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Cascaded quadratic soliton compression of high-power femtosecond fiber lasers in Lithium Niobate crystals

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Summary

The output of a high-power femtosecond fiber laser is typically 300 fs with a wavelength around λ = 1030 − 1060 nm. Our numerical simulations show that cascaded quadratic soliton compression in bulk $LiNbO_3$ can compress such pulses to below 100 fs.

Introduction

The major part of near-IR fs fiber laser oscillators (using, e.g., Yb-doped fibers as gain medium) deliver pulses that are $>$ 100 fs. In particular high-power fiber lasers and amplifiers deliver around 300 fs pulses, and external compression using e.g. grating pairs is needed in order to obtain shorter pulses. We propose an alternative based on the cascaded quadratic soliton compressor (CQSC), which is an extremely simple and flexible method (see Fig. 1): The laser pumps a quadratic nonlinear crystal where phase-mismatched second-harmonic generation (SHG) occurs. Due to the cascaded energy transfer from the pump (fundamental wave, FW) to the second harmonic (SH), the FW experiences a strong Kerr-like nonlinear phase shift, whose sign can be made self-defocusing. Thereby soliton compression becomes possible with normal dispersion [1], and allows this soliton compressor to work also in the visible and near-IR [2]. Here we seek to compress 300 fs near-IR pulses in a bulk lithium niobate ($LiNbO_3$, LN) nonlinear crystal. As we will show with numerical simulations, in such a setup high-energy pulses (μJ–multi-mJ energy level) can be compressed to below 100 fs.

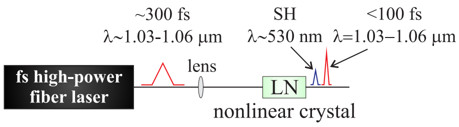

Fig 1. Schematic of the cascaded quadratic soliton compressor for compressing fs near-IR pulses from a fiber laser: the pump generates pulses of $\sim$ 300 fs duration, and upon propagation in the nonlinear crystal the phase-mismatched SHG process compresses the FW to below 100 fs.

Cascaded quadratic nonlinearities in lithium niobate

LN is a widely used quadratic nonlinear crystal for frequency conversion in the IR, while in the near-IR it is less commonly used for SHG because the SH (located in the visible) becomes very dispersive; thus, the group-velocity mismatch (GVM) between the FW and SH is very large. This gives a poor CQSC performance unless the input intensity is kept very low, which in turn implies that the compression occurs over large propagation distances. Here LN in the near-IR becomes advantageous because of its large group-velocity dispersion (GVD), so the pulse can compress in a realistic crystal length. LN is attractive due to extremely large nonlinearities in a type 0 SHG configuration, where adequate phase matching has to be achieved by quasi-phase matching (QPM). However, LN can also be used in a type I (oo→e) configuration, where birefringent phase matching is possible. A drawback is that the quadratic nonlinear tensor components are almost an order of magnitude smaller than the d_{33} component used for type 0. However the flexibility of the type I configuration makes it attractive for our purpose, and we will show that compression to sub-100 fs in the near-IR is possible.

The CQSC performance is mainly determined by the phase mismatch and the GVM (zero and first order dispersion) [4, 5]. Because LN has such a large GVM when pumped at 1060 nm, the CSQC is in the so-called *nonstationary regime* [4, 5], where Raman-like effects from GVM severely distort the solitons. However, the CQSC performance is determined by the effective soliton order $N_{\rm eff}^2 = N_{\rm SHG}^2 - N_{\rm Kerr}^2$ related to the difference between the soliton orders from the cascaded nonlinearities and the detrimental Kerr self-focusing nonlinearity [3]. And if $N_{\rm eff}$ is low enough, the GVM effects are less severe. The problem with lowering $N_{\rm eff}$ is that pulse compression occurs after increasing propagation lengths, but due to the high GVD of LN this length is reduced. In fact, as shown in Fig. 2(a) the 300 fs input pulse compresses to 90 fs after 100 mm propagation in a LN crystal (a realistic crystal length). The distorted temporal profile in Fig. 2(c) of the weak SH is caused by nonlocal effects that induce the spectral peak/hole at $\Omega = -120$ THz [see also Fig. 2(b)]. This frequency can be predicted using nonlocal theory [5], and is a consequence of the strong GVM effects in the nonstationary regime. The input pulse has $N_{\rm eff} = 1.7$, and for a larger $N_{\rm eff}$ the Raman-like GVM effects increase, and for a smaller $N_{\rm eff}$ the compression becomes weaker and will occur after longer propagation. The phase mismatch $\Delta k = 60$ mm^{-1} was chosen because a smaller Δk would lead to increased GVM effects and for $\Delta k > 82$ mm^{-1} no solitons can be excited. The input pulse is assumed to be de-focused enough to avoid transverse effects by making the Rayleigh length much longer than the crystal length: the pulse energy required to achieve this is around $10 - 20$ μJ. Note that the effective nonlinearity is defocusing, so there are no self-focusing problems, and the optimal soliton order can be achieved by adjusting the spot size as to tune the intensity of the input beam or by adjusting the phase mismatch. This large flexibility makes the CQSC using LN attractive for compressing high-energy fs pulses to the sub-100 fs regime.

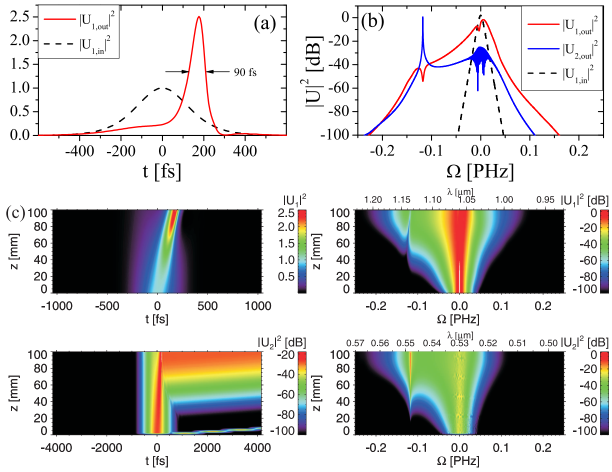

Fig 2. Numerical simulation of cascaded quadratic soliton compression in LN (congruent melt) with $\lambda_1 = 1060$ nm, $T_{\rm in}^{\rm FWHM} = 300$ fs, $\Delta k = 60$ mm^{-1} and $I_{\rm in} = 13.6$ GW/cm^2 (implying $N_{\rm eff} = 1.7$). The FW pulse compresses to ~ 90 fs (FWHM) after propagating 100 mm. App. 4% is converted to the SH. $|U_j|^2$ are normalized to the peak input intensity.

Conclusions

To conclude, 300 fs pulses at 1060 nm from a high-power fs fiber laser can be compressed to below 100 fs by phase-mismatched type-I SHG in a bulk lithium niobate crystal. An improvement can be expected in an optimized type-0 QPM configuration.

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