Experimental verification of soliton mode locking using only a slow saturable absorber

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We demonstrate experimentally that solid-state lasers with strong solitonlike pulse shaping can be mode locked by a slow saturable absorber only, i.e., the response time is much slower than the width of the soliton. A Ti:sapphire laser mode locked by a low-temperature-grown GaAs absorber with 10-ps recovery time generates pulses as short as 300 fs without the need for Kerr-lens mode locking and critical cavity alignment. An extrapolation of this result would predict that an ≈100-fs recovery time of a semiconductor absorber could support pulses into the 10-fs regime.

Over the past few years great progress in the generation of femtosecond pulses has been achieved. Kerr-lens mode-locked Ti:sapphire lasers[1–3] have generated pulses below 10 fs.[4,5] It has always been assumed that at steady state a net gain time window as short as the pulse itself is necessary to stabilize ultrashort pulses. In a dye laser the short net gain window is formed by both the saturation of a slow saturable absorber that opens the net gain window and the subsequent saturation of the gain that closes the window after passage of the pulse. In solid-state lasers the upper-state lifetime is much longer than the pulse repetition rate, which prevents dynamic pulse-to-pulse gain saturation, and a fast saturable absorber was assumed to be necessary to create a net gain window during the pulse duration.

Initially we experimentally discovered that a bitemporal saturable absorber with recovery time constants of 200 fs and ≈ 10 ps can support ≈100-fs pulses without Kerr-lens mode locking[6] (KLM). Furthermore, we demonstrate that an acousto-optically mode-locked Nd:glass laser generated pulses as short as 300 fs without KLM.[7] In both cases the net gain time window is longer than the pulse length, which strongly contradicts previous mode-locking theories. Our recently developed theory, however, explains that femtosecond solid-state lasers with solitonlike pulse shaping can be mode locked only by a slow loss modulator[8] or a slow saturable absorber with a recovery time much longer than the pulse width[9] without any additional dynamic gain saturation. We refer to this mode-locking technique as soliton mode locking with a slow saturable absorber. In this Letter we present a detailed experimental verification of the theory with a soliton mode-locked Ti:sapphire laser producing pulses that are 35 times shorter than the recovery time of the absorber (Fig. 1).

The slow saturable absorber used here is an antiresonant Fabry–Perot saturable absorber[10,11] (A-FPSA) with a low-temperature-grown (i.e., 350 °C) 330-nm-thick GaAs bulk layer grown on top of a $AlAs/Al_xGa_{1-x}As$ ($x = 0.2$) Bragg mirror with an 80% SiO_2/TiO_2 top mirror. We measured the impulse response with 100-fs pulses at a center wavelength of 800 nm with a typical energy fluence used in the laser in a standard degenerate pump–probe measurement (Fig. 1). We observed only a single recovery time T_A of 10 ps as a result of the reduced carrier lifetime in low-temperature-grown semiconductors because the photoelectrons are excited high into the conduction band, which strongly speeds up the intraband thermalization (i.e., ≪100 fs). Therefore no significant faster time constant is obtained for mode locking of pulses longer than 100 fs. The A-FPSA provides a maximum modulation depth of 1.2% (i.e., a maximum amplitude loss modulation per round trip $q_0 = 0.006$), a nonsaturable insertion loss of 1.6%, and with a focused laser beam radius of 18 μm an effective saturation energy E_A of 6 nJ.[12]

We used the A-FPSA to soliton mode lock a cw argon-ion-laser-pumped Ti:sapphire laser with a standard dispersion compensated delta cavity, using a 0.15%-doped, 4-mm-thick Ti:sapphire crystal plate inserted at Brewster's angle between two 10-cm radius-of-curvature high-reflector mirrors, a 3% output coupler, two SF10 prisms separated by 45 cm, and a curved mirror of 10-cm radius that focuses the laser mode onto the A-FPSA. The pulse repetition rate was 100 MHz. In addition, we used a pellicle as an intracavity filter that predetermines the filter losses of the soliton. This results in a well-defined effective gain bandwidth that permits a quantitative compari-

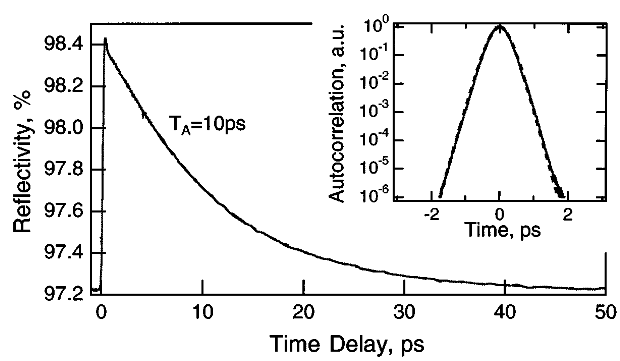

Fig. 1. Measured impulse response of the A-FPSA using 100-fs pulses with an energy fluence equal to that used inside the laser. The inset shows high-dynamic-range autocorrelation trace of the solitonlike pulse with 300 fs FWHM, achieved with soliton mode locking.

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son with theory. The measured filter bandwidth is $\Omega_f = 2\pi\ 23$ THz, which is equal to a bandwidth of $\Delta\lambda = 98$ nm at a center frequency of 800 nm. The 3% output coupler and the unsaturable linear losses of the A-FPSA result in a frequency-independent intracavity amplitude loss coefficient of $l \approx 0.02$.

To verify the soliton mode-locking theory, we show the transition from stable fundamental soliton generation to unstable behavior (Fig. 2) by reducing the negative group-velocity dispersion (GVD). Figure 2 is similar to data observed in dye lasers.[13,14] In contrast to our case, the pulse stabilization mechanism in dye lasers employs a slow saturable absorber and gain saturation that again create a net gain time window of the order of the pulse width. In our case of soliton mode locking we developed an analytical theory with constant gain that results in different stability criteria. This soliton mode-locking theory discussed below correctly predicts this stability limit and the obtained pulse duration of ≈300 fs. The slow saturable absorber provides efficient self-starting of the mode-locking process but otherwise only stabilizes soliton formation. This stabilization process is sufficiently fast that a high-dynamic-range autocorrelation measurement (Fig 1, inset) shows no background pulses and no deviations from an ideal soliton pulse shape over 6 orders of magnitude even though the net gain time window is open for longer than 35 times the pulse duration.

Before we expand further on this result, we demonstrate as follows that no KLM is responsible for the obtained pulses. The laser mode is focused into the Ti:sapphire crystal to a spot size of $A_L = \pi(35\ \mu\text{m} \times 22\ \mu\text{m})$ if the crystal is placed in the center of the cavity. Using *ABCD* matrix calculations, we can show that an appreciable effective fast saturable absorber from KLM is formed under certain cavity conditions (Fig. 3), which we experimentally verified by producing stable KLM with the A-FPSA replaced by a high reflector. To prevent KLM we moved the Ti:sapphire crystal 2 mm out of the focus of the laser mode, which tripled the mode size in the laser crystal, and moved the A-FPSA 4.9 cm away from the curved mirror.

We can now compare our experimental results (Fig. 2) with the soliton mode-locking theory given in Ref. 9. At an average output power of 200 mW the laser is 1.7 times above threshold and we have an intracavity power of 6.7 W and an intracavity pulse energy of $W = 67$ nJ, which is 11 times the saturation energy of the absorber. Thus one pulse strongly saturates the absorber, as was assumed in the analytical solution.[9] With a nonlinear refractive index of $n_2 = 3 \times 10^{-16}\ \text{cm}^2/\text{W}$ we obtain a self-phase modulation coefficient of $\delta = (2\pi/\lambda_0)n_2 2L_c/A_{\text{eff}} = 0.27/\text{MW}$ and therefore a nonlinear phase shift Φ_0 of ≈0.03, which is the dominant effect and allows for soliton perturbation theory. The soliton is formed by the interplay between self-phase modulation and negative GVD but loses energy through the other elements such as the saturable absorber, gain and filter bandwidth, and losses. This lost energy will spread in time because its intensity is not high enough to balance GVD and self-phase modulation and is therefore called the continuum. We have shown[9] that, if the response of the absorber essentially depends only on the energy of the soliton, then to first-order perturbation theory the soliton couples only to the continuum but the continuum does not couple back to the soliton. When the soliton is stable it saturates the gain to a value such that its net gain per round trip is zero, i.e., the saturated gain is equal to the loss $g = l + l_s$, where l_s is the additional loss experienced by the soliton as a result of the finite filter and gain bandwidth and the saturable absorber. For a slow saturable absorber l_s is given by

$$l_s = D_{g,f}/3\tau^2 + \frac{q_0 E_A}{W}\left[1 - \exp\left(-\frac{W}{E_A}\right)\right],$$

where $D_{g,f} = g/\Omega_g{}^2 + 1/\Omega_f{}^2 \approx 1/\Omega_f{}^2$ is the gain and intracavity filter dispersion. The FWHM pulse duration (Fig. 4) is given by the soliton $\tau_{\text{FWHM}} = 1.76\tau$, with $\tau = 4|D|/\delta W$, where D is the intracavity GVD. The soliton is stable as long as the continuum is below threshold, i.e., the continuum modes experience net loss per round trip, $l_s < \text{Re}(E_n)$, for $n = 0, 1, 2, \ldots$, where E_n are the eigenvalues of the operator in Eq. (5) of Ref. 9. The real parts of its eigenvalues are related to the round-trip loss $l_c = \text{Re}(E_0)$ of the corresponding continuum mode (Fig. 4). The continuum is spread in time because of dispersion and therefore experiences enhanced losses in the recovering absorber. If the intracavity GVD is much bigger than the intracavity filter dispersion $D_{g,f}$ (i.e., $D_{g,f} \approx 47\ \text{fs}^2$) the real parts of the eigenvalues E_n depend only on the normalized recovery time $w = T_A\sqrt{q_0/|D|}$. Therefore it is useful to represent the stability regime as a function of w and $|D|$ (Fig. 4). For $W \gg E_A$, l_s can be reduced

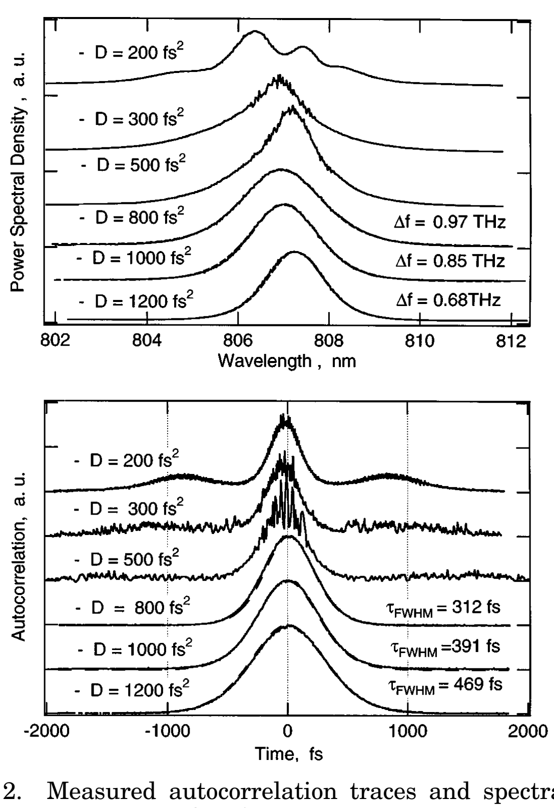

Fig. 2. Measured autocorrelation traces and spectra for different intracavity GVD's at an average output power of 200 mW.

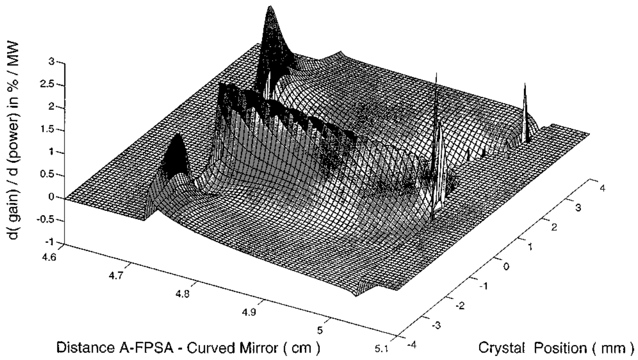

Fig. 3. Computed equivalent fast saturable absorber coefficient from KLM as a function of the laser crystal position and the distance between the A-FPSA and the folding mirror.

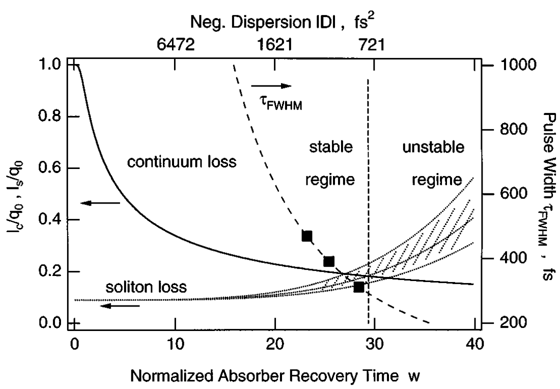

Fig. 4. Stability diagram for a soliton mode-locked laser stabilized by a slow saturable absorber according to Ref. 9. The filled boxes give the experimentally measured pulse width in the stable regime; the dashed curve gives the ideal soliton pulse width $\tau = 4|D|/\delta W$ as a function of dispersion or normalized recovery time $w = T_A\sqrt{q_0/|D|}$. The hatched area within the dotted curves shows the soliton loss for $w_0 = 53 \pm 5$.

to $l_s \approx (q_0 E_A/W) + (1/3\Omega_f{}^2\tau^2)$. This results in

$$\frac{l_s}{q_0} \approx \frac{E_A}{W} + \left(\frac{w}{w_0}\right)^4, \qquad w_0 = \left(\frac{4\Omega_f T_A{}^2 q_0{}^{3/2}\sqrt{3}}{\delta W}\right)^{1/2}. \tag{1}$$

For the experimental parameters extracted above, we obtain $w_0 = 53 \pm 5$. Figure 4 shows that for $|D| < 750\ \text{fs}^2$ the soliton formation becomes unstable because the continuum reaches threshold. This is in good agreement with our experimental results (Fig. 1) denoted by symbols in Fig. 4.

Leaving the regime of fundamental soliton generation, we observed the coexistence of a soliton with an appreciable amount of continuum, which leads to a noisy autocorrelation trace with strong coherence spikes because the whole spectrum is no longer phase locked. Further reduction of the negative GVD to $D = -200\ \text{fs}^2$ leads again to a clean and stable autocorrelation trace and spectrum. We then enter the area of higher-order soliton and continuum generation, which is beyond the scope of this Letter.

In conclusion, we have generated soliton pulses that are 35 times shorter than the recovery time of the absorber and are stabilized by the slow saturable absorber only. Thus the experiment verifies the theoretical predictions of soliton mode locking with a slow saturable absorber.[9] The large value of 35 for the ratio between absorber recovery time and pulse width achieved was possible only because of the weak filtering (see Fig. 4). With stronger filter action from finite gain bandwidth or output couplers the boundary between the stable and the unstable regimes (Fig. 4) moves toward smaller normalized absorber recovery times. However, with full saturation of the absorber at a normalized absorber recovery time $w \approx 10$ we still have approximately 30% of absorption available to overcome any kind of filter or higher-order dispersion losses experienced by the soliton. Therefore we predict that the ≈100-fs thermalization time in semiconductors should be fast enough to generate 10-fs pulses. This approach opens the possibility of choosing a design of the laser so that it reliably self-starts without overdriving the nonlinearities when the laser reaches the 10-fs regime. The shortest self-starting pulses achieved so far with pure soliton mode locking are 34 fs.[15] Currently, the pulse width is limited only by the Bragg mirror supporting the absorber and not by the mode-locking mechanism.

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References

1. D. E. Spence, P. N. Kean, and W. Sibbett, Opt. Lett. **16,** 42 (1991).
2. D. K. Negus, L. Spinelli, N. Goldblatt, and G. Feugnet, in *Advanced Solid-State Lasers*, G. Dubé and L. Chase, eds.,Vol. 10 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1991) p. 120.
3. U. Keller, G. W. 'tHooft, W. H. Knox, and J. E. Cunningham, Opt. Lett. **16,** 1022 (1991).
4. A. Stingl, M. Lenzner, Ch. Spielmann, and F. Krausz, Opt. Lett. **20,** 602 (1995).
5. J. Zhou, G. Taft, C.-P. Huang, M. M. Murnane, H. C. Kapteyn, and I. P. Christov, Opt. Lett. **19,** 1149 (1994).
6. U. Keller, T. H. Chiu, and J. F. Ferguson, Opt. Lett. **18,** 1077 (1993).
7. D. Kopf, F. Kärtner, K. J. Weingarten, and U. Keller, Opt. Lett. **19,** 2146 (1994).
8. F. X. Kärtner, D. Kopf, and U. Keller, J. Opt. Soc. Am. B **12,** 486 (1995).
9. F. X. Kärtner and U. Keller, Opt. Lett. **20,** 16 (1995).
10. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
11. U. Keller, Appl. Phys. B **58,** 347 (1994).
12. L. R. Brovelli, U. Keller, and T. H. Chiu, J. Opt. Soc. Am. B **12,** 311 (1995).
13. F. Salin, P. Georges, and A. Brun, Opt. Commun. **79,** 443 (1990).
14. H. Avramopoulos and G. H. C. New, Opt. Commun. **71,** 370 (1989).
15. L. R. Brovelli, I. D. Jung, D. Kopf, M. Kamp, M. Moser, F. X. Kärtner, and U. Keller, Electron. Lett. **31,** 287 (1995).