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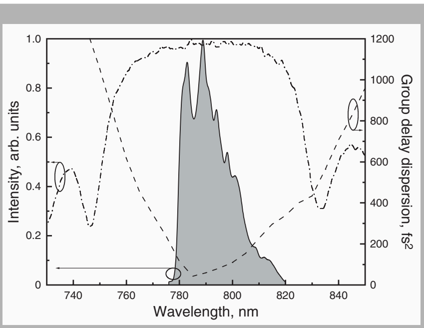

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Investigation of a 200-nJ chirped-pulse Ti:Sapphire oscillator for white light generation

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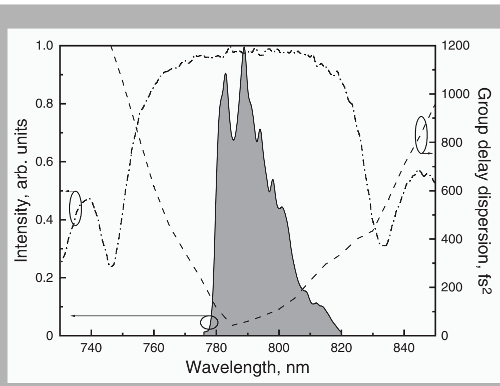

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1. State-of-the-art and challenges in chirped-pulse oscillator technology

Ti:Sapphire laser oscillator technology has undergone significant advances in the past $3-4$ years. With the introduction of the so-called long cavity oscillator concept energetic femtosecond pulses became available directly from laser oscillators approaching the μJ level [1–6]. With these pulses focused intensities exceeding 10^{14} W/cm^2 were demonstrated in a pioneering strong-field light-matter interaction experiment [5], moreover such light sources are also much more attractive to femtosecond micromachining applications than master-oscillator power-amplifier (MOPA) systems. The main objective of laser technology development in this field was the increase of the pulse energy. A trivial way to achieve this is to make the cavity longer even though this route has its own limitations to be described below. Apart from cavity lengthening, a further development step combines this concept with cavity dumping [6] opening the door to the possibility of the construction of μJ-level Ti:S oscillators.

State-of-the-art chirped pulse oscillators are constructed exploiting some novel solutions. The resonator length of these lasers is increased with a so-called Herriott-cell (a mirror system with a unity ABCD matrix [7]). Since in mode-locked lasers such a cavity extension results in a decrease of the repetition rate (while the average output

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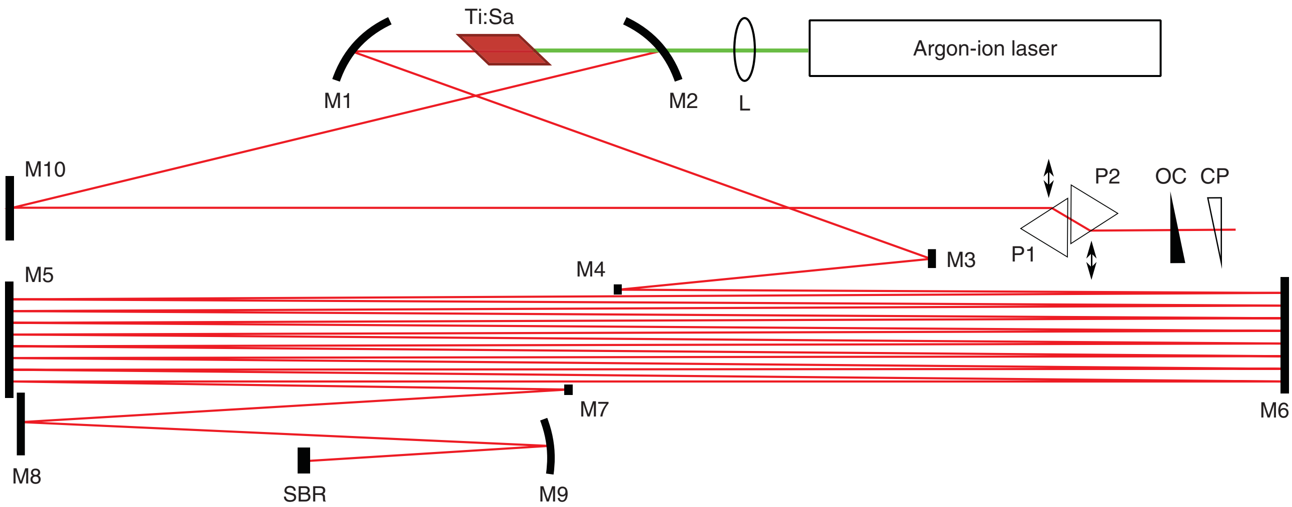

Figure 1 (online color at www.lphys.org) The setup of the long cavity, chirped-pulses oscillator used for the experiments. M1–M10: chirped mirrors (all flat except for M1, M2, M5, and M9 with radii of curvature $R_{M1} = R_{M2} = 10$ cm, $R_{M5} = 16$ m, $R_{M9} = 60$ cm), P1, P2: Brewster prisms for fine-tuning intracavity dispersion, OC: output coupler, CP: compensation plate, L: lens with 60 mm focal length, SBR: saturable Bragg reflector. The telescope system is not depicted fully realistically for more illustrativeness. Successive bounces on the mirrors form a circular pattern instead of a linear one

power usually stays the same) the energy of the individual outcoupled pulses can be increased. However, drastic increase that could be conceived easy by an arbitrarily huge cavity lengthening is limited by nonlinearities arising from the interaction of the focused pulses with the laser crystal. The result is pulse splitting, double pulsing and other unwanted phenomena that clamp maximum intracavity pulse intensity in solitonically mode-locked oscillators. This drawback can be overcome by either setting the net cavity dispersion highly negative [1,2] or positive [1,3], as opposed to the slightly negative net cavity dispersion regime in which soliton-like mode locking comes about. As a result, in both cases, circulating mode-locked pulses in the oscillator will become heavily chirped with a lower peak intensity hindering the appearance of the above-mentioned nonlinearities. Outcoupled pulses will also be strongly chirped but their phase modulation can be compensated for by, for example, a simple prismatic pulse compressor (in case of positive intracavity dispersion). Since it was also noticed that the increase in cavity length results in the destabilization of the oscillator and hinders easy starting of mode-locking a saturable Bragg reflector (SBR) is introduced in the cavity which enables easy build-up and the stabilization of mode-locked operation.

In spite of these solutions proliferating in the past $2-3$ years there are some unresolved issues when it comes to the utilization of these lasers. Since their bandwidth is limited by the group delay dispersion oscillations of the chirped mirrors in the Herriott-cell the shortest pulse duration available from the laser (and the linear pulse compressor) is limited to $30-60$ fs [1–6]. The corresponding spectral content may be sufficient for several experiments these oscillators are ideal for, such as material processing and nanofabrication, but especially some spectroscopic, pump-probe and strong-field-like experiments call for broadening the output spectrum (and eventually pulse compression, if few-cycles pulses are necessary). Even though a way to overcome this problem is to evacuate the cavity thereby eliminating the need for chirped mirrors, the bandwidth of such an oscillator is also limited to $35-40$ nm [5]. In this paper we report on cavity length and dispersion optimization of a chirped pulse oscillator to maximize the intensity of the outcoupled pulses for a given pump laser. With such pulses successful extracavity spectral broadening experiments can be carried out, that will be reported in another publication.

2. Layout optimization for pulse energy maximization

For the setup of the oscillator we started out from a scheme depicted in Fig. 1. This is based on a standard Ti:Sapphire laser cavity which was pumped at 9 W delivered by 5 lines of an Ar-ion laser. The crystal path length was 3.0 mm and the doping resulted in an $\alpha = 3.4$ cm^{-1} absorption coefficient for the pump light. The folding mirrors have radii of curvature of 10 cm. One of the end mirrors is a 20% output coupler, the other one is a SBR which plays a role by enabling simple start and stabilization of mode-locking. We introduced a closely spaced prism pair that enables fine tuning the cavity dispersion. The cavity was than extended by the above-mentioned Herriott-cell system by adding an

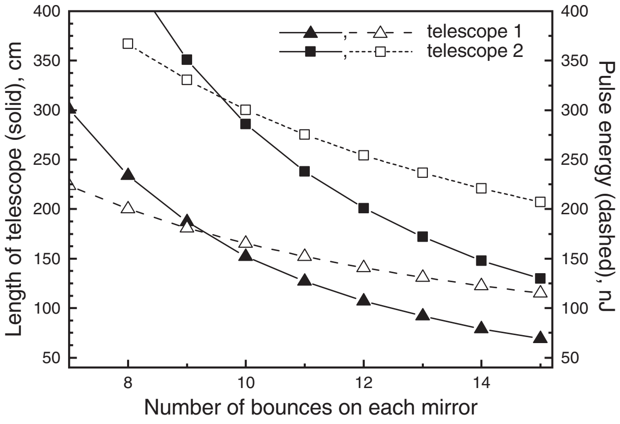

Figure 2 Conditions for pulse energy increase by increasing the M5–M6 distance (see Fig. 1) for two different telescope systems. Telescope system 1: $R_{M5} = \infty$ and $R_{M6} = 16$ m. Telescope system 2: $R_{M5} = \infty$ and $R_{M6} = 30$ m. Symbols indicate the necessary telescope length (full symbols) and the achievable pulse energy (empty symbols) at a given number of bounces on these mirrors to achieve a unity ABCD matrix for this section of the laser cavity. The connection lines between the symbols are guides to the eye. By applying a larger mirror separation the number of bounces has to be decreased, but in spite of these countereffective measures the pulse energy can still be increased. For further details see text

extra beam path of ~ 80 m to a round-trip by bouncing the beam several times between two 2” mirrors, one of which is flat (M5), while the other has a radius of curvature of 16 m (M6).

We carried out an optimization to assess the optimum distance between mirrors M5 and M6. One can determine how far these mirrors should be placed from one another for a given number of bounces by setting the ABCD matrix of the whole Herriott-cell (M4–M7) unity. According to this calculation in the following we will examine two cases. In the first we take mirrors with fixed radii of curvature (denoted by R) corresponding to our experimental conditions (available mirrors). In the second more general considerations are introduced for mirrors with arbitrary R.

We first examine the case $R_{M6} = 16$ m and $R_{M5} = \infty$. At first glance, one would think that increasing the number of bounces pays off, but in a somewhat counterintuitive manner it turns out that the repetition rate of the laser can be decreased (and thus the pulse energy can be increased) by placing the mirrors further apart even though the number of bounces has to be reduced in this case to achieve a unity ABCD matrix (see Fig. 2). This way the only limitation posed is the length of the optical table at one’s disposal. For our conditions we ended up with an M5-M6 separation of 234 cm, with 8 bounces on each mirror (in single pass, for a whole cavity round-trip one has to take 16 bounces into account). The repetition rate was 3.6 MHz which is thus the minimum achievable for the given mirror radii and table length. In our calculations we also estimated the achievable pulse energy for each case by assuming constant average output power (which was 720 mW in our experiments). According to this it is also worth noting that pulse energy can not be increased proportionally with the telescope length (because the number of bounces has to be reduced for longer and longer telescopes).

Assuming more freedom in the choice of mirrors M5 and M6 we can draw more general conclusions. As it can be seen in Fig. 2, increasing the number of bounces results in a decrease in the achievable pulse energy for given radii of curvature due to the need to decrease the telescope length to preserve the unity ABCD matrix. This drawback can be overcome by choosing mirrors with higher radii of curvature. If the only limitation is the table length, it is clear that increasing the number of bounces pays off (provided that mirrors with matching radii of curvature are available) as it is obvious from Fig. 2. Usually the upper limit to the number of bounces is also posed by the mirror diameter since it becomes increasingly difficult to accommodate a large number of spots on the mirror and picking the beam with M7 from the telescope without clipping other beams. It also has to be noted that increasing the number of bounces also results in a higher amplitude of any potential group delay dispersion (GDD) oscillations resulting from improperly matched chirped mirrors and thereby this could compromise smooth oscillator dispersion and thereby bandwidth, as well. By pushing these parameters to the limits we estimate that an oscillator with μJ pulses and 1.4 MHz repetition rate is achievable by having 15 bounces on 3” mirrors separated by 345 cm provided that sufficient pump power is available. By combining this technique with cavity dumping [6] a further factor of $2-3$ pulse energy boost could be achieved.

3. Intracavity GDD tuning for pulse duration minimization

In our case with the above-mentioned M5–M6 mirror separation of 234 cm and closing the cavity with the SBR (onto which the beam was focused by M9 with $R_{M9} = 60$ cm) we achieved output pulses of 200 nJ pulse energy with a 3.6 MHz oscillator repetition rate in a highly stable way. The oscillator spectrum was limited to a width of about 40 nm at the base. Limitations arose mainly from two factors, as depicted in Fig. 3. One was the overall GDD curve of the resonator which stays well-behaved for $\lambda > 780$ nm, where the residual third order dispersion (TOD) of the cavity stays negative and relatively small. This dispersion behavior is mainly limited by the dispersion of the 2” Herriott-cell mirrors since a higher number of bounces magnifies any detrimental effect resulting from their spectral GDD oscillations. The measured spectrum is also in accordance with simulations since the effect of the non-vanishing mirror TOD can be obviously seen in the

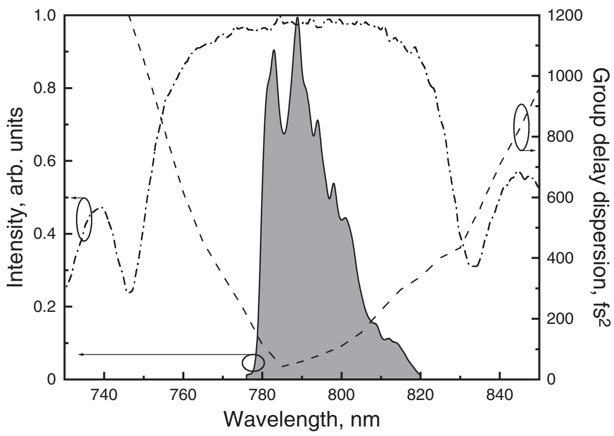

Figure 3 The spectrum of the chirped pulse oscillator (solid line with shaded area) together with the reflectivity of the SBR used (dash-dotted line) and the intracavity GDD of the laser (dashed line) as a function of wavelength

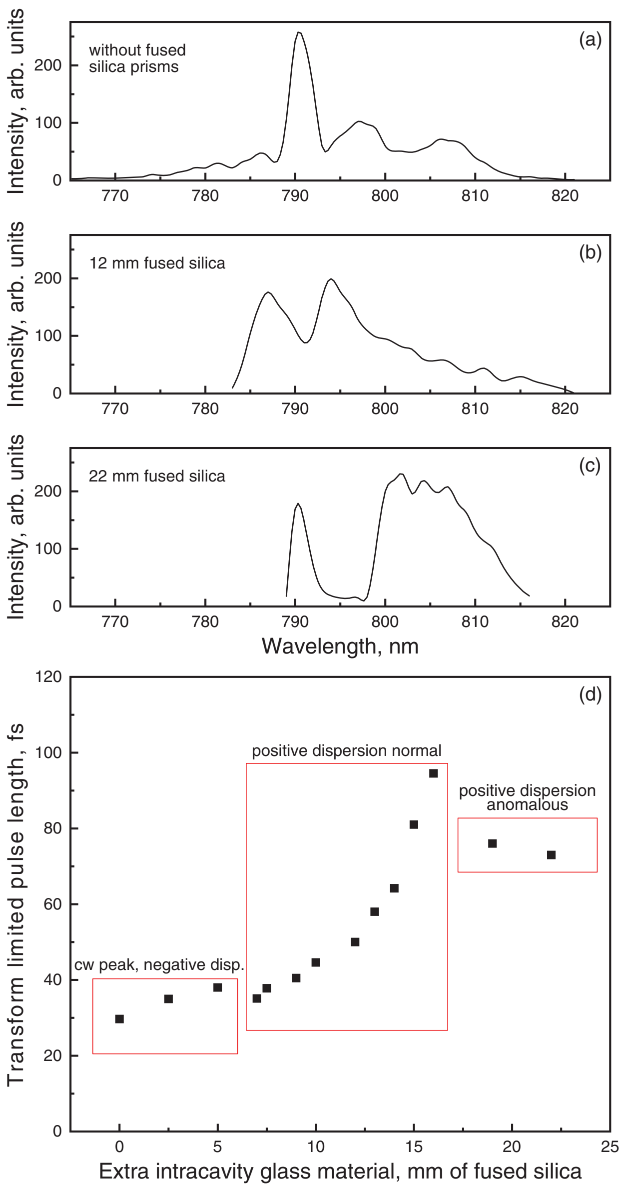

Figure 4 (online color at www.lphys.org) Cavity group delay dispersion tuning and the resulting spectra in three characteristic regimes: (a) negative net intracavity dispersion, (b) relatively small amounts of positive dispersion, and (c) large positive dispersion. Transform-limited FWHM pulse lengths calculated from the measured spectra are depicted in (d) with the three distinctive regions marked with boxes

observed asymmetric spectrum as supported by detailed simulations of Kalashnikov et al. [8]. It is expected that by the usage of more carefully dispersion-engineered mirrors with more accurately matched GDD oscillations one could get rid of this unwanted feature. The other bandwidth limiting factor is the reflectivity of the SBR we used. Its high reflectivity region is limited to a 50 nm wide spectral range the red end of which coinciding with the red cut-off of the oscillator spectrum (Fig. 3). Using a more broadband SBR would be a solution; however, it is not trivial to manufacture such a multilayer.

To investigate and to optimize the temporal structure of the laser output we systematically investigated the dispersion properties of the laser. This very important degree of freedom also determines the maximum focused intensity of the oscillator pulses by affecting the output bandwidth. To assess optimum conditions we carried out systematic measurements of the oscillator spectrum during tuning intracavity dispersion by the P1/P2 prism pair (see Fig. 1.). Thus, we obtained the spectral shapes depicted in Figs. 4a–4c. Fig. 4d depicts the transform-limited FWHM pulse length calculated from different measured oscillator spectra as a function of the intracavity glass insertion (geometric path length in the prism glass).

First we started out from the most negative GDD that could be achieved by removing P1 and P2 from the cavity. It can be seen that without the prisms the oscillator operates in the negative dispersion regime. The absence of the sharp spectral cutoffs and the appearance of the cw spike are a clear signature for this [4,8]. The spectral shape and the cw-like spike indicate that in this regime a long and a short pulse circulates in the cavity. The bandwidth of the probably several-100 femtosecond pulse corresponds to the spectral range where the cavity GDD is negative. In this limited spectral range soliton-like mode-locking can build up and create such a pulse. Most likely, there is also a heavily chirped picosecond pulse in the cavity corresponding to the typical mode-locking mechanism of chirped-pulse oscillators.

Upon increasing dispersion (by introducing more and more prism material) the positive dispersion regime sets in (Fig. 4b). At this point the oscillator spectrum can have different widths depending on the actual value of intracavity dispersion. This can be explained by the pulse-forming dynamics of the oscillator. The more chirped the circulating pulses are the less self-phase modulation occurs in the crystal thereby reducing the spectral width. This effect can be clearly seen in the central region 2 of Fig. 4d, where one can observe a quasi-exponential increase in transform-limited pulse length as a function of intracavity glass insertion. In this region the oscillator can be operated in a highly stable way. By inserting too much glass an unstable regime sets in again (region 3 in Fig. 4d). In this anomalous regime a bichromatic spectrum appears the origin of which is unclear. The oscillator becomes unstable and the achievable minimum pulse length decreases slightly (it is, however, quite likely that irrespective of the spectral width, perfect phase correction and pulse compression is much more difficult in this anomalous regime).

By characterizing the output pulses with a commercial autocorrelator (APE GmbH, PulseCheck) we could also assess that in the above-mentioned small positive intracavity dispersion range (region 2 in Fig. 4d) the strongly chirped output pulses of the laser were in the $2.4 - 5.0$ ps range, and after pulse compression with a simple prismatic pulse compressor 35 fs is achievable.

As a summary, for the above-mentioned reasons it is obvious that the oscillator has to be operated at the left-hand-side edge of region 2 to minimize the length of the outcoupled (chirped) pulses. Since we observed that in this region the pulse energy remains unchanged at different values of intracavity dispersion, this solution provides the highest achievable intensity and optimum conditions for further applications of the oscillator pulses. After such an optimization procedure our oscillator was used for extracavity white light generation experiments for e.g. spectroscopic applications where a broader spectral content is desired and also with few-cycle pulse compression in mind. The results of these experiments will be published elsewhere.

4. Summary and outlook

Chirped-pulse Ti:Sapphire oscillators find applications in more and more areas of basic and applied science. In this paper we examined such a system experimentally in detail in terms of its cavity length and intracavity dispersion. Thus we provided additional data for the optimization of such oscillators to achieve higher pulse energies and shorter pulses. These results can help fitting these laser systems for a broad spectrum of applications ranging from micro- and nanomachining purposes to extracavity spectral broadening and pulse compression experiments (to increase the spectral content of their output and/or to reach the few-cycle regime with these pulses), as well as to strong-field laser-atom interaction studies. In the future this kind of laser technology will gain more importance due to its relative simplicity, easy reproducibility and the resulting broad availability in many fields.

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