Generation of fs laser pulses from a ps pulse-pumped optical parametric amplifier with a beat-wave seed signal

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ABSTRACT

We describe a method of ultrashort-pulse and ultrafast-pulse-train generation through optical parametric amplification of a laser beat wave. Numerical simulation shows that 250-fs laser pulses at 1.55 μm are generated from a beat-wave seeded optical parametric amplifier pumped by a 30-ps laser at 1064 nm. The pulse compression is attributable to sideband generation and parametric amplification under group velocity mismatch. Our experimental result confirms efficient generation of comb-like sidebands for the mixing waves from such an optical parametric amplifier.

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1. Introduction

Laser sources with a femtosecond pulse width are important for a variety of applications requiring temporal resolution. Some biochemical and environmental-chemical researches are particularly interested in mid- or far-infrared ultrafast pulses for exciting molecular groups in some pump–probe experiments. Since efficient and economic ps lasers, such as the mode-locked Nd:YVO₄ laser, are readily available, it is useful to develop a technique to convert a ps near infrared laser into a femtosecond mid-infrared laser. Recent advancement on relativistic electron radiation [1] and acceleration [2] also call for the need of ultrafast laser pulses repeating near THz frequencies.

Previous simulation works, conducted in 70s and 80s [3–5], described a strong dependence of pulse shortening on the conditions of group velocity mismatch (GVM) and pump depletion in optical parametric generation (OPG) using the second-order optical nonlinearity. Later, there were a number of experimental works concerning the creation of shortened OPG pulses in the femtosecond range [6]. Pulse width conservation with high OPG conversion efficiency was also achieved by a traveling-wave technique [7,8]. However, OPG amplifies the vacuum noise to an energy level comparable to the pump one, which requires very high pump intensity and has a large variation in the output energy, spectrum, and pulsewidth. Synchronously pumped optical parametric oscillator with a slightly detuned cavity has led to 20-fold pulse compression in the mid-infrared spectrum [9,10]. Although simultaneous pulse compression and second harmonic generation was demonstrated in chirped periodically poled lithium niobate, a theoretical study for extending the same technique to parametric down conversion has concluded with an insufficient parametric bandwidth [11]. However, as will be shown below, one can overcome the bandwidth limitation by operating the parametric process in the high-gain regime or supply the parametric system with a broad signal bandwidth.

In the literature, several previous works [12–18] have described the generation of ps and fs pulses with a high repetition rate by using a frequency-modulated pump laser in an optical fiber. This technique employs the much weaker third-order optical nonlinearity to obtain the results and usually requires a km-long dispersion-controlled fiber to demonstrate the effect without wavelength conversion. In this paper, we study a beat-wave seeding scheme for generating fs frequency-down-converted laser pulses from a ps pulse-pumped optical parametric amplifier (OPA) with a signal...
pulse rate either the same or greatly enhanced from that of the pump pulse. This scheme can effectively shorten the pump pulse width, convert the pump wavelength, and enhance the pulse rate in a centimeter long second-order nonlinear optical medium.

2. Theoretical model

We investigate the collinearly phase-matched, pulse-pumped OPA seeded by a laser beat wave by using a MATLAB program to solve the following time-dependent coupled-wave equations [19]:

\[
\begin{align*}
\frac{\partial E_1}{\partial t} + \frac{\partial E_1}{\partial z} - \frac{1}{2} D_1 \frac{\partial^2 E_1}{\partial t^2} &= -j\sigma_1 E_1 E_2 \exp(j\Delta kz) \\
\frac{\partial E_2}{\partial t} + \frac{\partial E_2}{\partial z} - \frac{1}{2} D_2 \frac{\partial^2 E_2}{\partial t^2} &= -j\sigma_2 E_1 E_3 \exp(j\Delta kz) \\
\frac{\partial E_3}{\partial t} - \frac{1}{2} D_3 \frac{\partial^2 E_3}{\partial t^2} &= -j\sigma_3 E_1 E_2 \exp(-j\Delta kz)
\end{align*}
\]

where the subscripts 1, 2 and 3 denote the variables relevant to the signal, idler, and pump waves, respectively, \( j = \sqrt{-1} \) is the imaginary unit, \( z \) is the wave propagation direction, \( D \) is the group velocity dispersion (GVD), \( E \) is the envelope field of the wave, \( \sigma_i = \omega_i d_{ij} / (n_i c) \) is the nonlinear coupling coefficient with \( p \) the pump wave speed, \( d_{ij} \) is the effective nonlinear coefficient, \( n \) is the refractive index, and \( \omega \) is the angular frequency, \( \tau = 1 - z/V_g \) is the time variable measured from the pump pulse center, \( V_g \) is the group velocity of the pump pulse, \( \Delta k = (1/V_g - 1/V_e) \) is the GVM between the wave i and the pump wave, and \( \Delta k \) is the wave-vector mismatch among the mixing waves.

To be practical, we use the most popular quasi-phase-matched (QPM) nonlinear optical material, periodically poled lithium niobate (PPLN), as the OPA gain medium in our situation study. The effective nonlinear coefficient of PPLN is about \( d_{31} = 17 \, \text{pm/V} \). For a collinearly phase-matched-wave-mixing process in a QPM material, the wave-vector mismatch becomes \( \Delta k = k_2 - k_1 - k_3 - k_g \), where \( k_i, i = 1, 2, 3 \), is the wave number of the mixing wave and \( k_g \) is the grating wave number of the PPLN crystal. For a nominal grating period of 30 \( \mu \text{m} \) in PPLN, the signal and idler wavelengths for a 1064-nm pumped OPA subject to \( \Delta k = 0 \) and \( \alpha_3 = \alpha_1 + \alpha_2 \) are 1.550 and 3.393 \( \lambda \) at 140 \( ^\circ \text{C} \), respectively. The corresponding GVM parameters for the optical parametric amplifier are \( \alpha_3 = -10^{-10} \, \text{s/m} \) and \( \alpha_2 = -5.2 \times 10^{-10} \, \text{s/m} \), and the GVD parameters are \( D_1 = 1.1 \times 10^{-26} \, \text{s}^2/\text{m} \), \( D_2 = 8.2 \times 10^{-25} \, \text{s}^2/\text{m} \), and \( D_3 = 2.5 \times 10^{-25} \, \text{s}^2/\text{m} \).

In our simulation, we first study the bandwidth broadening of the mixing waves with a monochromatic seed signal and present the results in Fig. 1. For the beat-wave seeded OPA presented in Figs. 2 and 3, the seed signal is a laser beat wave comprising two equal-amplitude fields shifted in frequency. The center wavelength of the beat wave is fixed at 1550 nm. We limit the beat frequency in our simulation to be about 0.1\% of the carrier frequency of the signal wave. Since a high-gain 1064-nm pumped OPA can easily support a THz bandwidth [20], we set \( \Delta k = 0 \) in Eq. (1) to ease our simulation study. The maximum input intensity of the laser beat wave is \( 6.37 \times 10^3 \, \text{W/cm}^2 \), corresponding to 25-mW laser power in each frequency component focused to a 100-\( \mu \text{m} \) waist radius. This laser beat wave can be conveniently arranged by seeding two continuous-wave (CW) wavelength-tunable diode lasers near 1550 nm through an Er-doped fiber amplifier. If the frequency spacing between the two beat-wave components is in the GHz range, an electro-optic amplitude modulator can be used to modulate a single seed laser to generate the desired beat wave. To include the vacuum noise, we inserted a noise photon into the idler channel during the pump time. However, in the high-gain and pump-depleted regime, the simulation result is insensitive to the number of initial idler photons. The pump laser is a Gaussian laser pulse at 1064 nm with a 30-ps width between the half intensities. For what follows, we choose the pump intensity between 0.16 and 0.22 GW/cm\(^2\), corresponding to peak laser power between 25 and 35 kW focused to a 100-\( \mu \text{m} \) waist radius. Those pump parameters are fairly typical for a commercial mode-locked Nd:YVO4 laser.

3. Simulation results

To compress a transform-limited laser pulse, it is necessary to first broaden the pulse bandwidth. The bandwidth increase in an OPA can be understood from the spectral and temporal evolution of the laser pulses in a monochromatic-wave seeded OPA. We first study such a 1064-nm pumped OPA seeded with a single-frequency signal at 1550 nm. Fig. 1a shows the temporal evolution of the pump (grey curve) and signal (black curve) intensities at several \( z \) locations in the PPLN crystal for initial pump and seed intensities of 0.22 GW/cm\(^2\) and \( 6.37 \times 10^2 \, \text{W/cm}^2 \), respectively. The horizontal axis is the co-moving time \( \tau \). All the curves are normalized to the peak intensity of the initial pump pulse. Between \( z = 0 \) and 2 cm, the signal gradually gains energy with the pump pulse kept constant. If the frequency difference between the pump and the laser is not much different from the initial Gaussian pump pulse. As shown in Fig. 1a, the center part of the pump pulse is strongly depleted between \( z = 2.0 \) and 2.5 cm but is re-grown from the sum frequency generation of the signal and idler in the region \( z > 2.5 \, \text{cm} \). The signal-pulse shape is nearly the inversion of the pump-pulse one, because the energy flows back and forth between the pump and the signal waves. The intensity distribution of the idler wave at 3.3 \( \mu \text{m} \) is similar to that of the signal wave at 1.55 \( \mu \text{m} \), except that the idler intensity is about half the signal intensity according to the Manley-Rowe relationship. A closer look at Fig. 1a reveals some asymmetry in the plots about the \( \tau = 0 \) line. This asymmetry is attributable to the GVM between the pump and signal pulses, given by \( \Delta = 1 \, \text{ps/cm} \) for lithium niobate.

Fig. 1b shows the corresponding spectral powers of the pump (grey curve) and signal (black curve) normalized to their peak values. The zero frequency point in each plot coincides with the main carrier frequency of the initial waves. For a pulsed OPA seeded by a monochromatic signal, the bandwidth of the pump pulse can be first encoded into the idler spectrum, which is further mixed with the pump spectrum to produce a broadened signal spectrum through difference frequency generation. As the signal and idler powers grow to some appreciable level, sum frequency generation of the spectrally broadened signal and idler can effectively increase the bandwidth of the pump spectrum. The broadened pump bandwidth can further increase the signal and idler bandwidths through difference frequency generation. This cascading process eventually generates much broader output bandwidths for all the mixing waves. Fig. 1b shows a slightly broadened signal bandwidth at about \( z = 2 \, \text{cm} \) due to the high parametric gain [20] and quick expansion of the pump bandwidth in the re-grown pump energy after \( z > 2.5 \, \text{cm} \) due to backward conversion from the strong signal and idler powers. The signal spectrum is further broadened in synchronization with the spectral broadening of the pump laser.

As will be shown below, this broadened signal bandwidth permits the generation of a signal pulse much shorter than the pump one. It is interesting to see that in Fig. 1b the broadened spectral power is not continuously distributed in frequency, but shows sidebands separated by \( \sim 0.25 \, \text{GHz} \), which is about the inverse of the 40-ps separation between the two peaks of the center-depleted pump pulse near \( z \sim 2.5 \, \text{cm} \). Those pump sidebands are quickly encoded into the signal and idler spectra in the region \( z > 2.5 \, \text{cm} \).

After knowing the highly efficient spectral-broadening mechanism in an OPA, we first introduce a beat frequency of 30 GHz into the seed signal of the OPA to generate a single compressed signal pulse. The peak pulse intensity is still fixed at 0.22 \( \times \text{GW/cm}^2 \). For this numerical simulation, the full width of the pump pulse...
$\sim 30 \times 2 = 60 \text{ ps}$ is approximately covered by two beat-intensity lobes. At the OPA input, we let the null of the beat wave coincide with the peak of the pump pulse. Fig. 2a shows the temporal evolution of the pump (grey curve) and signal (black curve) intensities propagating down the PPLN crystal. All the curves are normalized to the peak intensity of the initial pump pulse. It is seen from Fig. 2a that initial synchronization of the beat-wave null and the pump peak forms a small low-power channel before $z = \sim 3 \text{ cm}$, be-
cause the signal cannot grow fast enough due to the negligible seeding power. Beyond \( z > 3 \) cm, while the signal power in the channel starts to shoot up, the high signal power outside the channel flows back to the pump to form a narrow, isolated signal pulse at \( z = 4 \) cm. The GVM between the signal and pump pulses also allows the signal pulse to sweep over the pump–pulse peak and extract the pump energy, which avoids backward conversion from the signal to the pump during the signal-pulse buildup. As can be seen from Fig. 2a, the GVM effect causes the compressed signal pulse to slippage ahead of the pump center or move to the left of the \( \tau = 0 \) line. As the result, compared with the initial pump pulse width, the signal pulse width is reduced by 120 times at the crystal output. This large compression ratio effectively converts a 30-ps laser at 1064 nm into a 250 fs laser near 1.55 \( \mu \)m. The vertical scale of the plot also shows that the peak power of the output signal is nearly three times that of the input pump. In our simulation study, we also found that the pulse compression ratio remains nearly the same, as long as the relative power variation of the two beat-wave components is kept within 5%. Fig. 2b shows efficient generation of sidebands in the pump and signal spectra in the crystal due to the cascading nonlinear wave-mixing process.

With the beat-wave OPA scheme, it is also possible to generate comb-like signal outputs in both time and frequency domains. We chose a beat frequency of 250 GHz to illustrate this technique. In this simulation the pump intensity was reduced by 20% from the last study. Fig. 3a shows the temporal evolution of the signal and pump intensities along the crystal length. It is seen that the beat-wave signal is first amplified with the characteristic beat-wave lobes and gradually becomes a comb of narrow spikes near the end of the PPLN crystal. It is clearly seen from the plot that at \( z = 4 \) cm the generated beat pulses are greatly compressed from the original beat-wave lobes and their peak intensities are several times that of the initial pump pulse. The widths of the three central beat pulses are also about 250 fs. This means that in Fig. 2 the synchronization between the null of the seed signal and the maximum of the initial pump pulse has to be within ±4 ps. It is easier to explain the formation of the narrow beat pulses in the frequency domain. Fig. 3b shows the evolution of the spectral power of the signal and the pump waves along the crystal, indicating gradual formation of a frequency comb due to the cascading wave-mixing process in the nonlinear crystal. The output signal spectrum at \( z = 4 \) cm consists of a large amount of frequency sidebands from the cascading nonlinear wave-mixing process, which has helped to reduce the width of the signal spike in the way like the longitudinal modes do in a mode-locked laser. The GVM between the signal and pump also avoids the back flow of the energy from the signal spike to the pump when temporal hole burning occurs to the depleted pump pulse.

4. Experiment

We performed a proof-of-principle experiment by using a 4.2-cm long PPLN crystal as the gain medium of a beat-wave seeded OPA. The pump laser of the OPA is a single-longitudinal-mode, passively Q-switched Nd:YAG laser at 1064 nm, producing ~500-ps pulses at a 1-kHz repetition rate. The 29.6-\( \mu \)m grating period of the PPLN crystal allows phase-matched signal wavelengths near 1.54 \( \mu \)m and idler wavelengths near 3.44 \( \mu \)m at room temperature.

The seeding beat wave was generated by combining a distributed-feedback diode laser at 1538.98 nm and an external-cavity diode laser tuned to 1544.98 nm. The 6-nm wavelength separation corresponds to a 0.76-THz spacing in the frequency domain. The two diode lasers are coupled into and amplified by an Erbium-doped fiber amplifier (EDFA). After the EDFA, 17.5-mW power in each of the two signal components is injected into the OPA. Fig. 4 shows the measured signal (left) and pump (right) spectra at the output of the 1064-nm pumped beat-wave seeded OPA. The pump laser was operated at 65-\( \mu \)J pulse energy and focused to a 166-\( \mu \)m waist radius at the center of the PPLN crystal. The total output energy of the signal waves was 16 \( \mu \)J, corresponding to an overall parametric
efficiency of 37%. The comb-like sidebands in the signal output spectrum are evident in Fig. 4 and are consistent with the simulation predictions in Figs. 2b and 3b. The uneven power in the different comb components of the signal spectrum is due to the uneven parametric gain at different signal wavelengths.

Fig. 4. Measured signal (left) and pump (right) output spectra of the 1064-nm pumped, beat-wave seeded OPA using a 4.2 cm long PPLN as its gain medium. The beat frequency of the seeding signal was set at 0.76 THz. The spectra clearly show comb-like sidebands with frequency separation of 0.76 THz, as predicted in our numerical simulation. The uneven power in the different comb components of the signal spectrum is due to the uneven parametric gain at different signal wavelengths.

between the beat wave and the pump pulse should not be a problem. We also demonstrated in the numerical simulation an effective means of generating comb-like laser pulses and frequency sidebands. With a beat frequency of 250 GHz in the signal wave, we generated a 250-GHz pulse train at 1.55 μm in the 30-ps pump-pulse envelope. The width of the signal pulse is narrowed down to about 250 fs due to generation of copious sidebands in the signal spectrum. A proof-of-principle experiment was carried out to confirm the comb-like sideband generation in the pump and signal output spectra of a beat-wave seeded OPA.

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5. Summary

Beat-wave seeded optical parametric amplification is an effective means of generating shortened, frequency-down-converted laser pulses. In our numerical simulation, a 30-ps pump pulse at 1064 nm is converted into a 250-fs signal pulse at 1.55 μm in a PPLN OPA seeded by a CW beat wave with a beat frequency of 30 GHz. To obtain the 120-fold pulse compression, it is important to synchronize the pump pulse center to a beat-wave null so that an isolated signal spike can be obtained though the interplay of exponential gain, GVM, and backward conversion in the parametric process. Since the 30-GHz amplitude modulation to a CW 1.55 μm diode laser can be done electronically, the phase synchronization

References