Operation of a femtosecond Ti:sapphire solitary laser in the vicinity of zero group-delay dispersion

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We report the operating characteristics of a self-mode-locked Ti:sapphire solitary laser at reduced group-delay dispersion. The generation of ≈12.3 fs near-sech^2 optical pulses at 775 nm is reported, together with experimental evidence for the dominant role of third-order dispersion (TOD) as a limiting factor to further pulse shortening in the oscillator. At reduced second-order dispersion excessive residual TOD is shown to lead to dispersive wave generation, and the position of the dispersive resonance is used to determine the ratio of the net second- and third-order intracavity dispersions. Since the magnitude of TOD rapidly decreases with increasing wavelength in prism-pair dispersion-compensated resonators, the oscillator presented has the potential for producing sub-10-fs pulses in the 800-nm wavelength region.

The operation of self-sustaining mode-locked Ti:sapphire lasers[1] at reduced net second-order group-delay dispersion (GDD) previously permitted the generation of sub-20-fs pulses directly from a laser.[2,3] The pulse shaping in these lasers is a result of the discrete solitonlike interplay between the GDD and self-phase modulation in the gain medium, with the shortest pulses generated for small net round-trip negative GDD.[4–6] Since a reduction of the net negative GDD in solitary lasers calls for low round-trip intracavity third-order dispersion[7] (TOD), the resonator has to be optimized for minimum TOD if short pulses are to be generated.[8–10] In this Letter we report the generation of 12-fs pulses from a Kerr lens mode-locked Ti:sapphire laser optimized for maximum self-amplitude modulation and minimum intracavity TOD. We discuss the operating characteristics of the laser at reduced GDD that provide evidence for the limiting role of TOD and report what is to our knowledge the first observation of dispersive waves as a result of TOD in a solitary laser.

The laser is constructed by using an X cavity configuration and a 4-mm-long Brewster-cut Ti:sapphire rod (Crystal Systems). The cavity design follows the layout of a previous design[9] and uses single-stack reflective optics comprising two 100-mm radius-of-curvature high reflectors, a flat high-reflector fold mirror and a flat high-reflector end mirror. Two Brewster-angled fused-silica prisms are positioned in the longer arm of the resonator, with an apex-to-apex separation of 59.5 cm, and a flat 5% wedged output coupler is positioned in the dispersive cavity end to couple out the solitary pulse with the shortest duration.[6] The laser is pumped with 5 W of 527.5-nm pump light from a cw actively mode-locked (76 MHz), frequency-doubled Nd:YLF laser (Quantronix 4216D). Mode locking of the Ti:sapphire laser is achieved by using synchronous pumping and a vertical slit in the short nondispersive cavity arm, with the cavity focusing mirrors positioned to maximize the passive amplitude modulation.[11] A second external prism pair is used to remove residual spatial chirp and permits compensation for chirp introduced by the output mirror substrate and precompensation for the finite thickness of the autocorrelator beam splitter. The pulse duration is measured by collinear interferometric autocorrelation by use of a 30-μm-thick barium borate doubling crystal. In Fig. 1 the variation of the mode-locked pulse spectrum is displayed as a function of increasing intracavity glass, with optimum mode locking corresponding to the central region of the diagram. It can be seen that, as the net negative GDD is reduced, the spectrum

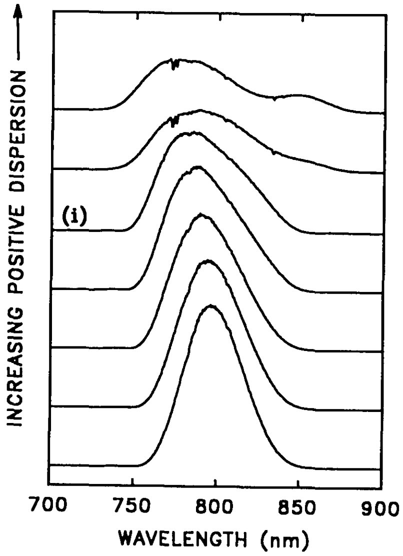

Fig. 1. Mode-locked spectra recorded by an optical multichannel analyzer at the dispersive cavity end as a function of increasing prism glass path for fixed values of intracavity pulse energy and aperture width. The relative change in net intracavity GDD between the adjacent spectra is $\Delta D \approx 10$ fs^2 for the initial reference $\lambda = 0.8$ μm. The discontinuities in some of the spectra at 775 nm are due to damaged detector array elements.

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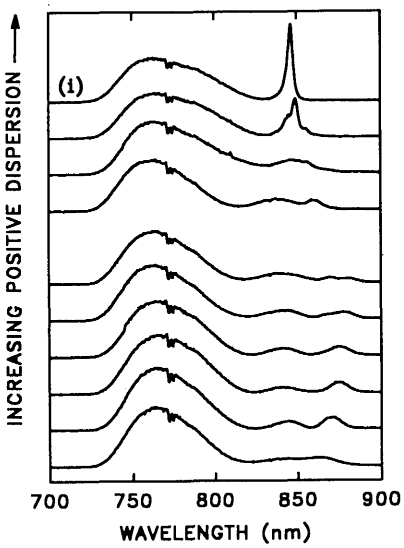

Fig. 2. Mode-locked spectra as a function of increasing prism glass path as the minimum operating GDD for stable operation is approached. The relative change in GDD from the top scan of Fig. 1 to the first scan in Fig. 2 is ≈ 5 fs^2. Here $\Delta D \approx 1$ fs^2 at $\lambda = 0.8$ μm and was controlled by translating the second prism on a precision micrometer stage. In curve (i) the shift of energy is into a dispersive resonance at a higher wavelength.

broadens and the peak wavelength shifts to shorter wavelengths; this change is understood to be due to the blue shift of the negative dispersion regime with increasing prism insertion. The lack of any significant spectral broadening with subsequent reduction in GDD, from curve (i) of Fig. 1 onward, is a strong indication of the dominance of TOD in limiting further pulse shortening. The spectra in Fig. 2 continue on from Fig. 1 and display the rapid spectral variation observed as a function of glass insertion as the zero-dispersion wavelength approaches the solitary pulse spectrum. The secondary spectral features are in the positive dispersive regime and correspond to a longer pulse copropagating with the short solitary pulse, a behavior similar to that observed in colliding-pulse mode-locked dye lasers.[12,13] In proximity to the minimum operating GDD, energy extraction from the main pulse by means of dispersive waves becomes dominant [curve (i) in Fig. 2]. Further reduction of the GDD from this point causes the laser to stop mode locking. The appearance of a sharp dispersive resonance[14,15] (dispersive wave generation) has not been observed in femtosecond dye lasers, presumably because of the strong intracavity passive amplitude modulation present in the cavity.

The *in situ* measurement of the operating GDD by the method described by Knox[16] was attempted; however, reproducible wavelength tuning with a slit in the dispersive arm of our laser has not been possible with bandwidths in excess of 50 nm. Nevertheless, dispersion characteristics at the pulse center frequency ω_0 can be obtained by considering the relative positions of the spectral features in curve (i) of Fig. 2. A rigorous relation in the presence of dispersive waves can be obtained by using the knowledge that the dispersive wave can efficiently extract energy from the main solitary pulse only if the two waves are phase matched. A phase-matching condition can thus be derived by using an extension to the treatment given by Gordon[17] and is depicted graphically in Fig. 3. Phase matching occurs where the dispersive wave number $k_r = (1/L_r)[(D\Delta\omega^2/2) + (D_3\Delta\omega^3/6)]$ and the solitary-pulse wave number $k_s = -(1/L_r)(D/2T^2)$ coincide. Here L_r is the round-trip resonator length, D and D_3 represent the net round-trip GDD and TOD at the solitary pulse center frequency ω_0, respectively, and $\Delta\omega$ is the frequency shift from ω_0. The constant $T = \tau_p/1.76$, where τ_p is the solitary pulse duration. The phase-matching condition can now be written as

$$\Delta\omega_r^2 + \beta\Delta\omega_r^3 = -(1/T^2), \tag{1}$$

where $\Delta\omega_r$ is the frequency spacing between the dispersive resonance ω_r and the center frequency ω_0 and $\beta = D_3/3D$. When the measured solitary pulse width $\tau_p \approx 18$ fs and $\Delta\omega_r \approx -0.24$ fs^{-1} corresponding to curve (i) of Fig. 2 are used, substitution into Eq. (1) yields $\beta \approx 4.9$ fs. Now we can exploit the relative insensitivity of the calculated net TOD to errors in the measurement of the prism insertion to determine the net intracavity GDD. Substituting the calculated TOD of $D_3 \approx -800$ fs^3 into the expression for β gives $D \approx -50$ fs^2 for curve (i) of Fig. 2.

The shortest mode-locked pulses are produced under conditions corresponding to those shown by curve (i) of Fig. 1, where the broadest structureless spectra are generated. For this operating regime, typical single-scan interferometric autocorrelations of pulses from the dispersive arm of the laser

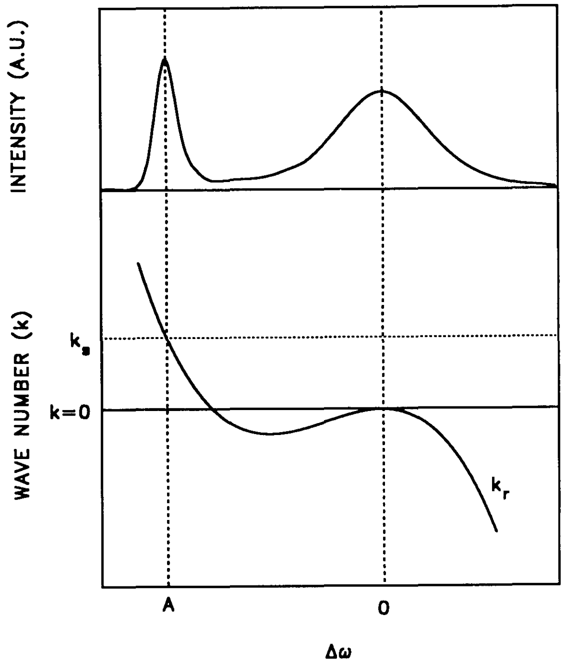

Fig. 3. (Top) Plot of an ideal solitary pulse mode-locked spectrum in the presence of dispersive waves. (Bottom) Dispersion diagram for a solitary pulse (k_s) and a dispersive wave (k_r) in the presence of GDD and TOD in the cavity. Dashed line A denotes the dispersive resonance position, $\Delta\omega_r$.

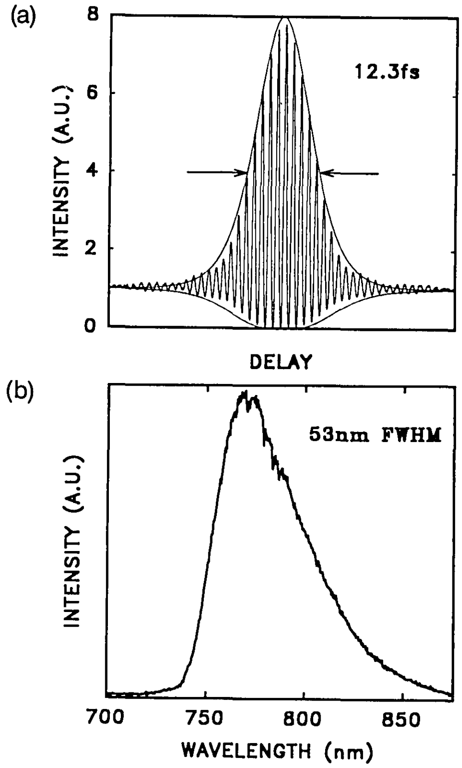

Fig. 4. (a) Interferometric autocorrelation of the shortest mode-locked pulses from the dispersive cavity arm of the laser, together with an ideal sech^2 pulse envelope. (b) The corresponding pulse spectrum.

and the pulse spectrum are shown in Figs. 4(a) and 4(b), respectively. A sech^2 fit to the envelopes of the fringes is displayed with the measured autocorrelation trace, yielding a pulse duration of 12.3 fs and a time–bandwidth product of ≈ 0.33.

For an absorbed pump power of ≈ 2.5 W the average mode-locked output power is 160 mW, yielding an intracavity pulse energy of $W \approx 40$ nJ and an output pulse peak power of 0.17 MW. Using the value of GDD determined from Eq. (1) and curve (i) of Fig. 2, and knowledge of the relative prism insertion, we estimate the operating GDD for optimum mode locking at 775 nm to be $D \approx -80$ fs^2. From the calculated value for the round-trip nonlinear phase shift $\phi = 1.5 \times 10^{-6}$ W^{-1}, the predicted solitary-pulse duration[6] for the described system is ≈ 10.5 fs, in reasonable agreement with the experimental result.

In summary, we have reported the reproducible operation of a sub-15-fs Ti:sapphire laser in the vicinity of the zero-dispersion point and confirmed the observation of spectral splitting as a result of third-order dispersion. The results provide evidence that further pulse shortening is limited by residual intracavity TOD in our Ti:sapphire solitary laser. Since the magnitude of the net intracavity TOD rapidly decreases with increasing wavelength, it is anticipated that shorter pulses may still be obtained by using suitable reflective optics to force the laser to oscillate at higher wavelengths (≥ 800 nm).

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