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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 generation (SHG), where the fundamental wave (FW) and SH dispersion. According to the nonlocal theory the GVM effects dominate for \(\Delta k < d_{12}^2/2k_2(2)\): this nonstationary regime is controlled by the oscillatory response function \(R_-\). For \(\Delta k > d_{12}^2/2k_2(2)\) 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]

\[
[i\partial_{\tau} - \frac{1}{2}\partial_{\tau\tau}] U_1 - N_{\text{eff}}^{(2)} U_1^2 |U_1|^2 = N_{\text{SHG}}^2 [i\sigma_{\text{R,SHG}} U_1^2 \partial_{\tau} U_1 + \frac{1}{2} s_b U_1^* \rho(\tau, U_1)],
\]

where \(s_b = 1\) \((s_b = -1)\) in the stationary (non-stationary) regime, and \(s_0 = \text{sgn}(d_{12}k_2(2))\). The LHS is an NLSE supporting solitons if the effective soliton order \(N_{\text{eff}} = (N_{\text{SHG}}^2 - N_{\text{Kerr}}^2)^{1/2}\) is above unity. \(N_{\text{eff}}\) also controls the compressor performance through the NLSE-like scaling laws [5]. The RHS gathering 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 \(U_1^* \rho(\tau, U_1)\) containing oscillatory components with periods dictated by \(\tau_0\) and \(\tau_{\text{SHG}}\), which explains the trailing oscillations often observed in the nonstationary regime, see Fig. 1(a) for \(\Delta k = 30 \text{ mm}^{-1}\), \(\rho(\tau, U_1)\) 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 $\rho(t, U_1)$ 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 ($\tau_{TR,\text{SHG}} \propto \Delta k^{-1}$), 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 $\Omega_+ \text{+}$ 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 $\Omega_+ \text{-}$, 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 $\lambda_1 = 1064 \text{ nm}$ 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.