Generation of 33-fs optical pulses from a solid-state laser

F. Krausz, Ch. Spielmann, T. Brabec, E. Wintner, and A. J. Schmidt

Technische Universität Wien, Abteilung für Quantenelektronik und Lasertechnik, Gusshausstrasse 27, A-1040 Wien, Austria

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Using the results of recent theoretical research, we present practical guidelines for the optimization of femtosecond solid-state oscillators and demonstrate reproducible sub-40-fs pulse generation in a synchronously pumped Ti:sapphire laser.

Remarkable progress has recently been achieved in the development of passively mode-locked solid-state lasers. Novel mode-locking techniques have resulted in the generation of sub-100-fs optical pulses in a number of different cavity configurations.[1–9] A common feature of these solid-state systems is that the high intracavity intensity and long gain medium (compared with those of dye lasers) lead to strong self-phase modulation of the mode-locked pulses. Once a relatively weak passive amplitude modulation is introduced by a fast saturable absorber or a related all-optical modulator, this phase-affecting nonlinearity can be utilized for efficient pulse shortening with the addition of negative group-delay dispersion (GDD). The interplay between positive self-phase modulation and negative GDD well separated between time and space provides a strong quasi-solitonlike shaping, which dominates the pulse-shortening process in femtosecond solid-state systems. Recently, an empirical theory has been developed on the basis of computer simulations that describes this novel class of femtosecond sources, referred to as solitary lasers.[10,11] In this Letter we briefly summarize the relevant results of these investigations from a practical point of view. Following the design guidelines deduced from these considerations, we have developed a Ti:sapphire laser and demonstrated reliable and reproducible generation of sub-40-fs optical pulses.

The schematic diagram in Fig. 1 illustrates the most important pulse-shaping effects in solid-state lasers. If the amplitude modulation is much weaker than the phase modulation, which is almost always the case in practice, Fig. 1 represents an ideal solitary system.[10] However, in real mode-locked lasers there are other dispersive effects in addition to the negative GDD introduced on purpose, such as gain dispersion, positive group-velocity dispersion in the Kerr medium, and third-order dispersion of different components, which all adversely affect the formation of ultrashort pulses.[11] Therefore the design of a femtosecond solid-state laser should pursue the goal of reducing these undesirable effects as far as possible. Gain dispersion can be reduced by selecting a broadband laser medium. A small positive dispersion in the Kerr medium calls for a short laser material, which serves as the Kerr medium in most cases. Since the ratio of third-order dispersion to second-order dispersion in dispersive delay lines based on refraction (e.g., a prism pair) is much greater than in optical materials, a shorter gain medium also allows for a reduction of the net third-order dispersion D_3 in the cavity. For the same reason, the optical path lengths in the prisms should be minimized.[3]

In the absence of the dispersive effects discussed above and under the assumption of a weak amplitude modulation, the steady-state pulse duration of a solitary system is given by[10]

$$\tau = \frac{3.53|D|}{\phi W} + \alpha\phi W, \tag{1}$$

where $D < 0$ is the net round-trip GDD, $\phi P(t)$ is the round-trip nonlinear phase shift in the Kerr medium, $P(t)$ denotes the intracavity power, $W = \int P(t)\mathrm{d}t$ denotes the pulse energy, and $\alpha = \alpha(z)$ is a numerical factor that depends on the position at which τ is measured in the cavity. The pulse duration is found to be the shortest near z_1, with $\alpha(z_1) \approx 0.10$, whereas the pulse is predicted to be longer by $\Delta\tau = 0.15\phi W$ at the other end of the resonator. This suggests that the pulse should be coupled out of a solitary laser at the dispersive end of the cavity. Decreasing the negative dispersion in the cavity gives rise to shorter pulses, but this kind of pulse shortening is limited by the onset of instabilities inherent in solitary systems. The minimum $|D|$ is expected to depend sensitively on the depth of passive amplitude modulation.

With these findings in mind, we have developed a Ti:sapphire laser synchronously pumped by an actively mode-locked, frequency-doubled Nd:YLF laser (Quantronix 4216D with a lithium borate doubler). The optical setup of the femtosecond oscillator is shown in Fig. 2. It is based on a previous design that produced pulses of 70–80 fs.[7] Owing to the broad fluorescence line of Ti:sapphire, gain dispersion may be neglected even for pulse durations well below 100 fs. The Ti:sapphire rod, which also functions as the Kerr medium, is as short as 8 mm to reduce the positive GDD in the nonlinear medium and absorbs ≈75% of the pump radiation. So far, all femtosecond solid-state systems[1–9] have employed a pair of prisms made of some heavy flint glass, e.g.,

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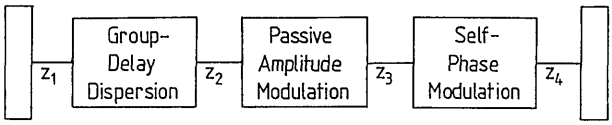

Fig. 1. Schematic diagram of a solitary system.

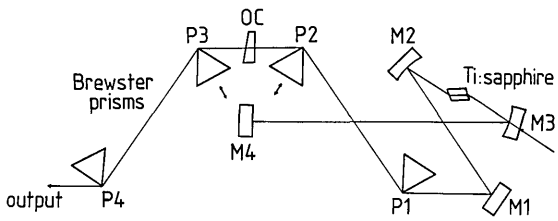

Fig. 2. Layout of the Ti:sapphire laser. OC, 2% transmitting output coupler; M2, M3, curved broadband mirrors with radii of 10 cm; M1, M5, flat broadband mirrors; P1–P4, Brewster-angled prisms made of flint glass (Schott F2).

SF10 or related materials. These dispersive delay lines offer the possibility of large negative GDD with relatively small prism separations but exhibit large third-order dispersion. By replacing the heavy glass prisms with F2 prisms (Schott, $n = 1.61$) and minimizing the glass pathway in the prisms, we reduced $|D_3|$ by more than a factor of 3 compared with that in the previous system.[7]

The reduction of the unfavorable dispersive effects leads to a more or less ideal solitary system with the shortest pulses generated near the dispersive end of the cavity. The spatial chirp on the pulse coupled out by output coupler OC is eliminated by an identical prism delay line outside the cavity as shown in Fig. 2. In addition, the external delay line offers the possibility of compensating for some residual linear chirp carried by the pulse[12] and of precompensation for the dispersion of optical components before the target when it comes to the experiments.

Passive amplitude modulation originates from self-focusing in the laser rod, which affects the spatial properties of the cavity mode. The intensity-dependent change in the beam profile gives rise to a change in the round-trip gain Δg owing to its interaction with the soft aperture provided by the spatial profile of the gain. Under optimized conditions, this self-amplitude modulation can be described by $\Delta g(t) = \kappa P(t)$, with $\kappa > 0$, and is able to mode lock the laser passively.[13] The effective modulation coefficient κ sensitively depends on the intensity distribution of the cavity mode in the gain medium. As a consequence, the depth of modulation can be maximized by carefully adjusting the distance between the focusing mirrors M2 and M3 within the stability region. The greater κ is, the less sensitive is the start-up of passive mode locking for the initial pulse width in the synchronously pumped laser, i.e., the more cavity length detuning is tolerated.

With a 2% output coupling the average output power of the femtosecond Ti:sapphire laser is $\approx$70 mW when it is pumped with 3 W of absorbed pump power at 527 nm. Passive mode locking immediately starts if the cavity length is tuned to that of the pump laser to within $\approx$10 μm. With κ optimized, stable long-term operation is achieved with amplitude fluctuations of less than $\pm$5%, which is attributed principally to the pump laser. As predicted by the theoretical investigations, decreasing the amount of negative dispersion leads to instabilities, and the shortest pulses are generated at the smallest negative GDD that allows stable mode locking, in our case $D \approx -5 \times 10^2$ fs^2 (prism separation $\approx$45 cm, prism insertion $\approx$5 mm). This represents an exceptionally low negative dispersion for solid-state lasers, which is the consequence of a moderate intracavity pulse energy ($W = 45$ nJ), a low round-trip third-order dispersion ($D_3 \approx -6 \times 10^3$ fs^3), and an enhanced amplitude modulation with respect to phase modulation ($\kappa/\phi \approx 0.03$–0.05). Owing to these improvements the solitary pulses have shortened from 70–80 fs (Ref. 7) to 55–60 fs at the nonlinear end of the cavity (mirror M4). At the same time the laser produces sub-40-fs pulses at the dispersive end of the resonator. The shortest pulses, with a duration of 33 fs (assuming a sech^2 pulse shape), have been obtained by optimizing the net external GDD, D_{ext}, between the output coupler and the nonlinear crystal in the autocorrelator. To our knowledge, these are the shortest optical pulses generated in a solid-state laser so far. The absence of a coherence spike in Fig. 3(a) and the presence of coherence in the wings of the fringe-resolved autocorrelation in Fig. 3(b) clearly demonstrate that the

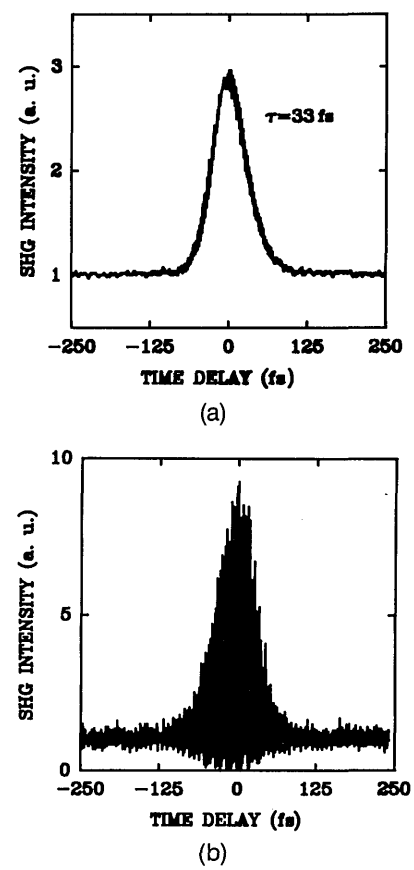

Fig. 3. (a) Single-scan collinear autocorrelation trace and (b) fringe-resolved diagram of a 33-fs pulse. The noise beyond the principal autocorrelation feature is of electrical origin.

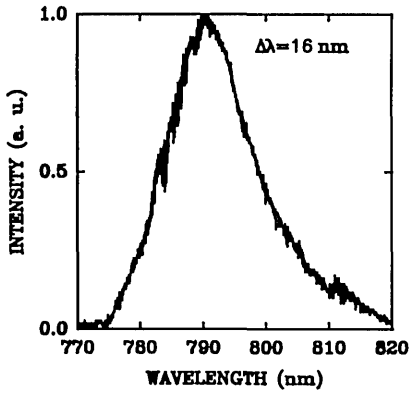

Fig. 4. Single-scan optical spectrum of the laser.

pulses have a smooth envelope and are free from phase modulation, i.e., they are bandwidth limited. The small value of $|D_{\text{ext}}|$ indicates that the pulses at the laser output are transform limited within a factor of 1.2.

Substituting our parameters, $W = 46$ nJ, $\phi = 2.8 \times 10^{-6}\ \text{W}^{-1}$, and $D = -5 \times 10^2\ \text{fs}^2$, into the above relations, we obtain $\tau \approx 27$ fs and $\Delta\tau \approx 20$ fs. The small discrepancy between theory and experiment can be attributed to the nonnegligible positive dispersion of the Kerr medium at these pulse durations.[11] It is instructive to evaluate the different contributions to the solitary pulse width. The first term on the right-hand side of Eq. (1) represents the duration of the $N = 1$ soliton in a corresponding soliton-supporting system with D and ϕ continuously distributed in the resonator, while the second perturbation term is a consequence of the discreteness of the solitary system.[10] The calculated solitary pulse width of 27 fs is nearly twice as long as the duration of the corresponding soliton, $\tau_s \approx 14$ fs. The period length of the solitary pulse (twice the cavity length) relative to the soliton period can be written as[10] $r = (1/2\pi)(\phi W)^2/|D|$. With increasing r, the solitary laser deviates more and more from a soliton-supporting system and becomes unstable if r reaches a critical value. In our case $r = 5.4$, which makes the significant difference between τ and τ_s plausible. The pulse shape is also predicted to noticeably deviate from sech^2 at such high values of r. In fact, the 16-nm spectral width of the laser output (Fig. 4) yields a time–bandwidth product of 0.26, which is 20% smaller than that of a sech^2 pulse.

The maximum value of r that allows stable operation increases with κ/ϕ, the ratio of the depth of amplitude modulation to the peak nonlinear phase shift during one round trip in the resonator.[10] Therefore pulse shortening by means of reducing $|D|$, i.e., increasing r, is ultimately limited by the small value of κ/ϕ in solid-state lasers. On the other hand, with a given amplitude modulation, i.e., at a fixed maximum value of r, the minimum pulse duration can be shortened by reducing the intracavity pulse energy. This implies that hybrid systems with additional mode-locking mechanisms facilitating self-starting will, in general, achieve better steady-state mode-locking performance.

In conclusion, we have presented guidelines for the design of femtosecond solid-state systems using well-defined, easily obtainable parameters. These design considerations led to the construction of a Ti:sapphire laser capable of producing optical pulses as short as 33 fs. The performance of such an optimized solitary laser is well predictable in terms of a few parameters, and the ultimate limitations can be clearly formulated. Owing to the simplicity and solid-state nature of the system, the described performance is easily reproduced from day to day, a feature that makes this novel class of femtosecond sources especially attractive for practical applications.

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