Tuning the output parameters of a femtosecond oscillator with an intracavity prism pair and an external sequence of chirped mirrors

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It is natural for experimentalists to desire to fully explore the capabilities of their lasers, and to use them to their full potential in subsequent experiments. In the case of laser oscillators with resonators constructed with chirped mirrors [1] and/or completely sealed, these possibilities are quite limited. On the contrary, in classical femtosecond oscillators containing pair of prisms for intracavity dispersion control [2-4], this is possible and relatively simple. This is also the likely situation at the first stage of development of a home-built femtosecond oscillator. A prerequisite of course is, that the necessary diagnostic equipment is available. This paper is devoted to a detailed characterization of a Ti:sapphire Kerr-lens mode-locked femtosecond laser oscillator with an intracavity prism pair and an external sequence of chirped mirrors [5,6] to fully exploit the possibilities of tuning its output parameters.

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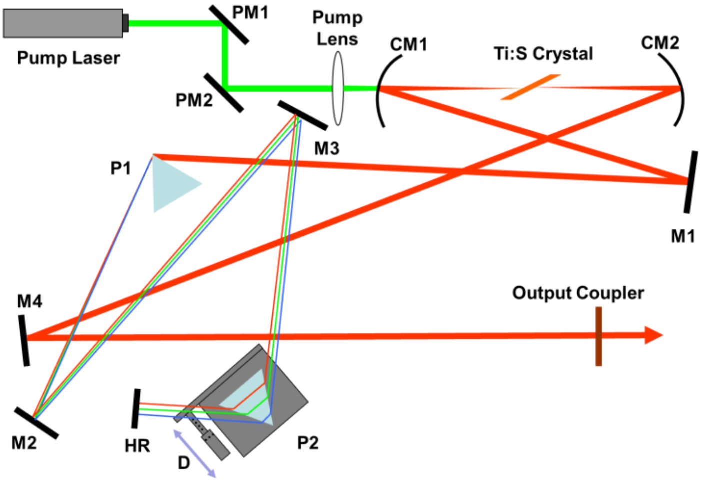
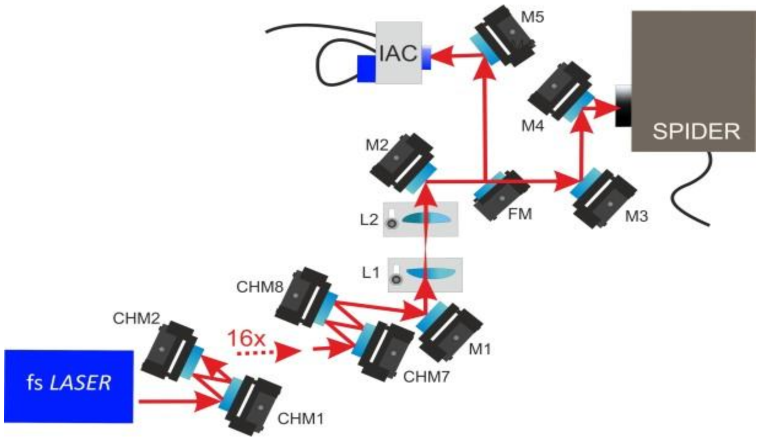
1. Introduction

The optical scheme of the used commercial femtosecond oscillator is shown in the top panel of Fig. 1. The oscillator is pumped by the second-harmonic of a continuous-wave Nd:YVO$_4$ laser (λ_{pump} = 532 nm) and having pump power of mere 3W, can deliver more than 200mW with a central wavelength at about 800 nm. The oscillator has been designed and optimized to generate pulses that, subsequently, are amplified from several nJ at repetition rate 80 MHz to several mJ at a repetition rate of 1 kHz in an amplifier based on the chirped pulse amplification technique. In the course of its use, it was noticed that it had unexploited potential for further shortening its pulses.

Our aim is to study the possibility to tune the output parameters of this oscillator by changing the beam's penetration into the intracavity prism P2 without interrupting the mode locking. The bottom panel of figure 1 shows the external 16 reflections of the beam on 8 chirped mirrors (CHM1...CHM8; 2 reflections from each mirror). The inverted telescope composed by lenses L1 and L2 is aligned to reduce the beam size influenced by the diffraction. Mirror FM can be flipped to alternatively redirect the beam either to the interferometric autocorrelator (IAC; see e.g. [7]) or to the device performing spectral interferometry for direct electric field reconstruction (SPIDER; [8]). Both devices used: IAC and SPIDER are commercially available.



(a)



(b)

Fig. 1. (a) Scheme of the femtosecond laser oscillator. PM1, PM2 – pump mirrors. CM1, CM2curved mirrors. M1...M4 – flat mirrors. P1, P2 – Brewster-cut quartz prisms of the double-pass intracavity prism compressor. HR – back high-reflection mirror. Reproduced from [9] with permission from SPIE, the international society for optics and photonics; (b) Used external equipment. CHM1...CHM8 – chirped mirrors. The beam is reflected 16 times, i.e. twice on each mirror. M1...M5 – flat mirrors. FM – flat mirror on a flipping mount. IAC – Michelson-type interferometric autocorrelator. SPIDER – device performing spectral interferometry for direct electric field reconstruction (colour online)

2. Results and discussion

The first step in the measurements was to find the dependence of the duration of the output laser pulses (measuring their full width at half height; FWHM) on the position *D* of one of the intracavity prisms. As the reader can deduct from Fig. 1 (a), larger values of *D* correspond to a larger penetration of the prism in the laser beam. The measurements are performed at two different values of the injection current of the laser diodes pumping the used green pump laser (Nd:YVO$_4$ with an intracavity second harmonic generation at 532 nm wavelength), namely at 19.2 A and at 19.5 A. Under both conditions we had a long-term stability of the femtosecond pulse trains and corresponding average output powers of 168 mW and 188 mW, respectively. At each of these currents, the pulse durations were measured with a classical interferometric autocorrelator (IAC) and with the aforementioned device performing spectral interferometry with direct electric field reconstruction (SPIDER). The obtained results are presented in Fig. 2, separately for the two pumping currents. A clear trend of decreasing pulse durations with increasing the prism penetration into the beam can be seen. This shortening of the pulses with the (minimal) increase of the material dispersion in the resonator is to be expected, since at the output of the laser we used 16 reflections on chirped mirrors that apparently overcompensate for the intrinsic resonator dispersion. It can also be seen that at the higher current the range of prism positions at which the femtosecond pulse train is stable, is wider. At an excitation current of 19.2 A, practically the same value of the pulse shortening by a factor of 1.7 was recorded with both devices. At the higher excitation current of 19.5 A, the SPIDER device and the autocorrelator measured slightly lower shortening of 1.5 times. The shortest laser pulse duration of 16 fs was recorded at a current of 19.2 A and a relatively large prism penetration of *D* = 2.5 mm.

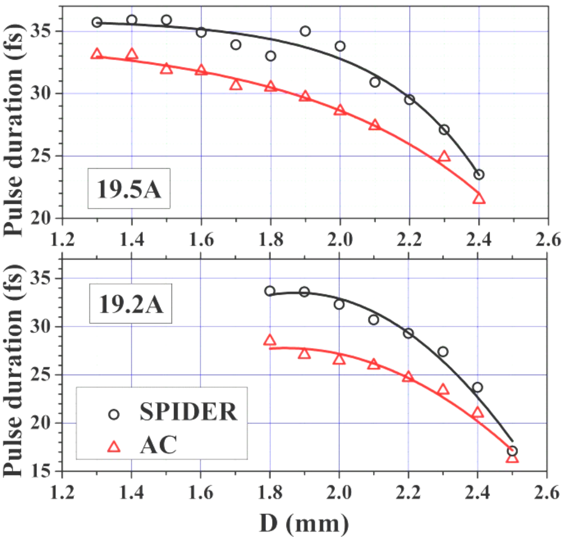


Fig. 2. Dependencies of the pulse durations (FWHM) on the position D of one of the intracavity prisms for two different pump currents of the green pump laser measured with an interferometric autocorrelator (AC) and with a SPIDER device. Chirped mirrors present at the exit of the system (colour online)

An important parameter of the output laser emission is its average power P_{mean}, which is related to the peak power P_{peak} of the pulses, to their duration Δt and to their repetition rate f by the relation $P_{mean} = P_{peak}.f.\Delta t$. The measured average output power versus position *D* of one of the intracavity prisms for the two different pump currents of the green pump laser is shown in Fig. 3(a). It is clearly seen that the smaller the penetration of the prism *D* into the beam, the higher the average output power. The asymptotic relationship is the same for both currents used. This is interesting, but a related important question is what is the dependence of peak pulse power Ppeak on *D*, assuming that the pulse repetition rate (78 MHz) remains unchanged. Data derived from these shown in Fig. 3(a) and in Fig. 2 are presented in Fig. 3(b) and (c). At a pump current of 19.5 A, considering the data from the two measuring devices, the peak pulse powers increase with increasing prism penetration *D*. This is a consequence of the 0.8-fold decrease in average pulse power at *D* = 2.4 mm combined with the 1.5-fold shortening of the pulse (measured with the SPIDER device). The reported data indicate that the highest pulse peak power, reached in this experiment, just after the oscillator is 115 kW, corresponding to pulse peak energy of approximately 3 nJ. At the lower pump current of 19.2 A the peak pulse power seems to saturate at higher penetration *D* of the intracavity prism into the beam.

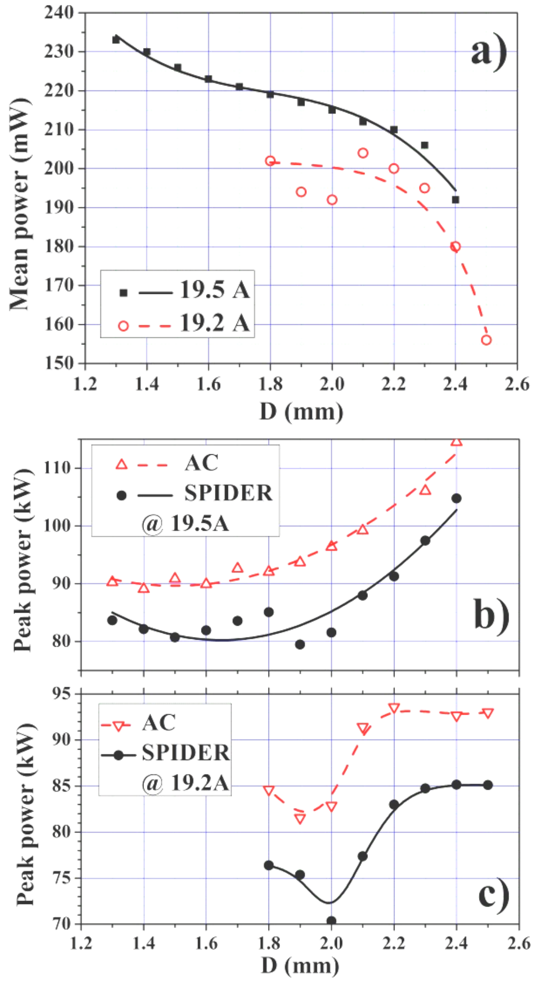


Fig. 3. (a) Measured mean output power vs. position D of one of the intracavity prisms for two different pump currents of the green pump laser. (b) Calculated pulse peak power vs. position D for pump current 19.5 A. (c) The same as (b) for pump current 19.3 A. In frames (b) and (c) the pairs of curves correspond to the pulse durations measured with the autocorrelator (AC) and with the SPIDER device (colour online)

3. Discussion

In the following, we will discuss the experimental data in dependence on the laser output power. In our opinion, this is appropriate because of the clear linear dependence of the laser output power on the laser diode pumping current of the excitation laser (Nd:YVO$_4$; λ = 532 nm.) This linear dependence is perfectly approximated (with a standard error below 2%) by a function of the form P(mW)=-1065.2+64.22I(A).

In Fig. 4(a) we combine the dependence of the measured pulse duration (open circles and dashed curve; see left scale) on the mean output power $P = P_{mean}$ of the laser with the dependence of the pulse spectral width Δλ (solid circles and solid curve; see right scale). The values of both parameters are simultaneously provided by the SPIDER device. Although in this measurement the change of the pulse durations is not as impressive as this shown in Fig. 2, the clear tendency is that the shorter the pulse duration, the larger the pulse spectral width Δλ. Such dependence is expected for transform-limited pulses. Is this the case? Unfortunately, no. In Fig. 4(b) we combine the power-dependence of the Fourier-transform-limited pulse duration estimated by the SPIDER (solid squares and right axis) with the simultaneous real measurement of the duration of the emitted laser pulses (hollow circles and left axis).

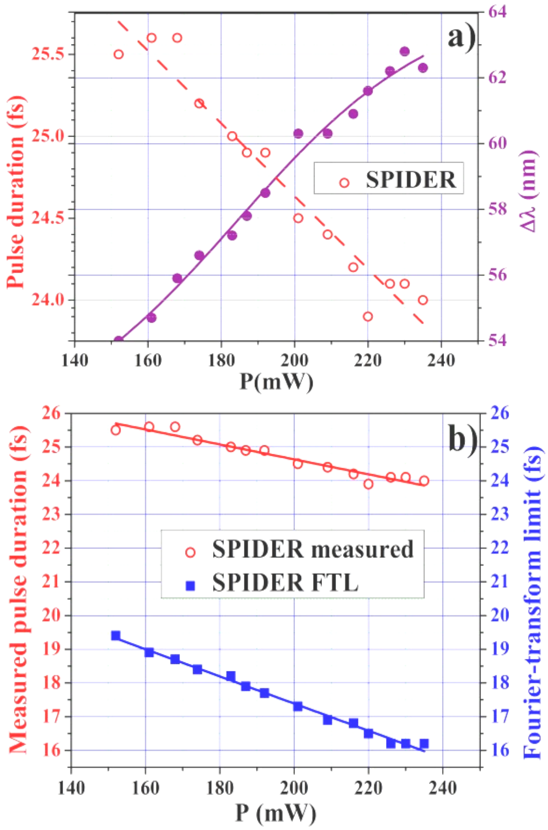


Fig. 4. (a) Dependences of the measured pulse durations (FWHM; open circles and dashed curve; see left scale) and of the pulse spectral widths (FWHM; solid circles and solid curve; see right scale) on the mean output power of the laser; (b) Real pulse durations (open circles; see left scale) and Fourier-limited pulse durations (solid squares; right scale) measured/estimated by the SPIDER device (colour online)

The respective solid lines are intended to guide the eye only. However, it is noticeable that the straight lines are at a small angle to each other (i.e. they are approximately parallel), but the generated femtosecond pulses have the potential to be further shortened. In our opinion, the approximately constant difference between the actual measured and the minimum achievable pulse durations is due to uncompensated third (and higher) order dispersion.

In Fig. 5(a) we present the measured monotonic dependence of the central wavelength of the spectrum of the femtosecond laser on the mean output power *P* (equally valid - on the pump current of the laser diodes of the pump green laser). It is remarkable that the dependence of the group delay dispersion GDD Fig. 5(b) [10] on *P* looks like a mirror image of the dependence in Fig. 5(a). Near P_{mean} = 185 mW the GDD changes its sign. At this mean power there is an inflection point in the $\lambda_0(P)$ dependence in figure 5(a). This value is also near the point of the curves shown in Fig. 4, at which the curves cross. This mean power corresponds to a pump current of 19.5A and to prism penetration *D* = 2.4 mm.

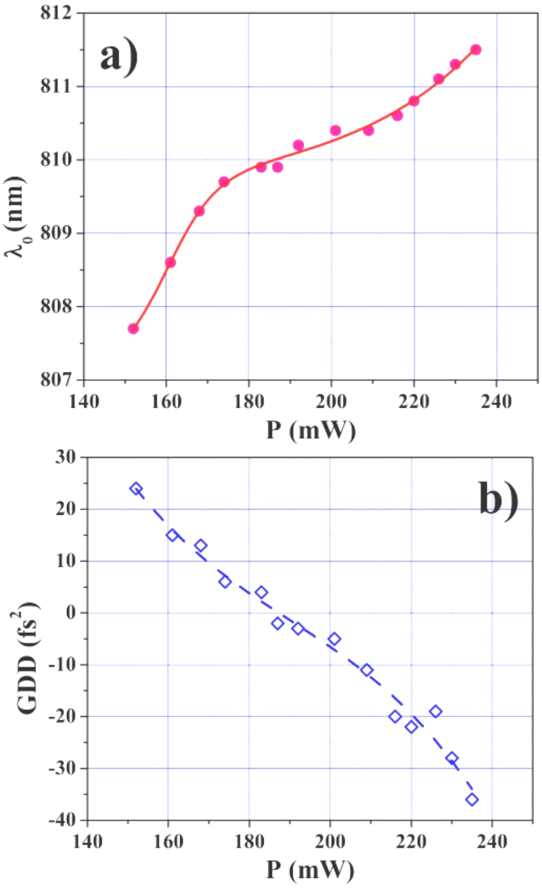


Fig. 5. Power-dependent central wavelength of the spectrum λ_0 *of the femtosecond laser (a) and power-dependent group delay dispersion GDD (b), both measured with the SPIDER device. Chirped mirrors present at the exit of the laser (colour online)*

At the end of this analysis, we checked quantitatively the fidelity of the determined values of the GDD. In figure 6 we show the GDD measured by the SPIDER device for two cases with chirped mirrors present at the exit of the laser system (for pump currents of 19.2 A and 19.5 A) and compared the data with data obtained with no chirped mirrors (at a pump current of 19.2 A). Data is recorded for different prism penetrations *D* into the beam in the cavity. The results allowed as determining the GDD introduced by the cascade of chirped mirrors (see CHM1… CHM8 in the bottom panel of Fig. 1). For a pump current of 19.2 A, we estimated the average GDD per single reflection to be -36 fs^2. Similarly, for a pump current of 19.5 A the average GDD per single reflection was found to be -38 fs^2. These values are reasonably close to the -40 fs^2 given by manufacturer's specification for a single reflection on the chirped mirror of this batch.

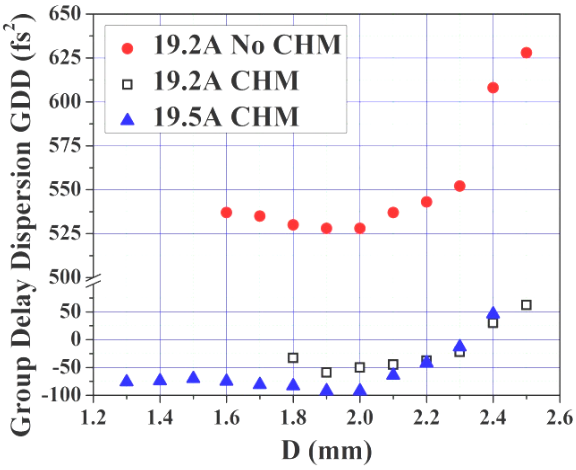


Fig. 6. Group delay dispersion (GDD) in units of (fs^2) measured with the SPIDER device at pump currents 19.2 A (hollow black squares) and 19.5 A (solid blue triangles) in the presence of the chirped mirrors (CHM1… CHM8 in the bottom panel of figure 1), compared with the measured GDD in the absence of these mirrors, for a pump current of 19.2 A, at different prism penetrations D (colour online)

4. Conclusion

In this paper, we reported a detailed study of the output parameters of a femtosecond laser oscillator with an intracavity prism pair after 16 reflections from chirped mirrors outside the laser cavity. We varied the penetration of one of the intracavity prisms in the beam into the resonator, as well as the pump current of the laser diodes exciting the pumping green laser ($Nd:YVO_4$ with intracavity second harmonic generation). Data recorded with a commercially-available Michelson interferometric autocorrelator and a spectral interferometry system with direct reconstruction of the electric field (SPIDER) are presented and discussed. For the laser investigated, having a 78 MHz pulse repetition rate, it was found that the pulse durations could be varied from 16 fs to about 36 fs, while varying the average output power from 155 mW to about 230 mW and with achievable peak powers of 110 kW. The measured average GDD introduced in the pulses after a single reflection from one of the chirped mirrors is found to agree quantitatively with the value specified by the manufacturer. This could be regarded as an independent check for the fidelity of the pulse width characterization.

Acknowledgments

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