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13. ABSTRACT (Maximum 200 words) This grant supported a MURI Fellow to work on topics in the area of Quantum Information Technology. Specifically, Jay E. Sharping worked on the following research tasks: i) Generation of polarization-entangled photon-pair pulses near 1.5 micron wavelength by use of the Kerr nonlinearity of standard dispersion-shifted optical fiber and ii) applying the same techniques to obtain polarization-entangled photon-pair pulses near the 0.8 micron wavelength by use of novel micro-structured optical fibers (also called holey fibers). In both cases, nondegenerate four-wave mixing was used to simultaneously generate signal/idler photon pairs. Thorough studies of the classical nonlinear optical processes were performed and several useful applications such as parametric amplification, parametric oscillation, and all-optical switching were demonstrated. Direct detection and photon counting techniques were used to experimentally verify quantum-correlated signal/idler pair production. Photon counting tools for detection at wavelengths of 1.5 micron were built and characterized. Time and polarization multiplexed four-wave mixing processes were then used to generate polarization-entangled photon pairs, and the quality of the entanglement was evaluated through quantum interference and Bell-inequality-violation measurements.				
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Final Progress Report

(1) Foreword (optional)

(2) Table of contents (if more than 10 pages)

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(3) List of appendixes, illustrations and tables (if applicable)

N/A

(4) Statement of the problem studied

Quantum entanglement, which refers to the nonclassical dependency of physically separated quantum systems, is an essential ingredient that must be freely available for implementing many of the novel functions in quantum information processing, such as database searching, clock synchronization, teleportation, computing, and cryptography. Therefore, the efficient generation, transmission, and storage of quantum entanglement are of prime importance.

As part of this MURI Fellow project, we undertook major experimental and theoretical studies to demonstrate the efficient generation and transmission of polarization-entangled photon pairs. The experiments, which were conducted at Northwestern University, rely on sources of polarization-entangled photon pairs that utilize the $\chi^{(3)}$ parametric processes in optical fibers. One such source utilizes nondegenerate four-wave mixing in fibers [standard dispersion-shifted fiber as well as novel microstructure (holey) fibers were used]. A key objective is to develop capabilities to distribute shared entanglement over long distances (~100km) and this fiber-based source integrates nicely with the propagation medium, which is standard optical fiber used in its 1.5- μm low-loss transmission window.

(5) Summary of the most important results

In our efforts to develop fiber-optic sources of polarization-entangled photon pairs, we worked on two different fronts. The first was geared towards obtaining entangled photon pairs in the 1.5- μm low-loss transmission window of standard fiber, and the second used microstructure fibers (MFs) for obtaining the photon pairs in the 800nm region in order for them to be compatible with rubidium-based quantum memory. Both experiments utilize nondegenerate four-photon scattering (two pump photons interacting through the Kerr nonlinearity to create a signal photon and an idler photon) 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.

Entanglement in the 1.5- μm wavelength low-loss fiber transmission window:

- We assembled and characterized a nondegenerate four-wave mixing apparatus using standard dispersion-shifted fiber. Using this apparatus we 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 differenced detection.
- We built and characterized photon-counting modules based on commercial InGaAs avalanche photodiodes operating in the gated Geiger mode. Use of these counters allowed us to verify the

simultaneous production of the signal and idler photon pairs. We reported demonstrations of the quantum nature of the four-photon scattering process at the "single" photon level (that is, two pump photons scattering through the Kerr nonlinearity to create simultaneous signal and idler photons).

- We were successful in measuring high-visibility quantum interference and violations of Bell's inequalities with each of the four Bell states. This success depended heavily on a series of experimental enhancements: implementation of a time/polarization multiplexing scheme to generate polarization entanglement, assembly of a double-grating detection filter, and implementation of a phase control process.
- We successfully measured high-visibility quantum interference for the "up/up + down/down" Bell state after the pairs had propagated through 50km of fiber.
- We performed theoretical and experimental characterizations of spontaneous Raman scattering, which represents a fundamental limitation to the quality of the entanglement generated in this system.

Entanglement generated using microstructure fibers (MFs):

- The early work was focused on understanding the classical nonlinear optics in MFs. We reported a detailed study of our observation of four-wave mixing with >13dB gain in the 750nm-wavelength region using the MF obtained from OFS, Inc. We also reported experiments where we used the cross-phase modulation effect in MFs to demonstrate all-optical switching. 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 proceeded to implement procedures needed to quantify the fiber birefringence and group-velocity dispersion coefficients, and armed with this new knowledge, we demonstrated a four-wave-mixing oscillator, with an eye towards compatibility with the rubidium-based quantum memory.
- We have also demonstrated quantum correlations between the signal and idler photons wherein we used MF for photon-pair production, a double-grating configuration for filtering the pump, signal, and idler photons, and commercially available single photon counting modules for detection.

(6) Listing of publications and technical reports

Papers published in peer-reviewed journals:

1. J. E. Sharping, M. Fiorentino, and P. Kumar, "Observation of twin-beams type quantum correlation in optical fiber," *Optics Letters*, Vol. 26, No. 6, 2001, pp. 367–369.
2. J. E. Sharping, M. Fiorentino, A. Coker, P. Kumar, and R. S. Windeler, "Four-wave mixing in microstructure fiber," *Optics Letters*, Vol. 26, No. 14, 2001, pp. 1048–1050.
3. M. Fiorentino, J. E. Sharping, P. Kumar, M. Vasilyev, and D. Levandovsky, "Soliton squeezing in a Mach-Zehnder fiber interferometer," *Physical Review A*, Vol. 64, 031801(R) (2001).
4. M. Fiorentino, J. E. Sharping, P. Kumar, A. Porzio, and R. S. Windeler, "Soliton squeezing in microstructure fiber," *Optics Letters*, Vol. 27, No. 8, 2002, 649–651.
5. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "Optical-parametric oscillator based on four-wave mixing in microstructure fiber," *Optics Letters*, Vol. 27, No. 19, 2002, pp. 1675–1677.
6. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "All-optical switching based on cross-phase modulation in microstructure fiber," *IEEE Photonics Technology Letters*, Vol. 14, No. 1, 2002, 77–79.
7. M. Fiorentino, P. L. Voss, J. E. Sharping, and P. Kumar, "All-fiber photon-pair source for quantum communications," *IEEE Photonics Technology Letters*, Vol. 14, No. 7, 2002, pp. 983–985.

8. M. Fiorentino, J. E. Sharping, P. Kumar, and A. Porzio, "Amplitude squeezing in a Mach-Zehnder interferometer: numerical analysis of experiments with microstructure fiber," *Optics Express*, Vol. 10, No. 2, 2002, 128–138.

Papers published in non-peer-reviewed journals or in conference proceedings:

1. M. Fiorentino, J. E. Sharping, P. Voss, P. Kumar, D. Levandovsky, and M. Vasilyev, "Soliton squeezing in asymmetric and symmetric fiber Mach-Zehnder nonlinear interferometers," presented at the 2001 Quantum Electronics and Laser Science Conference (QELS'2001), Baltimore, MD, May 6–11, 2001; paper QMC7. See QELS'01 Technical Digest (Optical Society of America, Washington, D.C. 2001), pp. 11–12.
2. J. E. Sharping, A. Coker, M. Fiorentino, P. Kumar, and R. S. Windeler, "Four-wave mixing in microstructure fiber," presented at the 2001 Conference on Lasers and Electro-Optics (CLEO'2001), Baltimore, MD, May 6–11, 2001; paper CThQ2. See CLEO'01 Technical Digest (Optical Society of America, Washington, D.C. 2001), p. 508.
3. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "Experimental nonlinear optics in microstructure fiber," presented at the 14th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS'01), San Diego, CA, November 12–15, 2001, Paper WV3. See pp. 572–573 of the LEOS'01 Conference Proceedings (IEEE, Piscataway, NJ, 2001).
4. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "Optical-parametric oscillator based on four-wave mixing in microstructure fiber," presented at the Conference on Lasers and Electro-Optics, Long Beach, CA, May, 19–24, 2002: Paper CTuB2. See pp. 141–142 of the *CLEO'02 Conference Proceedings* (OSA, Washington, DC, 2002).
5. M. Fiorentino, P. S. Voss, X. Li, J. E. Sharping, G. A. Barbosa, and P. Kumar, "All-fiber photon-pair source for quantum communications," post-deadline paper presented at the Quantum Electronics and Laser Science Conference, Long Beach, CA, May, 19–24, 2002: Paper QPD4. (OSA, Washington, DC, 2002).
6. P. Kumar, X. Li, M. Fiorentino, P. L. Voss, J. E. Sharping, G. A. Barbosa, "Fiber-optic sources of quantum entanglement," presented at the 6th International Conference on Quantum Communication, Measurement, and Computing, Cambridge, MA, July 21–26, 2002. To appear in the *QCM&C'02 Conference Proceedings* (Rinton Press, New Jersey, 2003), see quant-ph/0209112.
7. P. Kumar, M. Fiorentino, J. E. Sharping, and P. L. Voss, "Fiber-optic sources for quantum communication," presented at the Conference on Nonlinear Optics (NLO'2002) Maui, Hawaii, July 29–August 2, 2002; paper MC1. See *Nonlinear Optics Technical Digest*, (Optical Society of America, Washington, D.C. 2002), pp. MC1.1–MC1.3.
8. X. Li, P. L. Voss, J. E. Sharping, M. Fiorentino, and P. Kumar, "An all-fiber source of polarization-entangled photon pairs in the 1550 nm telecom band," *postdeadline paper* presented at the Conference on Nonlinear Optics (NLO'2002) Maui, Hawaii, July 29–August 2, 2002. See *NLO Technical Digest*, Postconference Edition (Optical Society of America, Washington, D.C. 2002).
9. X. Li, P. Voss, J. E. Sharping, P. Kumar, "Violation of Bell's inequality near 1550 nm using an all-fiber source of polarization-entangled photon pairs," presented at the 2003 Quantum Electronics and Laser Science Conference (QELS'2003), Baltimore, MD, June 3–5, 2003; paper QTuB4. See QELS'03 Technical Digest (Optical Society of America, Washington, D.C. 2003).

Papers presented at meetings, but not published in conference proceedings:

1. J. E. Sharping, M. Fiorentino, and P. Kumar, "Observation of twin-beams type quantum correlations in optical fiber," presented at the 2000 Optical Society of America Annual Meeting, Providence, Rhode Island, October 22–26, Paper WM2.
2. M. Fiorentino, J. E. Sharping, P. Kumar, and R. S. Windeler, "Soliton squeezing in a microstructure fiber," *invited paper* presented at the 7th International Conference on Squeezed States and Uncertainty Relations (ICSSUR'01), June 4–8, 2001, Boston, MA.
3. M. Fiorentino, P. Voss, J. E. Sharping and P. Kumar, "Fourth-order quantum interference at 1550 nm," presented at the 2001 Optical Society of America Annual Meeting, Long Beach, CA, October 14–19, 2001; Paper ThF2.
4. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, "Nonlinear fiber optics in microstructure fiber," presented at the 2001 Optical Society of America Annual Meeting, Long Beach, CA, October 14–19, 2001; Paper ThD2.
5. X. Li, M. Fiorentino, P. L. Voss, J. E. Sharping, G. A. Barbosa, and P. Kumar, "All-fiber photon-pair source for quantum communications," presented at the 2002 Optical Society of America Annual Meeting, Orlando, FL, September 19–October 3, 2001; Paper ThG1.

(7) List of participating scientific personnel including any advanced degrees

Fully supported individuals:

Jay E. Sharping

2001 New Focus Award from the Optical Society of America

2002 McCormick School Cabell Fellowship Award

2003 Doctor of Philosophy

Other participants in the conducted research:

Ayodeji Coker (2002 Master of Science), Paul Voss, Jun Chen, Ning Li, Marco Fiorentino, Alberto Porzio, and Xiaoying Li

(8) Report of inventions

1. "Optical processing using nonlinearities in photonic crystal fiber," disclosed to Northwestern University by P. Kumar, J. E. Sharping, and G. S. Kanter.
2. "All-fiber photon-pair source for quantum communications," Provisional patent filed by Northwestern University, Inventors: P. Kumar, M. Fiorentino, P. L. Voss, and J. E. Sharping.
3. "Microstructure Fiber Optical Parametric Oscillator," Provisional patent filed by Northwestern University, Inventors: P. Kumar and J. E. Sharping.

(9) Bibliography

Please refer to the publications listed in Section (6) for complete bibliographic information.

(10) Appendices

None