Manipulating the Colors and Shapes of Single Photons for the Quantum Internet

Michael G. Raymer* and Kartik Srinivasan**

* Department of Physics and Oregon Center for Optics, University of Oregon, Eugene, OR 97403
** Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD 20899

1. The Quantum Internet and the Photon

Quantum physicists envision a futuristic information processing and communication system—the Quantum Internet[1]. (See the description in Box 1). It will likely use single photons to communicate between computational nodes, because photons interact weakly with their environment and hence are good carriers of information. For this to succeed, scientists will need to be able to control and manipulate the states of single photons in ways that have not been done before. To appreciate what this means, consider what is meant by 'single photon.' In the original conception put forth by Planck and Einstein between 1900 and 1905, the light quantum (named 'photon' in the 1920s) was a carrier of a precise amount of energy. For a given mode of the electromagnetic field with frequency f, the energy content was postulated to be equal to an integer (the number of 'photons,' from a particle viewpoint) times the quantity hf, with h being Plank's constant. This view of photons was made more sophisticated by Dirac's formal quantization of the electromagnetic field. In this theory, a convenient set of eigenstates for describing photon states is defined by four quantum numbers, one for the projection of spin along the propagation axis (helicity or polarization) and one each for the three components of momentum. Alternatively one can specify an eigenstate by telling its polarization, its energy (frequency), and two quantum numbers related to the remaining two components of momentum.

But such eigenstates of light are not created when a single excited-state atom decays. What is created is a superposition involving ranges of these eigenvalues. For example, the spread of energies is given by the inverse of the atomic lifetime, in accordance with the uncertainty principle. That is, the state of the single emitted 'photon' (or equivalently the state of the electromagnetic field following decay of the atom) is a linear superposition of single-photon energy eigenstates. This forms a coherent wave packet with a particular temporal and spatial shape, several of which are illustrated in Figure 1. This single-photon state is created smoothly and deterministically, in spite of the image one might have of a random process producing a photon spontaneously at an unpredictable time. At times much longer than the excited-state lifetime, the atom is in its ground state and the photon is described by a coherent wave packet traveling in space. As long as we don't observe or otherwise perturb it, the photon's state evolves deterministically according to the Schrodinger equation. This insight offers the potential to manipulate the states of photons in a coherent manner.

A goal of current research is to learn how to manipulate in a controlled way such coherent wave-packet states of single photons in all their degrees of freedom. Such manipulation can be used in quantum information systems (see Box 1). This topic brings together diverse fields of research: atomic physics, nonlinear optics, microwave physics, superconducting circuits, and opto-mechanics, all of which provide opportunities for coherently manipulating the states of single photons.

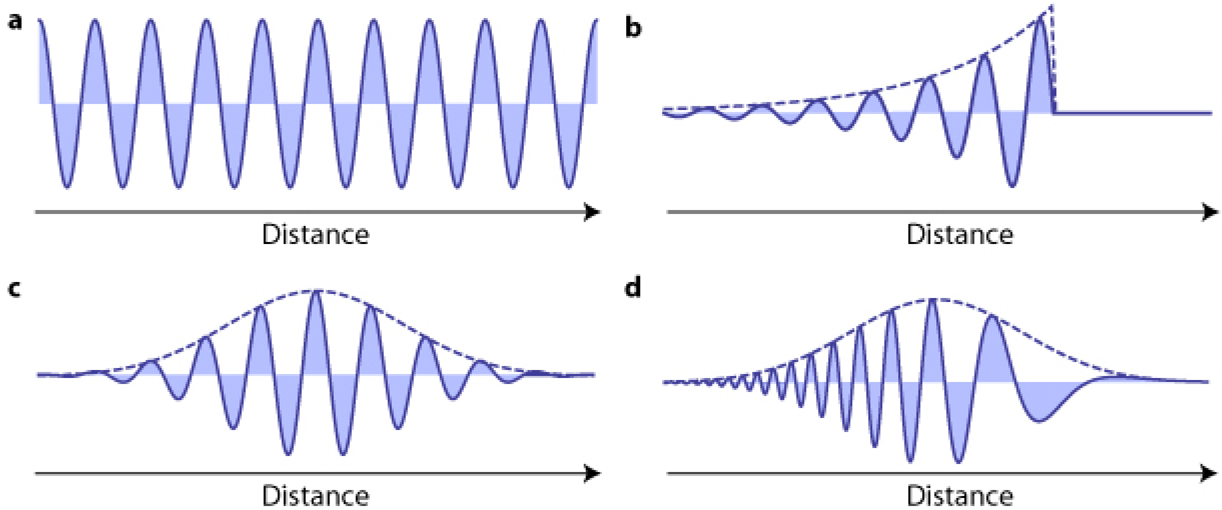


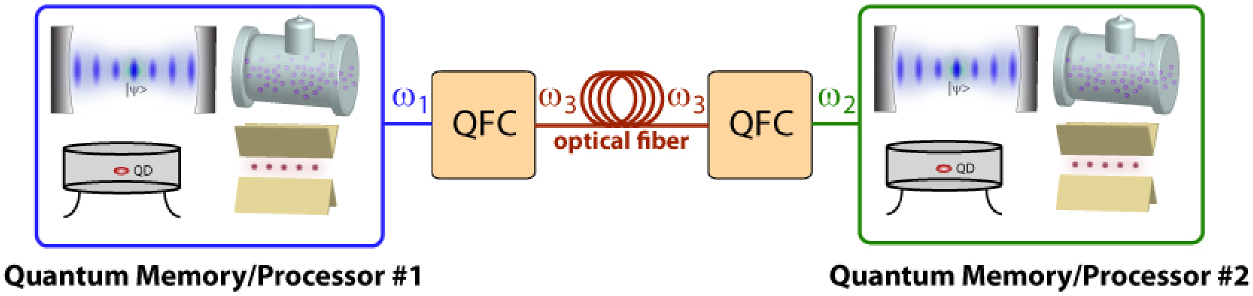
Figure 1 Examples of single-photon temporal shapes, with envelopes shown as dashed lines. **a** Monochromatic photon state, created by an ideal laser, **b** Decaying-exponential packet, created by spontaneous emission from an excited atom, **c** Gaussian packet, created by nonlinear optical processes, **d** ‘Chirped-frequency’ packet, resulting from dispersive propagation in optical fiber.

Box 1 – The Quantum Internet

The idea behind quantum information processing is to use quantum superposition states to transmit, store, and process information in ways not possible using only incoherent (either/or) mixtures of states, as described by classical physics. The classical bit, which can be either 0 or 1, is replaced by the qubit—a physical object that can be prepared in a coherent (phase-stable) superposition of states representing 0 and 1. This leads to computational and communication abilities not known to exist when using classical hardware.

Future quantum information processors and communication systems are unlikely to be composed of units based on only one type of atom, ion, semiconductor, or superconductor, etc. A *hybrid* network is expected to emerge, with different types of physical systems (atoms, ions, etc.) playing different roles. An internet consisting of computation nodes containing quantum memories comprised of atoms, ions, semiconductors, or superconductors will be interconnected by photons traveling in optical fibers or through free space. The physical systems in these nodes will act as quantum memories and processors in the Quantum Internet (or *Quantumnet*). To communicate quantum information, each will absorb and emit photons at its own natural resonance frequency with a particular spectral line width. (See text.) This diversity of frequencies and spectral shapes creates a challenge—how to convert single photons between different frequencies and alter their wave-packet shapes to optimally “fit” with different material systems? That is, since two types of memories are speaking a different "language", a translating device is needed to convert ("translate") photons between the two.

An example is shown in the figure, wherein quantum frequency conversion devices (QFC) connect a quantum memory or local quantum processor operating at photon frequency ω_1 to a memory or processor operating at frequency ω_2 through an optical fiber that optimally transmits light at frequency ω_3. The eventual goal is to spread quantum-state entanglement throughout a large network of memories.



--End of Box 1--

As a preview, we describe perhaps the simplest way to implement quantum frequency conversion, defined here as changing a single photon's frequency or color without changing in uncontrollable ways its other state properties. Our example is the Doppler shift. Assume that a single-photon wave packet is known to have been created and to be traveling in a known direction (how we do this is described below). To shift its center frequency, simply reflect it from a mirror moving uniformly with respect to a detector. If the mirror velocity v is small compared to the vacuum speed of light c, the frequency shift will be $f - 2(v/c) f \cos\theta$, where θ is the angle of incidence. While Doppler shifts by moving mirrors are limited to about 1 MHz in the visible spectrum, and fast electronic modulators can create shifts of tens of GHz, experiments using nonlinear optics have demonstrated frequency shifts of single photons of hundreds of THz shifts. These experiments are reviewed below in Section 3.

2. Quantum Frequency Conversion via Nonlinear Optics

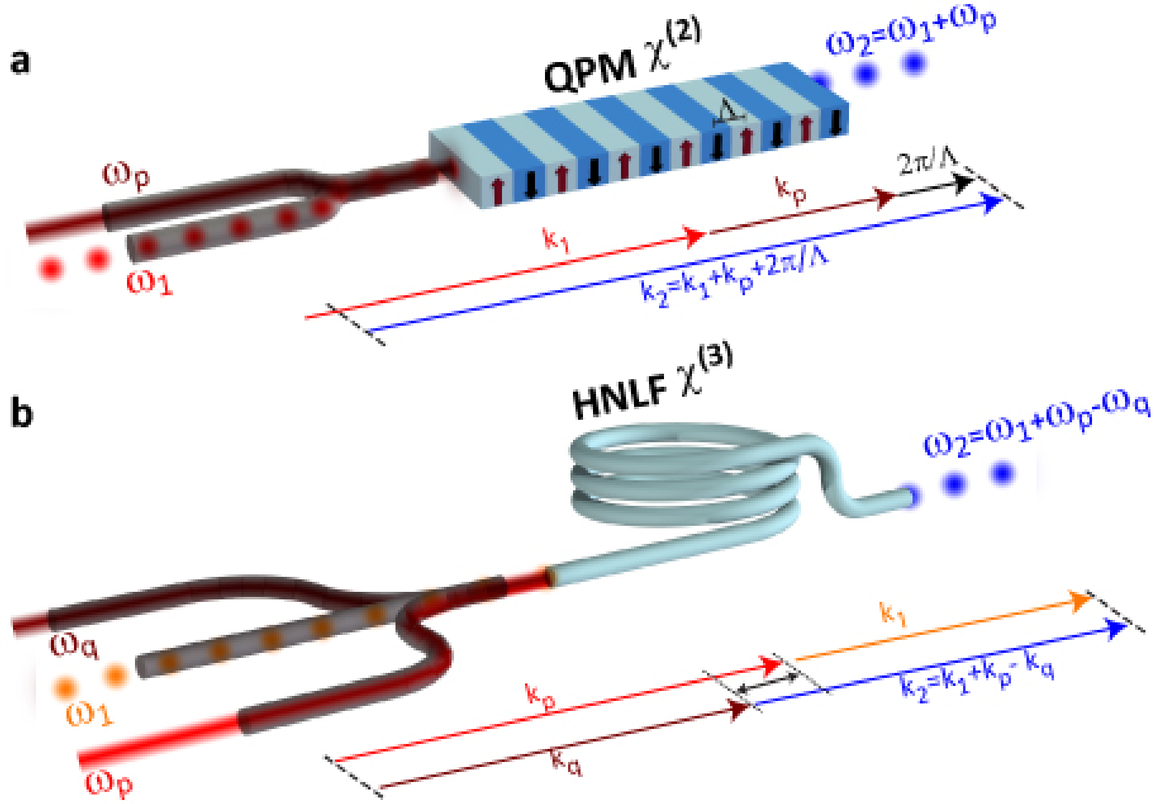
Most phenomena in nonlinear optics[2] are based on parametric oscillations, which occur in any oscillatory system if its parameters (usually taken as constants) are varied in time. For example, in a mechanical system, periodically varying the length of a pendulum at twice the pendulum's resonant frequency can pump energy into the resonant oscillation. Alternately, in electrical oscillators, varying the separation between the plates of a capacitor in an LC circuit at twice the circuit's resonant frequency can pump energy into it at the resonant frequency. In optics, the varied parameter is typically the medium's electronic susceptibility, which is the proportionality factor between the induced electric dipole and the driving field at a particular frequency. If this susceptibility is caused to oscillate through the influence of some other strong light fields at other frequencies, then energy can be redistributed between optical modes of various frequencies. In a given medium, the dominant effect (described using a perturbation theory expansion) is either the second-order susceptibility, called $\chi^{(2)}$, in the case of non-centro-symmetric media such as certain crystals like lithium niobate or gallium arsenide, or the third-order susceptibility, called $\chi^{(3)}$, in the case of centro-symmetric media such as glass or silicon. Both are useful for quantum frequency conversion.

Weak light of a given frequency ω_1 can be converted to a different frequency ω_2 using either the second-order or third-order nonlinear optical response of a transparent medium.[2] In the former case, a strong laser field (the "pump") modulates the medium's susceptibility at frequency ω_p, leading to light being generated at the sum and difference frequencies $\omega_2 = \omega_1 \pm \omega_p$. Frequency increases are called up-conversion while decreases are called down-conversion. To build up an appreciable amount of power in the frequency-converted beam, momentum conservation among the photons involved (termed phase-matching) is required, and can be controlled by the size and shape of the medium, along with its linear dispersion properties. (Recall that the momentum of a photon depends on the refractive index of the medium it is traveling in.) Remarkably, a single photon at ω_1 can be converted to ω_2 with efficiency approaching 100%, while not changing its other state properties in uncontrolled ways[3,4].

In the case of a third-order nonlinear optical response, two strong and mutually coherent fields (pumps *p* and *q*) modulate the medium's susceptibility at their difference frequency $\delta\omega = \omega_p - \omega_q$, leading to light at ω_1 being converted to the up- or down-shifted frequencies $\omega_2 = \omega_1 \pm \delta\omega$. This process, called four-wave-mixing Bragg scattering, allows smaller frequency shifts than in the second-order case, and thereby offers distinct capabilities for designing optical interconnections between nodes in a quantum network. Box 2 discusses the physical devices that are used to implement QFC.

Box 2 – Devices for Quantum Frequency Conversion

One of the important developments in the field of nonlinear optics over the past five decades has been in showing that frequency conversion processes can be very efficient, indeed approaching 100%. This represents an improvement of eight orders of magnitude over the efficiency demonstrated in the first experimental work in nonlinear optics - the second harmonic generation experiments of Peter Franken and co-workers. This vast improvement is the result of efforts to identify materials with large nonlinear optical coefficients, the use of strongly confining waveguides to increase optical intensities and enhance effective nonlinearities, and the application of new methods to achieve the requisite phase-matching.[5] Phase-matching, which amounts to momentum conservation for the photons involved, plays a crucial role in nonlinear optics. In vacuum, it is guaranteed because the photon frequency ω and wavevector *k* (which plays the role of momentum) are linearly related by the speed of light. In materials, however, phase-matching is not guaranteed because materials exhibit dispersion – light at different wavelengths propagates at different speeds. Examples of devices for frequency up-conversion based on second-order and third-order nonlinear optical materials are shown in parts **a** and **b** of the figure. The second-order material uses a strong pump laser at ω_p to convert input photon pulses at ω_1 to $\omega_2 = \omega_1 + \omega_p$. Because the material by itself would not satisfy phase-matching ($k_2 \neq k_1 + k_p$), this device employs "quasi-phase-matching" (QPM), where a periodic change in the nonlinear medium properties (with spatial periodicity Λ) compensates for the momentum mismatch between the three fields ($k_2 = k_1 + k_p + 2\pi/\Lambda$). The third-order medium is a highly nonlinear optical fiber (HNLF). Phase-matching is achieved by compensating for the material's natural dispersion by "waveguide dispersion." Waveguide dispersion occurs because the exact distribution of the optical field within a waveguide (which consists of a central core region and a surrounding cladding region, each having different material properties) depends on wavelength. Furthermore, HNLF confines light to very small cross-sectional areas, which along with new material composition, enables an increase in the effective nonlinearity relative to standard silica fiber. In the figure, input photon pulses at ω_1 are combined with strong pump lasers at ω_p and ω_q to generate up-converted photon pulses at $\omega_2 = \omega_1 + \omega_p - \omega_q$.



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3. Demonstrations of Quantum Frequency Conversion

The quantum description of parametric nonlinear processes was developed by William Louisell, Amnon Yariv, and Anthony Siegman and by Nicolaas Bloembergen and Ron Shen and colleagues in the 1960s[6]. This theory implied that QFC should be possible. Nevertheless, its specific description as a useful resource wasn't realized until Prem Kumar pointed it out in 1990, and defined QFC as a process by which "it is possible to change the frequency of an input light beam while maintaining its quantum state."[3,7] Here the quantum state of a light beam refers to a particular superposition of occupation numbers for each electromagnetic mode within some narrow range of frequencies and propagation directions. QFC is defined as a process that changes the center frequency of the beam's spectrum, while leaving the quantum state of the other variables unchanged.

Kumar's work focused on second-order nonlinear processes for achieving QFC, and for many years afterwards, QFC was almost exclusively discussed within this context. However, in 2005, Colin McKinstrie and colleagues theoretically showed that the third-order nonlinear process described in Section 2–four-wave-mixing Bragg scattering–is also suitable for QFC[5], thus opening up this application to a whole other class of materials (notably glass optical fiber and silicon photonic devices).

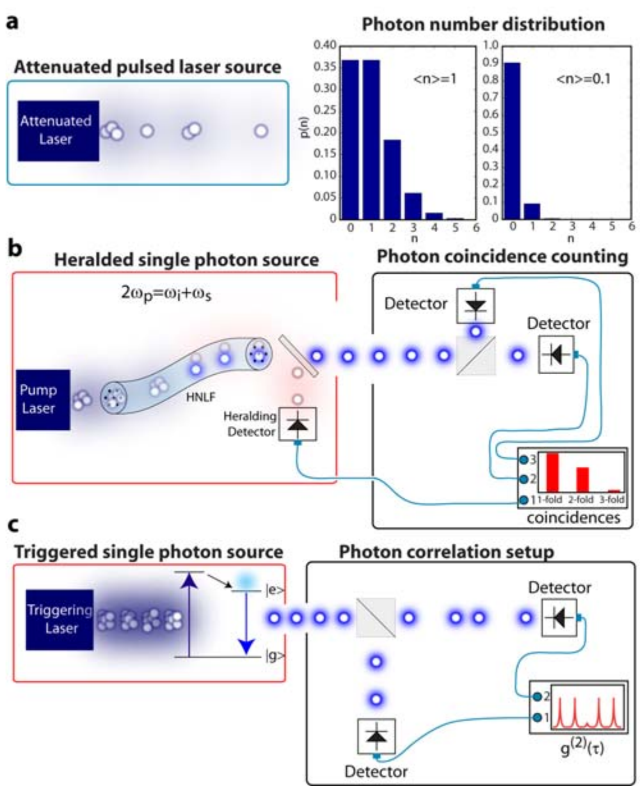
One early envisioned application of QFC was in developing a tunable source of 'squeezed' light. Squeezing in quantum optics is a phenomenon in which the fluctuations in some observable quantity (such as the electric field's amplitude) are reduced to a level below that allowed in a classical theory of optical fields, albeit at the expense of increased fluctuations in a complementary observable (in this case, the electric field's phase). Squeezed states of light have found applications in interferometry, where the noise reduction in one observable can lead to improvements in precision measurements, such as those needed in the Laser Interferometer Gravitational Wave Observatory (LIGO). QFC could allow one to generate squeezed light in a system optimized for squeezing, and then convert the wavelength to that which is most suitable for the interferometer. Kumar and colleagues demonstrated QFC for a two-mode squeezed state of light, which exhibits highly correlated intensity fluctuations in two optical beams, so that their intensity difference yields a noise level below that expected classically. They showed that these non-classical photon-number correlations were preserved when one of the twin beams was converted to a new frequency, in this case via the second-order frequency up-conversion process.[7]

Another reason one might desire to change the wavelength of a quantum state of light is to improve the ability to detect it, by moving from a wavelength for which existing detectors have low performance (in terms of detection efficiency, speed, or noise) to one for which better options exist. This was recognized in the 1960s by several groups seeking to exploit frequency up-conversion to enable the detection of infrared light from sources like CO_2 lasers or astronomical objects by using conventional photomultipliers. More recently, several groups have considered frequency conversion as a means to perform efficient detection of photons in the telecommunication windows around 1.55 μm and 1.3 μm (where loss and dispersion are minimized in optical fibers) using visible wavelength detectors[8]. Researchers have demonstrated quantum key distribution (a communications protocol whose security is guaranteed by the laws of quantum mechanics) that used QFC to enable improved single photon detection in the telecommunications band[9].

Driven in part by potential applications in quantum information technology (Box 1), researchers have developed an ever-increasing set of approaches for generating various quantum states of light, some of which have been used in experimental demonstrations of QFC. For example, in many quantum information protocols, entanglement is a central resource. Entanglement means that the state of two separated systems is nonseparable (not expressible as a product), and may involve any of the various degrees of freedom for photons described in Section 1. In 2005, Sebastien Tanzilli and co-workers performed QFC on one member of a pair of entangled photons, where they showed that a form of entanglement (called time-bin entanglement) is preserved even after one photon of the pair is up-converted from the telecommunications band to the visible[10]. A recent similar experiment demonstrated the opposite process, that is, that entanglement is preserved when one photon of the pair is down-converted from the visible to the telecommunications band[11].

Recently, the QFC of single-photon states has been demonstrated in a number of experiments. Such states (Box 3) have been generated by a variety of mechanisms in different physical systems, and as a result their wavelengths and temporal shapes and widths can be dramatically different. To confirm the production of single-photon states, researchers perform a Hanbury-Brown and Twiss (photon-number correlation) measurement, which was first applied to stellar interferometry in the 1950s. As schematically depicted in part **c** of the figure in Box 3, incoming light is split equally into two paths, and each path is incident on a single-photon counter, which provides a record of the arrival times of the incident photons. A histogram of the difference in arrival times between the two paths is generated. If there are truly single photons entering the beam splitter, at most one of the detectors will observe a photon at any given time. As a result, the histogram should show an absence of coincidences at zero time delay between the two paths, an effect called photon antibunching—first demonstrated by H. Jeff Kimble, Mario Dagenais, and Leonard Mandel in the 1970s[12]. Such measurements of photon statistics are often done to characterize quantum light sources. Photon pairs, for example, are sources in which two photons are generated at the same instant, so that in a Hanbury-Brown and Twiss measurement, there are a much greater number of coincidences at zero time delay than at other delays. Light from a laser, on the other hand, shows an equal number of coincidences across all time delays. Coincidence counting thus allows researchers to distinguish between different quantum states of light which might all have the same average power level when measured with a standard optical detector.

Box 3 – Sources of Single Photons



A simple approach to generating single-photon states is to strongly attenuate a pulse of laser light. This source has a fundamental limitation, however, as the output of a laser exhibits a Poissonian distribution in photon number. For an average photon number of 1, there is a strong probability of having two or three photons (part **a** of the figure), so that much weaker pulses (average photon number of 0.1) are needed to limit the multi-photon probability. While the multi-photon probability is indeed limited for weaker pulses, the single-photon probability is also small, so that most pulses contain no photons.

Nonlinear optics provides an improved approach to generating single photons. Certain types of materials, such as highly nonlinear fiber, allow for the process of photon pair generation (part **b** of the figure), where two pump photons at frequency ω_p are converted to pairs of simultaneously emitted photons at frequencies ω_i and ω_s. Generation of photon pairs is probabilistic, however, so the exact timing of when the pairs are generated is unknown. However, because the photons are produced in pairs, spectrally separating the pair and detecting one of the two, called heralding, provides assurance that its partner photon is present. Heralding does not remove the probabilistic nature of these kinds of sources, but does allow them to be used in a variety of quantum information processing applications. In the photon coincidence counting setup shown in the figure, perfect heralded single photon emission implies a complete lack of 3-fold coincidences (simultaneous clicks on all three detectors).

A third approach to single-photon generation involves the use of single quantum emitters, which are materials in which a single optical transition can be isolated. Such systems include single atoms, ions, quantum dots, and molecules. Laser pulses are used to prepare the system in its excited state, and when the system relaxes to its ground state, a photon is emitted. Sources based on such systems are called on-demand or triggered single photon sources because in principle, a single photon should be produced with each excitation pulse (part **c** of the figure).

While the above represent the most common types of single photon sources, novel mechanisms for enabling single photon generation continue to be explored.[cite S&D]

-- end of Box 3 --

Recent QFC experiments have focused on demonstrating that the single-photon character of these quantum states is preserved after frequency conversion, as confirmed by photon antibunching measurements. Like for the other experiments we have described, QFC of single-photon states is theoretically expected. Nevertheless, the existence of practical, high-fidelity single-photon QFC is a remarkable fact, given that the average power of the pump fields used can be fifteen orders of magnitude larger than that of the single-photon states – one might worry that some experimental non-ideality would ruin the single-photon character of the frequency converted light. Indeed, the devices used for QFC (Box 2) can support a variety of unwanted background processes, typically associated with the strong pump field(s), that generate noise photons which get frequency converted along with the desired quantum state. These include processes like spontaneous Raman scattering and parametric fluorescence. Much work is thus focused on developing methods to eliminate such noise sources, through narrow-band spectral filtering (to reject out-of-band noise photons) and by modifying the pumping schemes and device conditions to limit the generation of noise. Rejection of noise while maintaining high overall efficiency in the QFC setup is an important goal; experimentally, efficiency values greater than 50% have been achieved.

Using such high-efficiency, low-noise frequency conversion, Matthew Rakher and coworkers up-converted single-photon states in the telecommunications band to the visible[13]. Down-conversion from the visible to the telecommunications band has also been shown by R. Ikuta and colleagues[11]. Hayden McGuinness and coworkers demonstrated single-photon QFC using four-wave-mixing in fibers[14] (Box 2), enabling small or large frequency shifts to be achieved while maintaining the single-photon number statistics. The experimental demonstrations have encompassed a wide range of physical systems, including single photons produced by the radiative decay of a single quantum dot[13] or "heralding" of a photon pair source produced by nonlinear down-conversion in crystals or in photonic crystal fibers[11,14] (Box 3). Another recent experiment used an atomic ensemble to demonstrate a quantum memory interfaced with telecommunications light[15]. Here, the atomic system supports both near-infrared and telecommunications-band optical transitions, so that both frequency up-conversion and down-conversion can be performed. As a result, an elementary link with QFC interfaces, similar to that shown schematically in Box 1, was demonstrated. An excitation written into the atom-based memory was mapped to a 780 nm wavelength photon, which was then down-converted to the 1300 nm telecommunications band in an atomic QFC medium. The photon then traveled over 100 m of optical fiber before being up-converted back to 780 nm through the same atomic QFC medium, after which it was mapped back into the quantum memory.

Finally, there is strong interest in not just performing QFC over visible and near-infrared wavelengths, but in fact covering even more widely separated portions of the EM spectrum, namely, between the microwave region and the optical region. Recently, there have been many impressive quantum information processing elements demonstrated in the microwave region using, for example, systems like superconducting qubits coupled to coplanar waveguide resonators and nanomechanical oscillators[16]. While microwaves are suitable for quantum information transfer within a single computer chip (particularly when superconducting transmission lines are used), it is likely that transfer over larger distances will require conversion to optical wavelengths, where optical fibers offer low-loss transmission. Researchers are considering a number of approaches to achieve microwave-to-optical conversion. This includes conventional nonlinear materials, atomic and molecular systems supporting both microwave and optical transitions, and optomechanical systems. In the latter, microwave and optical cavities are coupled to a common mechanical oscillator that acts as an intermediary, enabling conversion even though the microwave and optical fields never directly interact.

4. Beyond Quantum Frequency Conversion: Temporal-Spectral Control of Photon Wave-Packets

In addition to its central frequency, a photon wave-packet state is characterized by its temporal shape, examples of which were shown in Figure 1. When a photon undergoes frequency conversion, its shape may be altered as a result of changes in its spectral content and phase structure. This reshaping can be controlled and put to good use. For example, a medium (atom, ion, quantum dot) comprising a quantum memory typically emits a photon wave packet with a negative-exponential decaying temporal tail, as in Figure 1b. For propagation in a fiber or for “writing” into a different memory, one may need to convert this shape into a gaussian packet or an exponential packet with a decay (or growth) constant that is different from the original one.

Single photon pulse reshaping can be accomplished in various ways. While there are several methods, such as coherent control of a single atom’s emission process and classical pulse shaping through dispersive optics and control of spectral amplitude and phase, which do not employ frequency conversion, here we focus on those techniques which do. Referring to Figure 1, say that Memory #1 emits photon wave packets with “long,” 1.5 ns duration, while Memory #2 will efficiently absorb a photon only if its duration is 350 ps. One way to convert a longer-duration wave packet into a shorter one, while also converting its frequency, is to pump an up-conversion process with a strong laser pulse that has a shorter duration which is equal to the desired photon duration. Figure 2a illustrates this process, which was demonstrated recently[17]. Single photons emitted at wavelength 1300 nm by a particular semiconductor quantum dot have an exponentially decaying temporal profile with a time constant 1.5 ns. They are converted to wavelength 710 nm by up-conversion driven by a pump laser with a gaussian temporal profile with duration 350 ps. If all three pulses travel with the same group velocity, then the up-conversion process simply “slices out” a short segment of the original photon wave packet and up-converts it to the new frequency, while leaving behind the rest of the original packet. Because photons are indivisible under such linear transformations of their wave-packet states, both components—the original frequency one and the up-converted one—persist as parts of a quantum superposition state. But if the frequency of the photon is (irreversibly) measured then only one component survives. The fact that the up-converted portion of the packet is sliced from the original packet means that the overall efficiency of the up-conversion process can never exceed the ratio of the durations of the final and initial packets.

In some cases one needs to perform frequency conversion of single photons with efficiencies approaching 100%, while strongly altering the duration and shape of their wave packets. Experimental studies in this direction are in their infancy, but already several promising theoretical proposals have been developed. A key ingredient in achieving efficient shaping of single-photon waveforms is the ability to tailor the dispersion of the frequency conversion device, to enable the signal photons to travel through the optical medium at different speeds. Christine Silberhorn’s group proposed that this can be done in up-conversion by three-wave mixing using specially designed nonlinear-optical crystal wavegudies having tailored dispersion so that one of the single-photon packets travels at the same speed as the pump pulse but at a different speed from the other photon packet[18]. As shown in Figure 2b, if a short pump pulse is initially behind a longer initial photon wave packet, then catches up to and passes through the photon wave packet, the up-conversion process can “sweep out” all of the initial photon amplitude and efficiently compress it into a shorter frequency-converted packet. Conversely, if the initial photon packet is initially behind a longer pump pulse, then catches up to and passes through the pump pulse, the up-converted packet can be stretched. (This latter case is not shown in the figure.)

Single-photon packet compression or stretching can also be accomplished using four-wave mixing in a fiber (see Figure 2c), which has some advantages as predicted by McKinstrie et al[19]. In this case the strategy is to match the initial photon wave packet shape to that of one of the pump pulses (*p* or *q* in the figure), depending on whether up- or down-conversion is implemented (which depends on the dispersion properties of the fiber). The dispersion is tailored so that the initial photon wave packet travels with the same group velocity as this pump pulse. The dispersion is also chosen so that the frequency-converted photon travels with the same group velocity as the other pump pulse, which may have a different shape from the first pump pulse. Then the frequency-converted photon takes on roughly the temporal shape of the other pump pulse (*q* or *p*).

A fourth type of photon reshaping scheme during frequency conversion, proposed by David Kielpinski and colleagues, is shown in Fig. 2d in the case of three-wave mixing[20]. If the pump pulse is tailored in spectrum and temporal phase, then those characteristics will be transferred to the converted photon. In the example shown, the pump has a time-varying frequency and the original signal photon is a negative exponential of a certain frequency. Upon up-conversion, the new signal photon has a temporally varying frequency, which allows pulse compression and shaping by using a dispersive delay line (typically made with diffraction gratings).

Such schemes allow for complex operations, such as converting a photon packet from one temporal shape to another that is mathematically orthogonal with the original shape but still overlapping in time. Using such a scheme, it can be envisioned to use the temporal shapes of single-photon packets to define a qubit—a quantum object that can be in one of two orthogonal states.

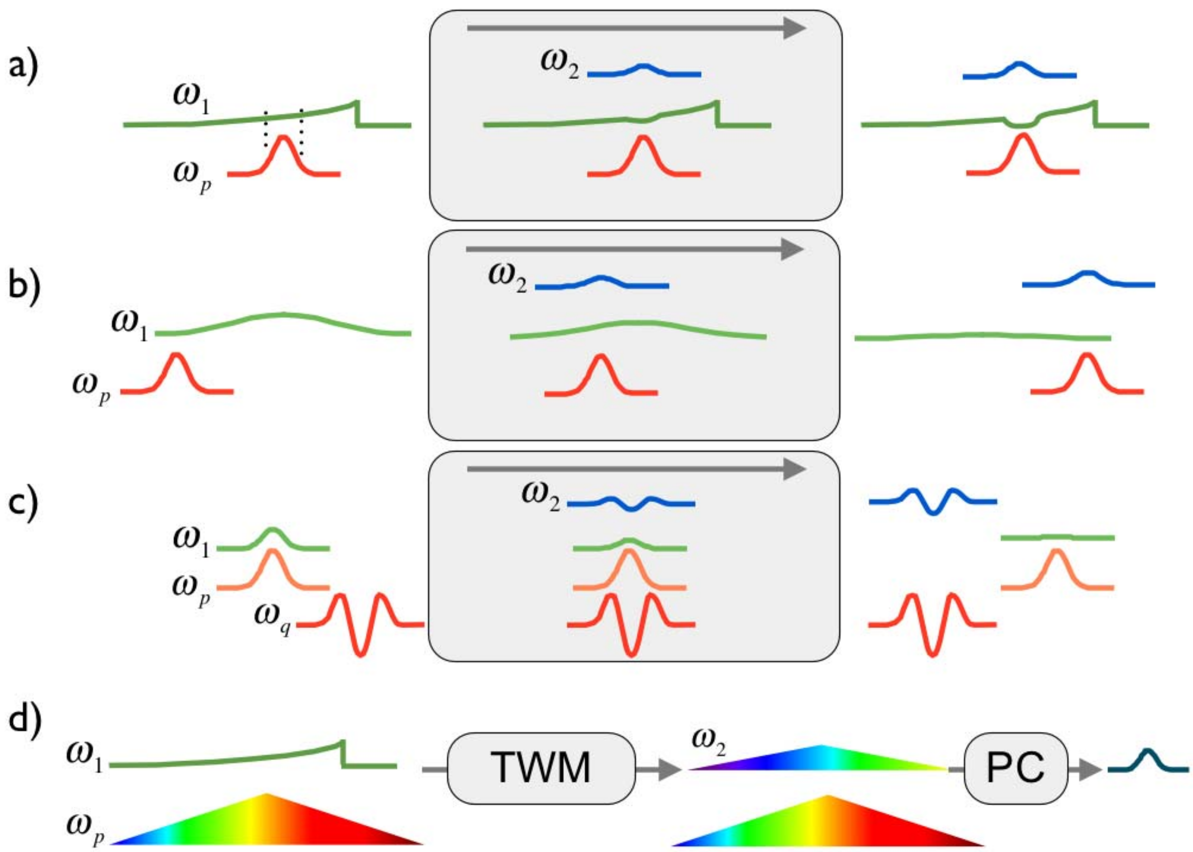


Figure 2 Reshaping of single-photon wave packets can occur during frequency conversion. The packet envelopes, rather than the rapidly oscillating fields, are shown here. a) The photon (green) is up-converted by three-wave mixing (TWM) in a nonlinear optical medium. The pump pulse (red) is shorter than the photon wave packet, so the photon is converted, with some probability, to a new frequency (blue) and a shorter duration[17]. b) If the photon (green) travels more slowly than the pump pulse (red), then the pump pulse "sweeps out" the longer photon wave packet and creates a shorter-duration frequency-converted (blue) photon[18]. c) If four-wave mixing (FWM) is used, with one pump pulse (orange, *p*) traveling with the same speed as the initial photon packet, and the other pump (red, *q*) traveling more slowly, then the converted photon (blue) has a shape that mimics that of the slower pump pulse[19]. d) The pump pulse has a time-varying frequency (shown as color) and the original signal photon is a negative exponential of a certain frequency (shown green). After up-conversion, the new signal photon can be compressed and shaped by a pulse compressor (PC) comprised of a dispersive delay line[20].

5. Photon Color and Shape as a Quantum Information Resource

Researchers in the field of quantum information are currently excited about learning how to manipulate the frequencies and temporal shapes of single-photon wave packets, because this will play a critical role in hybrid quantum information networks. Single-photon manipulation by quantum frequency conversion allows matching photons—both spectrally and temporally—into quantum memories, communication channels, and detectors. Quantum entanglement is the essential physical resource for enabling quantum information systems to outperform classical ones. Therefore researchers must also learn how to control entanglement of quantum states involving material and photonic qubits across wide ranges of the spectrum.

Challenges remain in doing this with high efficiency, fidelity, and low background noise. For QFC by second-order nonlinear-optical processes, crystals and devices with tailorable dispersion properties are needed in order to efficiently convert a photon's frequency while altering its duration and shape to the desired form. For QFC by third-order processes, optical fibers with better controlled longitudinal uniformity are needed in order to ensure optimal control over the QFC process. In addition, future quantum information processing networks will likely be composed of large numbers of nodes, so that in principle, a large number of QFC interfaces may be needed, potentially consuming significant resources. The development of technology to translate QFC to microchip-scale devices in materials for which scalable fabrication methods exists is an active area of research.

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