Frequency Translation Using Backward-Wave Spontaneous Parametric Downconversion

Paulina S. Kuo,[1,*] Dileep V. Reddy,[2,3] Varun Verma[3], Sae Woo Nam[3], Andrius Zukauskas[4], and Carlota Canalias[4]

[1] *Information Technology Laboratory, National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, MD 20899*
[2] *Department of Physics, University of Colorado Boulder, Boulder, CO 80309*
[3] *Physical Measurement Laboratory, NIST, 325 Broadway, Boulder, CO 80305*
[4] *Department of Applied Physics, KTH—Royal Institute of Technology, AlbaNova Universitetscentrum, 10691 Stockholm, Sweden*

[*] *paulina.kuo@nist.gov*

Abstract: We experimentally investigate using backward-wave spontaneous parametric downconversion for frequency translation, where spectral characteristics of the pump wave are transferred to the signal wave.

Recently, there has been increasing interest in backward-wave (BW) three-wave mixing for classical applications such as optical parametric oscillation [1–3], and quantum applications such as spontaneous parametric downconversion [4]. These experiments have been enabled by the achievement of sub-micrometer poling periods [5] that are required for efficient phasematching of BW nonlinear interactions. The phasematching constraints of BW three-wave mixing lead to several unique spectral properties including that spectral characteristics of the pump wave can be transferred to the signal wave [2, 3]. In this work, we experimentally investigate frequency translation in backward-wave spontaneous parametric downconversion (BW SPDC).

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

$$\Delta k = k_\mathrm{p} - k_\mathrm{s} + k_\mathrm{i} = 2\pi\left(\frac{n_\mathrm{p}}{\lambda_\mathrm{p}} - \frac{n_\mathrm{s}}{\lambda_\mathrm{s}} + \frac{n_\mathrm{i}}{\lambda_\mathrm{i}}\right) = \frac{2\pi m}{\Lambda_\mathrm{QPM}}, \tag{1}$$

where $k_j = 2\pi n_j/\lambda_j$, n_j is the refractive index, λ_j is the wavelength of wave j; p, s and i refer to the pump, signal and idler, respectively; Λ_QPM is the quasi-phasematching (QPM) period and m is the QPM order. The sign of k_i is reversed compared to the co-propagating idler case, which results in qualitatively different behavior compared to the co-propagating case. Firstly, Δk for the BW case is quite large and requires rather small Λ_QPM/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 periods needed. Secondly, from Eq. 1, it can be shown [2] that the idler bandwidth is very narrow and that there is very weak dependence of the idler tuning with respect to pump tuning. If the idler is very narrowband and fixed in frequency, then by energy conservation, any spectral modulation of the pump must be transferred to the signal wave, and this is the concept behind frequency translation using BW three-wave mixing. In this work, we experimentally observe translation of spectral modulation at the pump to the signal in BW SPDC.

We performed type-0 BW SPDC in a periodically poled Rb-doped $KTiOPO_4$ (PPKTP) crystal with 500 nm (first-order) QPM period, 6 mm length and 1 mm thickness. Fabrication of this crystal is described in [6]. The crystal was pump near 800 nm and produced signal and idler near 1400 nm and 1870 nm, respectively. Figure 1

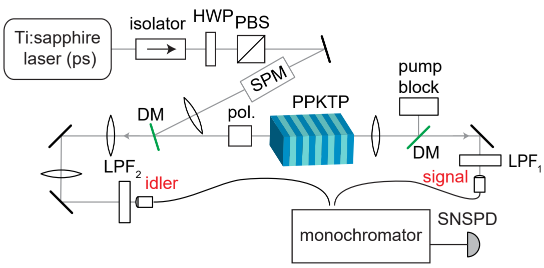

Fig. 1. The Ti:sapphire laser pumps the PPKTP crystal. Signal and idler are collected and sent individually to a monochromator with SNSPD. HWP, half-wave plate; PBS, polarizing beam splitter; SPM, self-phase modulation fiber; DM, dichroic mirror; pol., polarizer; LPF, long-pass filter.

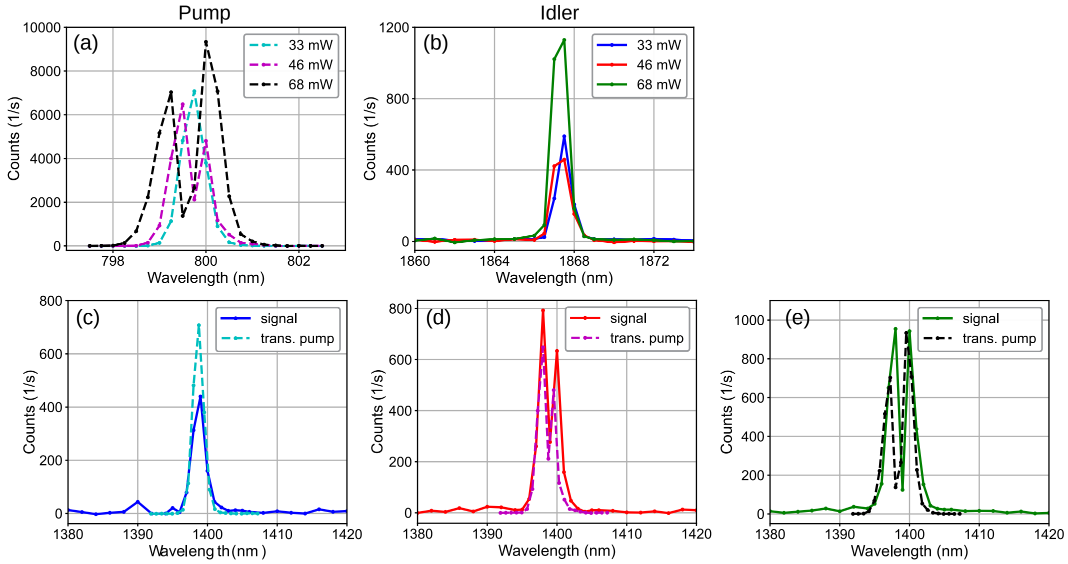

Fig. 2. Spectral measurements of BW SPDC with a self-phase modulated pump. (a) Pump spectra with SPM at different average pump powers, and corresponding (b) BW SPDC idler spectra. Comparisons of SPDC signal spectra with translated pump spectra for average pump powers of (c) 33 mW, (d) 46 mW and (e) 68 mW, where the pump power is measured after the SPM fiber.

shows the experimental setup. A mode-locked Ti:sapphire laser with 1.6 ps pulse duration and 76 MHz repetition rate was sent to a 3.2 m length of HI780 fiber to induce self-phase modulation (SPM). The modulated pump was then sent to the PPKTP. The forward-going signal and backward-going idler were coupled into fibers and sent to a monochromator connected to a superconducting nanowire single-photon detector (SNSPD) to measure spectra.

Figure 2 shows results of the BW SPDC experiment in the presence of the self-phase modulated pump. Figs. 2a and 2b show the pump and idler spectra, respectively, at different average pump powers. Figures 2c-e show the measured signal spectra and the translated pump spectra (with pump counts reduced by factor of 10). The translated pump spectra are calculated by assuming the idler is fixed at $\lambda_{i,0} = 1867.5$ nm, and applying energy conservation such that $1/\lambda_{\mathrm{trans}} = 1/\lambda_{\mathrm{p}} - 1/\lambda_{i,0}$. There is good agreement between the signal spectra and the translated pump spectra, confirming that BW SPDC can be employed for frequency translation and spectral shaping of the signal.

In conclusion, we have demonstrated that BW SPDC can be used to transfer spectral modulation of the pump wave to the signal wave. However, as noted in [2], frequency and phase translation using BW three-wave mixing differs from that of optical parametric amplification (OPA). OPA acts like a perfect phase-sensitive amplifier, which enables processes like quantum frequency conversion [7]. In contrast, the momentum conservation condition, Eq. 1, forces the phase of the counter-propagating idler to be nearly constant ($\phi_{\mathrm{i}} \simeq$ constant) [2], leading to frequency translation between the pump and signal, but this transfer is only approximate and not perfect. Further study is needed to investigate the fidelity of frequency and phase translation in BW SPDC.

References

1. C. Canalias and V. Pasiskevicius, “Mirrorless optical parametric oscillator,” Nat. Photonics **1**, 459 (2007).
2. G. Strömqvist, V. Pasiskevicius, C. Canalias, and C. Montes, “Coherent phase-modulation transfer in counterpropagating parametric down-conversion,” Phys. Rev. A **84**, 023825 (2011).
3. A.-L. Viotti, F. Laurell, A. Zukauskas, C. Canalias, and V. Pasiskevicius, “Coherent phase transfer and pulse compression at 1.4 μm in a backward-wave OPO,” Opt. Lett. **44**, 3066-–3069 (2019).
4. P. S. Kuo, D. V. Reddy, V. Verma, S. W. Nam, A. Zukauskas, and C. Canalias, “Observation of Backward-Wave Spontaneous Parametric Downconversion in Sub-μm PPKTP,” in *Frontiers in Optics + Laser Science 2022*, Technical Digest Series (Optica Publishing Group, 2022), paper FM5B.7.
5. C. Canalias, V. Pasiskevicius, R. Clemens and F. Laurell, “Sub-micron periodically poled flux grown $KTiOPO_4$,” Appl. Phys. Lett. **82**, 4233 (2003).
6. P. Mutter, A. Zukauskas, and C. Canalias, “Domain dynamics in coercive-field engineered sub-μm periodically poled Rb-doped $KTiOPO_4$,” Opt. Mater. Express **12**, 4332-–4340 (2022).
7. P. Kumar, “Quantum frequency conversion,” Opt. Lett. **15**, 1476–1478 (1990).