Invited Paper

Domain-engineered PPLN for entangled photon generation and other quantum information applications

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ABSTRACT

We describe the design and application of domain-engineered, periodically poled lithium niobate (PPLN) for use to produce entangled photons and for other tools in quantum information and communications. By specially designing and controlling the PPLN poling pattern, multiple nonlinear optical processes can be simultaneously phasematched. This capability can be used to generate polarization-entangled photon pairs through type-II spontaneous parametric downconversion. The single PPLN crystal is designed to produce both the $|HV\rangle$ and $|VH\rangle$ states where the downconverted photons are distinguishable by wavelengths, which enables generation of post-selection-free, polarization-entangled twin photons. We describe the design and fabrication of the PPLN crystal, and initial experimental results for downconversion of a 775 nm pump to 1532 nm and 1567 nm orthogonally polarized photons. We also discuss other applications of engineered optical frequency conversion for quantum information including the use of dual-wavelength upconversion as a beamsplitter to route or analyze photons.

Keywords: quantum optics; nonlinear optics, parametric processes; polarization entangled pair source; spontaneous parametric downconversion; entanglement

1. INTRODUCTION

Optical frequency conversion is an important tool for quantum information technologies. It can be used to interface between quantum systems that operate at different wavelengths[1-4], to shape photons to improve indistinguishability[5,6], and to produce a source of entangled photons[7,8]. Frequency conversion has been performed in a number of nonlinear optical materials, but here we focus on periodically poled $LiNbO_3$ (PPLN). Some advantages of PPLN include its large d_{33} nonlinear coefficient, its wide availability and mature processing technologies, and the engineering opportunities provided by the periodic poling and quasi-phasematching[9]. For high-efficiency sum- and difference-frequency generation used for quantum frequency conversion[1], PPLN waveguides are the devices of choice due to their high internal conversion efficiencies achieved with relatively low pump powers[10]. Of particular interest is the ability of PPLN to provide engineered optical frequency conversion, for instance, allowing multiple wavelengths to be efficiently converted simultaneously[11].

Entangled photon pairs are needed in quantum communications and quantum information systems for distributing entangled states to connect different quantum subsystems. Photons are attractive for distributing entanglement since they can be easily generated, have long lifetimes and can be sent over very long distances. Photons generated near the 1550-nm telecom wavelength are particularly attractive for long-distance entanglement distribution over existing fiber links[12], which is important for the realization of practical quantum information networks. In this paper, we describe engineered optical frequency conversion in PPLN and its applications for entangled-photon generation and for other tools in quantum information systems.

2. BACKGROUND AND THEORY

2.1 Engineering optical frequency conversion

In a nonlinear optical process, the conversion efficiency depends on the phase-mismatch. Consider a three-frequency process involving pump (ω_p), signal (ω_s) and idler (ω_i) where

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$$\omega_p = \omega_s + \omega_i \tag{1}$$

with phase-mismatch, Δk,

$$\Delta k = k_p - k_s - k_i \,. \tag{2}$$

k_a is the wave vector for frequency ω_a. In general, dispersion in the material makes it difficult to satisfy $\Delta k = 0$ and obtain efficient nonlinear optical frequency conversion. By applying quasi-phasematching (QPM)[9] and introducing periodic domain inversions, the phase-mismatch can be compensated and efficient conversion can be achieved when

$$\Delta k = k_p - k_s - k_i \pm \frac{2\pi}{\Lambda_{QPM}} = 0\,, \tag{3}$$

where Λ_{QPM} is the period of the domain inversion pattern. The spectrum of the conversion is proportional to $\mathrm{sinc}^2(\Delta kL/2)$ where $\mathrm{sinc}(x) = \sin(x)/x$ and L is the grating length, which is maximized when $\Delta k = 0$.

Advanced techniques have been developed to modify the domain inversion pattern in order to engineer the frequency conversion spectrum. Periodic phase reversals[13] and an aperiodic lattice of domain inversions[14] have been used to broaden the conversion bandwidth, to engineer the optical frequency conversion spectrum or to convert multiple wavelengths at the same time. The aperiodic lattice method uses numerical techniques such as simulated annealing to calculate the optimal pattern for achieving a target conversion spectrum. Also, phase modulation of the QPM grating has been used to produce multi-wavelength conversion[15,16]. In this technique, the domain positions within each period Λ_{QPM} are shifted with a shift characterized by a phase that ranges from 0 to 2π. The phase-shift pattern is periodic with period Λ_{ph}. We investigate the phase modulation technique for simultaneously phasematching different nonlinear optical processes.

Let us consider multiple nonlinear frequency conversion processes that we wish to phasematch using the same QPM grating with each process indexed by the integer j:

$$\omega_{p,j} = \omega_{s,j} + \omega_{i,j} \,. \tag{4}$$

A phase-modulated QPM grating can phasematch the conversion process when[15,16]

$$\Delta k = 2\pi\left(\frac{1}{\Lambda_{QPM}} + \frac{m_j}{\Lambda_{ph}}\right) = 0\,. \tag{5}$$

where m_j is the integer associated with process j (see Eq. (4)).

For generation of polarization-entangled photons in PPLN, we are interested in two simultaneous type-II nonlinear processes. Consider a z-cut PPLN crystal such that the horizontal (H) polarization corresponds to the ordinary wave and the vertical polarization (V) is the extraordinary wave. The two simultaneous frequency conversion processes are

$$\begin{aligned} \omega_p^H &= \omega_s^V + \omega_i^H \\ \omega_p^H &= \omega_s^H + \omega_i^V \end{aligned} \,. \tag{6}$$

The wavelengths and bandwidths of the two processes should be identical so that the photons will be distinguishable only by their polarizations. We choose Λ_{QPM} and Λ_{ph} such that

$$\begin{aligned} k_p^H - k_s^V - k_i^H &= 2\pi\left(\frac{1}{\Lambda_{QPM}} + \frac{1}{\Lambda_{ph}}\right) \\ k_p^H - k_s^H - k_i^V &= 2\pi\left(\frac{1}{\Lambda_{QPM}} - \frac{1}{\Lambda_{ph}}\right) \end{aligned} \tag{7}$$

so that the indices m_j are equal to 1 and –1. The phase-modulation technique described by Eq. (4) has also been successfully applied to multi-wavelength upconversion[11].

2.2 Entangled photon generation

Spontaneous parametric downconversion (SPDC) is often used to produce entangled photon pairs. In SPDC, a high-intensity pump at frequency ω_p is incident upon a nonlinear optical crystal. Due to the presence of zero-point energy[17], a pump photon may spontaneously split into a pair of lower energy photons (signal and idler). If we can successfully achieve the simultaneous frequency conversion described by Eq. (6), the output state resulting from SPDC is

$$\left|\Psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|V_s\right\rangle\left|H_i\right\rangle + e^{i\phi}\left|H_s\right\rangle\left|V_i\right\rangle\right). \tag{8}$$

The phase ϕ can be adjusted by placing a phaseplate after the SPDC crystal. To correctly produce the state $\left|\Psi\right\rangle$, the states $\left|V_s\right\rangle\left|H_i\right\rangle$ and $\left|H_s\right\rangle\left|V_i\right\rangle$ need to be indistinguishable. Also according to Eq. (8), the amplitudes of the two components need to be equal, which is a non-trivial task for this design because the same pump beam (ω_p^H) is used for both processes. We must adjust the phase-modulation design in order to obtain equal strengths for both processes.

Several techniques involving SPDC have been used to produce the state $\left|\Psi\right\rangle$ in Eq. (8). One simple approach is to use two collinear, co-rotated crystals at non-degenerate wavelengths[18,19]. By working at unequal wavelengths for the photon pair, the two down-converted photons can be easily separated using spectral filtering and sent to two separate paths. In contrast, when the two down-converted photons have the same wavelength, the pair must be separated by a probabilistic 50:50 beamsplitter and then post-selection is required to detect when exactly one photon goes to each path, leading to 50% loss of the photon pairs[20,21]. Instead of using two co-rotated crystals, SPDC has been performed in two consecutive gratings with different QPM periods[20,22]. The two QPM periods phasematch the two processes described by Eq. (6) above. Recently, several techniques have been proposed using advanced QPM grating structures including use of an interlaced bi-periodic structure[21], doubly periodic poling[23], multiple QPM grating orders[24], and by a dual-periodically-poled crystal[25]. These methods and the phase-modulated QPM method described here are attractive because they produce collinear, polarization-entangled, non-degenerate photon pairs that may be subsequently coupled into optical fibers.

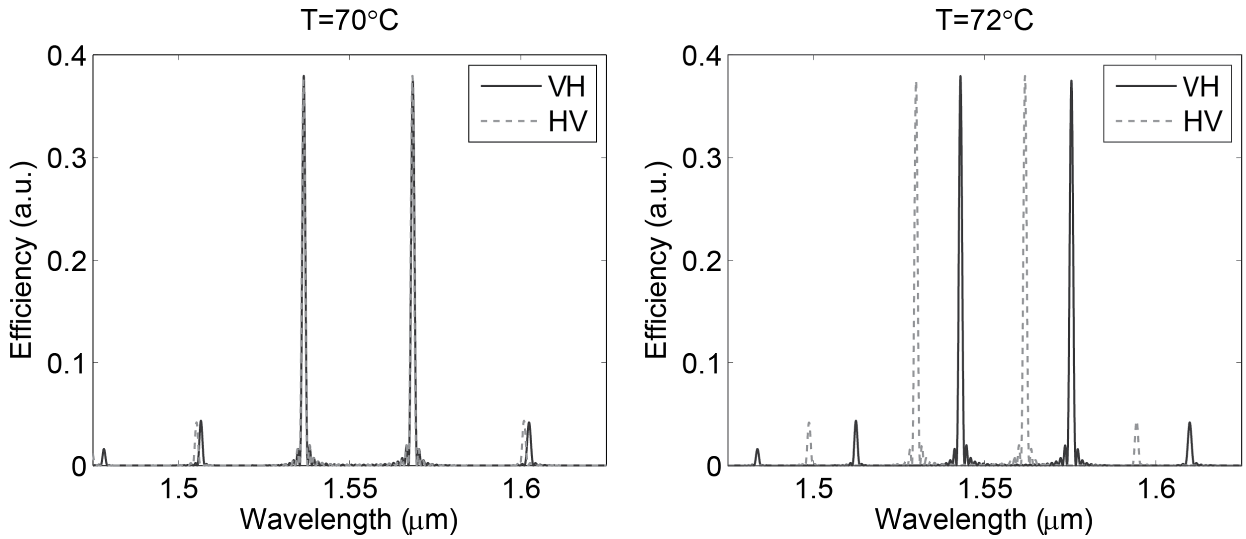
We noted that these methods require temporal compensation to erase the distinguishability associated with temporal walkoff between the different polarization states. In birefringent materials like $LiNbO_3$, the group velocities of the horizontal and vertical polarizations are different. For $LiNbO_3$ specifically, the group velocity of the extraordinary wave is higher than the group velocity of the ordinary wave. Therefore at a given wavelength, the V polarization always arrives at the end of the crystal earlier than the H polarization, leading to temporal distinguishability[26–28]. This distinguishability is due to birefringence of the crystal and is separate from distinguishability that may arise when two separate crystals or QPM periods are used to generate the entangled photon state. For the latter form of distinguishability, inserting a waveplate in the pump beam or using long pump pulses can eliminate distinguishability[26]. For temporal walkoff due to birefringence, compensation can be achieved using a Michelson interferometer[22], inserting a crystal of the same material as the SPDC crystal but with half the length and rotated by 90° [7,8,20,27,28], or using a separate birefringent crystal with specially chosen length[18,19]. Temporal compensation of walkoff due to birefringence is required regardless of whether SPDC is performed in two rotated crystals or in a phase-modulated QPM grating where both processes occur simultaneously.

3. DEVICE DESIGN AND FABRICATION

We designed and fabricated MgO:PPLN phase-modulated QPM gratings. The devices were produced for near-degenerate operation with pump wavelength at 776 nm, and signal and idler centered at 1552 nm with wavelength spacings $\Delta\lambda = |\lambda_i - \lambda_s|$ = 32 nm, 35 nm or 38 nm. Using the temperature-dependent dispersion relations for MgO:PPLN[29], we calculated the required QPM grating periods and phase-modulation periods using Eq. (7) for MgO:PPLN at 70 °C (see Table 1). We also varied the phase-modulation pattern to change the relative conversion amplitudes of the two simultaneous processes. As noted above, this is important since the amplitudes are fixed in the crystal design and can not be easily adjusted during the experiment.

Table 1. Calculated QPM and phase-modulation periods for dual-polarization SPDC in a MgO:PPLN grating at 70 °C.

$\Delta\lambda$	Λ_{QPM}	Λ_{ph}
32 nm	9.4 μm	1.92 mm
35 nm	9.4 μm	1.75 mm
38 nm	9.4 μm	1.61 mm



(a) (b)

Figure 1. Calculated down-conversion efficiency in a 25 mm long, 9.4 μm QPM period, 1.92 mm phase-modulation period MgO:PPLN grating structure at temperature (a) 70°C and (b) 72°C. The VH curve represents the state $|V_s\rangle|H_i\rangle$.

Figure 1 shows the calculated tuning curves for a 25 mm long, phase-modulated QPM grating. The bandwidth of signal and idler in both $|V_s\rangle|H_i\rangle$ and $|H_s\rangle|V_i\rangle$ states are nearly matched at Δλ = 1.0 nm. Temperature tuning is required to match the wavelengths of the two orthogonally polarized, photon pairs. Finally, we note the presence of small side peaks, which are due to the phase-modulation technique. Using these and similar designs, an array of gratings were fabricated in MgO:PPLN.

4. DEVICE CHARACTERIZATION

We characterized the phase-modulated QPM gratings using second-harmonic generation (SHG), sum- and difference-frequency generation (SFG and DFG). Initial measurements showed that the actual operating temperature was higher than the temperature calculated from theoretical dispersion relations[29]. Instead of operating near 70 °C, in order to phasematch the wavelengths of interest, the PPLN device needed to be operated at 140 °C or higher. Figure 2a shows the measured SHG tuning curve for a phase-modulated QPM grating at 140 °C. Two peaks are clearly visible, indicating that two nonlinear processes are simultaneously phasematched.

We also measured the SFG tuning curves. We used two tunable, C-band, external cavity diode lasers. The two lasers were combined using a fiber beam combiner to ensure perfect co-alignment, and the beams were focused into the PPLN grating. Figure 2b shows observed sum-frequency tuning curves for the same grating at 140 °C. Because of the type-II nonlinear interaction, the two beams near 1550 nm must be orthogonally polarized. We fixed the vertically polarized beam to 1551.1 nm or 1562.3 nm wavelength and swept the horizontally polarized beam. Increasing the wavelength of the vertically polarized beam causes the tuning curve for the horizontal polarization to shift to shorter wavelengths.

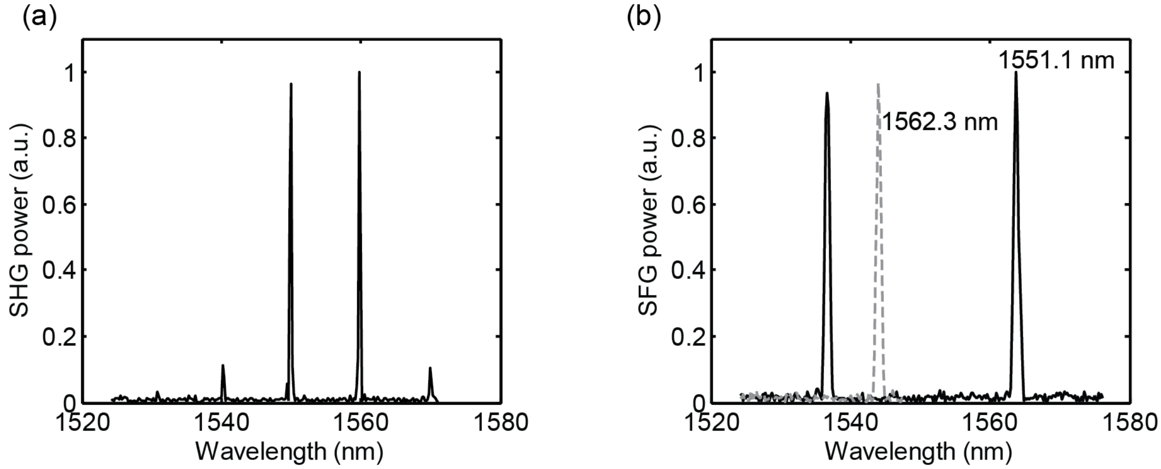


Figure 2. Measured (a) second-harmonic generation and (b) sum-frequency generation tuning curves at T=140 °C. For SHG, the fundamental beam is polarized at 45° to the crystal axes for the type-II interaction. For SFG, the vertically polarized beam is fixed to 1551.1 nm (solid) or 1562.3 nm (dashed) while the horizontally polarized beam is swept in wavelength. For the solid curve, both peaks are visible, while for the dashed curve, the second peak fell outside the tuning range of the laser around 1517 nm.

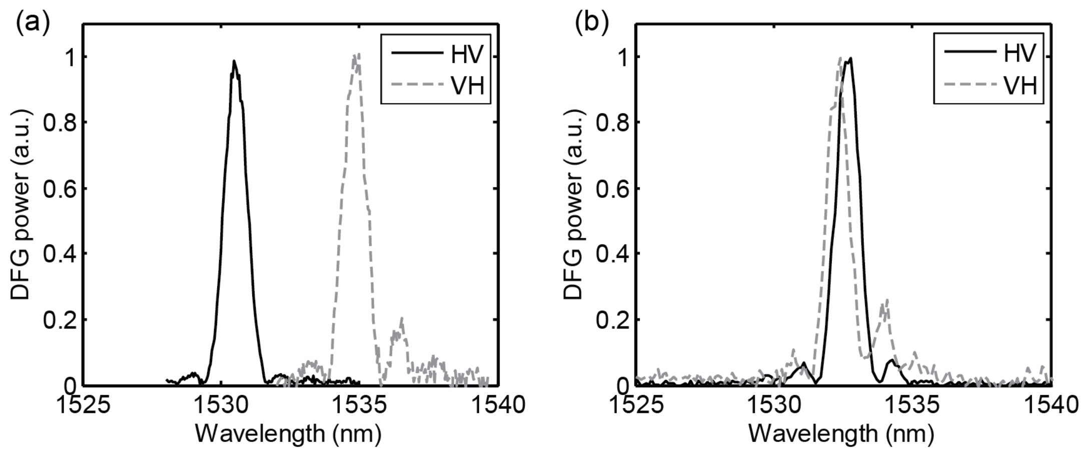


Figure 3. Difference-frequency generation spectra at two crystal temperatures, (a) 140 °C and (b) 143.5 °C. The horizontally polarized pump is fixed to 774.8 nm. The HV curve represents the state $|H_s\rangle|V_i\rangle$, that is, the signal beam near 1530 nm is vertically polarized while the corresponding idler near 1570 nm is vertically polarized.

After determining the proper operating temperature through the SHG and SFG measurements, we performed DFG using the phase-modulated QPM gratings. We used a fixed-wavelength, distributed feedback diode laser at 774.8 nm and a tunable external cavity diode laser near 1550 nm. A Glan-Thompson polarizer after the PPLN was used to reject the signal beam and transmit the generated difference-frequency (DF) beam. A 1550 nm dichroic edge filter was also used to improve separation of the signal and DF beams. The DF beam was detected with an InGaAs detector. Results of DFG measurements are presented in Fig. 3. At 140 °C, the spectrum for the $\left|H_s\right\rangle\left|V_i\right\rangle$ process does not overlap with the spectrum for the $\left|V_s\right\rangle\left|H_i\right\rangle$ process. By increasing the temperature to 143.5 °C, we achieve good spectral overlap. We also observed that the spectral bandwidths are nearly equal, which is important for preserving entanglement. Preliminary measurements indicate the amplitudes of the two DFG processes are unequal, but we may equalize them using better optimization of the grating.

5. DISCUSSION

These measurements show that the phase-modulated QPM gratings are suitable for generating polarization-entangled photon pairs near 1550 nm. Experiments are ongoing to efficiently couple the down-converted photons into optical fibers and analyze the quantum properties of the photons. We are interested in efficient fiber collection in order to study the use of this source for tests of Bell's inequality and eliminating the detector loophole[30,31]. These tests require low losses between when the entangled photon pair is produced and when the photons are detected. Efficient fiber collection of SPDC has been studied[32-34] with up to 84% collection efficiency demonstrated[35]. Our source will serve as a test bed for future quantum information experiments including demonstration of quantum teleportation[36], interfaces with quantum memories[4] and other applications.

6. DOMAIN-ENGINEERED PPLN FOR OTHER QUANTUM OPTICS APPLICATIONS

We have also shown that engineered optical frequency conversion in PPLN has other useful applications for quantum information applications. We have applied phase-modulated QPM gratings to demonstrate efficient dual-wavelength upconversion[11]. We designed, fabricated and demonstrated a PPLN waveguide that performed two simultaneous SFG processes: 1302 nm + 1556 nm $\rightarrow$ 709 nm and 1302 nm + 1571 nm $\rightarrow$ 712 nm. Both "channels" showed 70% internal conversion efficiency.

This novel device can be used as either an active beamsplitter (for multiplexing or demultiplexing signals) or as a passive beamsplitter. The 1302 nm photons can be sent to the 709 nm channel or the 712 nm channel. Since conversion requires the presence of the pump with appropriate wavelength, the dual-wavelength frequency converter can be used to route signals. Specifically, we showed that when the detector speed limits the data rate, the dual-wavelength upconverter can be used with interleaved pump pulses to multiplex two detectors together, thereby doubling the maximum detectable data rate.

The dual-wavelength upconversion PPLN waveguide can also be used as a passive beamsplitter, which is an important tool in quantum-optical experiments. We have demonstrate use of this device as a beamsplitter to measure second-order correlation functions, $g^{(2)}(\tau)$, of light sources[37]. Figure 4 presents $g^{(2)}(\tau)$ measurements of coherent and pseudo-thermal light performed with the dual-wavelength frequency converter acting as a beamsplitter and wavelength translator. These types of demonstrations illustrate the interesting applications offered by engineered optical frequency conversion in PPLN.

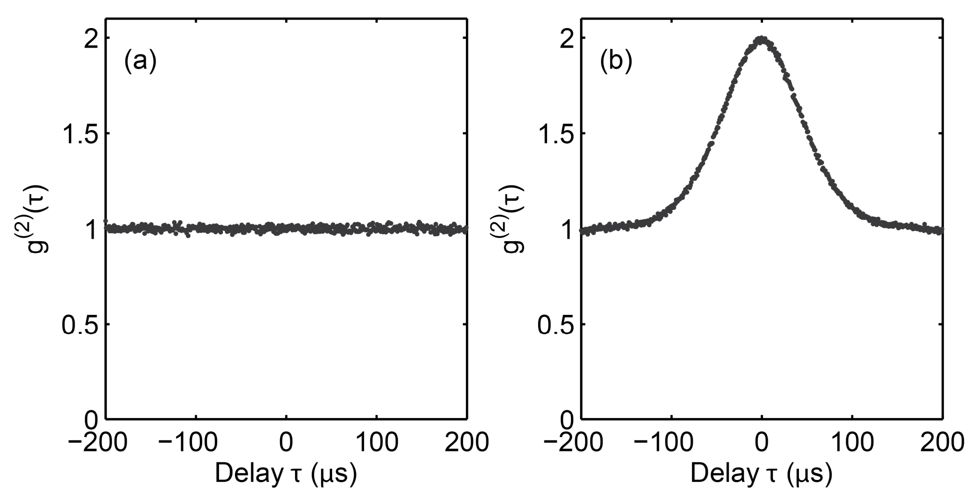


Figure 4. Second-order correlation function, $g^{(2)}(\tau)$, measured using the dual-channel upconversion detector of a (a) coherent light source and (b) a pseudo-thermal light source.

7. CONCLUSION

We have described the design and initial experimental measurements using PPLN-based, engineered optical frequency conversion as a source of polarization entangled photons. The PPLN grating was designed to simultaneously phasematch two type-II downconversion processes having (a) vertically polarized signal and horizontally polarized idler, or (b) horizontally polarized signal and vertically polarized idler. Due to birefringence in the crystal, these two processes have different phase mismatches. The device was designed for near-degenerate operation with signal and idler both near 1.55 μm and pump at 775 nm. By operating at closely spaced signal and idler wavelengths, the bandwidths of the two processes are nearly matched. Such a device can be used for post-selection-free generation of polarization-entangled twin photons. We also describe a domain-engineered PPLN grating that converts to two different wavelengths and its use as a beamsplitter and multiplexer, which are useful tools for quantum optics experiments. Both the sources and frequency translating devices will be important for future quantum communications networks[2-4].

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