tang, and K. Srinivasan, "Simultaneous wavelength translation and amplitude modulation of single photons from a quantum dot," *Physical Review Letters,* vol. 107, no. 8, p. 083602, 2011.

[30] L. Ma, O. Slattery, T. Chang, and X. Tang, "Non-degenerated sequential time-bin entanglement generation using periodically poled KTP waveguide," *Optics express,* vol. 17, no. 18, pp. 15799-15807, 2009.

[31] O. Slattery, L. Ma, K. Zong, and X. Tang, "Background and Review of Cavity-Enhanced Spontaneous Parametric Down-Conversion," *Journal of Research of the National Institute of Standards and Technology,* vol. 124, pp. 1-18, 2019.

[32] O. Slattery, L. Ma, P. Kuo, and X. Tang, "Narrow-linewidth source of greatly non-degenerate photon pairs for quantum repeaters from a short singly resonant cavity," *Applied Physics B,* vol. 121, no. 4, pp. 413-419, 2015.

[33] L. Ma, X. Tang, and O. Slattery, "Optical quantum memory and its applications in quantum communication systems," *Journal of Research of the National Institute of Standards Technology,* vol. 125, p. 125002, 2020.

[34] S. Bhushan, O. Slattery, X. Tang, and L. Ma, "Terahertz Electromagnetically Induced Transparency in Cesium Atoms," in *Frontiers in Optics*, 2020, p. JTu1B. 40: Optical Society of America.

[35] L. Ma, O. Slattery, and X. Tang, "Optical quantum memory based on electromagnetically induced transparency," *Journal of Optics,* vol. 19, no. 4, p. 043001, 2017.

[36] L. Ma, O. Slattery, and X. Tang, "Noise reduction in optically controlled quantum memory," *Modern Physics Letters B,* vol. 32, no. 14, p. 1830001, 2018.

[37] L. Ma, O. Slattery, and X. Tang, "Spectral characterization of single photon sources with ultra-high resolution, accuracy and sensitivity," *Optics Express,* vol. 25, no. 23, pp. 28898-28907, 2017.

[38] O. Slattery, L. Ma, and X. Tang, "A cascaded interface to connect quantum memory, quantum computing and quantum transmission frequencies," in *Frontiers in Optics*, 2019, p. JW3A. 125: Optical Society of America.

[39] L. Ma, X. Tang, O. Slattery, and A. Battou, "A testbed for quantum communication and quantum networks," in *Quantum Information Science, Sensing, and Computation XI*, 2019, vol. 10984, p. 1098407: International Society for Optics and Photonics.

[40] T. Gerrits *et al.*, "Calibration of free-space and fiber-coupled single-photon detectors," vol. 57, no. 1, p. 015002, 2019.