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Operation of a femtosecond Cr:LiSAF solitary laser near zero group-delay dispersion

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Abstract

We report the characteristics of a self-mode-locked Cr:LiSAF solitary laser which is operated at reduced group-delay dispersion (GDD). The mode-locked laser produces 37-fs pulses with the spectral width of 41 nm. The spectral change with increasing prism insertion is found to be different from that in a Ti:sapphire laser. We observed dispersive waves generated from the mode-locked Cr:LiSAF solitary laser and estimated the GDD and third-order dispersion (TOD) of the laser cavity under the lasing condition. A large TOD is shown to limit the possible reduction of the absolute value of GDD.

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Self-mode-locked Cr:LiSAF lasers are attractive femtosecond (fs)-pulse sources which can directly be pumped by compact diode lasers. So far, the self-mode-locked Cr:LiSAF lasers pumped by Kr- and Ar-ion lasers have been reported to produce ultrashort pulses as short as 150 fs [1] and 33 fs [2], respectively. Several experiments of diode-pumped self-mode-locked Cr:LiSAF lasers have also been demonstrated [3–5]. Use of an intracavity multiple-quantum-well saturable absorber yielded 220-fs pulses [3], and subsequently, an antiresonant Fabry-Perot saturable absorber reduced pulse durations to 45 fs [4]. Recently, 18-fs pulses were generated with Kerr-lens mode locking [5]. The ultrashort-pulse formation in these self-mode-locked lasers is a result of the discrete soliton-like interplay between the second-order group-delay dispersion (GDD) and the self-phase modulation in a gain medium [6–8]. In a Ti:sapphire solitary laser, dispersive waves were observed at a reduced GDD as a result of excessive residual third-order dispersion (TOD) [9].

In this communication, we report, to our knowledge, the first observation of the dispersive wave in a Cr:LiSAF solitary laser and discuss the characteristic spectral change different from that of a Ti:sapphire solitary laser. We have estimated the GDD and the TOD of the Cr:LiSAF-laser cavity under the lasing condition, and a large TOD is found to limit the reduction of the absolute value of GDD.

The schematic diagram of the self-mode-locked Cr:LiSAF solitary laser is shown in Fig. 1. The Z-fold laser cavity is composed of two 100-mm radius-of-curvature folding mirrors and two flat output couplers. All the cavity mirrors are highly reflecting at 810–920 nm. The laser contains a 1.5%-doped 5-mm-long Brewster-cut Cr:LiSAF crystal

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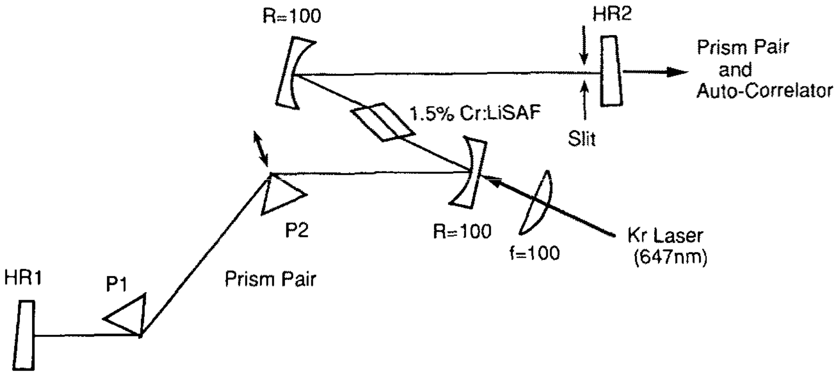

Fig. 1. Schematic diagram of the self-mode-locked Cr:LiSAF laser. HR1 and HR2, high reflectors; P1 and P2, Brewster-cut prisms.

(Lightning Optical Corp.). The crystal temperature is stabilized at 15.0°C. The two intracavity fused-silica prisms are separated by 500 mm. The Cr:LiSAF crystal is pumped with a 647-nm Kr-ion laser (Laser Ionics) which output is focused by a 10-cm focal-length lens. Self-mode-locking was achieved by introducing a vertical slit placed close to the output mirror on the opposite side of the prism pair. The output power was 9.3 mW at the absorbed pump power of 390 mW. The stable self-mode-locking was observed in a range of the absorbed pump power of 230–500 mW.

The self-mode-locked laser favors oscillation in the region of negative GDD. The laser cavity was arranged to have a negative GDD large enough to be self-mode-locked, and then the amount of insertion of the prism P2 was slowly increased to approach a nearly zero GDD. The mode-locked laser spectra for various prism insertions are shown in Fig. 2. The relative changes of the prism P2 insertions from (a) to (b), (b) to (c), (c) to (d), and (d) to (e) are 1.84 mm, 1.00 mm, 0.12 mm, and 0.10 mm, respectively. The pulse duration observed was shortest for the spectrum (e) in Fig. 2, and then the spectral width (FWHM) and the central wavelength were 41 nm and 910 nm, respectively. An example of the autocorrelation trace is shown in Fig. 3. Assuming a sech^2 pulse shape, the pulse width (FWHM) was 37 fs. This value was limited by the resolution of the autocorrelator used. This was confirmed by the observation that the pulse width did not become shorter

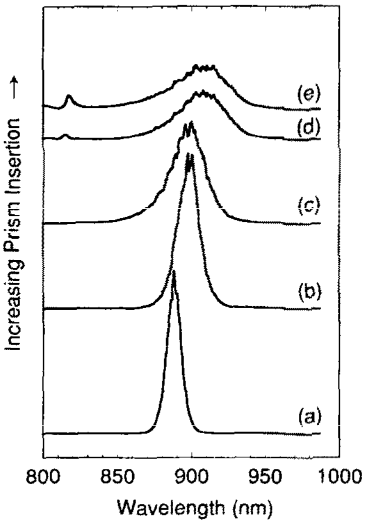

Fig. 2. Mode-locked laser spectra for the various prism insertions.

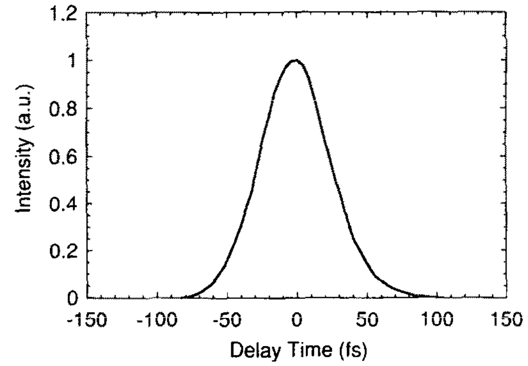

Fig. 3. Autocorrelation trace for the spectrum (e) with the spectral width (FWHM) of 41 nm in Fig. 2. The pulse width (FWHM) is 37 fs, assuming a sech^2 pulse shape.

for broader spectral width. From the spectral width observed, the transform-limited value of the pulse width is calculated to be 21 fs.

The results shown in Fig. 2 represent that, with increasing prism insertion, the spectrum broadens and the peak wavelength shifts to a longer-wavelength region. This characteristic spectral change is due to the red shift of the negative-dispersion region with an increase of the prism insertion. This is in contrast to the blue shift observed in the self-mode-locked Ti:sapphire laser operating at ~ 780 nm [9]. At a nearly zero GDD ((e) in Fig. 2), a sharp resonance (dispersive wave) appears in a wavelength region much shorter than the spectral peak. A further increase in the prism insertion shifted the resonance toward the main peak and eventually stopped the mode locking.

The dispersive wave can efficiently extract energy from the main solitary pulse if the two waves are phase-matched, i.e., $k_s = k_d$, where k_s and k_d are the wave numbers of the solitary pulse and the dispersive wave, respectively. The phase-matching condition [9] can be written as

$$\Delta\omega^2 + \beta\Delta\omega^3 = -1/T^2. \qquad (1)$$

Here $\Delta\omega$ is the dispersive-wave frequency shift from the solitary-pulse center frequency ω_0. The constant β and T are given by $\beta = D_3/3D_2$ and $T = \tau_p/1.76$, where D_2 and D_3 represent the net round-trip GDD and TOD at ω_0, respectively, and τ_p is the solitary pulse width (FWHM). We can determine the ratio D_3/D_2 for the Cr:LiSAF solitary laser by substituting the observed values of $\Delta\omega$ and T into Eq. (1), as in the calculation of Curley et al. for a Ti:sapphire solitary laser [9]. The central wavelength of 910 nm and the dispersive-resonance shift of 92 nm observed for the Cr:LiSAF laser (see (e) in Fig. 2) yield $D_3/D_2 = -14.6$ fs, where the transform-limited value of $\tau_p = 21$ fs is used. The position of the dispersive-wave spectrum in the mode-locked Cr:LiSAF laser is different from that in the mode-locked Ti:sapphire laser operating at ~ 780 nm, because the sign of the ratio D_3/D_2 for the Cr:LiSAF laser is opposite to that for the Ti:sapphire laser [9].

The dispersion of Cr:LiSAF crystal at ω_0 is calculated from the Sellmeier equation [10], and that of the fused-silica prism pair can be calculated for any prism insertion. Assuming that the total dispersions D_2 and D_3 originated only from the Cr:LiSAF crystal and the fused-silica prism pair used in the laser cavity, we can evaluate the dispersions for the spectrum of (e) in Fig. 2 by choosing such a prism insertion that satisfies the equation $D_3/D_2 = -14.6$ fs. We obtained $D_2 = -55.6$ fs^2 and $D_3 = 809$ fs^3. These values are insensitive to uncertainties in the measurement of the prism insertion. In this calculation, we have neglected the TOD of mirrors, because the total TOD of the laser cavity was estimated to be much larger than that (~ 120 fs^3) of mirrors. (The total TOD of mirrors is estimated by the data in a catalog of the CVI laser corp.) From the equations of the wave numbers k_s and k_d [9], we obtain the curves of the solitary-pulse round-trip relative phase shift $\phi_s = k_s L$ and the dispersive-wave round-trip relative phase shift $\phi_d = k_d L$ as a function of wavelength, as shown in Fig. 4, where L is the round-trip cavity length. Here, ϕ_d becomes zero at the center wavelength of 910 nm. The dispersive wave is generated at the wavelength of the intersection of ϕ_s and ϕ_d.

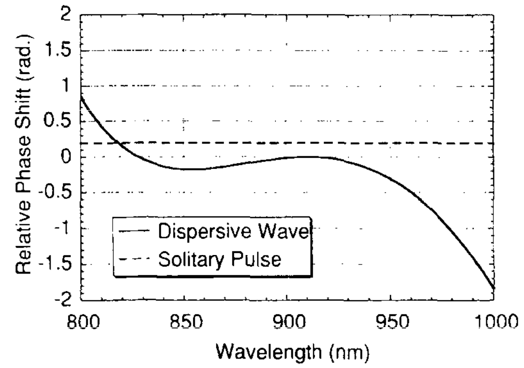

Fig. 4. The curves of the solitary-pulse round-trip relative phase shift ϕ_s and the dispersive-wave round-trip relative phase shift ϕ_d for the spectrum (e) in Fig. 2. ϕ_d becomes zero at the center wavelength of 910 nm.

Using the GDD and TOD values obtained and the relative prism insertions, we estimated the dispersions for each spectrum (a)–(e) in Fig. 2, and the results are shown in Fig. 5. Here, we took account of the change in the center wavelength of each spectrum. The GDD approaches to zero from (a) to (c) in Fig. 5 as the prism insertion increases. However, the GDDs for (d) and (e) in Fig. 5 are no longer

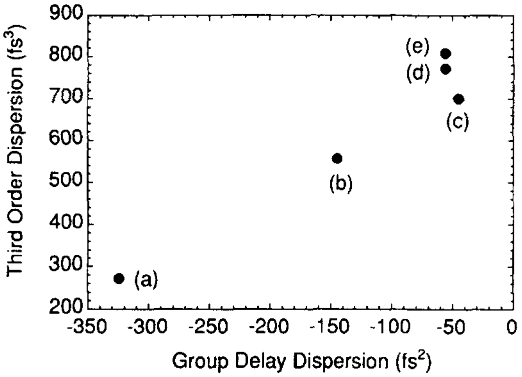

Fig. 5. Third-order dispersion as a function of group-delay dispersion for each spectrum (a)–(e) in Fig. 2.

decreased. This is due to the large TOD introduced with increasing prism insertion.

When the variation of the GDD over the spectral width $\Delta\omega_p$ (FWHM) becomes comparable to the value of the GDD at the center wavelength, i.e., $|\Delta D_2/D_2| \sim |D_3\Delta\omega_p/D_2| \sim 1$, the effect of TOD cannot be ignored in the short-pulse formation [11]. For example, $|D_3\Delta\omega_p/D_2| = 0.021$, 0.15, 0.93, 1.20, and 1.36 for (a), (b), (c), (d), and (e) in Fig. 5, respectively. For (d) and (e) in Fig. 5, the large TOD becomes effective, and the curves of the solitary-pulse round-trip relative phase shift ϕ_s and the dispersive-wave round-trip relative phase shift ϕ_d have an intersection near the pulse spectrum, as shown in Fig. 4. The larger TOD value makes the wavelength of the intersection closer to the solitary-pulse center wavelength, which leads to an increase in the energy flow from the solitary pulse to the dispersive wave and eventually to the unstable mode locking. The solitary pulses are sustained by a small increase in the center wavelength so that the absolute value of GDD does not decrease, as shown in Fig. 5.

In summary, we have studied the characteristics of a self-mode-locked Cr:LiSAF solitary laser in the vicinity of zero GDD and discussed the spectral change with increasing prism insertion which is different from that in a Ti:sapphire laser operating at ~ 780 nm. The dispersive wave was observed, and the GDD and the TOD of the laser cavity were estimated under the lasing condition. It has been shown that the reduction of the absolute value of GDD is limited by a large TOD value. The effects of both GDD and TOD should be taken into account to optimize the mode-locked Cr:LiSAF laser. When a fused-silica prism pair is used for the Cr:LiSAF solitary laser, the GDD and the TOD can be equal to zero simultaneously at a shorter wavelength near 800 nm. Shorter fs-pulse generation is also possible in a longer wavelength region by selecting the other glass material for a prism pair [5,12].

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