Cascaded soliton compression of energetic femtosecond pulses at 1030 nm

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Abstract: We discuss soliton compression with cascaded second-harmonic generation of energetic femtosecond pulses at 1030 nm. We discuss problems encountered with soliton compression of long pulses and show that sub-10 fs compressed pulses can be achieved.

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Ultrafast fiber laser systems using Yb-doped laser materials are rugged, cheap and compact platforms that currently are undergoing a rapid development, and by employing the chirped pulse amplification technique high-energy femtosecond pulses can be generated with μJ–sub-mJ pulse energies. In the same way solid-state Yb-based amplifiers can give multi-mJ pulse energies and interesting alternatives to Ti:Sapphire systems because they can be diode-pumped. However, the limited gain bandwidth of Yb systems implies an amplified pulse duration of around 500 fs, and efficient post-compression methods are therefore needed to reach sub-100 fs. The standard way of compressing energetic pulses today is to use 0.5-1.0 m long hollow gas-filled fibers [1], where spectral broadening is achieved through the formation of a filament using the self-focusing nonlinearities of the gas. Temporal compression is then achieved by a pair of gratings. With this technique compression from 500 fs to 60 fs was observed at $\lambda = 1.03~\mu$m [2].

We here propose to use cascaded (phase-mismatched) second-harmonic generation as pulse compressor. With this technique high-energy pulse compression of the pump pulse towards few-cycle duration has been achieved [3–7]. These studies were motivated by the possibility of creating a negative (self-defocusing) Kerr-like nonlinearity. Thus, self-focusing problems encountered in Kerr-based compressors are avoided, and the input pulse energy is practically unlimited [3]. Moreover, small-scale self-focusing does not occur either since there is no spatial modulation instability gain for self-defocusing nonlinearities. Furthermore both spectral broadening and temporal compression can occur in a single nonlinear material through solitons [4]. Solitons are stable nonlinear waves that exist as a balance between nonlinearity and dispersion, which for a negative nonlinearity is achieved with normal dispersion. Thus, in cascaded SHG solitons can form in the near-IR where the majority of lasers operate and where most materials have normal dispersion. Here we investigate the potential for using cascaded soliton compression at the operating wavelength of Yb-based laser amplifiers. We first show that compression of 500 fs pulses towards few-cycle duration is possible, but that it requires very long interaction length. We discuss how to address this issue. We also show pulse compression to few-cycle duration in short crystals assuming as input 60 fs compressed pulses from a hollow-fiber compressor.

In cascaded SHG the conversion process L is strongly phase-mismatched $|\Delta kL| \gg 1$: up-conversion to the second harmonic (SH) is after a coherence length $\pi/|\Delta k|$ followed by the reverse process of down-conversion to the fundamental wave (FW). On continued propagation the SH is therefore cyclically generated and back-converted. In this cascaded nonlinear interaction the FW experiences a nonlinear phase shift due to the difference in phase velocities, and the magnitude and sign of the phase shift is determined by the phase-mismatch parameter $\Delta k = k_2 - 2k_1$ [8], where $k_j = k_j(\omega_j)$, $k_j(\omega) = n_j(\omega)\omega/c$ is the wavenumber, and $n_j(\omega)$ is the linear refractive index. Due to the cascading process the pump field can approximately be described by an equation, which is similar to a nonlinear Schrödinger equation (NLSE). Neglecting for simplicity higher-order dispersion, self-steepening effects and Kerr cross-phase modulation (XPM), and assuming normal group-velocity dispersion (GVD) $k_1^{(2)} \equiv d^2k_1(\omega)/d\omega^2|_{\omega=\omega_1} > 0$ it is given by [9–11]

$$\left(i\frac{\partial}{\partial\xi} - \frac{\partial^2}{\partial\tau^2}\right)U_1 + N_{\rm Kerr}^2\left(U_1|U_1|^2 - \tau_R U_1\frac{\partial|U_1|^2}{\partial\tau}\right) - {\rm sgn}(\Delta k)N_{\rm casc}^2\left(U_1|U_1|^2 + i{\rm sgn}(d_{12})\tau_{R,{\rm casc}}|U_1|^2\frac{\partial U_1}{\partial\tau}\right) = 0 \quad (1)$$

The normalization is chosen to give soliton units, so $\xi = z/L_{D,1}$, $\tau = t/T_{\rm in}$ and $|U_1|^2 = I_1/I_{\rm in}$. This equation describes self-phase modulation (SPM) from material Kerr effects, and we have also included a term describing the delayed Raman nonlinearity (here expressed under the approximation of a narrow spectrum), and the normalized Raman time parameter is $\tau_R = T_R/T_{\rm in}$. For most materials $T_R < 5$ fs. The Kerr nonlinear strength is governed by the

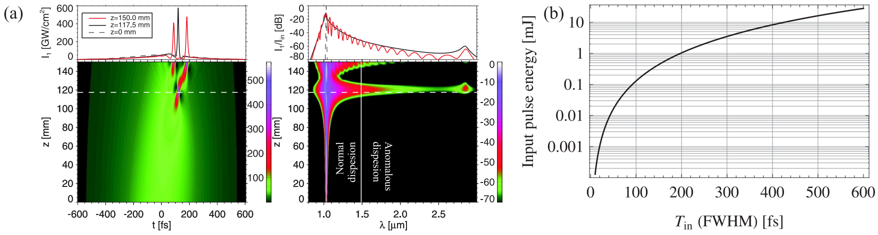

Figure 1. (a) Numerical simulation of soliton pulse compression in BBO, showing the evolution along z of the pump vs. time (left) and wavelength (right). The input pulse is a $\lambda_1 = 1.03\ \mu$m sech-shaped 500 fs FWHM pulse and $I_{\rm in} = 54\ {\rm GW/cm}^2$ such that $N_{\rm eff} = 10$. The simulation was done using the coupled SHG slowly-evolving envelope equations in the plane-wave limit [9] including self-steepening, Kerr SPM and XPM effects, exact dispersion from the Sellmeier equations of Ref. [13], and using the parameters $n^I_{\rm Kerr} = 5.8 \times 10^{-20}\ {\rm m^2/W}$ [14], $\Delta k = 60\ {\rm mm}^{-1}$ and $d_{\rm eff} = 2.09$ pm/V. Kerr Raman effects were neglected. (b) The minimum input pulse energy required to avoid spatial walk-off during propagation, shown vs. the input pulse FWHM.

Kerr soliton order $N^2_{\rm Kerr} = L_{D,1}\frac{\omega_1}{c} n^I_{\rm Kerr} I_{\rm in}$, where $L_{D,1} = T^2_{\rm in}/|k^{(2)}_1|$ is the pump dispersion length, $T_{\rm in}$ is the input pulse duration, $n^I_{\rm Kerr} > 0$ is the self-focusing material Kerr nonlinear refractive index, and $I_{\rm in}$ is the peak input intensity. The cascaded nonlinearity is shown under the weakly nonlocal approximation [10], which holds when the phase mismatch is large enough to be in the *stationary regime* $\Delta k > \Delta k_{\rm sr} = d^2_{12}/2k^{(2)}_2$. The cascading gives a SPM term whose strength is given by the cascading soliton order $N^2_{\rm casc} = L_{D,1}\frac{\omega_1}{c}|n^I_{\rm casc}|I_{\rm in}$, where the cascading nonlinear refractive index is $n^I_{\rm casc} \simeq -4\pi d^2_{\rm eff}/c\varepsilon_0\lambda_1 n^2_1 n_2 \Delta k$ [8], and $d_{\rm eff}$ is the effective quadratic nonlinearity. Note that the strength and sign is controlled by Δk, and for $\Delta k > 0$ the cascading term is self-defocusing. The cascading also gives a Raman-like perturbation of the pump, which is characterized by the normalized parameter $\tau_{R,\rm casc} = |d_{12}|/2T_{\rm in}\Delta k$ [10, 12]. This Raman-like perturbation is caused by group-velocity mismatch (GVM), $d_{12} = k^{(1)}_1 - k^{(1)}_2$ is the GVM parameter, and the perturbation affects both intensity and phase unlike the material Raman effect that only affects the phase. Importantly, from Eq. (1) the total pump SPM can be described by an effective nonlinear refractive index $n^I_{\rm eff} = n^I_{\rm casc} + n^I_{\rm Kerr}$. For the case $\Delta k > 0$ and total self-defocusing effective nonlinear refractive index $n^I_{\rm eff} < 0$ we can introduce an effective soliton order $N^2_{\rm eff} = N^2_{\rm casc} - N^2_{\rm Kerr}$: This parameter conveniently characterizes the cascaded soliton behavior [9].

We have previously studied cascaded soliton pulse compression at $\lambda_1 \simeq 1.03 - 1.06\ \mu$m: in Ref. [9, 11] we used a critical (type-I) phase-mismatched β-barium-borate (BBO) nonlinear crystal though an $oo \rightarrow e$ interaction. We show in Fig. 1(a) a simulation for cascaded pulse compression in BBO using a 500 fs FWHM sech-shaped pulse as input. The phase mismatch $\Delta k = 60\ {\rm mm}^{-1}$ was chosen so compression occurs in the stationary regime ($\Delta k_{\rm sr} = 48\ {\rm mm}^{-1}$), and the intensity was chosen to give $N_{\rm eff} = 10$. Such a soliton order should give a compression factor $f_c = 4.7(N_{\rm eff} - 0.86) = 43$ [9], and indeed the pulse compresses to 11 fs FWHM (3 optical cycles) after 120 mm [this distance also agrees well with Eq. (2)]. At the compression point a dispersive wave forms in the anomalous (linear) dispersion regime [14], and after this pulse splitting is observed. Thus, efficient pulse compression to few-cycle duration is possible in BBO at $\lambda_1 = 1.03$, but the compression ony happens after 120 mm, which is much longer than standard crystal sizes. The problem can be explained from the scaling law of the optimal compression point $z_{\rm opt}$, i.e. the point at the initial compression stage where the soliton pulse duration is the shortest. For large effective soliton orders it is [9]

$$z_{\rm opt} \simeq L_{D,1}\tfrac{\pi}{2}0.44/N_{\rm eff} = 0.44 T_{\rm in}\sqrt{\pi\lambda_1/[8k^{(2)}_1|n^I_{\rm eff}|I_{\rm in}]} \qquad (2)$$

Thus long pulses, low GVD and a low effective nonlinearity all result in increasing compression lengths. Secondly, the spatial walk-off angle of BBO (around $\rho = 3^\circ$ for the considered wavelength and phase mismatch) was obviously neglected in the plane-wave simulation. The walk-off length is $L_{\rm wo} = w_0/\tan\rho$, where w_0 is the Gaussian waist of the beam. We remind that for a sech-shaped pulse, the pulse energy $W_{\rm in} = \pi w^2_0 T_{\rm in} I_{\rm in}$, so if we take a 2 mJ pulse energy, then choosing $w_0 = 2.0$ mm gives the chosen intensity of Fig. 2(a). This choice gives $L_{\rm wo} = 40$ mm. If we had more pulse energy available we could expand the beam to increase $L_{\rm wo}$, but keep the same intensity. We can calculate how much pulse energy we need to avoid walk-off effects from Eq. (2) by requiring $z_{\rm opt} = L_{\rm wo}$ and get $W_{\rm in}\ ({\rm min}) = \tan^2\rho\, 0.44^2\pi^2\lambda_1 T^3_{\rm in}/[8k^{(2)}_1|n^I_{\rm eff}|]$, which holds for a sech-shaped pulse where $T_{\rm in} = T^{\rm FWHM}_{\rm in}/\ln(1+\sqrt{2})$. This requirement is shown in Fig. 1(b) for the BBO case, and we see that around 16 mJ input energy is needed for a 500 fs FWHM pulse. Much less energy is needed for lower input pulse durations. We finally mention that both problems could be solved by having several crystals in a row (increased length) and flipping the optical axis for each segment to compensate for the walk-off [15]. This is not an inexpensive or simple solution, though. We could also choose a crystal with much higher GVD, and we did that in Ref. [16] using type I interaction in lithium niobate (LN). LN has a

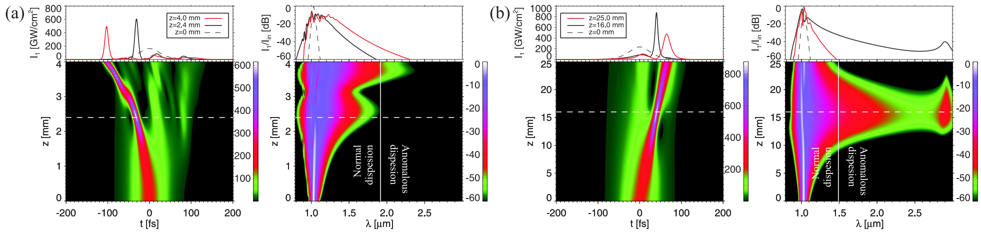

Figure 2. As Fig. 1 but taking $T_{\rm in} = 60$ fs FWHM and $N_{\rm eff} = 2.5$. (a) Cascaded soliton compression in noncritical LN with $I_{\rm in} = 160$ GW/cm^2, (b) in BBO with same settings as in Fig. 1(a) except for $I_{\rm in} = 235$ GW/cm^2. Parameters for the LN simulation can be found in Ref. [7].

huge GVD (5 times larger than BBO), but unfortunately compression in the stationary regime is not possible.

A noncritical (type 0) phase-matching configuration would eliminate the walk-off problem. We recently showed experimentally that LN in a type 0 $ee \rightarrow e$ interaction can compress pulses towards few-cycle duration: 50 fs FWHM pulses with $\lambda_1 = 1.3\ \mu$m were compressed to 16 fs in a 1 mm long crystal [7]. This was possible because of the huge GVD in LN. Unfortunately the Kerr nonlinearity was estimated to be $n^I_{\rm Kerr} = 30 \times 10^{-20}$ m^2/W and at $\lambda_1 = 1.03\ \mu$m we can only achieve $n^I_{\rm casc} = -22 \times 10^{-20}$ m^2/W so the effective nonlinearity is focusing and no solitons can form. This would be different if we use a much shorter input pulse. LN has namely a quite strong Raman response (we found in Ref. [7] a large Raman fraction $f_R = 0.51$, so the pure electronic Kerr nonlinearity is only around $n^I_{\rm Kerr,el} = 15 \times 10^{-20}$ m^2/W. For short input pulses we must namely replace the Kerr term in Eq. (1) with $(1 - f_R)U_1|U_1|^2 + f_R U_1 \int_{-\infty}^{\infty} dt' R(t')|U_1(\tau - t')|^2$. This means that the pure SPM term felt by the input pulse becomes $1 - f_R$ smaller, and this makes it possible to excite solitons since $n^I_{\rm eff} = n^I_{\rm casc} + (1 - f_R)n^I_{\rm Kerr} < 0$. Fig. 2(a) shows a simulation with $N_{\rm eff} = 2.5$ and using as input a 60 fs FWHM sech-shaped pulse from a hollow-fiber compressor. The pulse compresses after only 2.5 mm to 10 fs. Some pulse splitting is seen, which is due to Raman effects [7], and these also cause the spectrum to red shift. Compare this result with compression in BBO with a similar pulse in (b): the same pulse duration is achieved, but after 5 times longer propagation. Instead the lack of Raman effects gives a cleaner pulse.

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