Third-order dispersion in femtosecond fiber lasers

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We experimentally investigate the effects of third-order dispersion (TOD) on ultrafast sources, using dispersion-compensated femtosecond fiber lasers. By *in situ* measurement of the intracavity dispersion, we identify spectral resonances that are due to coupling of the cavity pulse energy to dispersive wave components at the phase velocity and group-velocity-matched wavelengths. We obtain pulse widths as short as 91 fs by partially compensating the TOD. We relate the observed effects to consequences for soliton transmission and operation of other solitary-pulse lasers.

Since the first demonstration of the figure-eight laser[1] (F8L), all-fiber lasers mode locked by means of fiber Kerr nonlinearity have become commonplace, producing pulses of <100 fs. As previously found for other ultrafast lasers (dye, Ti:Al_2O_3, etc.), a key to obtaining short pulses is to minimize the total cavity group-velocity dispersion (GVD) k_0''. Minimum pulse widths of $\tau_{\min} \sim \sqrt{k_0''}$ are obtained for fiber lasers operating in the overall negative-dispersion regime.[2,3] One can reduce the GVD by shortening the cavity, by using dispersion-shifted fiber components or dispersion-compensating fiber (DCF) within the cavity, or by using any combination of these.[4–7] As the total dispersion approaches zero, third-order (or cubic) dispersion (TOD) becomes a limiting pulse-shaping mechanism for pulse widths $\tau_0 \sim k_0'''/k_0''$, where k_0''' is the total TOD and $\tau_0 = 0.57\tau_{1/2}$ for a full width at half-maximum of $\tau_{1/2}$. The TOD has been shown to perturb the propagation and interactions of solitons in a fiber, leading to the development of resonantly enhanced dispersive waves in both the normal- and the anomalous-dispersion regimes.[8,9]

Ultrashort pulse fiber lasers serve as a practical experimental model for studying the effects of TOD on soliton propagation, as the periodic gain or loss experienced by the intracavity pulse over a round trip is closely analogous to the propagation of guiding center solitons in a periodically amplified transmission link.[10] In this Letter we report an investigation of the effects of the TOD on the operation of mode-locked fiber lasers that have been dispersion compensated to yield pulse widths of 90–150 fs. We extend the technique of characterizing the cavity dispersion by analyzing the spectrum of dispersive wave resonance sidebands to determine the TOD in these cavities.[3,7,11] A broad spectral enhancement in the normal-dispersion regime is shown to be due to matching of the dispersive wave group velocity to that of the nonlinear pulse. Our results are compared with similar phenomena observed in mode-locked dye and Ti:Al_2O_3 lasers (Refs. 12–14) and with theoretical results for both mode-locked lasers[15–17] and soliton transmission.[9,18] We present results for a system operating at the zero-GVD wavelength, in which the TOD is partially compensated by fiber with β_3 (TOD per unit length) opposite that of standard fiber.

Perturbation of a propagating soliton by loss, gain, or varying dispersion causes a linearly propagating *dispersive wave* to be shed from the pulse. Over each round trip in a laser, constructive interference between successively generated dispersive waves yields a series of spectral sidebands.[19] The frequency offset $\Delta\omega_N$ of the Nth sideband from the pulse central frequency satisfies[3]

$$N = -\frac{1}{4\pi}k_0''\left(\Delta\omega_N{}^2 + \tau_0{}^{-2}\right) - \frac{1}{12\pi}k_0'''\Delta\omega_N{}^3 . \quad (1)$$

Note that N is taken to be positive when the linear phase velocity is greater than the soliton phase velocity. The total GVD and TOD are obtained from the quadratic and cubic terms of a fit of the order number versus the sideband frequency.[3]

Our experiments were conducted on a variety of F8L's[1] and nonlinear birefringence mode-locked ring lasers.[6] Dispersion-shifted fiber components were used primarily, and all pigtails were kept as short as practicable (~25–40 cm). Gain fiber with a moderately high doping (~1200 parts in 10^6 by weight, $\beta_2 = -13\ \mathrm{ps^2/km}$) was used to minimize cavity length. Residual dispersion was canceled by addition of appropriate lengths of a DCF ($\beta_2 = 125\ \mathrm{ps^2/km}$, $\beta_3 = 0.41\ \mathrm{ps^3/km}$ at 1550 nm). We obtained ~100-fs pulses in both F8L and ring configurations. As is typical for standard (uncompensated) fiber lasers, pulsing is initiated by manipulation of the component fiber, yielding multiple arbitrarily spaced pulses per cavity round trip.

Figure 1 illustrates the method of determining the dispersion parameters, particularly the effect of increasing relative TOD. We obtained the curves from a 7.0-m base F8L by adding lengths of DCF. For each cavity, a spectrum is recorded (on a logarithmic scale) and the sideband wavelengths identified. For cavities with relatively small TOD, as in curves (a) and (b), the assignment of the order numbers is straightforward. With large TOD, as in curve (c) of Fig. 1 or in Fig. 2, usually only one assignment will yield a plausible fit (with continuity in numbering and component fiber dispersions taken into account.) Whereas the TOD is the predominant effect for cavities with low GVD, fourth-order dispersion is in fact

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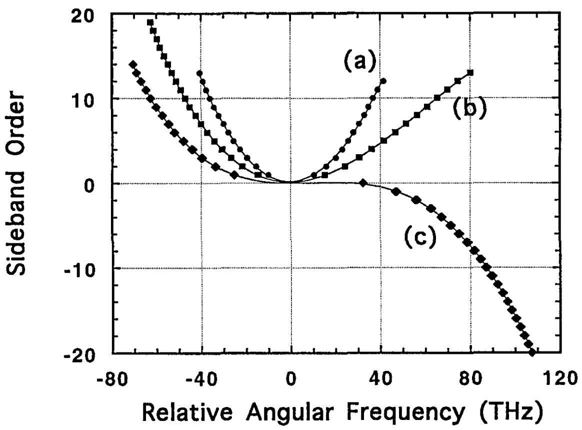

Fig. 1. Variation of the sideband spectra with increasing relative third-order dispersion. (a) Base cavity, $k_0'' - 0.093\ \mathrm{ps}^2$, $k_0''' = 0.46 \times 10^{-3}\ \mathrm{ps}^3$; (b) 35-cm DCF, $-0.045\ \mathrm{ps}^2$, $0.76 \times 10^{-3}\ \mathrm{ps}^3$; (c) 71-cm DCF, $-0.015\ \mathrm{ps}^2$; $1.06 \times 10^{-3}\ \mathrm{ps}^3$.

required in order to fit spectrum (c) of Fig. 1 out to the farthest sideband with ($N = -60$, at ~150 THz). Note the zero crossing in curve (c) of Fig. 1—the sideband with $N = 0$—corresponding to the wavelength where the average linear phase velocity is equal to that of the soliton.

Figure 2(a) shows a typical spectrum for a dispersion-compensated F8L with a pulse length of 125 fs. Each sideband is marked with its corresponding order number. From the fit to Fig. 2(b), the total GVD and TOD is $-0.0174\ \mathrm{ps}^2$ and $0.0011\ \mathrm{ps}^3$. The sharp feature at 1531 nm corresponds to a weak-background cw oscillation of the laser and is of no significance here. The broad enhancement of the spectrum toward the blue, centered at ~1512 nm [marked GM in Fig. 2(a) and indicated by a solid triangle in Fig. 2(b)], falls very near the local maximum of the dispersion curve fit, indicating that it has the same group velocity as the pulse central frequency. To confirm that this enhancement corresponds to the GVD matched wavelength, Fig. 3 illustrates variation of the group-velocity-matched wavelength in a system in which one could tune the pulse central wavelength by varying the polarization controller settings.[11] The total cavity dispersion was determined to be $-0.174 \pm 0.003\ \mathrm{ps}^2$ at 1560 nm, with the zero-dispersion wavelength at 1540.7 ± 0.9 nm. The plotted line has slope 1 and fits well to within the uncertainty (estimated at ±2 nm) in estimating the center wavelength of these broad spectral features.

The effect of shifting the wavelength of zero GVD into the pulse spectrum (i.e., by completely compensating the dispersion at the operating wavelength) is illustrated in Fig. 4. The system was a 14.5-m F8L with dispersion-shifted fiber components, 0.15 m of DCF immediately before the loop mirror, and 6.9 m of a TOD compensating fiber ($\beta_2 = 10 \pm 4\ \mathrm{ps}^2/\mathrm{km}$, $\beta_3 = -0.04 \pm 0.02\ \mathrm{ps}^3/\mathrm{km}$, estimated from the profile) in the loop mirror. Despite the long cavity, a very short, 91-fs pulse is obtained. Roughly half of the spectrum is in the normal-dispersion regime, so a soliton is not obtained—the observed time–bandwidth product of $\tau\Delta\nu = 0.41$ is ~30% higher than for a sech^2 pulse. The observed spectrum is similar to that obtained in the numerical simulations of Tzelepis *et al.*[16] and is reminiscent of that reported by Wai *et al.*[20] and of analogous observations in a mode-locked dye laser.[12]

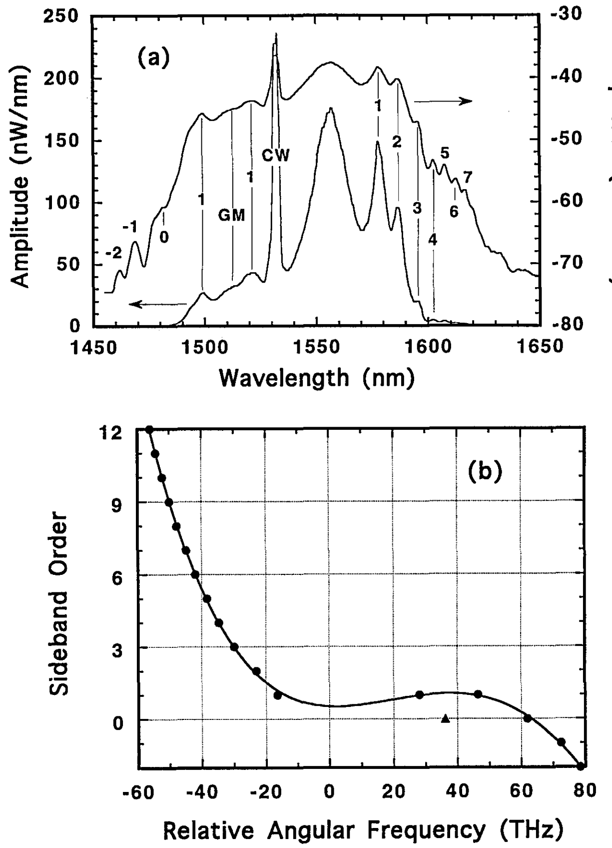

Fig. 2. Spectrum of the output of a laser with large intracavity dispersion. (a) Linear and logarithmic spectra with the sidebands labeled with their corresponding order numbers. (b) Cavity dispersion relation obtained by fitting the sideband spectrum. The triangle denotes the center of the group-velocity-matched sidelobe.

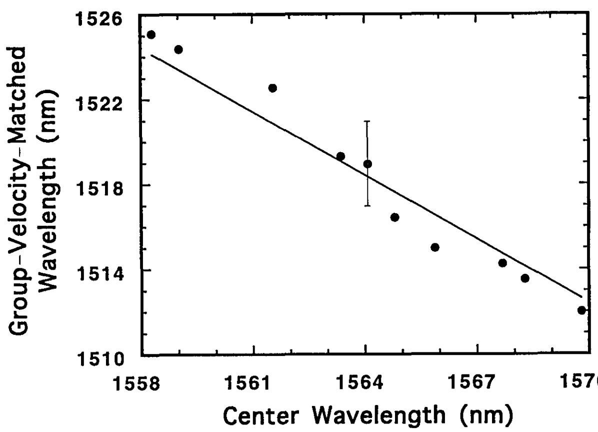

Fig. 3. Positions of the group-velocity-matched sidelobe as a function of the pulse center wavelength. The zero-dispersion wavelength was determined to be 1540.7 ± 0.9 nm. Estimated uncertainty for all points is indicated by the plotted error bar.

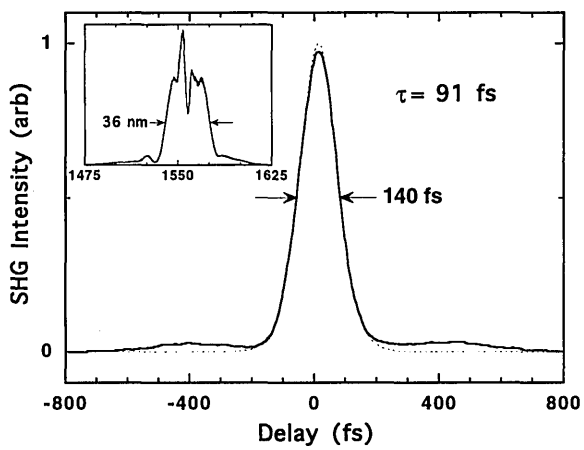

Fig. 4. Autocorrelation for a cavity with partially compensated TOD, operating near the zero-GVD wavelength. The pulse width is 91 fs, assuming a $sech^2$ pulse. Inset: spectrum, showing that the wavelength of zero GVD is within the spectrum of the pulse. SHG, second-harmonic generation.

We have used dispersive wave resonance sidebands in passively mode-locked fiber lasers to study extensively the effects of TOD. Our experimental results accurately match the predictions of Eq. (1) and previous numerical simulations,[9,16] even in the presence of large TOD. Coupling of soliton energy to dispersive waves has important implications for operation of the entire class of solitary-pulse mode-locked lasers and soliton-based telecommunications. Phase-matched dispersive wave ($N = 0$) coupling is observed in $Ti{:}Al_2O_3$ lasers[14] and corresponds to a pulse-width-limiting loss mechanism,[15,17] just as the $N \neq 0$ sidebands limit the pulse width in standard fiber lasers.[2,3] Whereas the $N \neq 0$ sidebands result from periodic perturbation, the $N = 0$ sideband represents a continuous coupling to the dispersive wave and so is generated in otherwise unperturbed soliton propagation.[8] The presence of the dispersive wave enhancement at the group-velocity-matched wavelength has been observed also in dye lasers[13] and is evident in simulations of F8L operation.[16] Physically, this is a consequence of passive amplitude modulation: Light at this wavelength copropagates through the saturable absorber with the primary pulse and so sees comparatively little loss. Passive amplitude filtering via nonlinear loop mirrors has been proposed for removing dispersive wave and noise components in long-distance soliton propagation[18]; our results imply that the supplemental frequency-domain filtering included in their formulation is essential for suppression of the group-velocity-matched dispersive wave. Finally, by obtaining sub-100-fs pulses in a relatively long fiber laser, we have demonstrated that TOD effects can be alleviated by all-fiber compensation, thus permitting operation with very low overall dispersion.

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References

1. I. N. Duling III, Electron. Lett. **27,** 544 (1991).
2. M. L. Dennis and I. N. Duling III, Appl. Phys. Lett. **62,** 2911 (1993).
3. M. L. Dennis and I. N. Duling III, IEEE J. Quantum Electron. **30,** 1469 (1994).
4. M. Nakazawa, E. Yoshida, and Y. Kimura, Electron. Lett. **29,** 63 (1993).
5. M. E. Fermann, M. J. Andrejco, M. L. Stock, Y. Silberberg, and A. M. Weiner, Appl. Phys. Lett. **62,** 910 (1993).
6. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, Opt. Lett. **18,** 1080 (1993).
7. I. N. Duling III and M. L. Dennis, "Dispersion compensated fiber lasers," in *Nonlinear Guided Wave Phenomena*, Vol. 15 of 1993 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1993), pp. 360–362.
8. P. K. A. Wai, C. R. Menyuk, Y. C. Lee, and H. H. Chen, Opt. Lett. **11,** 464 (1986).
9. Y. Kodama, M. Romagnoli, S. Wabnitz, and M. Midrio, Opt. Lett. **19,** 165 (1994).
10. A. Hasegawa and Y. Kodama, Opt. Lett. **15,** 1443 (1990); **16,** 1385 (1991).
11. M. L. Dennis and I. N. Duling III, Electron. Lett. **29,** 409 (1993).
12. F. W. Wise, I. A. Walmsley, and C. L. Tang, Opt. Lett. **13,** 129 (1988).
13. F. Salin, P. Grangier, P. Georges, and A. Brun, Opt. Lett. **15,** 374 (1990).
14. P. F. Curley, Ch. Spielmann, T. Brabec, F. Krausz, E. Wintner, and A. J. Schmidt, Opt. Lett. **18,** 54 (1993).
15. H. A. Haus, J. D. Moores, and L. E. Nelson, Opt. Lett. **18,** 51 (1993).
16. V. Tzelepis, S. Markatos, S. Kalpogiannis, Th. Sphicopoulos, and C. Caroubalos, J. Lightwave Technol. **11,** 1729 (1993).
17. T. Brabec and S. M. J. Kelly, Opt. Lett. **18,** 2002 (1993).
18. M. Matsumoto, H. Ikeda, and A. Hasegawa, Opt. Lett. **19,** 183 (1994).
19. N. Pandit, D. U. Noske, S. M. J. Kelly, and J. R. Taylor, Electron. Lett. **28,** 455 (1992).
20. P. K. A. Wai, C. R. Menyuk, H. H. Chen, and Y. C. Lee, Opt. Lett. **12,** 628 (1987).