Observation of Backward-Wave Spontaneous Parametric Downconversion in Sub-μm PPKTP

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Abstract: We observed backward-wave spontaneous parametric downconversion in sub-μm periodically poled Rb-doped KTP. Pumped at 800 nm, forward-wave signal at 1400 nm and backward-wave idler at 1868 nm were obtained.

Backward-wave (BW) three-wave mixing was first proposed in 1966 [1], but due to the very small quasi-phasematching (QPM) [2] periods required (typically $< 1\mu$m for first-order QPM), it was not experimentally realized until 2007 [3]. There have been several theoretical studies of BW spontaneous parametric downconversion (SPDC) [4, 5]. Recently, the first demonstration of BW SPDC in a third-order QPM grating was performed [6]. Photons pairs near 1570 nm were detected using superconducting nanowire single photon detectors (SNSPDs). The spectra of the downconversion was characterized using stimulated emission tomography (difference frequency generation). In this work, we report on the first demonstration of BW SPDC in a first-order, periodically poled $KTiOPO_4$ (PPKTP) grating and direct measurement of the SPDC spectra.

In BW three-wave mixing, the pump and signal are co-propagating while the idler is counter-propagating. The phase-mismatch is given by

$$\Delta k = k_p - k_s + k_i = 2\pi \left(\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i} \right) = \frac{2\pi m}{\Lambda_G}, \tag{1}$$

where $k_j = 2\pi n_j/\lambda_j$, λ_j is the wavelength of wave j; and p, s and i refer to the pump, signal and idler, respectively. The required QPM period, Λ_G, is $2\pi m/\Delta k$ where m is the QPM order [2]. The sign of k_i is reversed compared to the conventional co-propagating idler case, which results in large Δk requiring small Λ_G/m. First order ($m = 1$) QPM is desirable because it gives the largest nonlinear conversion efficiency, but it is very challenging due to the sub-micron QPM periods.

In this work, we used a periodically poled Rb-doped KTP crystal with 500 nm QPM period whose fabrication is described in [7]. The crystal was designed to have all waves z-polarized with wavelengths 800 nm $\longrightarrow$ 1.4 μm + 1.87 μm. The crystal was 6 mm long and 1 mm thick. Figure 1 shows a sketch of the experimental setup. A mode-locked Ti:sapphire laser with 1.6 ps pulse duration, 76 MHz repetition rate focused to 44 μm beam waist was used to pump the uncoated PPKTP crystal. Dichroic mirrors (DM) that

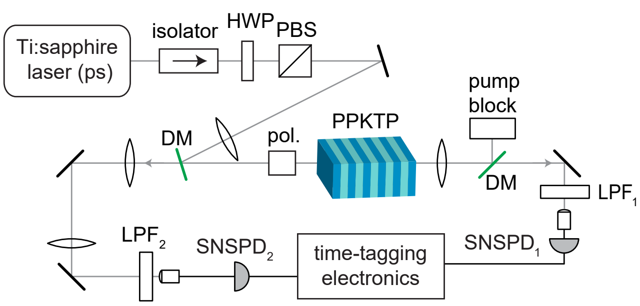

Fig. 1. Ti:sapphire laser pumps the PPKTP crystal. The signal and idler are collected into fibers and sent to SNSPD1 and SPSND2, respectively. HWP, half-wave plate; PBS, polarizing beam splitter; DM, dichroic mirror; pol., polarizer; LPF, long-pass filter

reflect the pump and transmit the signal and idler were used to direct the pump to the crystal and reject it afterwards. The forward-going signal and backward-going idler were coupled into fibers and sent to $SNSPD_1$ and $SNSPD_2$, respectively. Long-pass filters (LPFs) were placed before the fiber couplers to remove any residual pump photons. A polarizer was placed before the PPKTP crystal to ensure the pump was polarized along the crystal z-direction.

To detect the infrared photons, we used SNSPDs with broadband infrared sensitivity coupled to SMF28 single-mode fibers. The fibers connected to $SNSPD_1$ (signal) and $SNSPD_2$ (idler) were coiled with 40 mm and 60 mm diameters, respectively, to reduce dark counts caused by blackbody radiation while transmitting the wavelengths of interest [8]. We estimated the system detection efficiency of $SNSPD_1$ to be 88% at 1400 nm, and $SNSPD_2$ to be 85% at 1875 nm. Using these SNSPDs, we detected SPDC from the PPKTP and also analyzed the downconverted photons by passing them through a grating monochromator.

We first measured the signal and idler count rates and coincidence rate. Using 120 mW incident average power, we observed 4.7×10^5 counts/s and 1.5×10^5 counts/s at $SNSPD_1$ (signal) and $SNSPD_2$ (idler) (with background count rates of 3.6×10^3 counts/s and 6.3×10^3 counts/s, respectively). The coincidence rate was 1.1×10^4 coincidences/s, from which we estimated the signal and idler collection efficiencies [9] to be 8.5% and 2.8%, respectively.

We then directed the fiber-coupled photons to a grating monochromator (with 600 groove/mm grating blazed at 1.5 μm) and collected the diffracted light into a fiber attached to $SNSPD_2$. Fig. 2 shows the spectra measured with the monochromator and $SPSND_2$. Fig. 2a shows the pump transmitted through the PPKTP crystal, while Figs. 2b and 2c show the signal and idler spectra. The signal was detected at 1400 nm and the idler at 1868 nm, which agreed with phasematching predictions.

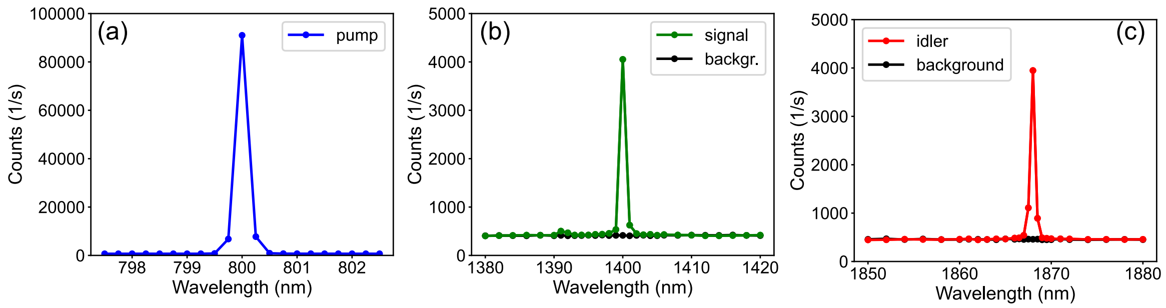

Fig. 2. Measured spectra for the (a) pump transmitted through the PPKTP, (b) signal and (c) idler. For the latter, we also show background counts (measured with the pump to the experiment blocked).

In conclusion, we have demonstrated for the first time first-order BW SPDC using sub-micron-period PPKTP. This experiment involved developing tools for analyzing single photons at infrared wavelengths beyond 1550 nm. Because of the unique phasematching condition, BW SPDC produces minimal spectral correlations in the photon pair [4] as well as two distinct output ports for the signal and idler. The backward-wave downconversion source could be used as a narrow-bandwidth source of entangled photons or heralded single photons.

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References

1. S. E. Harris, “Proposed backward wave oscillation in the infrared,” Appl. Phys. Lett. **9**, 114 (1966).
2. M. M. Fejer, et al., “Quasi-Phase-Matched Second Harmonic Generation: Tuning and Tolerances,” IEEE J. Quantum Electron. **28**, 2631 (1992).
3. C. Canalias and V. Pasiskevicius, “Mirrorless optical parametric oscillator,” Nat. Photonics **1**, 459 (2007).
4. A. Christ, A. Eckstein, P. J. Mosley and C. Silberhorn, “Pure single photon generation by type-I PDC with backward-wave amplification,” Opt. Express **17**, 3441 (2009).
5. C.-S. Chuu and S. E. Harris, “Ultrabright backwardwave biphoton source,” Phys. Rev. A **83**, 061803 (2011).
6. Y. C. Liu, et al., “Observation of frequency-uncorrelated photon pairs generated by counter-propagating spontaneous parametric down-conversion,” Sci. Rep. **11**, 12628 (2021).
7. A. Zukauskas, et al., “Cascaded counter-propagating nonlinear interactions in highly-efficient sub-μm periodically poled crystals,” Sci. Rep. **7**, 8037 (2017).
8. P. S. Kuo, “Using silica fiber coupling to extend superconducting nanowire single-photon detectors into the infrared,” OSA Continuum **1**, 1260 (2018).
9. S. V. Polyakov and A. L. Migdall, “High accuracy verification of a correlated-photon-based method for determining photon-counting detection efficiency,” Opt. Express **15**, 1390 (2007) .