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Compression limits in cascaded quadratic soliton compressors

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Abstract

Cascaded quadratic soliton compressors generate under optimal conditions few-cycle pulses. Using theory and numerical simulations in a nonlinear crystal suitable for high-energy pulse compression, we address the limits to the compression quality and efficiency.

Introduction

Soliton compressors are attractive because only a single nonlinear medium is needed to achieve many-fold pulse compression. In cascaded quadratic soliton compressors (CQSCs), soliton compression of high-energy fs pulses is possible, and few-cycle pulses can be reached in the near-infrared [1–6]. The cascaded quadratic nonlinearity is achieved by phase-mismatched second-harmonic generation (SHG), where the fundamental wave (FW) experiences a strong nonlinear phase shift from the cyclic energy transfer to the second harmonic (SH). Unique for the CQSC is that solitons exist with normal FW group-velocity dispersion, because the effective cubic nonlinearity induced by the cascaded SHG can be made self-defocusing [1]. Consequently, the CQSC can compress arbitrarily high-energy pulses, and soliton compression may occur even in the near-infrared where the absence of anomalous dispersion prevents traditional soliton compressors to work. It is well known that in the stationary regime clean compression is possible in the near-infrared [1–6]. The cascaded quadratic nonlinearity imposes a temporal nonlocal response on the FW, with the nonlocal response functions

\[ R_+ (\tau) = \frac{\tau_0^2 + \tau_0^2}{2\tau_0^2} \exp\left(-is_0 \tau/\tau_0\right) \exp(-|\tau|/\tau_0), \]

(2)

\[ R_-(\tau) = \frac{\tau_0^2 - \tau_0^2}{2\tau_0^2} \exp(-is_0 \tau/\tau_0) \sin(|\tau|/\tau_0) \]

(3)

where the dimensionless nonlocal time scales \( \tau_0 \) and \( \tau_0 \) depend on the FW and SH dispersion. According to the nonlocal theory the GVM effects dominate for \( \Delta k < d_{12}^2/2k_2 \) : this nonstationary regime is controlled by the oscillatory response function \( R_+ \). For \( \Delta k > d_{12}^2/2k_2 \) the cascaded nonlinearities dominate: this stationary regime is controlled by the localized response function \( R_+ \).

Weakly nonlocal limit

In the weakly nonlocal limit, where the nonlocal response is much faster than the response of \( U_1^2 \), Eq. (1) can be approximated as [6]

\[ [i\partial_\tau - \frac{1}{2}\partial_\tau^2] U_1 - N_{\text{eff}} U_1 U_1^2 \]

(4)

where \( N_{\text{eff}} = (N_{\text{SHG}}^2 - N_{\text{Kerr}}^2)^{1/2} \) is above unity. \( N_{\text{eff}} \) also controls the compressor performance through the NLSE-like scaling laws [5]. The RHS gathers two detrimental terms: (1) A GVM-induced Raman-like perturbation with a characteristic dimensionless time \( \tau_{\text{R,SHG}} \equiv 2|d_{12}/\Delta k|T_0 \), (2) A GVM-induced term \( U_1^2 \rho(\tau, U_1) \) containing oscillatory components with periods dictated by \( \tau_0 \) and \( \tau_0 \), which explains the trailing oscillations often observed in the nonstationary regime, see Fig. 1(a) for \( \Delta k = 30 \text{nm}^{-1} \), \( \rho(\tau, U_1) \) is caused by the oscillatory nature of \( R_- \), so it appears only in the nonstationary regime. The RHS of Eq. (4) holds another insight: for a given \( \Delta k \), increasing \( N_{\text{SHG}} \) by increasing...
the intensity does not necessarily lead to better compression because the Raman-like term, which causes strong pulse asymmetry and soliton splitting, scales as $N_{\text{SHG}}^2$. Similarly in the nonstationary regime, the detrimental oscillatory term $U_1^\dagger \rho(t, U_1)$ also scales as $N_{\text{SHG}}^2$.

**Numerical results and discussion**

Fig. 1 shows numerics all having the same soliton order $N_{\text{eff}} = 8$. Thus, the 200 fs input pulse should in all cases be compressed to 6.0 fs [5]. This is indeed observed in the stationary regime for $\Delta k = 50 \text{ mm}^{-1}$. For larger $\Delta k$, still in the stationary regime, Kerr XPM gradually degrades compression. For smaller $\Delta k$ the transition to the nonstationary regime is approached ($\Delta k = 43 \text{ mm}^{-1}$), where pulse compression is limited by the nonlocal time scale $t_b = \tau_b T_0$. In the nonstationary regime ($\Delta k < 42$), pulse compression degrades due to increasing Raman-like effects ($\tau_{R, \text{SHG}} \propto \Delta k^{-1}$), and to slow trailing oscillations (evident for $\Delta k = 30 \text{ mm}^{-1}$), caused by the GVM-induced oscillatory term $\rho$ in Eq. (4). All simulations have a FW peak around 3 $\mu$m, which is a dispersive wave phase-matched to the FW soliton, causing the fast trailing oscillations for $\Delta k = 50, 43, 41 \text{ mm}^{-1}$; these prevent reaching single-cycle pulses for larger $N_{\text{eff}}$. In the nonstationary regime a distinct red-shifted peak appears in the SH spectrum at a frequency $\Omega +$ determined by the nonlocal theory. In turn, close to the transition ($\Delta k = 41 \text{ mm}^{-1}$) the FW has a corresponding spectral hole at $\Omega +$, while further away ($\Delta k = 30 \text{ mm}^{-1}$) it becomes a spectral peak. We show in Fig. 1(d) the red-shifted holes/peaks found numerically versus $\Delta k$, with an impressive agreement with the nonlocal theory.

**Conclusions**

In summary the compression limits in the nonstationary regime are the GVM-induced Raman-like effects and oscillatory components. In the stationary regime the GVM-induced Raman-like effects, nonlocal effects, competing cubic nonlinearities and XPM effects, and dispersive waves, which only exist when taking into account higher-order dispersion, all limit compression.

**References**


Fig. 1: Soliton compression with $N_{\text{eff}} = 8$ of a 200 fs FWHM $\lambda_1 = 1064$ nm pulse in a BBO crystal. (a) FW time plot, (b) the FW and (c) SH spectra at the optimal compression point. (d) The red-shifted spectral peaks in the nonstationary regime from numerics (symbols) and nonlocal theory (lines). The full coupled SHG equations are used, including self-steepening on all nonlinear terms and higher-order dispersion.