All-Fiber Photon-Pair Source For Practical Quantum Communications

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Quantum entanglement refers to the nonclassical dependency of physically separated quantum systems. It is an essential resource that must be freely available for implementing many of the novel functions of quantum information processing, such as database searching, clock synchronization, teleportation, computing and cryptography.[1] The efficient generation and transmission of quantum entanglement is therefore of prime importance. With the ubiquitous standard optical fiber serving as the transmission medium and the widespread availability of efficient active and passive fiber devices, technological synergy between the generation and propagation components of the overall quantum network can be achieved by deploying sources of entanglement that rely on the nonlinearity of the fiber itself. Such fiber-based sources of quantum entanglement would also have the advantage of modal purity over their crystal counterparts,[2,3] which is very important for realizing complex networks that involve many quantum operations.

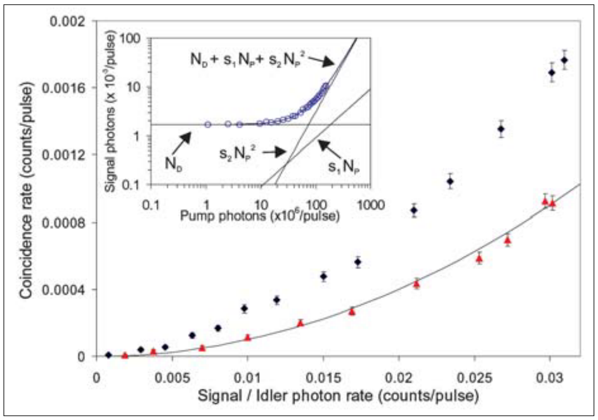

Figure 1. Coincidence rates as a function of the single-photon rates in two different cases: signal-idler fluorescence produced by a pump pulse (diamonds) and signal-idler fluorescence produced by two consecutive pump pulses (triangles). The line represents the calculated "accidental" counts. The inset shows a plot of the detected idler photons as a function of the injected pump photons (hollow circles). A second-order polynomial is shown to fit the experimental data. The contributions of the dark counts, linear scattering and quadratic scattering are plotted separately as well.

In our quest to develop fiber-based devices for quantum information processing, we have recently demonstrated an all-fiber source of quantum-correlated photon pairs.[4] The operating physical mechanism in this source is nondegenerate four-photon mixing, wherein two pump photons scatter through the Kerr nonlinearity of the fiber to create simultaneous signal and idler photons. Our experiment is conducted near the zero-dispersion wavelength of standard dispersion-shifted fiber, where such scattering is enhanced owing to phase matching of the photon wave functions. It must be pointed out here that in a conventional wavelength-division-multiplexed classical optical communication line, one strives to suppress the four-photon or four-wave mixing process, which otherwise causes cross talk between the wavelength channels and sets limits on the total data capacity of the communication line.

In our experiment, the four-photon mixing takes place in a nonlinear-fiber Sagnac interferometer (NFSI), which we previously used to generate quantum-correlated twin beams in the fiber.[5] The pump is a mode-locked train of ~3-ps-long pulses. The pulsed operation serves two important purposes: the NFSI amplifier can be operated at low average powers and the production of the signal/idler fluorescence photons is confined to well-defined temporal windows, allowing use of a gated detection scheme to increase the signal-to-noise ratio. To measure the nonclassical (i.e., quantum) correlations between the signal and the idler photons, one must effectively suppress the pump photons from reaching the detectors. Since a typical pump pulse contains ~10^8 photons and we are interested in detecting ~0.01 signal (idler) photons/pulse, a pump-to-signal (idler) rejection ratio in excess of 100 dB is required. We achieved this specification by sending the fluorescence photons through a free-space double-grating spectral filter that separates the signal and idler photons from each other and from the pump photons not rejected by the NFSI.

To demonstrate the quantum nature of the four-photon scattering at the "single" photon level, we assembled a photon-counting apparatus for detecting the signal and idler photons in coincidence. This apparatus is based on commercial InGaAs avalanche photodiodes operating in the gated Geiger mode.[4] In the inset in Fig. 1, we show the number of scattered photons, N_S, versus the number of pump photons, N_P, injected into the NFSI. We fit the experimental data with a second-order polynomial fit, including the number of dark counts during the gate interval, N_D. The fit clearly shows that the quadratic scattering ($\propto N_P^2$) in the fiber can dominate over the residual linear scattering ($\propto N_P$) of the pump, owing to imperfect filtering. The main body of Fig. 1 shows the coincidence-counting results. The diamonds represent the rate of coincidence counts versus the rate of the signal (idler) photons generated during the same pump pulse. The triangles represent the measured coincidence rate versus the signal-photon count rate when the signal is delayed with respect to the idler by one pulse period. For two independent photon sources, each with a count rate $R_S \ll 1$, the "accidental" coincidence rate R_C is given by $R_C = R_S^2$, regardless of the photon statistics of the sources. This quadratic relation is plotted as the solid line in Fig. 1, which fits the delayed-coincidence data (triangles) very well. These measurements show that while the fluorescence photons produced by the adjacent pump pulses are independent, those coming from the same pump pulse show a strong correlation, which is a signature of their non-classical behavior.

This work was supported by the Department of Defense Multidisciplinary University Research Initiative program administered by the Army Research Office under Grants DAAD19-00-1-0177 and DAAD19-00-1-0469, and by the U.S. Office of Naval Research under Grant N00014-91-J-1268.

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