Quantum frequency conversion using integrated nanophotonics

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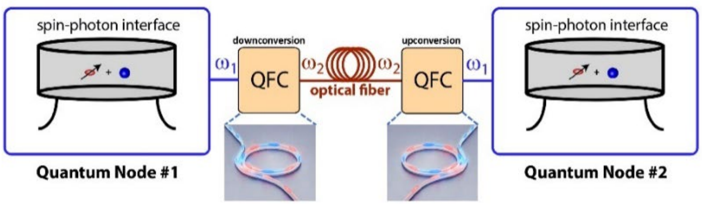
Status

Quantum frequency conversion (QFC) generally refers to the spectral translation of a quantum state of light, such as a single-photon state, between frequency bands. Its role in quantum information science and technology is well-defined in the context of quantum networks (Fig. 1), where it can enable telecom-wavelength fiber optic links between visible wavelength local quantum systems (e.g., quantum memories). More generally, QFC is needed to make interconnections between quantum systems operating at different wavelengths, for example, to connect a trapped ion quantum processor to a neutral atom ensemble quantum memory. QFC may also have relevance in being able to convert photons to wavelengths for which single-photon detectors have the highest performance, though ever-improving superconducting single-photon detector technology has now made efficient and low-noise detection from the ultraviolet to the near-infrared possible.

The two main requirements for QFC are high conversion efficiency, so that a large fraction of the input photon flux is frequency converted to the target output frequency, and low added noise, so that the output frequency channel is dominantly composed of light originating from the input source (rather than spurious photons). In the 30+ years since QFC was first discussed explicitly in the literature [1], efficient and low-noise QFC demonstrations have been powered by advances in nonlinear optical technology, in particular based on sum- and difference- frequency generation in quasi-phase-matched nonlinear crystals [2] and four-wave mixing in optical fibers [3], though multi-level atomic systems can also be used to mediate QFC, as has been demonstrated with cold atomic gases [4], for example. QFC with true single-photon sources has by now been demonstrated many times [5], and in recent years has been used to connect disparate systems such as a cold atomic gas (at 780 nm) and a solid-state crystal (at 606 nm) [6] and to enable entanglement of Rb quantum memories (at 780 nm) across a >20 km fiber optic link [7].

For many such experiments requiring discrete QFC elements, a blueprint for operation has been established. The dispersion of a material creates a phase-mismatch between the fields involved in a nonlinear process and without compensation, limits the maximum achievable conversion efficiency. Materials such as lithium niobate combine the ability to realize quasi-phase-matching by periodic poling [2] – a particularly effective approach for overcoming dispersion – with a strong nonlinear coefficient and broadband optical transparency, resulting in near-unity internal conversion efficiency being shown in some cases. Waveguide geometries provide a few centimeter interaction length while retaining bandwidths that are sufficiently wide for a broad range of quantum sources and memories. Low-noise operation typically involves having wide spectral separation between the pump source that mediates frequency conversion (whose power can easily be $>10^{13}$ that of the input quantum light source) and the input signal frequency and target output frequency. Together with appropriate spectral filtering, this limits the extent to which broadband processes (e.g., Raman scattering,



3 dB attenuation distance in SMF	
370 nm (Yb^+ ion):	<50 m
637 nm (NV^-):	300 m
780 nm (Rb):	750 m
940 nm (QD):	1.5 km
1300 nm (O-band):	10 km
1550 nm (C-band):	15 km

Figure 1. Potential use for quantum frequency conversion (QFC) in a quantum network consisting of nodes based on spins that are optically addressable at a visible frequency ω_1. QFC to and from a telecom frequency ω_2 can help mediate photonic connections between spins over a fiber optic network. Here, a nanophotonic QFC interface such as that from Ref. [11] is depicted. The table shows typical 3 dB attenuation lengths for single mode optical fiber (SMF) at different wavelengths, highlighting the benefits of telecom-band operation.

parametric fluorescence, and defect-mediated fluorescence) can produce noise that overlaps with the input and output frequency channels, particularly when a long wavelength pump can be selected [8].

Current and Future Challenges

Although existing QFC technology is thus already being used to help construct elementary quantum networks, there are many areas in which further development is needed. QFC across large spectral gaps – for example, from the visible (or ultraviolet) to the telecom remains a challenge, as the frequency separation of >300 THz ensures that in a single three-wave mixing process, the pump will need to be placed between the input and output frequency channels, making simultaneous high conversion efficiency and low added noise difficult to achieve. Wider frequency separations also tend to make poling (and other phase-matching techniques) more difficult. A challenge specific to heterogeneous quantum networks is the need to not only match photon frequencies, but also bandwidths (more generally, temporal profiles) to ensure optimal storage of a frequency-converted photon in a quantum memory, for example. Nonlinear optics provides some mechanisms by which such temporal shaping can be realized [9], though this issue can also be addressed by other quantum network components (e.g., in the quantum light generation or quantum memory stages).

One significant challenge is in making QFC systems extensively deployable. Along with the nonlinear medium and pump laser(s), QFC typically requires optical fiber coupling, wavelength (de)multiplexers, and narrowband optical filters to create a full setup (these components also reduce the overall conversion efficiency from near-unity to ≈ 50 %). This combination of lasers with linear and nonlinear optics is accessible in table-top setups, but the size, weight, and power requirements of such systems are not ideal for deployment in all environments. Integrated photonics provides a compelling route to combine such functions and create full QFC systems in a deployable and scalable platform.

Advances in Science and Technology to Meet Challenges

Integrated photonics is being developed in a wide range of materials of relevance to quantum photonics [10]. This section identifies several important aspects of this technology as it pertains to QFC.

Materials for QFC — Although the maturity of silicon nanophotonics provides strong motivation for its adoption when possible, applications often require functionalities such as gain, broadband optical transparency, and fast, low-loss switching, that are not easy to achieve in silicon. This has motivated research on platforms that have more suitable properties but are still amenable to similar nanofabrication processes. For nonlinear optics, lithium niobate remains a preferred choice for second-order processes, and its availability in thin film form offers new opportunities for dispersion control, power reduction, and integration. Aluminium nitride is another wide-bandgap, second-order nonlinear material available in thin-film form. For third-order nonlinear processes, silicon nitride and tantalum pentoxide offer broadband optical transparency and a nonlinear coefficient that is more than an order of magnitude larger than silica optical fibers, which have been the dominant four-wave mixing platform for decades and have been used in QFC experiments based on the four-wave mixing Bragg scattering process [11]. With an appropriate choice of material composition, III-V materials from the InGaP and AlGaAs families can provide both sufficiently broad optical transparency and a very large optical nonlinearity (both second-order and third-order), while diamond may be a natural choice for third-order QFC applications that involve its color center quantum emitters and/or spins. To that end, we also note that QFC approaches involving multi-level single quantum emitters coupled to nanophotonic elements have also been proposed [12].

Control of nonlinear processes — Nanophotonic geometries provide stronger optical confinement than conventional geometries such as optical fibers or silica planar lightwave circuits. One consequence of this confinement is its impact on dispersion, as the fraction of the field that resides within the waveguide core strongly depends on wavelength and core geometry. As a result, intrinsic material dispersion can often be compensated by precise tailoring of a nanophotonic geometry [13], thereby providing phase-matching that has enabled QFC configurations not easily accessible otherwise. For example, four-wave mixing QFC between 980 nm and 1550 nm (on-chip efficiency ≈ 60 %) was recently shown in silicon nitride microrings [14] and constituted a wider spectral gap than previous demonstrations in optical fibers; efficient and low-noise visible-to-telecom QFC has also been proposed using similar devices [15]. Geometric dispersion engineering can also be combined with quasi-phase-matching [16]. Moreover, nanophotonics can provide access to other frequency shifting mechanisms, for example based on acousto-optics, that can be used in some scenarios [17].

Low power QFC — A typical pump power for efficient QFC in conventional quasi-phase-matched waveguides is about 100 mW, while in optical fibers, Watt-level powers are often needed. Nanophotonic geometries can reduce such powers, particularly when microresonator geometries are employed, due to the combined effect of confinement and long photon lifetimes. The aforementioned silicon nitride microring QFC [14] achieved high efficiency at the ≈ 10 mW power level, and reduction to the 1 mW level should be possible through improved cavity performance (higher quality factors) or a more nonlinear material (e.g., a wide-bandgap III-V system). Such powers can easily be accessed by chip-integrated lasers; alternately, it would also allow a single off-chip pump laser to service multiple QFC elements. While a resonant cavity limits the photon conversion bandwidth, the $\approx$1 GHz bandwidth typical of high quality factor integrated microcavities is adequate for most high-performance quantum emitters, including InAs/GaAs quantum dots (as used in nanophotonic QFC in [18]).

Understanding and mitigating noise — One important task for nanophotonic QFC platforms is an understanding of added noise sources. While it can be expected that the main noise categories will include Raman scattering, spontaneous parametric processes, and fluorescence, each must be understood and characterized in the context of the material platform and geometry under investigation. Moreover, although a nanophotonic geometry can provide enhancement of the target QFC process, it may also enhance unwanted noise processes. Moving beyond creation of spurious photons, thermorefractive noise may limit the frequency stability of converted photons, which can be of importance when working with narrow linewidth sources.

Integration: One of the most compelling reasons for pursuing nanophotonic QFC is the potential for seamless integration with other photonics technologies, which can simplify the deployment of full QFC systems in applications. Along with combining the QFC element(s) with linear components such as filters and couplers, integration with pump lasers and other quantum photonic elements, such as single-photon sources and solid-state spins, is feasible, particularly in the context of hybrid photonic platforms that combine the advantageous characteristics of dissimilar materials [19]. Figure 2 gives two examples of nanophotonic QFC systems that can be envisioned based on current technology.

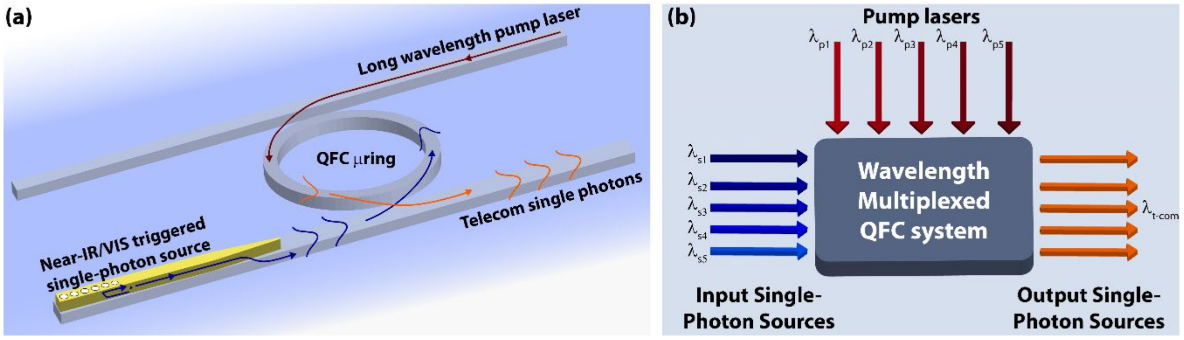


Figure 2. Representative opportunities enabled by integrated nanophotonic QFC systems. (a) Heterogeneous integration of a triggered single-photon source (bottom left, in yellow) with a telecom QFC interface. Single photons (for example, generated by an InAs quantum dot in a GaAs waveguide) are efficiently transferred into the QFC device layer (gray), where they are combined with a long wavelength pump laser (dark red arrow) to generate telecom-band single photons (orange). (b) Wavelength-multiplexed QFC system in which input single-photon sources at different wavelengths (λ_{s1},..,λ_{s5}) are combined with appropriate pump lasers (λ_{p1},...,λ_{p5}) to yield identical output telecom single-photon sources at wavelength $\lambda_{t\text{-com}}$. The QFC system could consist of many separate devices, each tailored for a specific $\lambda_s/\lambda_p/\lambda_{t\text{-com}}$ configuration, or a single device that can operate on a broad range of input wavelengths and has been engineered to inhibit competitive multi-pump processes. Such a device could enable other operations as well, for example, translating the input single photons to distinct output wavelengths using a single pump. Advances in heterogeneous integration, for example through transfer printing and pick-and-place approaches, suggest that both the single-photon sources and pump lasers (as well as auxiliary components not shown, such as filters and couplers) can be integrated with the QFC device(s) into a single photonic platform.

Concluding Remarks

Quantum frequency conversion (QFC) is an important physical resource for enabling photonic interconnects in quantum networks. While existing QFC devices based on conventional nonlinear waveguide geometries are already being used to build early-stage quantum networks, integrated nanophotonic platforms can play an important role in future construction of more complex and functional networks. They offer clear advantages with respect to control of nonlinear processes, size, weight, and power consumption, integration with pump lasers and other photonic components, and scalability of the underlying manufacturing processes. While much work remains to be done in understanding noise generation in these platforms, they offer the potential to make QFC a truly plug-and-play component for quantum information applications.

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