Pulse compression and gain enhancement in a degenerate optical parametric amplifier based on aperiodically poled crystals

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We describe theoretically a method of obtaining pulse compression and simultaneously improving amplification in a degenerate optical parametric amplifier by use of quasi-phase-matched engineered crystals. The scheme combines the possibility of increasing the signal spectral bandwidth that is offered by a degenerate parametric amplifier with the ability of engineered aperiodically poled crystals to compensate for group-velocity mismatch.

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Important practical applications of high-energy femtosecond laser sources are emerging in a variety of fields, including material processing, biotechnology, medicine, environmental monitoring, and ultrafast chemistry, and thus the development of compact and reliable sources with suitable pulse energies is of current high technological interest.[1–3] Such femtosecond-pulse energies can be obtained with regenerative laser amplifiers but with corresponding size and complexity complications. Single-pass optical parametric amplification offers a simpler alternative. In the particular case of ultrashort pulse interaction a special problem arises: group-velocity mismatch. This drawback traditionally has been solved by use of thin broadband crystals,[4–6] which, however, lead to poor conversion efficiencies.[5] More recently the issue was addressed by use of aperiodic quasi-phase-matched (QPM) engineered crystals in second-harmonic generation configuration.[7–9] These works exploit two effects to compensate for the group-velocity mismatch: the ability of aperiodic QPM crystals to convert the frequency components of the fundamental pulse at different locations in the crystal and the different velocities of the pulse-frequency components. When both effects are combined, the second-harmonic frequency components were shown to leave the crystal simultaneously as a transform-limited pulse, provided that the pump fundamental pulse is adequately chirped. Therefore, the dependence of the phase-matching bandwidth on crystal length is effectively removed, allowing thick crystals to be used efficiently. In this Letter we show that a similar idea can be extended to an optical parametric amplifier (OPA). We study theoretically the degenerate configuration in which the signal and the idler have the same wavelength. Our aim is to show that in a degenerate OPA the signal spectral bandwidth can be increased, allowing the compression of initially transform-limited pulses and the simultaneous improvement of parametric gain. We show that such a goal can be achieved by use of a pump pulse with a broader spectral bandwidth than the signal and aperiodic QPM crystals. In the usual configuration in which the signal and the idler have different wavelengths, aperiodic QPM crystals could have an important role in improving parametric gain and generating short idler pulses. However, compression of the signal so that a change in the pump spectral bandwidth mainly affects the idler bandwidth is not possible; the signal spectrum remains almost constant and consequently limits the possibility of signal compression.

The slowly varying envelope approximation equations that describe pulse evolution in a collinear degenerate OPA configuration are

$$i\,\frac{\partial A_1(z,t)}{\partial z} + i\,k_1{}'\,\frac{\partial A_1(z,t)}{\partial t} - \frac{1}{2}\,k_1{}''\,\frac{\partial^2 A_1(z,t)}{\partial t^2} + \sigma(z)\Gamma_1 A_1{}^*(z,t)A_2(z,t)\exp(i\Delta kz) = 0\,, \quad (1)$$

$$i\,\frac{\partial A_2(z,t)}{\partial z} + i\,k_2{}'\,\frac{\partial A_2(z,t)}{\partial t} - \frac{1}{2}\,k_2{}''\,\frac{\partial^2 A_2(z,t)}{\partial t^2} + \sigma(z)\Gamma_2 A_1{}^2(z,t)\exp(-i\Delta kz) = 0\,, \quad (2)$$

where A_i are the field amplitudes and the indices $i = 1, 2$ correspond to the signal and the pump, respectively. The group velocity is $\nu_g = 1/k'$, where $k' = \mathrm{d}k/\mathrm{d}\omega$, and k'' is the group-velocity dispersion $k'' = \mathrm{d}^2k/\mathrm{d}\omega^2$. Here k is the wave number $k = n(\omega)\,\omega/c$, where the refractive index n is found with the Sellmeier equations reported in Ref. 10. The parameter $\sigma(z)$ amounts to $+1$ or -1 depending on the crystal domain polarization, and $\Delta k = k_2 - 2k_1$

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is the phase mismatch. Equations (1) and (2) are solved with a 2048-point split-step Fourier method. The reliability of the numerical model here used was confirmed in previous work in which experimental results were reproduced theoretically.[11]

To allow direct comparison with experimental data, and for concreteness, we focus on particular pump conditions with periodically and aperiodically poled lithium niobate (PPLN and APPLN, respectively) as QPM crystals. The pump source is a Ti:sapphire centered at a wavelength of 820 nm, with a 67-fs FWHM transform-limited pulse, a repetition rate of 84 MHz, and an average power $P = 1$ W. The signal input is set to 110 fs centered at 1640 nm, with a 10-mW average power. All input pulses are assumed to feature a sech^2 intensity shape, and the beams are focused on the crystal input face with a 20-μm radius. The quasi-phase-matching period in this situation is approximately $\Lambda = 21.12\ \mu$m.

First, we show that it is possible to compress transform-limited signal pulses by use of a PPLN degenerate OPA configuration. Figure 1(a) shows that in this case the maximum efficiency is obtained for a 0.9-mm-long sample with a signal gain $g = P_{\text{out}}/P_{\text{inp}} = 15.7$, and an output signal duration of ~100 fs. Compression of the signal pulse duration can be obtained and gain can be improved by chirping–dispersion of the pump pulse, as shown in Fig. 1(b). The maximum signal compression of 84 fs with a gain of $g = 17.4$ is obtained if the pump is stretched with a linear delay line with group-velocity dispersion of $C_p = 3000\ \text{fs}^2$ (84-fs pump duration). Compression, which is only possible using a degenerate configuration of the OPA, is a consequence of the increase of the signal spectral bandwidth: The input signal bandwidth is 25.6 nm, whereas the output is found to be 36.4 nm. The output signal bandwidth hardly changes with the pump chirp; all the signal output pulses corresponding to Fig. 1(b) feature similar bandwidths. Chirping the pump is necessary only to allow the signal spectral components to leave the crystal together, thus forming a transform-limited pulse. The origin of the pulse is similar to that of pulse amplification in an inhomogeneous gain medium, where the bandwidth of the signal is broadened by a larger gain bandwidth, which in the OPA corresponds to the pump bandwidth when a sufficiently thin crystal is used. Thus, the larger the pump bandwidth, the larger the signal bandwidth broadening and, hence, the larger the signal compression.

To analyze APPLN-based OPAs, we define the poling-period variation in the crystal as a grating chirp, $G = d\Lambda/dz$. Here we show results obtained with three different grating chirps: $G_1 = 0.1$, $G_2 = 0.2$, and $G_3 = 0.3\ \mu$m/mm. The central period is the same as in the PPLN crystal. The corresponding pump chirps, C_p, were chosen to be $4.6 \times 10^4\ \text{fs}^2$ (1389-fs duration), $2.3 \times 10^4\ \text{fs}^2$ (709 fs), and $1.6 \times 10^4\ \text{fs}^2$ (507 fs), respectively, to yield the maximum gain for each grating chirp.

A critical parameter of a degenerate OPA is the initial phase difference ϕ_0 between the signal and pump waves. The results in Fig. 1 were obtained for the optimal condition $\phi_0 = 0$. However, conversion from the signal to the pump, resulting in signal loss, occurs when $\phi_0 = \pi/2$. To appreciate how the initial phase difference affects an APPLN-based OPA, in Fig. 2(a) we show the properties of the output signals as a function of ϕ_0, and in Fig. 2(b) we show four characteristic pulse phases and intensity profiles for a 5-mm-long crystal with grating G_3. A near-transform-limited pulse with a duration of 73 fs is obtained when $\phi_0 = 0$ (A), which implies a larger compression than in the case of a PPLN-based OPA. However, the pulse duration features a maximum duration of 131 fs near $\phi_0 = \pi/2$ (B). At both sides of this maximum there are two minimum duration points of 53 fs (C) and 50 fs (D). The corresponding intensity profiles show that such large variations of pulse duration are just a shaping effect that is due to backconversion from signal to pump that occurs in the center of the pulse, resulting in chirped double-peaked intensity profiles. Backconversion is also responsible for the low signal gain obtained for this initial phase difference.

Duration and gain as a function of the crystal thickness are analyzed in Fig. 3. The dashed curves are signal duration and gain when the initial phase difference between the pump and the signal is fixed to $\phi_0 = 0$ for grating G_3. In both plots the signal duration exhibits oscillatory behavior, with every maximum gain corresponding to transform-limited pulses. As was shown in Fig. 2, double-peaked pulses that are due to backconversion are always found to

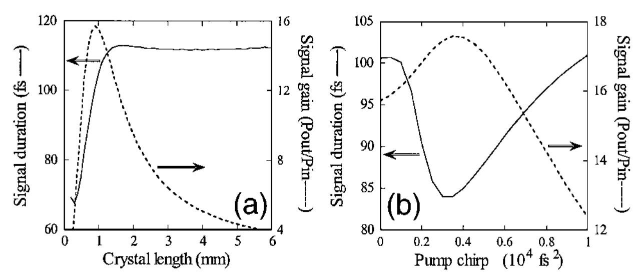

Fig. 1. Signal-pulse duration (solid curves) and gain (dashed curves) in a PPLN-based OPA. (a) Dependence in terms of (a) the crystal length and (b) the pump chirp when the crystal is cut to the optimal gain length (0.9 mm).

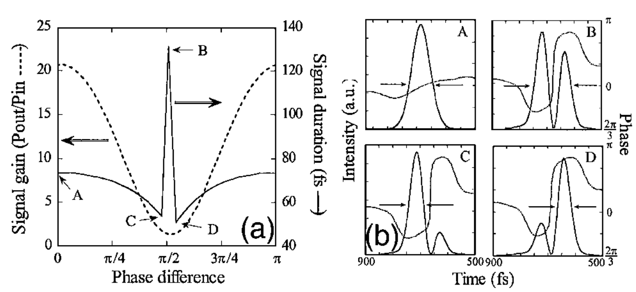

Fig. 2. (a) Signal-pulse duration (solid curves) and gain (dashed curves) in a 5-mm-thick APPLN OPA with grating G_3 as a function of the initial pump–signal phase difference ϕ_0. A–D indicate the corresponding intensity profiles shown in (b). The arrows in the intensity profile plots show the points where the pulse duration (FWHM) is calculated.

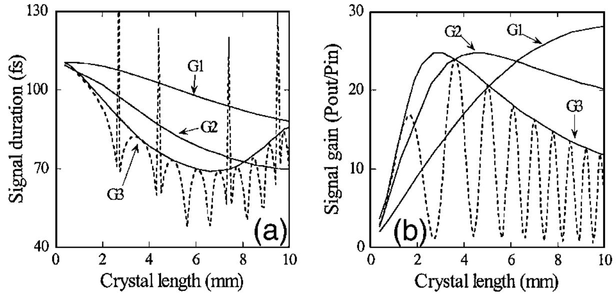

Fig. 3. Signal-pulse duration (a) and gain (b) in APPLN OPAs as a function of the crystal length. The dashed curves correspond to crystal grating G_3 when the initial pump–signal phase difference is $\phi_0 = 0$. The solid curves correspond to the duration when transform-limited output signal pulses and maximum gain are obtained for the three grating chirps.

occur when the gain reaches a minimum. We thus conclude that the initial phase difference that is necessary to maximize gain and achieve transform-limited signal pulses depends strongly on the crystal length. We explain such dependence by taking into account how propagation affects the central spectral components of both pulses, as follows. Because the central spectral components in both pulses are not QPM at the first half of the crystal, the phase difference $\phi(z)$ between the signal and the pump changes during propagation. When both pulses reach the center of the crystal, where they are QPM and thus larger conversion occurs, with a phase difference of $\phi(L/2) = \pi/2$, the result is signal-to-pump energy conversion [B in Fig. 2(b)]. However, when $\phi(L/2) = 0$, pump-to-signal conversion takes place [A in Fig. 2(a)]. Accordingly, the signal duration and gain with $\phi_0 = \pm\pi/2$ (not shown in Fig. 3) feature complementary behavior.

We obtained the solid curves in Fig. 3(a) by tuning ϕ_0 for each crystal length to obtain transform-limited pulses, i.e., when $\phi(L/2) = 0$ for all the crystal lengths. An important point is that each grating chirp exhibits an optimal crystal length for which compression is the highest. The improvement with respect to a PPLN-based OPA is clearly visible. We observe a minimum duration of 69 fs for grating G_3 with a 6.7-mm-long crystal. With grating G_2, we get a minimum of 70 fs with a 10-mm-long crystal, and with G_1 the minimum is 75 fs for much longer crystals (20–30 mm). The solid curves in Fig. 3(b) show the gain corresponding to the solid curves of Fig. 3(a), i.e., when we obtain the maximum gain by tuning ϕ_0. As occurs with compression, each grating chirp exhibits an optimal crystal length at which the gain is highest. However, the crystal lengths at which gain and compression are maximized do not coincide. Grating G_3 has a maximum gain of $g = 24.8$ at a crystal length $L = 2.8$ mm, and for grating G_2 is $g = 25$ at $L = 4.4$ mm, whereas grating G_1 shows a more flat response with a gain of approximately $g = 29$ in crystals of length $L = 10$–20 mm.

The results presented above, together with the simulations that we carried out with other gratings, allow us to identify general trends that hold for arbitrary QPM chirps and materials. By and large, the most important parameter for obtaining signal compression is the QPM crystal chirp. Large compression can always be realized with a large grating chirp. The larger the grating chirp, the shorter the crystal needed and the more efficient the compression. However, if the aim is to improve gain, then the important parameter is found to be the crystal thickness. Gain enhancement is higher when the crystal is thicker and the grating chirp is smaller. Nevertheless, one cannot improve gain indefinitely by increasing the length of the crystal. For example, in the cases shown here, crystals longer than 20 mm require a very small QPM chirp and highly chirped pump pulses. Thus, the gain decreases because such chirped pulses feature a very low intensity. However, in all the cases that we have investigated with crystal lengths in the range 2–20 mm, it has always been possible to improve both the gain and the compression simultaneously by choosing a suitable QPM chirp.

In conclusion, we have shown that, unlike with nondegenerate OPA, compression and gain can be improved in a degenerate OPA by use of pump pulses with a broader bandwidth than the signal. This improvement can be achieved by chirping of the pump and by use of thin periodically poled nonlinear crystals. However, we have shown that higher compression and gain can be simultaneously obtained by use of aperiodically poled nonlinear crystals. Here we focused on aperiodically poled lithium niobate, but the results hold for all materials with which QPM techniques can be implemented.

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