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Soliton-Effect Optical Pulse Compression in Bulk Media with $\chi^{(3)}$ Nonlinearity

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Abstract

Self-compression of visible optical pulse in bulk $\chi^{(3)}$ medium has been demonstrated taking the advantage of negative group-velocity dispersion of tilted pulses.

Keywords: temporal solitons, tilted pulses, self-phase-modulation, pulse compression

1 Introduction

Optical pulse compression is well-established technique for powerful ultrashort pulse generation. The technique is based on the pulse chirping in the nonlinear media and the chirp compensation utilizing dispersion obtained by gratings or prisms. Using bulk (free of aperture limitations) materials, pulse chirping under positive group-velocity dispersion (GVD) and compression was demonstrated more than a decade ago [1]. An alternate approach is to combine self-phase-modulation (SPM) and negative GVD utilizing the soliton compression effect. Experimental evidence of soliton-effect pulse compression dates back to early 80`s and was preferably studied in optical fibers with negative GVD [2,3]. A combination of SPM and negative GVD in bulk materials has been only considered theoretically in the sense of generation of “light bullets” [4] and directed to the case of wavelengths of around 1.5 μm that reach an anomalous dispersion region for fused silica and glass. However, the method is not widely applied for the pulse compression because of limited wavelength range (~1.5μm) and absence of well-developed laser sources emitting at this wavelength range.

Recently, temporal soliton formation was achieved in visible [5] and near IR [6] by use of tilted-front pulses and exploiting $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities of the optical crystals. More extended theoretical study [7] pointed that the negative GVD condition is readily achievable for a wide range of wavelengths and optical materials by appropriate pulse-front tilting. Moreover, it has been shown that pure $\chi^{(3)}$ nonlinearity also contributes for the temporal soliton formation along with $\chi^{(2)}$ nonlinearity being the driving one.

2 Numerical Model and Computer Simulation

The pulse propagation in a dispersive medium with instant $\chi^{(3)}$ nonlinearity is governed by the nonlinear Shroedinger equation that in one-dimensional case can be expressed as

$$\frac{\partial A}{\partial z}+\frac{1}{u}\frac{\partial A}{\partial t}-\frac{i}{2}g\frac{\partial^2 A}{\partial t^2}=in_2k_0\left|A\right|^2 A, \qquad (1)$$

where u is the pulse group velocity, $g=(d^2k/d\omega^2)\big|_{\omega=\omega_0}$ is the GVD coefficient, ω_0 is the carrier frequency, $k_0=\omega_0/c$ is the wave number and $n_2=(2\pi/n_0)\chi^{(3)}$ is the nonlinear refraction index satisfying the equation $n=n_0+n_2I$ with I being the applied intensity.

The light pulse is called tilted when it possesses a temporal delay across the transverse coordinate [8]. This means that the pulse front (the surface of constant intensity at a fixed time) is not parallel to the phase front (the surface of constant phase at a fixed time) and hence is not perpendicular to the direction of propagation. Usually the pulse front tilt is obtained by use of optical elements that introduce an angular dispersion, i.e. diffraction gratings or prisms. The GVD coefficient of the medium is then

$$g_T=g-\frac{1}{k_0}\left(\frac{\tan\alpha}{u}\right)^2, \qquad (2)$$

where subscript T refers to the tilted pulse, and α is the pulse-front tilt angle.

In Ref. 7 it was shown that in the large-beam approximation the propagation of a tilted pulse could be described by the Eq.1 with modified dispersion of the medium, according to the effective values given in Eq.2.

Obviously, the pulse-front tilting results in a material dispersion compensation or even in the anomalous dispersion. Fig. 1 illustrates the GVD coefficient of BK7 glass versus the tilt angle α for 527-nm, τ=165 fs pulses. The tilt angles starting from ~13 deg result in anomalous dispersion of BK7 glass (negative GVD coefficient). The nonlinear refractive index for BK7 glass

n_2=2.8×10^{-20} m^2/W was taken from Ref. 9. If the pulse intensity is high enough for SPM to occur, these

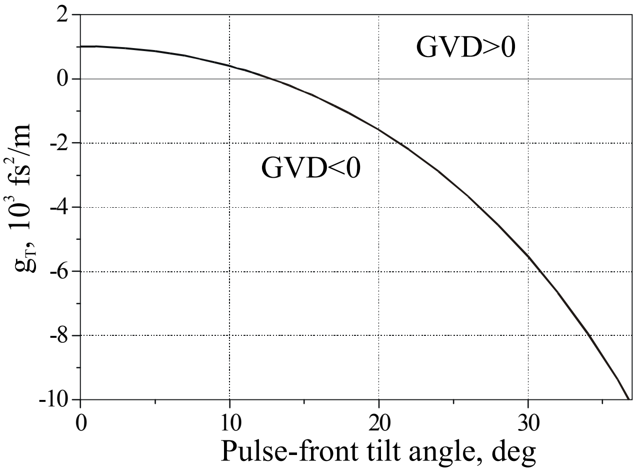

Fig. 1.Group velocity dispersion coefficient of BK7 glass as function of the pulse-front tilt angle α, calculated for 165-fs pulses.

conditions are supposed to cause a soliton-effect pulse compression. The main differences as compared to the optical fiber case are the following: 1) the pulse propagates freely without aperture limitation; 2) negative group velocity dispersion is predetermined by the pulse tilt rather than by the material dispersion; 3) due to angular dispersion the tilted pulses will not periodically reconstruct the temporal shape while propagating in the media.

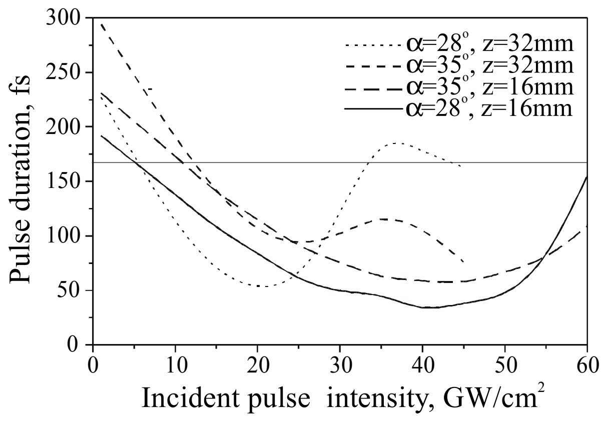

Fig. 2. Pulse duration dependence on the incident intensity for different pulse-front tilt angles and media length z.

The simulations were performed by numerically solving Eq.1 in the plane wave approximation. Results of numerical simulations are presented in Fig.2. For low

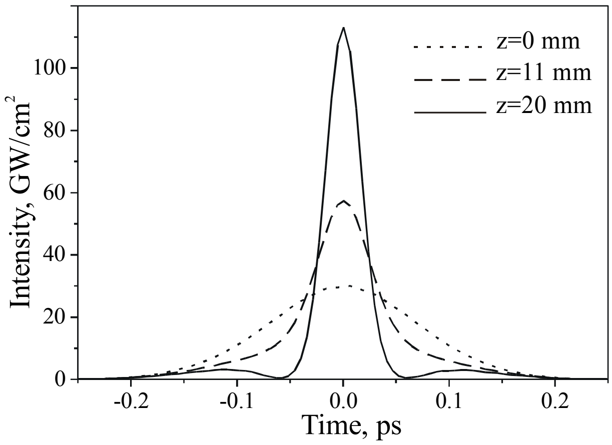

Fig. 3. Transformation of the pulse profile during the propagation though BK7 glass. Incident pulse front is tilted by 28 deg and I=30 GW/cm^2.

intensity pulses the negative GVD dominates over the SPM, and the result is pulse dispersive broadening. By increasing the input intensity the SPM drives the pulse to compress and at certain input intensity the SPM and negative GVD compensate for each other resulting in chirp-free short (<50 fs) pulse. Further intensity increasing leads to formation of higher order solitons. The typical transformation of pulse temporal profile is shown in Fig.3.

3 Experiment

The 165-fs pulse at 527 nm were delivered by fiberless CPA Nd:glass laser (*TWINKLE*, Light Conversion Ltd.), equipped by the nonlinear SH pulse compressor [10]. The output beam has diameter of 6 mm at FWHM and total energy of 3 mJ. The input pulse was tilted by 600 mm^{-1} diffraction grating operating at second diffraction order close to Littrow condition. The grating G1 was imaged by a telescope T1 onto the input face of 16-mm-long BK7 slab with beam size reduction factor of 1.66. The groove spacing of the grating and telescope magnification were chosen to achieve a tilt angle of 35 deg inside the glass slab. The identical set of optics was used for canceling the pulse-front tilt. The spacing between gratings and imaging optics was aligned for zero dispersion; it was justified by comparing input and output pulsewidths. In the presence of BK7 slab, the rear part of the setup (i.e. telescope T2 and grating G2 which were used to restore the untilted pulse) was realigned to image the exit face of the BK7 slab onto the second grating. In that way the net dispersion of whole arrangement was set by the dispersion produced through the pulse-front tilting as derived from Eq.2. The accessible range of intensities with all factors accounted (grating diffraction efficiency, beam-size reduction by imaging telescope, etc.) was up to 50 GW/cm^2.

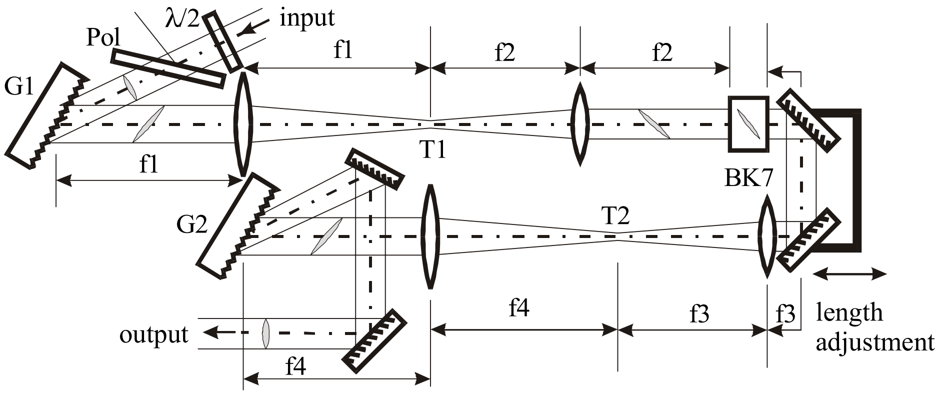

Fig. 4. Experimental setup. G1, G2 diffraction gratings; f1=f4=500 mm, f2=f3=300 mm, λ/2 half-wave plate, P polarizer, for the incident intensity adjustment.

With increasing the incident pulse intensity, spectrum broadening and pulse self-compression were observed. At the pump intensity of ~35 GW/cm^2 the compression yielded a pulse with autocorrelation width of 135 fs, see Fig. 5. Assuming the autocorrelation/pulsewidth factor of 1.4, which was obtained by numerical modelling, the duration of the self-compressed pulse was evaluated to be 95 fs. The Fourier transform of the measured spectrum revealed almost the same value, pointing to absence of the residual chirp. Qualitatively the pulsewidth dependence on the incident intensity followed the theoretical predictions; however, the observed pulses had somewhat longer duration. The duration of the compressed pulse versus the input intensity is depicted in Fig. 6.

The quantitative discrepancies between the numerics and the experiment may be explained as follows. At higher intensities (>40 GW/cm^2) spatially dispersed white light continuum was observed. The theoretical model also does not take into account the effect of stimulated Raman scattering whose impact may be more complex than just loss of intensity [11]. Another nonlinear process that was not taken into account was the two-photon absorption. For high intensities (above 25 GW/cm^2) nonlinear losses consumed up to 20 % of the incident pulse energy. These three aforementioned processes exhibit complex nonlinear loss mechanism and affect mostly the top of the pulse, which leads to the increase of pulse duration.

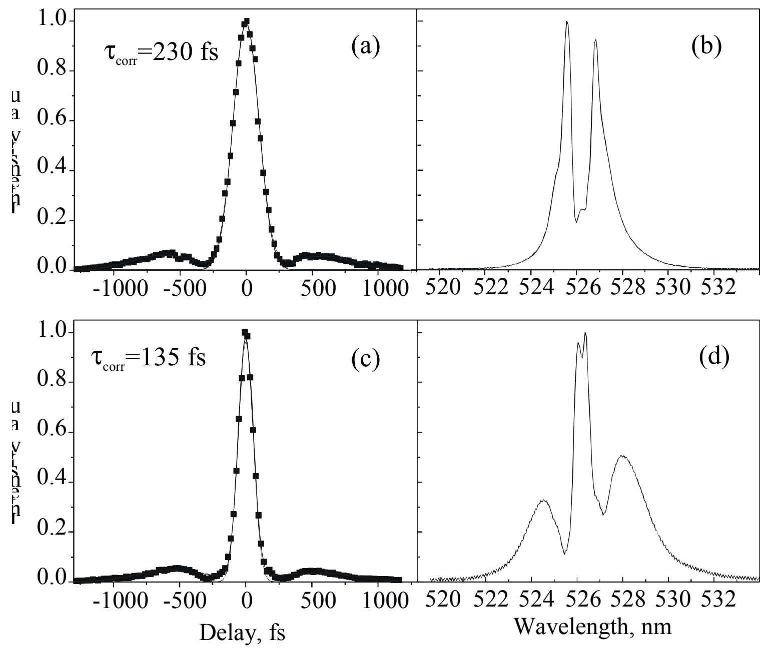

Fig. 5. Autocorrelation traces and spectra of incident (a), (b) and self-compressed (c), (d) pulses. The incident pulse spectrum (b) with two peaks is the characteristic one for nonlinear SH pulse compression [9].

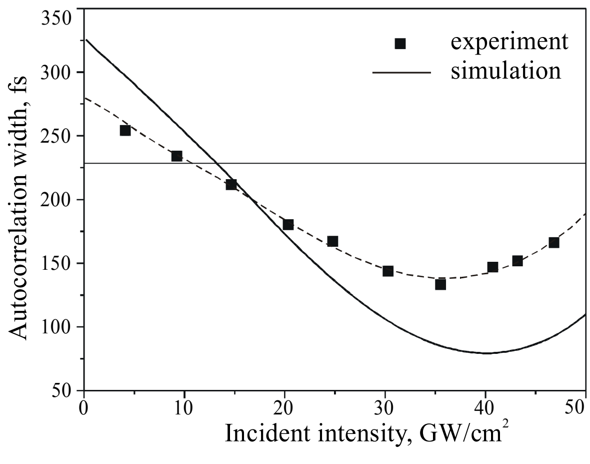

Fig. 6. Autocorrelation width dependence on the incident intensity.

Another shortcoming of the theoretical model is that it does not take into account the spatial distribution of the beam (plane-wave model was used). At finite beam diameter and near Gaussian intensity distribution high intensity beam must experience some onset of self-focusing. This means that the direction at which a particular spectral component propagates depends not solely on its wavelength but also on the curvature of spatial intensity profile at the spot it originates from.

In conclusion, the soliton-effect pulse compression in bulk $\chi^{(3)}$ medium has been experimentally demonstrated. Anomalous dispersion for 527-nm pulses in BK7 glass was achieved by an appropriate pulse-front tilting. Compression of 165-fs Nd:glass second-harmonic pulse down to 95 fs was observed.

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