Compression of picosecond light pulses of a hybridly mode-locked pulsed Nd:glass laser

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Intra-cavity self-phase modulated pulses of an active-passive mode-locked pulsed Nd:phosphate glass laser are compressed from approximately 5 ± 1 ps to approximately 0.7 ± 0.3 ps by a grating-pair arrangement.

1. Introduction

The frequency chirping by self-phase modulation [1–10] and the subsequent compression by dispersive (gratings [11–20], prisms [19–24], grating-prism combinations [20,25,26]) or absorptive (gain bandwidth limiting [27–33]) arrangements is widely applied to shorten picosecond or femtosecond light pulses. So far the shortest optical pulses (wavelength around 620 nm) of 6 fs duration have been generated by chirping pulses (input duration ≈ 50 fs) in a single-mode optical fiber and subsequently compressing them in a grating pair and four prism arrangement [25,26]. The additional insertion of spatial amplitude and phase filters in a dispersive compressor allows a tailored pulse shaping (beat pattern formation) [34–36].

In pulsed mode-locked Nd:glass lasers self-phase modulation occurs already in the laser oscillator ([37–39] and references therein). Only in the early part of the pulse train the pulses are bandwidth limited. Towards the end of the train they broaden considerably and approach the spectral bandwidth of the gain medium.

In this paper we study the temporal compression of self-phase modulated pulses in a grating-pair compressor. For pulses slightly beyond the pulse train maximum (duration ca. 5.3 ± 1 ps) we achieved a compression down to 0.7 ± 0.3 ps. The compression of pulses of a cw mode-locked and regenerative amplified Nd:phosphate glass laser has been reported earlier [40,41]. In this case self-phase modulation occurred in the regenerative amplifier. The temporal compression of intra-cavity self-phase modulated pulses of a pulsed active–passive modelocked Nd:YAG laser was reported in ref. [42].

2. Experimental

In the experiments a Nd:phosphate glass laser oscillator (Schott laser glass type LG703) is actively modelocked by an acousto-optic modulator [43,44] (IntraAction Model ML-50Q, 50 MHz acoustic frequency, 325 kHz mode-spacing) and passively modelocked by a saturable absorber [37–39,45] (Kodak dye No. 9860, single pass small signal transmission $T_0 = 0.85$). The acousto-optic modulator resonance frequency is tuned to the laser round-trip frequency by temperature adjustment. Single pulses are selected from the generated pulse train by a Kerr cell shutter which is operated by a laser triggered spark gap [46]. The temporal switching position is varied by the length of a coaxial cable between the spark gap and the Kerr cell. The selected pulses are increased in energy by passing twice through a Nd:phosphate glass amplifier. The pulses are injected to and ejected from the amplifier by a polarizer and a quarter waveplate.

The gratings of the compressor are classically ruled with $g = 600$ grooves per mm and they have a blaze angle of 26°45′. The ruled area is 26 mm × 36 mm.

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The gratings are operated in the -1st diffraction order. In the compression experiments the angle of incidence was $\theta_i = 30°$ and the grating distance was $d = 25$ cm. The laser light transmission in a complete double passage through the grating-pair–mirror assembly was measured to be 0.33 (light polarization is perpendicular to the plane of incidence).

The spectral distributions of the pulses before and behind the compressor were measured with two spectrometers and linear diode-array detectors. The durations of the compressed pulses were determined by the two-photon fluorescence technique [47]. The fluorescence traces were recorded with a SIT-vidicon (optical spectrum analyser of BuM Spektronik).

3. Results

The spectral width $\Delta\tilde{\nu}$ (fwhm) and the duration Δt_{in} of the laser pulses along the pulse train are plotted in figs. 1b and c, respectively. The shape of the pulse train is indicated in fig. 1a. The spectral width increases continuously along the pulse train due to the cumulative action of the self-phase modulation [1–10,39]. The pulse durations are slightly broadened along the pulse train due to two-photon absorption of the Nd^{3+} ions [39,48].

The pulse durations Δt_{out} of the compressed pulses as a function of the input spectral width $\Delta\tilde{\nu}$ are presented in fig. 2. For the applied grating arrangement the optimum shortening is obtained for $\Delta\tilde{\nu}^{opt} \approx 75$ cm^{-1}. At $\Delta\tilde{\nu}^{opt}$ the pulse duration scatters around 0.7 ps. The shortest measured duration was $\Delta t_{out}^{min} \approx 0.3$ ps. The scatter of the compressed pulse durations is mainly due to the scatter of the input pulse durations.

Two-photon fluorescence traces of an input pulse and a compressed pulse ($\Delta\tilde{\nu} \approx 70$ cm^{-1}) are shown in fig. 3.

The spectral shapes of the pulses before and behind the grating compressor are the same within the experimental accuracy. Two typical sets of spectra along the pulse train are shown in figs. 4 and 5. The spectra in fig. 4 remain a peak at the central wavelength. Such spectra are expected if the pulses become modulated temporally [49]. The combined action of self-phase modulation and spectral hole-burning in the inhomogeneously broadened gain medium may lead to a temporal pulse modulation towards the end of the pulse train [39,50]. The spectra of fig. 5 are characteristic of smooth temporal pulses [49]. The asymmetry of the spectral broadening compared to the central frequency position ($\lambda_L = 1054$ nm) reflects a temporal pulse asymmetry (difference in rising and trailing shape of the pulse, see fig. 27 of [39]).

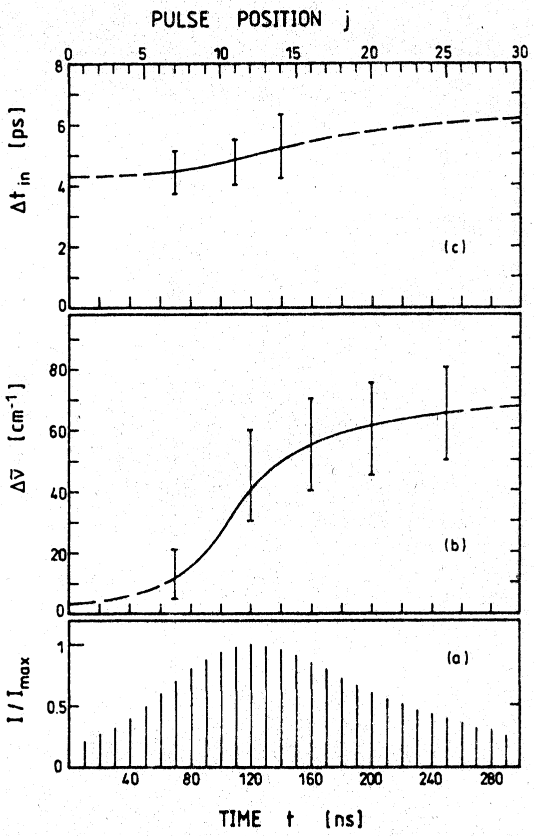

Fig. 1. Temporal and spectral pulse development along pulse train. (a) Pulse shape. (b) Spectral width. (c) Pulse duration.

4. Discussion

The intensity dependent refractive index variation of the components of the laser oscillator causes the self-phase modulation. The phase shift is $\phi(t) \propto \Delta n(t) \propto L_L(t)$ (Δn is the refractive index variation;

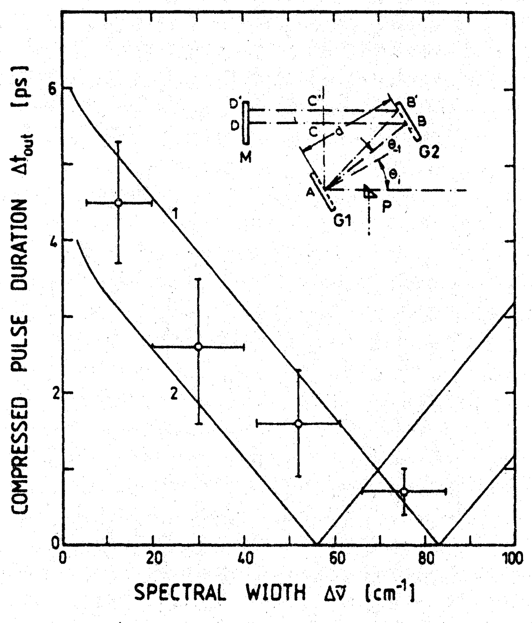

Fig. 2. Pulse shortening as a function of the spectral pulse width $\Delta\tilde{\nu}$ ($\Delta\tilde{\nu}=\Delta\tilde{\nu}_{in}=\Delta\tilde{\nu}_{out}$). Grating distance $d=25$ cm. Angle of incidence $\theta_i=30°$ (600 lines per mm). Circles are experimental averages. The curves represent Δt_c (eq. (5)) versus $\Delta\tilde{\nu}$ (eq. (7)) for $\Delta t_{in}=6$ ps (1) and 4 ps (2). The inset shows grating pair arrangement. G1 and G2, gratings. M, mirror. P, deflection prism.

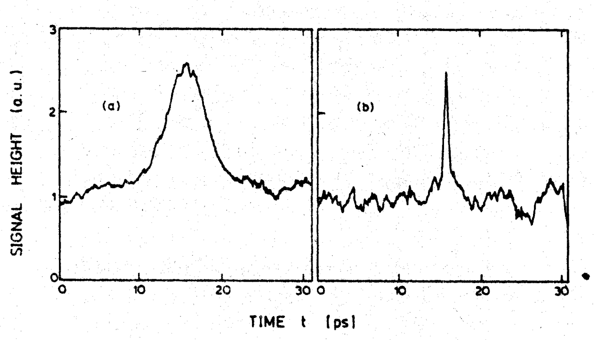

Fig. 3. Two-photon fluorescence traces of an input pulse (a) and a compressed pulse (b). $\Delta\tilde{\nu}_L\approx 70$ cm^{-1}. Grating arrangement as in fig. 2.

I_L is the laser intensity) [1–10]. The laser carrier frequency chirps according to $\nu(t)-\nu_0=-(2\pi)^{-1}(\partial\phi/\partial t)$. The spectral broadening $\Delta\nu_{br}$ due to self-phase modulation is $\Delta\nu_{br}=(\nu-\nu_0)_{max}-(\nu-\nu_0)_{min}$. The spectral shape of self-phase modulated pulses is structured by interference [51]. The various spectral components of the self-phase modulated pulses have different transit times through the grating compressor.

In the inset of fig. 2 the rays for the frequencies ν (passage along A, B, C, D) and $\nu'=\nu+\Delta\nu$ (passage along A, B′, C′, D′) are shown. The diffraction angles $\theta_{-1}(\nu)$ and $\theta_{-1}(\nu')$ are governed by the grating equation [12]

$$a(\sin\theta_m-\sin\theta_i)=m\lambda=m/\tilde{\nu}\,, \tag{1}$$

with the diffraction order $m=-1$; $a=g^{-1}$ is the groove spacing. The path length difference between ν' and ν in a double passage is

$$\Delta L=2(\overline{AB'}+\overline{B'C'}-\overline{AB}-\overline{BC})$$

$$=2d\left(\frac{1+\cos[\theta_i+\theta_{-1}(\nu')]}{\cos[\theta_{-1}(\nu')]}-\frac{1+\cos[\theta_i+\theta_{-1}(\nu)]}{\cos[\theta_{-1}(\nu)]}\right), \tag{2}$$

and the time lag is

$$t_{lag}=\Delta L/c_0\,. \tag{3}$$

d is the grating distance and c_0 is the speed of light in vacuum. For our grating assembly the time lag per 1 cm grating distance and 1 cm^{-1} wavenumber difference is -2.85 fs ($g=600$ min^{-1}, $\theta_i=30°$).

A crude estimate of the pulse duration behind the grating pair is obtained by

$$\Delta t_{out}=\max(\Delta t_c,\Delta t_u)\,, \tag{4}$$

with the compressed time

$$\Delta t_c=|\Delta t_{in}+t_{lag}|\,, \tag{5}$$

and the uncertainty limit

$$\Delta t_u\approx(\Delta\nu_{br}+\Delta t_{in}^{-1})^{-1}\,, \tag{6}$$

where Δt_{in} is the incident pulse duration.

The spectral width of the incident self-phase modulated pulse is

$$\Delta\tilde{\nu}=[(\Delta\tilde{\nu}_{br})^2+(\Delta\tilde{\nu}_{bwl})^2]^{1/2}\approx\Delta\tilde{\nu}_{br}\,, \tag{7}$$

$\Delta\tilde{\nu}_{bwl}=\kappa/(\Delta t_{in}c_0)$ is the spectral width of a bandwidth limited pulse (no self-phase modulation). For gaussian pulses the constant κ is given by $\kappa=0.441$ [52]. Δt_c curves are plotted in fig. 2 for input pulse

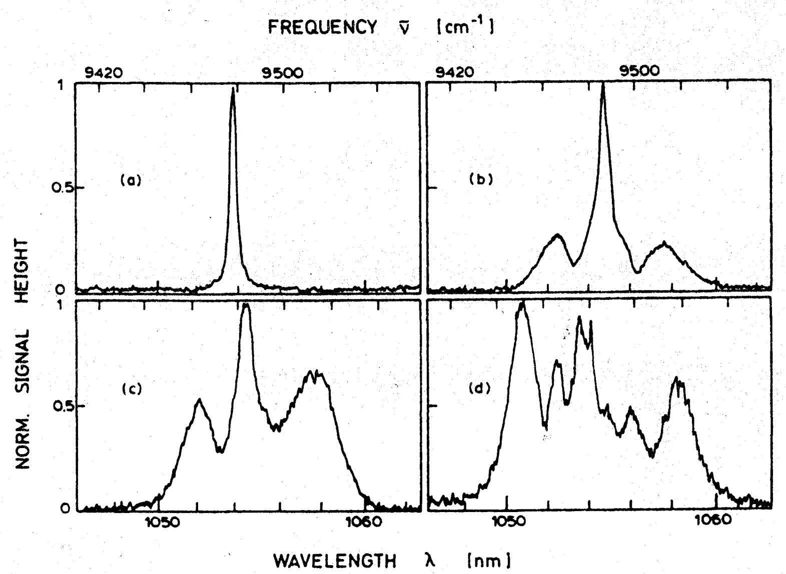

Fig. 4. Spectral pulse shapes along pulse train. Shapes indicate slight temporal modulation of the pulses (substructure). The switching positions according to fig. 1 are (a) $j=0$, (b) $j=4$, (c) $j=5$, and (d) $j=20$.

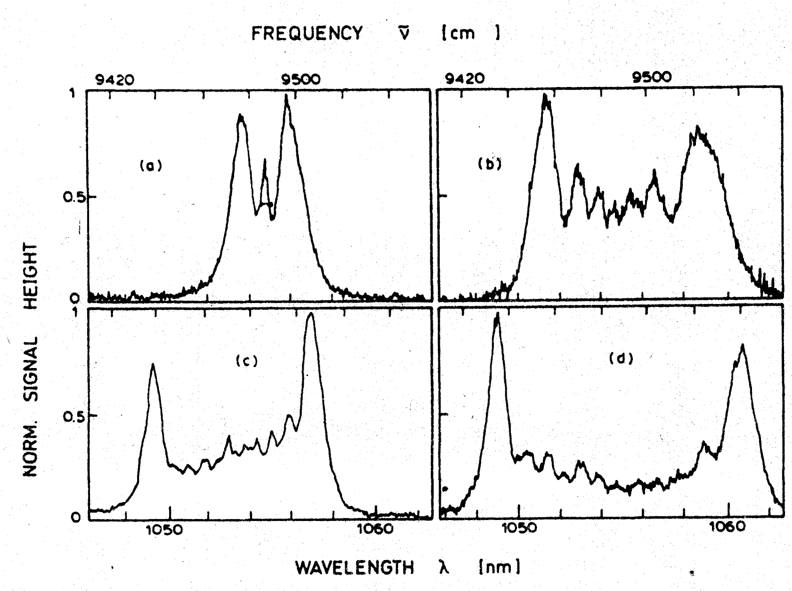

Fig. 5. Spectral pulse shapes along pulse train. Shapes indicate smooth temporal profile. The switching positions according to fig. 1 are (a) $j=6$, (b) $j=10$, (c) $j=16$, and (d) $j=20$.

durations of 4 ps and 6 ps.

An accurate analysis of the temporal and spectral pulse reshaping in a grating-pair compressor by fast Fourier-transformation is given elsewhere [49].

5. Conclusions

The temporal compression of intra-cavity self-phase modulated picosecond light pulses of a Nd-phosphate laser in a grating-pair arrangement was studied. The shortest compressed duration was $\Delta t_{min} \approx 0.3$ ps. The shot-to-shot pulse durations fluctuate somewhat because of the fluctuation of the input pulse durations and spectral widths. The spectral shapes of the self-phase modulated pulses are not changed in the grating-pair compressor. The laser has to be operated at the fundamental transverse mode in order to avoid a variation of the self-phase modulation and a subsequent variation of the pulse compression across the spatial beam profile.

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