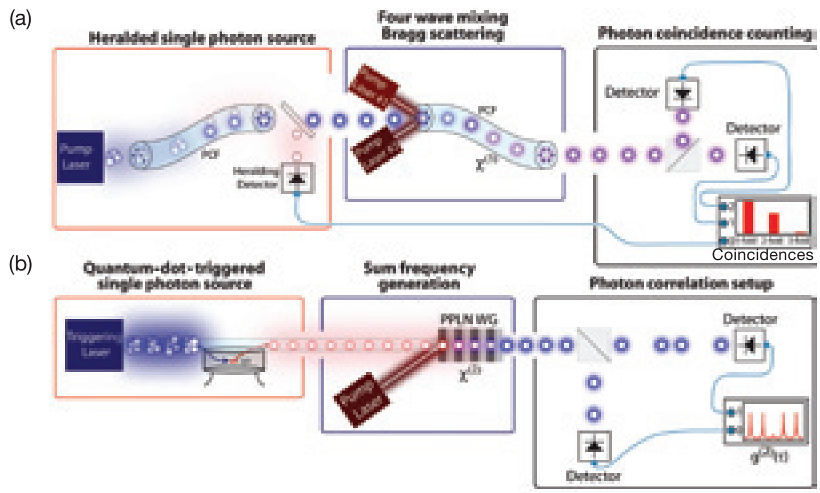
Quantum Frequency Translation of Single-Photon States

Kartik Srinivasan and Michael G. Raymer

Optics-based quantum information processing (QIP) has evolved in many systems, including trapped atoms and ions, semiconductor quantum dots and nonlinear optics. A hybrid quantum system has multiple platforms that are integrated to use each one's strengths while minimizing its limitations. For example, one envisions long distance transmission by photons in optical fibers at low-loss telecommunications wavelengths and data storage in quantum memories at visible wavelengths. Quantum frequency translation (QFT)[1,2]—the ability to change light's wavelength without altering its other quantum mechanical properties—would thus play a crucial role in QIP, and it has been demonstrated in the preservation of time-energy entanglement between two optical fields after one was frequency translated.[3] This year, two groups demonstrated QFT on single-photon states.[4,5]

A University of Oregon team used third-order nonlinear processes in photonic crystal fiber (PCF) for both single-photon generation and wavelength translation.[4] Single photons were created by spontaneous four-wave mixing, where two pump photons are annihilated and create simultaneous signal and idler photons, so that the detection of an idler photon "heralds" the presence of a signal photon. The signal photons, at 683 nm, are then sent into another length of PCF for QFT by third-order nonlinear Bragg scattering,[2] a process by which two pump photons (at 808 nm and 845 nm) create an effective grating that scatters the signal photon to a new, frequency-translated wavelength (659 nm) determined by the difference in energy between the two pump fields. Photon-number statistics measurements then confirm the single photon character of the frequency translated light.

A team from the National Institute of Standards and Technology used "triggered" single photons from a single, cryogenically cooled semiconductor quantum dot.[5] Behaving like an isolated two-level system, the quantum dot is repetitively excited with a pulsed laser, with each pulse placing the quantum dot into its excited state, and, upon relaxation into the ground state, generating a single photon at 1,300 nm. These photons are coupled into an optical fiber and combined with a strong 1,550-nm pump beam inside a periodically poled lithium niobate waveguide. Here, the second-order nonlinear process of sum-frequency generation produces new single photons at 710 nm. Photon correlation measurements confirm that the translated light was predominantly composed of single photons.



Quantum frequency translation via (a) nonlinear Bragg scattering[4] and (b) sum frequency generation.[5] (a) Heralded single photons generated in a photonic crystal fiber (PCF) are combined with two pump photons in another length of PCF to produce frequency translated single photons. (b) Triggered single photons generated by a single quantum dot are combined with pump photons in a periodically poled lithium niobate waveguide to produce frequency-translated single photons. Photon coincidence counting measurements were used to verify the single photon character of the frequency translated light.

The single-photon conversion efficiencies were estimated to be 29 percent[4] and 75 percent,[5] and are expected to approach near-unity conversion. Second-order nonlinear processes are well suited for wavelength translation over widely separated bands, circumventing the challenges of telecommunications-band single-photon counting by converting light to the visible. Alternately, the second pump beam in nonlinear Bragg scattering gives greater flexibility in achieving translation over arbitrary wavelength separations, including small separations for which second-order processes run into challenges. This can be used to produce indistinguishable photons from independent, non-identical single-photon sources. Altogether, QFT provides important tools for hybrid quantum systems that use photons for transmitting quantum information. ◭

Kartik Srinivasan (kartik.srinivasan@nist.gov) is with the Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, Md., U.S.A. Michael G. Raymer is with the department of physics and Oregon Center for Optics, University of Oregon, Eugene, Ore., U.S.A.

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