Quantum Frequency Translation of Single-Photon States

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Optics-based quantum information processing (QIP) has evolved in many systems, including trapped atoms and ions, semiconductor quantum dots, and nonlinear fiber optics. A "hybrid quantum system" is one in which multiple platforms are integrated to use each system'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 the wavelength of light without altering its quantum mechanical properties, would thus play a crucial role in QIP, and has been demonstrated [3] in the preservation of time-energy entanglement between two optical fields after one was frequency translated. This year, two groups demonstrated QFT on single-photon states of light for the first time [4,5] (Figure 1).

McGuinness et al. [4] used four-wave mixing in photonic crystal fiber (PCF) for both single photon generation and wavelength translation. 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 were then sent into another length of PCF for QFT by four-wave mixing Bragg scattering [2], a process by which two pump photons (at 808 nm and 845 nm in this experiment) create an effective grating that scatters the signal photon to a new, frequency-translated wavelength (659 nm) determined by the difference in energy of the two pump fields. Photon-number statistics measurements then confirmed the single photon character of the frequency translated light.

The experiment by Rakher et al.[5] used "triggered" single photons from a single, cryogenically-cooled semiconductor quantum dot (Figure 1). Behaving like an isolated two-level system, the quantum dot was 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 wavelength 1300 nm. These photons were coupled into an optical fiber and combined with a strong 1550 nm pump beam inside a periodically-poled lithium niobate waveguide. Here, the three-wave mixing process of sum frequency generation produced new single photons at 710 nm wavelength, and photon correlation measurements confirmed that the translated light was predominantly composed of single photons.

The single-photon conversion efficiencies in Refs. [4] and [5] were estimated to be 29% and 75%, respectively, and are expected to approach near-unity conversion. The two approaches are better fit for specific applications. Three-wave mixing is well-suited for wavelength translation over widely separated bands, circumventing the challenges of telecommunications-band single-photon counting by converting light to the visible. On the other hand, the addition of a second pump beam in four-wave mixing gives greater flexibility in achieving translation over arbitrary wavelength separations, including small separations for which three-wave mixing runs into challenges. This can be used to produce indistinguishable photons from independent, non-identical single-photon sources and in generating narrowly-spaced single-photon channels in a wavelength-multiplexed system.

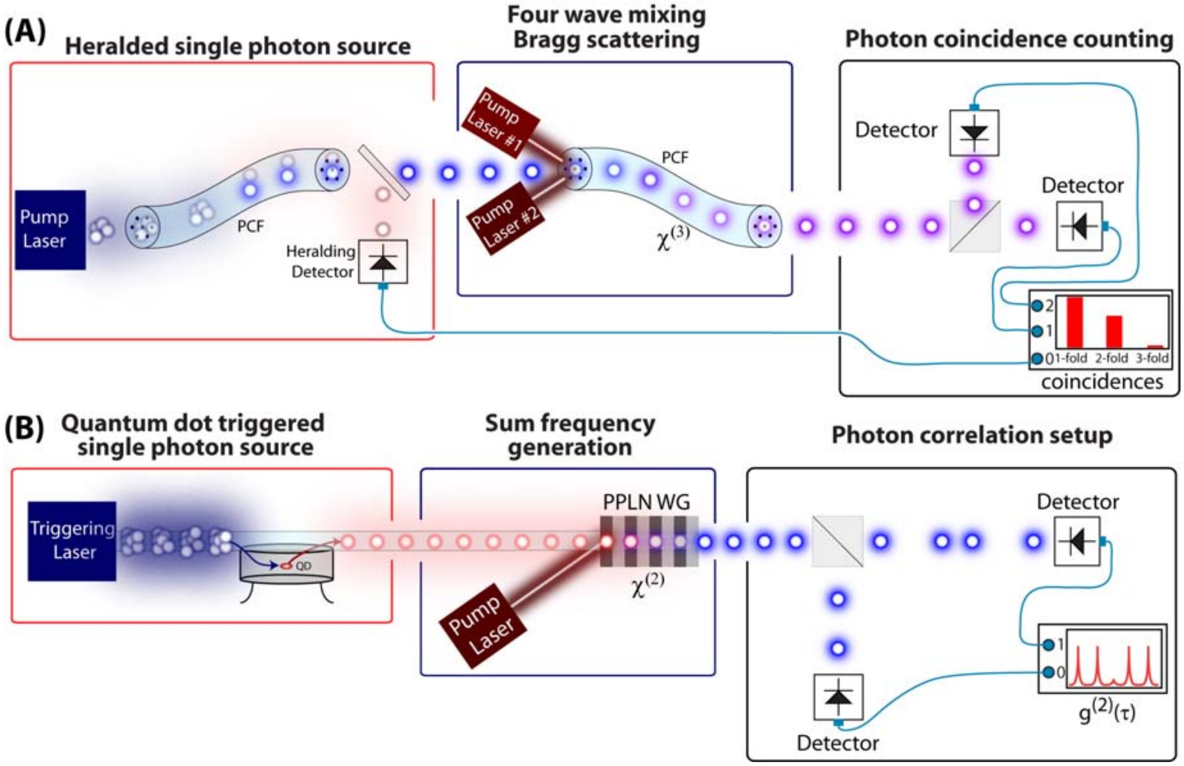

Figure 1. Quantum frequency translation via (A) four-wave mixing Bragg scattering [4] and (B) three-wave mixing sum frequency generation [5]. (A) Heralded single photons generated in a photonic crystal fiber (PCF) are combined with two pump photons in another length of PCF to produce frequency translated single photons. (B) Triggered single photons generated by a single quantum dot are combined with pump photons in a periodically-poled lithium niobate waveguide (PPLN WG) to produce frequency translated single photons. Photon coincidence counting measurements are used in both experiments to verify the single photon character of the frequency translated light.

References

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