Quantum Information Technology: Entanglement, Teleportation, and Memory

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ABSTRACT

A team of researchers from the Massachusetts Institute of Technology and Northwestern University worked to develop the technology elements needed to perform long-distance, high-fidelity qubit teleportation. In particular: this team developed novel sources of polarization-entangled photons based on chi-2 and chi-3 materials; it developed devices for high-efficiency quantum state frequency conversion and demonstrated long-distance entanglement distribution via optical fiber; and it worked toward realizing quantum memory elements in both trapped-atom and atomic-ensemble systems. The experimental work was supported by a variety of theoretical studies. Other theoretical work addressed more general issues in quantum communication and entanglement applications.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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“Precision Rotation Sensing and Interferometry Using Slow Light,” M.S. Shahriar, G.S. Pati, V. Gopal, R. Tripathi, G. Cardoso, P. Pradhan, M. Messal, and R. Nair, proceedings of QELS, Baltimore, MD, May 2005


Giovannetti, V., and S. Lloyd, L. Maccone, “Positioning and Clock Synchronization


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(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)


P. Kumar, K. F. Lee, J. Chen, X. Li, and P. L. Voss, "Quantum information processing with optical fibers," invited paper presented at the 9th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'05), Besançon, France, May 2-6, 2005; paper I-37.


X. Li, P. Voss, J. E. Sharping, J. Chen, and P. Kumar, "Generation and distribution of quantum entanglement in the telecom band with


X. Li, P. Voss, J E. Sharping, and P. Kumar, "Violation of Bell's inequality near 1550 nm using an all-fiber source of polarization-entangled photon pairs," presented at the Quantum Electronics and Laser Science Conference (QELS'2003), Baltimore, MD, June 1-6, 2003; paper QTuB4. See QELS'03 Technical Digest (Optical Society of America, Washington, D.C. 2003).

P. Voss and P. Kumar, "Room temperature IR InGaAs/InP APD photon counters for quantum optics experiments," invited paper presented at the Workshop on Single Photon: Detectors, Applications, and Measurement Methods, held at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, March 31 - April 1, 2003. The workshop was sponsored by NIST and ARDA.


J. E. Sharping, M Fiorentino, P. Kumar, and R. S. Windeler "Experimental nonlinear optics in microstructure fiber," presented at the 14th


"Ensemble-based Quantum Memory, Quantum Communication, and Quantum Computing,” Gour Pati, Kenneth Salit, Prem Kumar, and M.S. Shahriar, presented at the SPIE Photonics West Conference, San Jose, CA, January 2006 (invited).


“Light-Shift Imbalance Induced Dipole Blockade for Deterministic Quantum Information Processing using Atomic Ensembles”, M.S. Shahriar, presented at the International Conference on Quantum Optics, Hong Kong, December, 2005 (invited)

“Slow-Light in Cold Atoms for Single Photon Detection,” M.S. Shahriar, Midwest Workshop on Cold Atoms, Urbana, IL, November, 2005 (invited)

“Observation of Slow-Light and Matched Dispersion in Sodium Vapor for Applications to Laub-Drag Enhanced Rotation Sensing,” Renu


"Investigation towards realizing a slow-light based rotation sensor" G.S. Pati, R. Tripathi, P. Pradhan, R. Nair, V. Gopal, G. Cardoso, and M.S. Shahriar, presented at SPIE, Photonics West, 2005, San Jose, CA (invited)


"Observation of the Phase Of a Microwave Field via the Bloch-Siegert Oscillation," G. Cardoso, P. Pradhan, and M.S. Shahriar, the OSA Annual Meeting, Tucson, Az (October 2003) (Postdeadline Paper)


"Observation of the Phase Of a Microwave Field Using Single-Atom Nonlinear Optics," G. Cardoso, P. Pradhan, and M.S. Shahriar,
presented at the Progress In Electromagnetic Research Symposium 2003, Honolulu, HI, (October 2003) (Invited Paper)


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**(d) Manuscripts**


Number of Manuscripts: 13.00

Number of Inventions:

Graduate Students
Jay Sharping (100%)
Paul Voss (50%)
Jun Chen (100%)
Sarah Dugan (100%)
Ayodeji Coker (33%)
Ying Tan 50%
Jacob Morzinski (100%)
Joseph Vornehm (100%)
Alexander Heifetz (50%)
Kenneth Salit (100%)
Jong-Kwon Lee (50%)
Adam Smith (50%)
Eser Keskiner (25%)
Maxim Raginsky (25%)
Ranjith Nair (25%)
Marius A. Albota (0%)
Taehyun Kim, (0%)
Christopher E. Kuklewicz (100%)
Onur Kuzucu (25%)
Elliott J. Mason (0%)
Joe Aung (100%)
Saikat Guha (100%)
Brent J. Yen (20%)
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Baris Erkmen (20%)
Rosalind Takat (25%)

Names of Faculty Supported

Number of Graduate Students supported:  18.00
Total number of FTE graduate students:  14.00

Names of Post Doctorates

Marco Fiorentino (50%)
Friedrich. Koenig (30%)
Elliott J. Mason (0%)
Gaetan. Messin (0%)
Xiaoying Li (100%)
Jay Sharping (100%)
Paul Voss (50%)
Kim Fook Lee (33%)
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Venkatesh Gopal (50%)
Gour Pati (50%)
Renu Tripathi (20%)
Prabhakar Pradhan (20%)
George Cardoso (50%)
Parminder Bhatia (50%)
Lorenzo Maccone (50%)
Vittorio Giovannetti (50%)

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Total number of FTE Post Doctorates:  8.00

List of faculty supported by the grant that are National Academy Members

Names of Faculty Supported
Number of Faculty: 7.00

Names of Under Graduate students supported

Adil Gangat
Matthew Hall
Ning Li
Todd Levin
David Miller
Prem Gandhi
Mesfin Getaneh

Number of under graduate students: 7.00

Names of Personnel receiving masters degrees

Joseph Vornehm
Eser Keskiner
Emily Nelson
Joe Aung
Saikat Guha
Adam Smith
Ayodeji Coker

Number of Masters Awarded: 7.00

Names of personnel receiving PHDs

Ying Tan
Alexander Heifetz
Brent J. Yen
Christopher E. Kuklewicz
Elliott J. Mason
Jay E. Sharping
Paul Voss
Maxim Raginsky

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Names of other research staff

Franco N. C. Wong

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5 All-Fiber Photon-Pair Source for Quantum Communications

Patent Filed in US? (5d-1)  Y
Patent Filed in Foreign Countries? (5d-2)  N
Was the assignment forwarded to the contracting officer? (5e)  N
Foreign Countries of application (5g-2):

5a: Prem Kumar
5f-1a: Northwestern University
5f-c: 2145 North Sheridan Avenue
      Evanston       IL       60208

5a: Marco Fiorentino
5f-1a:
5f-c:

5a: Paul Voss
5f-1a:
5f-c:

5a: Jay E. Sharping
5f-1a:
5f-c:
Quantum Information Technology: Entanglement, Teleportation, and Quantum Memory

Research Summary

A team of researchers from the Massachusetts Institute of Technology (MIT) and Northwestern University (NU) worked to develop the technology elements needed to perform long-distance, high-fidelity qubit teleportation. In particular: this team developed novel sources of polarization-entangled photons based on $\chi^{(2)}$ and $\chi^{(3)}$ materials; it developed devices for high-efficiency quantum state frequency conversion and demonstrated long-distance entanglement distribution via optical fiber; and it worked toward realizing quantum memory elements in both trapped-atom and atomic-ensemble systems. The experimental work was supported by a variety of theoretical studies. Other theoretical work addressed more general issues in quantum communication and entanglement applications. This final report summarizes the major research accomplishment of our program. It begins with a review of the MIT/NU architecture for long-distance teleportation that was the basis for our program.

MIT/NU Qubit Teleportation Architecture

The MIT/NU architecture uses nonlinear optics to produce a stream of polarization-entangled photon pairs, i.e., signal and idler photon states of the singlet form

$$|\psi^-\rangle_{SI} \equiv (|HV\rangle_{SI} - |VH\rangle_{SI})/\sqrt{2}. \quad (1)$$
The signal and idler photons are routed down $L$-km-long lengths of standard telecommunication optical fiber—the signal photons proceeding down one fiber and the idler photons down the other—to a pair of quantum memories comprised of $^{87}$Rb atoms that are trapped inside high-$Q$ optical cavities [1]. One of these memories belongs to Alice and the other to Bob; the Bell-observable measurements are made in Alice’s memory, and the teleportation-completing transformations are performed in Bob’s memory. Without delving too much into details, see [2]–[5] for more information, the overall operation can be described in terms of architectural elements shown in Figs. 1–3.

Figure 1(a) shows a simplified energy diagram for the atomic levels in $^{87}$Rb that are used in storing the signal and idler qubits from $|\psi^-\rangle_{SI}$ in Alice’s memory and Bob’s memory, respectively. A photon of arbitrary polarization—expressed as a mixture of left-circular and right-circular components ($\sigma_-$ and $\sigma_+$, respectively) can be absorbed by a rubidium atom that is in the ground state $A$, transferring its coherence—the $\alpha$ and $\beta$ values that together characterize its polarization state—to the energy-degenerate excited levels $B$. By coherently pumping the $B$-to-$D$ transition with an appropriate laser field, this quantum coherence is transferred to long-lived $D$ levels for storage and processing. Whether or not a photon has been captured in this manner can be verified—in a non-destructive manner—by subsequently pumping the $A$-to-$C$ cycling transition with another laser field. If the atom has been transferred to the $D$ states, then no fluorescence will be seen on this cycling transition. Thus, Alice and Bob run a time-slotted memory loading protocol in which they repeatedly try to absorb photons, starting over at the end of each trial in which one or both of them see cycling transition fluorescence [4]. By employing an appropriate lattice of such trapped atoms, Alice and Bob can sequentially accumulate a reservoir of shared entan-
glement for teleporting quantum states between their respective quantum computers.

Figure 1: Essential components of the MIT/NU quantum communication architecture: (a) simplified energy-level diagram for the trapped rubidium atom; (b) source of polarization-entangled photon pairs.

Figure 1(b) sketches the structure of the entangled photon source in the MIT/NU architecture. It consists of two optical parametric amplifiers (OPAs), viz., resonant optical cavities each containing a second-order (χ(2)) nonlinear crystal in which photon pairs are produced whenever a photon from a strong pump laser of frequency ω_P fissions into a signal photon at frequency ω_S and an idler photon at frequency ω_I. Energy conservation, at the photon level, requires that ω_S + ω_I = ω_P. Momentum conservation, at the photon level, requires that the wave vectors associated with the
pump, signal, and idler obey $\vec{k}_S + \vec{k}_I = \vec{k}_P$. We assume type-II phase matching, in Fig. 1(b), which forces the signal and idler photons to be orthogonally polarized, as indicated by the bullets and arrows. With proper choice of nonlinear material, each OPA can be made to operate at frequency degeneracy, i.e., the center frequencies of the signal and idler will both be $\omega_P/2$. Making $\omega_P/2$ a cavity resonance for both the signal and the idler polarizations then dramatically increases the resulting signal-idler photon flux within the narrow (~15 MHz) bandwidth of the $^{87}\text{Rb}$ atomic line. Finally, by combining the outputs from two anti-phased, coherently-pumped OPAs on a polarizing beam splitter (PBS), we obtain the stream of polarization-entangled (singlet-state) photon pairs that are needed.

The $^{87}\text{Rb}$-atom quantum memory has its $A$-to-$B$ absorption line at 795 nm, but low-loss fiber propagation occurs in the 1.5-$\mu$m-wavelength window. Furthermore, standard telecommunication fiber does not preserve the polarization state of the light propagating through it. These obstacles to long-distance distribution of polarization-entangled photons to the Rb-atom memories are accounted for, within the MIT/NU architecture, by quantum-state frequency conversion [6] and time-division-multiplexed (TDM) polarization restoration (cf. [7]), as shown in Figs. 2 and 3. In particular, by applying a strong pump beam at 1570 nm to another second-order nonlinear crystal—chosen to satisfy the appropriate phase-matching condition—we can convert a qubit photon received at 1608 nm (in the low-loss fiber transmission window) to a qubit photon at the 795 nm wavelength of the $^{87}\text{Rb}$ quantum memory. For polarization

![Figure 2: Schematic diagram of quantum-state frequency conversion.](image-url)
restoration we postpone the PBS combining, shown in Fig. 1(b), until after fiber propagation. This is accomplished by transmitting time slices from the signal beams from our two OPAs down one fiber in the same linear polarization but in nonoverlapping time slots, accompanied by a strong out-of-band laser pulse. By tracking and restoring the linear polarization of the strong pulse, we can restore the linear polarization of the signal-beam time slices at the far end of the fiber. After this linear-polarization restoration, we then reassemble a time-epoch of the full vector signal beam by delaying the first time slot and combining it on a polarizing beam splitter with the second time slot after the latter has had its linear polarization rotated by 90°. A similar procedure is performed to reassemble idler time-slices after they have propagated down the other fiber.

Figure 3: Schematic diagram of time-division-multiplexed polarization restoration for the signal beam. HWP = half-wave plate, WDM MUX = wavelength division multiplexer, WDM DEMUX = wavelength division demultiplexer.

Once Alice and Bob have entangled the atoms within their respective memories by absorbing an entangled pair of photons, the rest of the qubit teleportation protocol is accomplished as follows. Charlie’s qubit message is stored in another 87Rb atom, which is trapped in the same optical cavity as Alice’s memory atom. By a coherence
transfer procedure [8], Charlie inserts his qubit into Alice’s memory atom in a manner that permits the Bell-observable measurement to be accomplished by determining in which of four possible states—not shown in Fig. 1(a)—that memory atom now resides. Alice sends the result of her Bell-observable measurement to Bob, who completes the teleportation process by standard atomic level manipulations that realize the phase-flip and bit-flip qubit operations. For details, see [3].

**Architectural Analyses**

**MIT/NU Performance Analysis**

During our program we have greatly refined our performance analysis for the MIT/NU qubit teleportation architecture. We first developed a complete cold-cavity treatment [5] that accounts for a wide variety of non-idealities that will be encountered in practice, such as imperfect polarization-restoration after fiber propagation, and pump-phase errors in the dual-OPA source. The cold-cavity work uses *ad hoc* lumped losses to account for coupling into the intra-cavity atoms. To fully assess the potential of the MIT/NU architecture, we began a hot-cavity treatment of its photon-atom interactions [11]. That work, although not yet complete, has already shown that photon-atom coupling may be far more forgiving of the photon’s temporal mode structure than might have been guessed in advance. In particular, it is not necessary to employ a time-reversed version of the hot-cavity decay pulse in order to achieve single-atom coupling efficiencies in excess of 50%. The hot-cavity loading analysis is continuing in collaboration with researchers at Hewlett-Packard Laboratories.
Duan-Lukin-Cirac-Zoller Quantum Communication

Because of the experimental challenges in trapping single atoms in high-$Q$ optical cavities—as is needed in the MIT/NU architecture—much excitement has been generated by proposals for distributing entanglement and performing teleportation between atomic ensembles in vapor cells by means of Raman scattering and photodetection (see below). We analyzed the Duan-Lukin-Cirac-Zoller (DLCZ) protocols for entanglement distribution and conditional teleportation within the same framework used for the cold-cavity analysis of the MIT/NU quantum communication architecture [9, 10]. This work has established the relative scaling behavior of these two approaches to long-distance quantum communication, and identified the DLCZ teleportation architecture’s previously unreported need for photon-number resolving detectors. In collaboration with researchers from Hewlett-Packard Laboratories, we plan to address other configurations that have been proposed for ensemble-based quantum communication.

Entanglement Generation and Transmission

$\chi^{(2)}$ Sources

We have demonstrated a number of polarization-entanglement sources based on spontaneous parametric downconversion (SPDC) in periodically-poled $\chi^{(2)}$ crystals with collinear propagation geometry. These sources produced streams of entangled-photon-pair outputs with high flux and high quantum-interference visibility. Periodically-poled KTiOPO$_4$ (PPKTP) and periodically-poled LiNbO$_3$ (PPLN) were used to allow phase matching at convenient user-selected wavelengths. In one case PPKTP was used to generate outputs at 795 nm [12], matching the transition wavelength of $^{87}$Rb.
D2 line associated with the MIT/NU architecture’s trapped-atom quantum memory [3]. In another SPDC device, PPLN was used to generate nondegenerate outputs at 795 and 1609 nm [13], the latter can be sent through a single-mode telecommunication optical fiber for transport over long distances. Coupled into single-mode optical fibers, this PPLN source is spectrally bright with a generation rate of 300 pairs/s/mW of pump in 1 GHz of bandwidth.

Previous SPDC sources generally used angle phase-matching with cone-shaped outputs such that only a small fraction of the output flux could be collected. Moreover, they required significant spatial and spectral filtering. We showed that collinear propagation in which the pump and the two downconversion outputs co-propagate along the crystal allow one to collect most of the beam-like output light, resulting in much higher flux [12]. Moreover, we demonstrated a bidirectional-pumping geometry that eliminated the need for spatial, spectral, or temporal filtering [13, 14] in a compact device with high output flux. By using a polarization Sagnac interferometer to implement the bidirectional-pumping geometry, we demonstrated a phase-stable downconversion source that yields the highest flux in a bulk crystal system to date: 5,000 pairs/s/mW of pump in 1 nm of bandwidth at a quantum-interference visibility of 97% [15]. The Sagnac source of polarization entanglement can be utilized in a variety of quantum information processing tasks requiring both high flux and high entanglement purity.

By inserting the nonlinear crystal inside an optical cavity, we modified our down-conversion outputs by the signal and idler double-resonance of the cavity obtaining a comb of narrowband outputs of polarization-entangled photons [16], fulfilling the original vision of a dual-OPA entanglement source [2]. The source output thus obtained exhibited collapses and revivals of the Hong-Ou-Mandel two-photon quantum-
interference dips. This source can be filtered by an external optical cavity to yield polarization-entangled photons with a narrow bandwidth of \( \sim 25 \text{ MHz} \), with an estimated flux of \( \sim 1 \text{ pair/s/mW} \) of pump in 1 MHz, which is currently the highest spectral brightness of all entanglement sources. This source is suitable for loading quantum memories based on atomic resonances that have narrow linewidths.

Typically biphoton entanglement exhibits entanglement in the time of creation between the two photons with anti-correlation between the frequencies of the two photons. We demonstrated biphoton entanglement in which the two photons have the same frequencies, hence anti-correlated in their times of arrival. By utilizing extended phase-matching [17, 18], in which there is zero group-velocity mismatch in the nonlinear crystal, coincident-frequency entanglement was demonstrated in PPKTP under pulsed pumping with a pulse width of 300 fs. This source produced biphotons with 1.3 ps coherence times [19]. The long biphoton coherence time, compared with the pump pulse width, indicated correlation times beyond what classical limits allow and thus was a manifestation of frequency entanglement. We utilized this extended phase-matching, pulsed-pumped downconverter to demonstrate a high-quality Hong-Ou-Mandel dip. Unlike all previous pulse-pumped experiments of this type, ours did not require narrowband filtering of the output light to produce high-quality quantum interference.

\( \chi^{(3)} \) Sources

We developed fiber-based sources of quadrature as well as polarization entanglement. Experiments were conducted in both the 800 nm and the 1500 nm portions of the electromagnetic spectrum. In the former case the experiments were done using microstructure fibers (MFs), also known as holey or photonic-crystal fibers, whereas in
the latter case both conventional fibers as well as MFs were used. Below we describe our main accomplishments in these $\chi^{(3)}$-source developments.

We implemented a polarization Mach-Zehnder interferometer that can be configured either as an asymmetric or a symmetric Sagnac loop. This configuration allowed us to obtain amplitude-squeezed soliton-like pulses with highly asymmetric setting of the beam splitters and squeezed-vacuum pulses with symmetric setting. Our apparatus yielded higher squeezing values than ever reported from a fiber-based device. A detailed experimental study of the generation of amplitude-squeezed soliton-like pulses was carried out with the interferometer containing standard polarization maintaining (PM) fiber [24]. Up to 4.4 dB of squeezing was directly observed, corresponding to 6.6 dB when the degradation due to losses external to the fiber was accounted for. Although the fiber-length dependence was in reasonable agreement with the quantum theory of soliton propagation in the fiber, the 6.6 dB value was considerably less than the $>10$ dB value predicted by the theory. Also, better squeezing was obtained with pulses that had peak powers roughly 50% higher than the soliton power. In order to account for these observations, we also undertook a detailed theoretical study of squeezing generation in our experiment [25]. Our study was based on the linearization approximation, in which the linearized quantum nonlinear Schroedinger equation is numerically solved. The novelty in our modeling is the inclusion of linear loss in the fiber, which is not negligible when MF is used [26]. Although the results of the numerical modeling correctly predict the experimental observation of larger squeezing at higher pulse peak powers than the soliton power, the predicted maximum-squeezing magnitude was still considerably larger than that observed in the experiment. We believe this discrepancy might be due to the Raman effect, which was not included in the theoretical model, but is significant for the 180 fs pulses used in our experiment.
To develop fiber-optic sources of polarization-entangled photon pairs, we conducted nondegenerate four-wave mixing experiments in dispersion-shifted fibers (DSFs) as well as MFs. To demonstrate the quantum nature of the four-photon scattering (FPS) process at the "single" photon level, that is, two pump photons scattering through the Kerr nonlinearity to create simultaneous signal and idler photons, we implemented novel pulsed coincident-counting schemes [27] with the goal of demonstrating fourth-order interference as well as violation of Bell’s inequalities in the fiber systems. We worked side-by-side on two different fronts. The first was geared towards obtaining entangled photon pairs in the 1550 nm low-loss transmission window of the standard fiber, whereas the second used MFs for obtaining the photon pairs in the 800 nm region in order for it to be compatible with the rubidium-based quantum memory. Both experiments were based on nondegenerate four-photon scattering near the zero-dispersion wavelength of the fiber, where the cross-section for such interaction is enhanced owing to phase matching of the photon wave functions.

In our 1550-nm experiments, we first observed twin-photon beams with external injection of signal photons to stimulate the four-photon scattering process. The resulting amplified signal photons and the generated idler photons showed sub-shot-noise quantum correlations in direct detection [28]. We further demonstrated for the first time the quantum nature of the four-photon scattering process at the "single" photon level by detecting the signal and idler photons in coincidence [29]. Because of the isotropic nature of the Kerr nonlinearity in fused-silica-glass fiber, the scattered, correlated photon-pairs are predominantly co-polarized with the pump photons in the scattering process. By coherently adding two such orthogonally-polarized FPS processes, we also demonstrated the generation of polarization entanglement [30]. Bells inequalities were violated by up to 10 standard deviations of measurement uncer-
tainty in these experiments and all four Bell states could be produced in the setup. Using such a fiber-based source, we then proceeded to demonstrate the storage of one photon of the pair in a 25 km loop of fiber while maintaining entanglement with the other and the long-distance distribution of polarization entanglement over 50 km of standard single-mode fiber with negligible decoherence of the entangled photon pairs [31]. This experiment demonstrated for the first time the viability of all-fiber sources for use in quantum memories and quantum logic gates. This fiber-based approach to photon-pair generation has been followed in many laboratories around the world. Northwestern University also applied and received a patent on this method of generating correlated and entangled photon-pairs in the telecom band and in the visible region using microstructure fiber [32].

In the early experiments, the ratio of the true coincidence counts to accidental coincidence counts was quite low due to the presence of background photons. A study of the cause of these background photons pointed the finger to the Raman effect, which is invariably present owing to its connection with the imaginary part of the same Kerr nonlinearity whose real part gives rise to the four-photon correlation [33, 34, 35]. By carefully optimizing the experimental parameters, we were able to consistently achieve ratios higher than ten [36]. Our work towards the end of the project focused on characterizing the fidelity of the fiber-based entangled photon sources. As noted above, the presence of Raman scattering in fibers sets the ultimate limits on the quality of two-photon entanglement that can be produced from fibers. In order to determine the limiting fidelity, as characterized by the visibility of two-photon interference fringes, we made extensive measurements of the spectra of the co- and cross-polarized Raman scattering in standard dispersion-shifted fiber for small detunings. We were able to make precise measurements of the Raman-gain spectra.
on both the Stokes and anti-Stokes sides because of our use of a photon-counting technique. Furthermore, the use of a pulsed pump eliminated Brillouin scattering and the use of a fiber Sagnac loop suppressed self-phase-modulation (SPM) induced spectral broadening from contaminating the measurements, thus enabling us to make precise measurement of the Raman gain down to a detuning of 0.17 THz from the pump [37].

We also developed a quantum theory for the pulsed four-photon interaction in the nonlinear fiber without inclusion of the Raman effect. In this theory, the pump is treated as a classical picosecond-duration pulse due to its experimental relevance. The signal and idler fields form a quantum mechanical two-photon (or “biphoton”) state with spectra that are specified by the filters placed in front of the detectors. Our goal was to study the dependence of the generation efficiency of the correlated photon pairs on various system parameters, including the shape of the pump pulse shape and the width of the filters placed in front of the detectors. Numerical predictions from the theory were shown to be in good agreement with the experimental results [38, 39].

We also constructed and characterized several versions of portable, telecom-band entangled-photon sources. Using a palm-sized femtosecond mode-locked fiber laser producing 100 fs pulses in the telecom band we constructed two portable entangled-photon sources, one based on the Sagnac-loop scheme used in our earlier experiments and the other using a counter-propagating scheme that directly yields polarization-entangled photons [40]. In both cases, highly-compact fiber-Bragg gratings and fiber-connected thin-film filters were used to obtain the required >100 dB rejection of the pump photons. Both sources are capable of being packaged into 18-inch rack-mountable boxes. In two-photon interference experiments, entangled photons from both sources yielded > 0% fringe visibilities without subtracting the Raman back-
ground [41]. Our experiments towards the end of the program indicate that up to 98% visibility is possible by cooling the fiber to liquid nitrogen temperatures.

In the 800-nm region we undertook detailed studies of four-wave mixing using the microstructure (holey) fiber obtained from Lucent [42]. We believe this was the first time four-wave mixing had been observed in such novel-structure fibers. For creating polarization-entangled photon pairs in the 800 nm region, most of our early effort was focused on understanding the classical nonlinear optics in MFs. This work was also part of the MURI Fellow funding for Jay Sharping. We reported a detailed study of our observation of four-wave mixing with >13 dB gain in the 750-nm-wavelength region using the MF obtained from Lucent [40]. In addition, we used the very efficient cross-phase modulation effect in MFs to demonstrate all-optical switching [43]. This work is relevant for advancing the state-of-the-art in classical all-optical communications and for implementing advanced fiber-optic communication networks. We also conducted experiments with MFs to demonstrate a four-wave-mixing oscillator, with an eye towards implementing our experiments in the continuous-wave regime for compatibility with the rubidium-based quantum memory [44]. Once the MF had been thoroughly characterized classically, we undertook experiments to demonstrate the generation of correlated photon pairs in the 800-nm region. These experiments suffered from high photon losses because the input and output coupling to the MF had to be done with free-space optics, as opposed to spliced connections in the 1500 nm experiments. Nevertheless, we were able to observe for the first time the generation of correlated photon pairs in the 800 nm band [45].
Quantum-State Frequency Conversion

The MIT-NU architecture requires that fiber-delivered photons at 1.55–1.6 µm wavelength be upconverted to the 795 nm wavelength of the Rb-atom memory with high efficiency and in a manner that preserves their polarization state. An efficient quantum-state frequency converter would also be useful for increasing the single-photon counting efficiency at near-infrared wavelengths. During our program we developed highly-efficient upconverters using both continuous-wave pumping of bulk nonlinear crystals and pulsed pumping of nonlinear-crystal waveguides. In particular, in our bulk-crystal experiments we demonstrated 90%-efficient frequency upconversion from 1550 nm to 633 nm at the single-photon level [46]. Sum-frequency generation in bulk PPLN using a strong pump at 1064 nm in a ring cavity converted input single photons at 1550 nm to output single photons at 633 nm. Polarization-insensitive upconversion was also demonstrated [47], in continuous-wave pumped bulk PPLN, that can be used to provide frequency translation with the quantum-state preservation for long-distance quantum communication. In our pulse-pumped waveguide experiment we demonstrated the first photon-counting measurements that reached a conversion efficiency of 100% within the waveguide [48].

Atomic Systems for Quantum Memory

Trapped-Atom Quantum Memory

In pursuit of the goal of demonstrating the MIT/NU architecture for long distance quantum teleportation [3], we developed two far-off-resonance traps integrated with high-Q optical cavities (cavity-FORT systems) loaded with rubidium atoms launched from magneto-optical traps (MOTs) [14]. Unfortunately, we fell short of achieving the
goal of trapping single atoms. Nevertheless, the apparatus we developed is likely to be useful in continued pursuit of similar experiments in the field of quantum information processing. Specifically, these two cavity-FORT systems are sufficiently versatile to explore a range of different experiments, by varying the number of atoms that are caught in the trap. Toward that end we developed two separate MOT chambers, each loaded with a chirp-slowed thermal Rb atomic beam. In each chamber, the atoms caught in the MOT are pushed vertically using a launch beam. In one chamber, the launched atoms are guided using a quadrupolar magnetic wire-guide. A high-$Q$, standing wave cavity was placed at this location, and stabilized to an atomic resonance using a 50% duty-cycle probe. For capturing the atoms, we used a FORT beam from a separate Ti-Sapphire laser. In the other chamber, we constructed a cavity system consisting of two intersecting traveling-wave (ring) resonators, each with a relatively low finesse (about 100). The intersection point also coincides with the location of the FORT. This was designed to demonstrate a quantum nondemolition single-photon detector using the extremely high Kerr nonlinearity that is predicted to occur under electromagnetically-induced-transparency (EIT) conditions in an atomic ensemble. Furthermore, either cavity by itself can also be used to test the light-shift imbalance induced blockade in ensemble excitation described below.

**Off-Resonant Raman Quantum Memory**

Recently, ensemble based quantum memory has been demonstrated using EIT, which employs optically resonant Raman excitation. This memory is inherently lossy, due to the fact that the photon pulse has a finite bandwidth, and the inherent absorption at frequencies away from the exact EIT condition leads to spectrally-dependent losses in the photon. The result is a loss of fidelity as well as distortion of the spatio-temporal
profile of the photon to be stored and recalled. We have pursued the development of a more robust ensemble quantum memory, employing off-resonant Raman excitation. This process is generally not employed due to the fact that one cannot employ a vapor-cell-based, narrowband, high-extinction filter to isolate the strong pump from the weak probe. However, we found [50, 51] that if $^{85}$Rb is used for the optically off-resonant Raman memory, then the pump can be resonant with a transition in $^{87}$Rb, so that a $^{87}$Rb vapor cell can be used for efficient isolation of the pump.

In our experiments, we initially used vapor cells made with the naturally occurring mixture of Rb isotopes. The Raman gain was studied using self-pumping as well as external optical pumping. In the presence of an external probe, the gain was observed to have a single peak, as expected. However, when spontaneous Raman scattering was observed using a photon counter, several different peaks were observed [51]. Our theoretical analysis showed that these lines resulted from light shifts of the hyperfine sublevels of both isotopes. The presence of such a multiplicity of peaks in the Raman scattering is expected to reduce the fidelity of a quantum memory that is based on such a system. As such, we next chose to operate under conditions where the light shifts were suppressed. Furthermore, we obtained vapor cells made from pure Rb isotopes. As a result, we were able to observe again just a single peak for the Raman scattering, as needed for the quantum memory application.

In order to demonstrate quantum memory operation in a deterministic manner, we used a source of entangled photon pairs developed in our program. When pumped by a laser operating at 532 nm, this source produces pairs of photons, one of which is at 795 nm while the other is around 1608 nm. The photon at 795 nm was to be captured by the Rb-cell quantum memory, prepared to be in the read mode using optical pumping as well as a Raman pump. Subsequently, the photon was to be
retrieved by applying a Raman read-out pulse, and recorded with a photon counter. The other photon was to be detected with a second photon counting system based on an InGaAs photodiode. Using electronic delay, the coincidence rate between these two processes can be determined, and compared with the corresponding coincidence rate when both photons are detected directly, without the quantum memory. The entangled-photon source had a very broad bandwidth. As such, the number of photons within the narrow Raman absorption bandwidth of Rb vapor was very small. In order for this approach to work well, it was necessary to filter the photons at 1608 nm with a Fabry-Perot filter as narrow as the vapor cell. Furthermore, this filter had to remain locked at the precise frequency at which the correlation is maximum. This can be done, for example, by using a super-stable, tunable, distributed-feedback stabilized laser of the type typically employed in testing DWDM communication system. Work on this quantum memory was not completed under our MURI program, but it is being continued under subsequent DARPA funding. We expect to realize such the necessary filtering and demonstrate the direct storage and recall of photons produced by the entangled-photon source.

As a more immediate alternative, we tested the quantum memory using a weak coherent-state source. The photon statistics of an attenuated coherent state were first established experimentally. The same beam was then stored in the quantum memory. Because the memory’s capture rate depends on the number of photons it captures, the statistics of the attenuated coherent state—after passing through the quantum memory for a given time interval—get altered in a well-defined way. The predicted photon statistics were then compared with the experimental results in order to determine how well the quantum memory was working. Similarly, the photon statistics of the quantum memory’s output, once the captured photons were
released—again at different rates—were compared with the theoretical predictions in order to establish the fidelity of the quantum memory. We obtained preliminary results for this sequence of experiments, and further optimization is underway to achieve the high fidelity expected from this device. This work too is continuing beyond the MURI program under DARPA funding.

**Atomic Ensembles as Qubits**

In addition to its use as a deterministic quantum memory, an optically-pumped vapor cell can be used for generating macroscopic entanglement, which in turn may be used in a quantum repeater or in quantum teleportation, provided that the condition for collective excitation is satisfied. However, unlike the quantum memory, the quantum repeater or quantum teleportation functions that are realized this way are not deterministic. This is because multi-photon processes are not forbidden. It has previously been realized that use of inter-atom dipole-blockade, for example, can suppress multi-photon processes, and render the system deterministic. However, given that the inter-atomic separations are randomly distributed, and the dipole-blockade depends on this separation, this approach is not likely to work for a vapor cell, nor for trapped atoms. We have devised a different mechanism for blockade that is uniform for all the atoms, via the process of light-shift imbalance [52, 53, 54, 55]. This process makes atomic-ensemble based quantum repeater and quantum teleportation operations into deterministic functions [53]. Furthermore, we have shown that this process can be used to realize a deterministic quantum bit based on atomic ensembles, and have shown explicit steps for realizing a CNOT gate between two such qubits [53]. Efforts are underway to test this mechanism using a trapped ensemble and a low-$Q$ cavity, as described later on. Realization of this technology would provide a potentially simpler
alternative for implementing a quantum Internet [56].

**Additional Research**

**Single-Photon, Two-Qubit Quantum Logic**

By utilizing both the polarization and momentum degrees of freedom of single photons as independent qubits, we demonstrated a polarization-controlled NOT (P-CNOT) gate [57], a momentum-controlled NOT (M-CNOT) gate, and a SWAP gate [58] that, together with single-qubit rotation using wave plates, form a universal gate set for single-photon two-qubit (SPTQ) quantum logic. SPTQ quantum logic can be used for manipulating qubits of hyperentangled photons and for enhancing quantum information processing tasks. We showed [59] that SPTQ quantum logic can be used to perform a complete physical simulation of the most powerful individual attack on Bennett-Brassard 1984 quantum key distribution, viz., the Fuchs-Peres-Brandt probe. Under DARPA funding we are now setting up an experiment to perform that simulation.

**Quantum-Enhanced Precision Measurements and Communication**

In theoretical work we showed that entanglement may be used to improve precision measurement, timing, and positioning [60]–[65]. We also demonstrated that entanglement could play a role in enhancing the power-limited capacity of communication channels in particular, and of dynamical evolution in general [66, 67, 68]. In studying applications for our techniques to distribute entanglement, we were led to our collaboration with Peter Shor on the entanglement-assisted capacity of Bosonic channels [69, 70].
By applying the fundamental physics of information processing, we were able to derive a series of results on the computational and communication capacity of physical systems [71]–[76]. This work included deriving fundamental limits to the accuracy with which measurement can take place, including measurement of space and time.

**Capacity of Bosonic Communications**

A principal goal of quantum information theory is evaluating the information capacities of important communication channels. At present, exact capacity results are known for only a handful of channels. We have considered the classical capacity $C$ of Bosonic channels with isotropic Gaussian noise. This study connects to a research line that began with the capacity derivation for the lossless (and hence noiseless) Bosonic channel [77, 78], and only very recently led to our deriving the capacity of the pure-loss Bosonic channel [79]. For that channel, we have the exact values of $C$ for single-mode operation under an average photon-number constraint at the input, and for wideband operation under an average power constraint at the input. In both cases quantum entanglement is not necessary to achieve capacity, and “classical” encoding procedures employing coherent states suffice. This means that the Holevo information of the pure-loss channel is additive. Moreover, at high average powers we have shown that heterodyne detection is asymptotically optimum for single-mode operation and for far-field, free-space communication. For active channel models—in which noise photons are injected from an external environment or the signal is amplified with unavoidable quantum noise—we have obtained upper and lower bounds for the capacity, which are asymptotically tight at low and high noise levels. Exact results for these active channels would follow from proving the conjecture that a coherent-state input minimizes the output entropy from such channels [80, 81]. In other channel
capacity work we derived the first results for the multiple-access capacity region of Bosonic channels [82], and we established the limit on channel capacity when orbital angular momentum spatial modes are employed in free-space propagation Bosonic communications [83].

Quantum Information Security and Processing

We created a protocol for anonymous key identification [84], which involves the use of quantum states for unconditionally secure agent identification.

In [85, 86], we showed why there is no impossibility proof for unconditionally secure quantum bit commitment. Protocol QBC1 in [86] and protocol QBC5 in [87] are indeed unconditionally secure. They will be rewritten in more understandable form for journal publication.

In [88] we showed that entanglement purification is much harder to achieve for continuous-variable teleportation compared to qubit teleportation. However, the comparison is not entirely general and there are also possibilities of using a whole infinite-dimensional space as a qubit. We have not, however, explored such avenues.

We found that the protocol of Ambanis, Smith and Yang is the only one in the literature that may be applicable to a real experimental system. It is still, however, too idealized and limited in capability. On the other hand, it may make possible a demonstration of some simple entanglement enhancement using just CNOT gates.

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