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Coherent phase transfer and pulse compression at 1.4 μm in a backward-wave OPO

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The frequency modulation transfer property of a backward-wave optical parametric oscillator (BWOP) is investigated in the context of near-IR pulse compression. The maximum transferrable bandwidth from the pump to the forward wave in a BWOP is determined by the group dispersion mismatch. In comparison, the third-order phase introduced in a single-grating compressor setup is more detrimental to achieve optimum compression of the BWOP forward wave. Nevertheless, we demonstrate a 220 GHz bandwidth transfer from 800 nm to 1.4 μm , with a compression factor of 115, leading to near-IR pulses as short as 1.3 ps with μJ energy. © 2019 Optical Society of America

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Counter-propagating devices, such as the backward-wave optical parametric oscillator (BWOP), have recently proven to have some of the required features for single-stage generation of near-IR picosecond pulses [1,2]. For these, the counter-propagating nonlinear interaction provides the positive feedback required for oscillation [3,4], thus removing the need for cavity mirrors. As a direct consequence of the counter-propagating interaction and the strong momentum constraint for BWOPs, the frequency, ω_b , of the backward-generated wave is narrowband and almost stationary in frequency, $\partial\omega_b/\partial\omega_p \approx -0.01$ [5]. The forward-generated wave, on the other hand, has a frequency response, ω_f , which closely follows that of the pump: $\partial\omega_f/\partial\omega_p \approx 1.01$. This can be of great interest for applications in telecommunication and microwave technology involving frequency translators [6,7], for which the signal encoded in the pump can be faithfully translated to another spectral range simply by launching it single pass through a BWOP. This is in large contrast to the spectral features of standard optical parametric oscillators (OPOs), where the momentum conservation condition is much less restrictive and typically results in output signal and idler spectra much broader than that of the pump, together with a poor temporal coherence. Moreover, optical frequency translators are mostly realized in waveguide structures with lower achievable powers. Single-pass BWOPs can easily provide μJ energies for the near-IR frequency translated bandwidths [2,8] and the

accessible wavelength range is much broader, thanks to the tuning capabilities of the forward wave with respect to the pump.

Furthermore, with BWOPs, one can generate short and tunable broadband pulses in the IR, useful for time-resolved spectroscopy, stimulated Raman spectroscopy, remote sensing, and bio-photonics, to mention a few applications [9–11]. Typical biological applications require short (<10 ps), stable high-power pulses with reasonable repetition rates (kilohertz range) and high pulse-to-pulse stability [12,13]. Additionally, tunable picosecond sources in the near-IR can serve as excitation sources for two-photon absorption spectroscopy, but also microscopy through coherent anti-stokes Raman scattering imaging [14]. Such light sources are primarily based on OPOs to provide the necessary tenability, where the spectral coverage is ultimately set by the phase-matching bandwidth of the nonlinear crystal [15]. An efficient single-pass nonlinear device, such as a BWOP, would be a simpler solution and provide means for new applications.

Practical implementations of BWOPs require a large artificial wave-vector to fulfill the momentum conservation, $k_p + k_b = k_f + K_G$, where p , b , s , and G refer to pump, backward and forward waves, and grating, respectively. In known nonlinear materials this can only be realized by the quasi-phase-matching (QPM) technique. For BWOPs operating in the near- to mid-IR, the grating period needs to be in the sub-micrometer range to allow for first-order QPM. Thanks to their quasi-one dimensional crystal structure [16] and improved poling technology, uniform and reliable periodically poled bulk samples can now be produced in crystals from the KTiOPO_4 (KTP) family [17].

In this Letter, we investigate the frequency transfer feature of a BWOP, prove that a coherent phase transfer is occurring from the pump to the forward-generated signal, and apply it to pulse compression. This is demonstrated by using strongly chirped pump pulses at 800 nm and building a single-grating compressor in which we compressed the signal from 150 ps, full width at half-maximum (FWHM), down to 1.3 ps. The current setup limitations for sub-picosecond pulse compression are also investigated in this Letter. A nonlinear temporal phase, due to group dispersion mismatch (GDM), emerged in the counter-propagating interaction, leading to a linear frequency modulation transfer bandwidth of 220 GHz when going from 800 nm

to 1.4 μm . Additionally, the grating compressor design introduces a third-order nonlinear phase which also limits achievable pulse compression.

In order to get an efficient BWOPO process, the pump pulse should be longer than the time it takes for it to travel through the sample, plus the time it takes for the backward wave (i.e., the idler in this study) to travel through the nonlinear crystal in the opposite direction. Thus, to manage a temporal overlap along the full length of the crystal, the pump is usually chosen to be at least on the scale of hundreds of picoseconds, which then results in a comparable pulse duration for the generated waves. The minimum pump pulse duration Δt_p which can be employed to ensure a good temporal overlap should then fulfill

$$\Delta t_p \geq L(\beta_{1,p} + \beta_{1,b}), \quad (1)$$

where $\beta_{1,p}$ and $\beta_{1,b}$ represent the inverse group velocities for the pump and backward waves, respectively, for a QPM grating of length L . The forward wave will get a pulse duration of the same order of magnitude as that of the pump, and should carry the same chirp [8].

For the experimental realization, we started with the uncompressed output of a Ti:sapphire regenerative amplifier operating at 1 kHz as the pump; see Fig. 1. The central wavelength of the chirped pump pulses was 800 nm, with a bandwidth of 5.5 nm (FWHM) and a pulse duration of 240 ps (FWHM). The BWOPO crystal was realized in periodically poled Rb-doped KTP (PPRKTP) [18], with a QPM period of 509 nm and a grating length of 7.3 mm. The sample was 1 mm thick and well poled using a technique based on coercive-field engineering [19]. With these pump pulses, the crystal generated a forward-propagating signal at 1.4 μm and a backward-propagating idler at 1.87 μm . Note that from Eq. (1), the estimated minimum pump pulse duration to have a complete overlap between idler and pump should be 85 ps.

The pump was loosely focused ($f = 200$ mm) into the BWOPO nonlinear crystal to a beam waist radius of 105 μm , and the power was controlled by a wave plate-polarizer arrangement. The pulses were polarized along the c-axis of the crystal and propagated along its a-axis to exploit the largest nonlinearity of the crystal (d_{33} coefficient). The BWOPO threshold was reached at a pump intensity of 0.72 GW/cm², and the conversion efficiency obtained was 42% at a maximum pump energy of 196 μJ [8].

At the pump energy of 196 μJ , the bandwidth of the depleted pump was measured to be 1.88 THz, while the

Fig. 1. Illustration of the experimental setup. The BWOPO crystal, pumped by 800 nm pulses, generates a forward signal at 1.4 μm and a backward idler at 1.87 μm . The remaining pump is filtered out after the crystal by a RG1000 long-pass filter.

generated signal at 1.4 μm had a bandwidth of about 1.91 THz [8]. The corresponding bandwidth of the backward idler wave was 28 GHz. These values are in good agreement with the momentum conservation rule in the quadratic temporal phase approximation, where the chirp rates of the pump and the signal should be almost equal. The chirp of the pump and the signal were measured using a homemade cross-correlation frequency-resolved optical gating (XFROG) setup. A small fraction of the compressed Ti:sapphire regenerative amplifier output (70 fs long) was used as the reference pulse. Figure 2 shows the XFROG traces for the pump and the BWOPO signal. Within the accuracy of the measurement, the pump and the BWOPO signal had the same positive linear chirp of 59 mrad/ps².

From the chirp rate, the estimated magnitude of the group delay dispersion (GDD) was 16.9×10^6 fs². However, this measurement does not discriminate the possible presence of a third-order phase in the BWOPO signal. When a BWOPO is pumped by broadband chirped pump pulses, the group velocity mismatch (GVM) of the interacting waves will result in slightly different chirp rate for the forward-generated (signal) wave, i.e., only the second-order temporal and spectral phases will be affected without compromising the compressibility of the wave. On the other hand, the GDM will induce higher-order phase distortions. For a purely linearly chirped pump, the GDM contributes with a third-order temporal (and spectral) phase. The BWOPO signal and idler temporal phases are estimated analytically to the third order using a power series expansion:

$$\varphi_{f,b}(t') \approx \int_0^{t'} \left[\omega_{f,b,0} + \partial_p \omega_{f,b} \partial_t \omega_p t + 0.5(\partial_p^2 \omega_{f,b} (\partial_t \omega_p)^2 + \partial_p \omega_{f,b} \partial_t^2 \omega_p) t^2 \right] dt, \quad (2)$$

where ∂_p and ∂_t denote derivatives over the pump frequency and time, respectively. The calculations assumed that the pump only contains linear frequency chirp, meaning that the last term in the kernel is reduced to zero. The appropriate derivatives for Eq. (2) can be obtained from momentum conservation.

In Fig. 3(a), the calculated phases for the pump and the BWOPO signal, as well as their phase difference are shown. The phase difference has primarily a quadratic time dependence, which indicates a slightly larger chirp rate of 59.7 mrad/ps² for the BWOPO signal. The third-order temporal phase is shown in

Fig. 2. XFROG measurements for (a) the pump pulses and (b) the BWOPO signal.

Fig. 3. (a) Time dependence of the pump (black) and the BWOPO signal (red) phases, and the phase difference between the pump and the signal (blue) as a function of time. (b) Calculated third-order phase (full phase minus GVM phase) of the signal (black), perfectly fitted by a cubic polynomial (red circles). A quadratic fit is also shown (blue).

Fig. 3(b) and can be readily visualized by subtracting the second-order term related to the GVM in Eq. (2) from the full signal phase.

The value of the third-order derivative of the temporal phase is 8.24×10^{-6} mrad/ps³, i.e., five orders of magnitude smaller than the second-order derivative. The calculations show that the total accumulated third-order phase would be below 40 mrad. For the chirp rates obtained in the experiment, the fidelity of the chirp transfer from the pump to the forward wave will eventually be limited by the accumulated third-order phase. In the case of a pump chirp rate of 59 mrad/ps², a third-order phase of π will be accumulated over a pump length of 1.32 ns, i.e., a pump bandwidth of 77.7 THz. The BWOPO can only accommodate a limited pump chirp rate; otherwise, the backward idler wave generated at the end of the crystal will encounter the pump frequencies at the beginning of the sample, which would then require generation of a signal at frequencies detuned from phase matching. From this picture, one can estimate the bandwidth of the idler as $\Delta\nu_b = 5.57/(2\pi L\beta_{1,b})$. This can be considered as a stationary bandwidth of the BWOPO idler and, for the specific BWOPO employed in this Letter, the bandwidth would be 18 GHz. This expression, associated with the backward-wave tunability [1], gives the limiting value for the pump chirp rate, where the conversion efficiency would decrease by half:

$$\left. \frac{\partial \omega_p}{\partial t} \right|_{\max} = \frac{5.57}{L^2 \beta_{1,b}^2} \frac{\beta_{1,f} + \beta_{1,b}}{\beta_{1,p} - \beta_{1,f}}. \quad (3)$$

The BWOPO used here would allow a maximum chirp rate of 149 mrad/ps², i.e., 2.5 times larger than our actual pump chirp rate.

In order to further investigate the contribution of the GDD mismatch, a single-grating Treacy compressor [20] was built, with four passes on the reflection grating, as shown in Fig. 1. The compressor consisted of a corner mirror to retro-reflect the angularly dispersed beam onto a gold-coated reflection grating (Spectrogon AB, 900 lines/mm, 30 × 110 × 16 mm) and a periscope which reversed the beam path, but at a different height on the grating. The corner mirror was placed on a translation stage in order to carefully adjust the amount of negative GDD introduced in the compressor. This scheme is free of spatial chirp and pulse front tilt, and the length of the compressor was reduced by half compared to a conventional design based on a grating pair [21].

Figure 4 shows the BWOPO signal spectrum, measured before and after the compressor. Note that the full spectral content was preserved through the compressor. The measured 2.8 THz bandwidth of the pulse corresponds to a Fourier transform limit of 157 fs (FWHM), meaning that sub-picosecond pulses can be obtained after the compressor in case of full dispersion compensation. The input power to the compressor was 30 mW, corresponding to a BWOPO pump intensity of 2.27 GW/cm² (three times over threshold), and the output power was about 6 mW, which corresponds to a pulse energy of 6 μJ at 1 kHz. The power loss is primarily ascribed to an unoptimized grating reflectivity. It had a maximum efficiency of 93% at a narrow reflection band around 1350 nm, slightly off our signal wavelength. To optimize the GDD compensation for a double-pass configuration and diffraction order m , the compressor length must be chosen according to [22,23]

$$\text{GDD} = -\frac{m\lambda^3}{\pi c^2} \frac{l_{\text{comp}}}{d^2 \cos^3 \theta_d}, \quad (4)$$

where θ_d is the diffraction angle measured from the normal to the grating surface, l_{comp} is the compressor length, λ is the wavelength, d is the grating groove spacing, and c is the speed of light in vacuum. In our case, the angle of incidence on the grating was 34.5°, giving a total compressor length of about 800 mm, which we folded in two for the single-grating design. The compressor adds third-order dispersion (TOD) according to [23]

$$\text{TOD} = -\text{GDD} \times \frac{3\lambda}{2\pi c} \left[1 + \frac{\lambda/d \times (\lambda/d - \sin \theta_i)}{1 - (\lambda/d - \sin \theta_i)^2} \right], \quad (5)$$

Fig. 4. Spectrum of the BWOPO signal before and after the compressor.

Fig. 5. Auto-correlation trace of the shortest compressed pulse obtained, fitted by a Lorentzian (1.3 ps FWHM).

which gives a magnitude of the TOD of 0.1 ps^3 . According to Ref. [24], high-quality pulse compression is obtained in a grating pair compressor, when the following criterion is fulfilled: $1/6 \times \text{TOD} \times (\Delta\omega)^3 \ll \pi$, where $\Delta\omega$ is the pulse bandwidth. With Eq. (5), we get a value of 155 rad, which refutes the criterion.

The output of the compressor was sent to a homemade auto-correlator based on a large aperture (5 mm) PPRKTP. The BWOPPO signal was 150 ps long (FWHM, Gaussian fit) before compression, i.e., almost half the duration of the pump pulse, matching the spectrum in Fig. 4. The shortest pulse was obtained for a compressor length of 37.9 cm, corresponding to a compression of almost 115 times. The auto-correlation trace is shown in Fig. 5 and best fitted with a Lorentzian shape, for a pulse length of 650 fs, i.e., a bandwidth of 218 GHz. This means that the added cubic phase in the grating compressor forms an Airy beam and limits the maximum compression achievable. The compressed output pulse (1.3 ps, 6 mW) would translate to a peak power of 4.6 MW.

In conclusion, a linearly chirped, broadband BWOPPO signal at $1.4 \text{ }\mu\text{m}$ was compressed 115 times down to 1.3 ps in a simple single-grating compressor. This demonstrates the excellent coherent phase transfer of about 220 GHz bandwidth for the BWOPPO process, converting the 800 nm pump to the $1.4 \text{ }\mu\text{m}$ (forward) signal wave. The transferable bandwidth will increase with pump intensity due to increasing pump depletion and the fact that the pump is chirped. The total bandwidth that can be transferred in the BWOPPO is limited by the accumulated effects of GDM, contributing to an additional nonlinear phase for the BWOPPO forward signal. This limitation can be overcome by designing an aperiodic QPM structure, or by optimizing the length of the PPRKTP crystal. However, the BWOPPO imprints much less TOD on the forward-generated pulse than the grating compressor itself, which adds a non-negligible third-order phase limiting the achievable compression. To overcome

this, a tailored compressor design would be required. A chirped volume Bragg grating could be employed to reach full dispersion compensation at $1.4 \text{ }\mu\text{m}$ [25] or the TOD could be tailored beforehand through phase modulation of the pump pulses in an acousto-optic programmable dispersive filter [26]. Additionally, the setup could be energy-scalable by seeding a broadband parametric amplifier with the BWOPPO signal, ensuring chirp rate conservation and compressibility of the near-IR wave.

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