Amplifier similaritons in a dispersion-mapped fiber laser [Invited]

William H. Renninger,* Andy Chong, and Frank W. Wise
Department of Applied Physics, Cornell University, Ithaca, New York 14853, USA
* whr6@cornell.edu

Abstract: Amplifier similaritons are generated in a dispersion-mapped fiber laser. Output pulse parameters are nearly independent of the net group velocity dispersion (GVD) owing to the strong local nonlinear attraction in the gain fiber, which dictates the pulse evolution. This constitutes a stable mode-locking regime that is capable of generating sub-100-fs pulses over a broad range of anomalous and normal GVD. These features are consistent with numerical simulations.

© 2011 Optical Society of America

OCIS codes: (320.7090) Ultrafast lasers; (320.5540) Pulse shaping; (060.2320) Fiber optics amplifiers and oscillators.

References and links
1. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, “77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser,” Opt. Lett. 18, 1080–1082 (1993).
2. F. O. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, “Self-similar evolution of parabolic pulses in a laser,” Phys. Rev. Lett. 92, 213902 (2004).
3. A. Chong, J. Buckley, W. Renninger, and F. Wise, “All-normal-dispersion femtosecond fiber laser,” Opt. Express 14, 10995–10100 (2006).
4. W. H. Renninger, A. Chong, and F. W. Wise, “Dissipative solitons in normal-dispersion fiber lasers,” Phys. Rev. A 77, 023814 (2008).
5. K. Kieu, W. H. Renninger, A. Chong, and F. W. Wise, “Sub-100 fs pulses at watt-level powers from a dissipative-soliton fiber laser,” Opt. Lett. 34, 593–595 (2009).
6. M. Baumgartl, F. Jansen, F. Stutzki, C. Jaureguy, B. Ortaç, J. Limpert, and A. Tünnermann, “High average and peak power femtosecond large-pitch photonic-crystal-fiber laser,” Opt. Lett. 36, 244–246 (2011).
7. D. Anderson, M. Desai, M. Karlsson, M. Lisak, and M. Quiroga-Teixeiro, “Wave-breaking-free pulses in nonlinear-optical fibers,” J. Opt. Soc. Am. B 10, 1185–1190 (1993).
8. K. Tamura and M. Nakazawa, “Pulse compression by nonlinear pulse evolution with reduced optical wave breaking in erbium-doped fiber amplifiers,” Opt. Lett. 21, 68–70 (1996).
9. V. Kruglov, A. Peacock, J. Dudley, and J. Harvey, “Self-similar propagation of high-power parabolic pulses in optical fiber amplifiers,” Opt. Lett. 25, 1753–1755 (2000).
10. V. Kruglov, A. Peacock, J. Harvey, and J. Dudley, “Self-similar propagation of parabolic pulses in normal dispersion fiber amplifiers,” J. Opt. Soc. Am. B 19, 461–469 (2002).
11. V. I. Kruglov, A. C. Peacock, and J. D. Harvey, “Exact self-similar solutions of the generalized nonlinear Schrödinger equation with distributed coefficients,” Phys. Rev. Lett. 90, 113902 (2003).
12. M. Ferrmann, V. Kruglov, B. Thomsen, J. Dudley, and J. Harvey, “Self-similar propagation and amplification of parabolic pulses in optical fibers,” Phys. Rev. Lett. 84, 6010–6013 (2000).
13. C. Finot, G. Millot, and J. M. Dudley, “Asymptotic characteristics of parabolic similariton pulses in optical fiber amplifiers,” Opt. Lett. 29, 2533–2535 (2004).
14. C. Finot and G. Millot, “Synthesis of optical pulses by use of similaritons,” Opt. Express 12, 5104–5109 (2004).
15. C. Finot, G. Millot, C. Billet, and J. Dudley, “Experimental generation of parabolic pulses via raman amplification in optical fiber,” Opt. Express 11, 1547–1552 (2003).
16. D. B. Soh, J. Nilsson, and A. B. Grudinin, “Efficient femtosecond pulse generation using a parabolic amplifier combined with a pulse compressor. II. Finite gain-bandwidth effect,” J. Opt. Soc. Am. B 23, 10–19 (2006).
17. T. Hirooka and M. Nakazawa, “Parabolic pulse generation by use of a dispersion-decreasing fiber with normal group-velocity dispersion,” Opt. Lett. 29, 498–500 (2004).
1. Introduction

Inherently superior in cost, alignment, spatial beam quality, thermal management, and compact design, fiber lasers have recently begun to directly compete with solid-state systems on peak power performance as well. Major advances in fiber laser research are driven by the need to compensate for optical nonlinearities imposed on the pulse by the small confinement area of single-mode optical fiber [1–4]. To date, dissipative soliton systems lead in performance, with 31-nJ, 80-fs pulses from a single-mode fiber laser [5], and 534-nJ, 100-fs pulses from a photonic-crystal fiber laser that sacrifices some of the practical advantages of single-mode fiber systems [6].

In parallel with high-performance oscillator design, new amplifier pulse propagation physics was developed in the form of the self-similar propagation of parabolic pulses. Building on previous work on parabolic pulses [7,8], a team from Auckland showed theoretically that self-similar pulses (similaritons) can occur in a fiber with gain, and Fermann et al. verified this experimentally [9–12]. Finot et al. studied the asymptotic characteristics of parabolic pulses [13], verified the robustness of the attractor to large input fluctuations [14], and also studied the extension of this regime to Raman amplifiers [15]. The limits of parabolic amplification have been addressed theoretically and have been shown to be ultimately limited by gain bandwidth, higher-order dispersion, and stimulated Raman scattering [16]. Self-similar parabolic pulses were also later shown to be an asymptotic solution in dispersion-decreasing passive fibers [17, 18]. As a practical advancement, this new wave-form has been used to achieve high performance in amplifier systems [19–21].

Recently, self-similar evolution of the pulse in the gain segment of a fiber laser was demonstrated in a laser with an anomalous-dispersion segment [22], in an all-normal-dispersion fiber laser [23], and in a Raman fiber laser [24]. In Ref. [23] it was shown that a narrow-band spectral filter is sufficient to stabilize the evolution, which yields high-energy and ultra-short pulses at large normal dispersion. In parallel with the experimental developments, Bale and Wabnitz showed that the pulse evolution can be completely characterized by solutions to the ordinary differential equations for the pulse characteristics in the fiber, along with scalar transfer functions for the spectral filter [25]. By scaling the fiber core size, 10-nJ and 42-fs pulses were generated following the design of Ref. [23], and these achieve a peak power of 250 kW [26]. With the large peak power that can be obtained from a rigorously single-mode fiber laser, am-
plifier similariton mode-locking promises to be very useful in applications.

Here we report an investigation of an amplifier similariton fiber laser with a dispersion map. Despite large changes in both the magnitude and sign of the total cavity group-velocity dispersion (GVD), the pulse parameters remain nearly constant. A narrow-band spectral filter is critical to facilitate the evolution toward the amplifier similariton solution. Strong nonlinear attraction to this asymptotic solution in the amplifier section of the laser underlies the pulse’s independence from the global cavity parameters. The freedom from global parameters allows for several scientifically-significant cavity designs which will, in addition, be important for applications:

- Large anomalous GVD: The dispersion-mapped amplifier similariton (DMAS) laser is a new mode of operation at large anomalous net GVD, which complements the well-known soliton operation. As a practical consideration, the DMAS laser generates shorter pulses with higher energy than soliton operation at large anomalous dispersion. As a consequence, the DMAS laser can eliminate length restrictions when designing oscillators at 1550-nm laser wavelength, e.g.

- Large normal dispersion: With appropriately-tuned net positive GVD, a DMAS laser can be designed to emit transform-limited pulses. The DMAS laser joins soliton lasers as sources of transform-limited pulses. In the DMAS laser, this occurs at the opposite sign of net GVD, and shorter pulses with greater energy are produced.

- Net zero GVD: The master equation, which governs prior mode-locked lasers, predicts an instability near zero GVD when the self-phase modulation exceeds the self-amplitude modulation, as is commonly the case. The DMAS laser, which is not governed by an average-parameter model, does not suffer from the same instabilities, and can be operated at net zero GVD. Because timing jitter is expected to be minimal at net zero GVD, the DMAS laser may be a route to low-noise frequency combs.

All modes of operation produce sub-100 fs pulses with nanojoule energies and should readily scale (as in Ref. [26]) to greater than 200-kW peak powers, even with single-mode fibers.

![Fig. 1. Schematic of the dispersion-mapped amplifier similariton fiber laser: QWP, quarter-wave plate; HWP, half-wave plate; DDL, dispersive delay line (diffraction grating pair).](image)

Fig. 1. Schematic of the dispersion-mapped amplifier similariton fiber laser: QWP, quarter-wave plate; HWP, half-wave plate; DDL, dispersive delay line (diffraction grating pair).

**2. Numerical simulations**

To assess the viability of a DMAS laser, numerical simulations were performed. The pulse propagation within a general fiber is modeled with the following nonlinear Schrödinger equation with gain:

\[
\frac{\partial A(z, \tau)}{\partial z} + \frac{i}{2} \beta_2 \frac{\partial^2 A(z, \tau)}{\partial \tau^2} = i|A(z, \tau)|^2 A(z, \tau) + g(E_{\text{pulse}}) A(z, \tau).
\]
$A$ is the electric field envelope, $\tau$ is the local time, $z$ is the propagation coordinate, $\beta_2$ represents the GVD, and $\gamma$ represents the Kerr self-focusing nonlinearity. A 35-cm segment of single-mode fiber precedes 200 cm of Yb-doped gain fiber, and a 150-cm segment follows it (Fig. 1), where all fibers have $\beta_2 = 230$ fs$^2$/cm and $\gamma = 0.0047$ (W m)$^{-1}$. In the Yb-doped gain fiber there is an additional saturating gain with $g = g_0/(1 + E_{\text{pulse}}/E_{\text{sat}})$, where $g_0$ corresponds to 30 dB of small-signal gain, $E_{\text{pulse}} = \int_{-T_R/2}^{T_R/2} |A|^2 dt$, where $T_R$ is the cavity round trip time and $E_{\text{sat}} = 240$ pJ. The fiber is followed by a monotonic saturable absorber with transmittance $T = 1 - l_o/[1 + P(\tau)/P_{\text{sat}}]$ where $l_o=1.0$ is the unsaturated loss, $P(\tau)$ is the instantaneous pulse power and $P_{\text{sat}} = 4.0$ kW is the saturation power. Increasing the saturable absorber modulation depth from 70% to 100% allows for the stabilization of pulses numerically without resorting to a full model incorporating nonlinear polarization evolution, as in Ref. [23]. Thus, the saturable absorber is important in this system for stabilizing the pulses from noise. The saturable absorber is followed by a linear segment of anomalous dispersion which is varied to set the net GVD of the cavity. The gain is assumed to have a Gaussian spectral profile with a 40-nm bandwidth, the output coupling is 60%, and a Gaussian filter with 4-nm bandwidth is placed after the dispersive delay. The governing equations are solved with a standard symmetric split-step propagation algorithm [27] (the linear terms are solved exactly in the Fourier domain and the nonlinear terms are solved with a fourth-order Runge-Kutta algorithm) and are run until the energy converges to a constant value.

The net GVD was varied from large normal (no anomalous dispersion section) to equally-large anomalous GVD and results for selected values are presented (Fig. 2). All of the simulated output pulses (output 1 in Fig. 1) have $\sim 1$-nJ pulse energy, $\sim 0.05$-ps$^2$ chirp, and 50-100 fs dechirped pulse duration, which is a clear indication that the dispersive delay has little effect on the soliton formation in the gain fiber. Mode-locking mechanisms are primarily distinguished by the pulse evolution through the cavity, and the parameter that most clearly illustrates the effects of the dispersion map is the pulse chirp (i.e., the quadratic spectral phase). In the cavity with large normal GVD, starting after the gain, the chirp increases in the normal dispersion fiber sections and then is pulled back toward $\sim 0.05$ ps$^2$ in the gain fiber (Fig. 2). For the other dispersion values, starting after the gain, the chirp increases slightly in the fiber section, decreases in the dispersive delay, slightly increases again in the next fiber section, and is then pulled back toward $\sim 0.05$ ps$^2$. The clear and powerful nature of the nonlinear attractor responsible for DMAS mode-locking is illustrated completely by the evolution of the chirp in the gain section (Fig. 2). Regardless of how much GVD is necessary to produce a pulse with $\sim 0.05$ ps$^2$
of chirp, the pulse nonlinearly grows the appropriate phase as it is attracted to the self-similar solution in the gain, as is most evident from the large anomalous dispersion (−0.09 ps²) case. We note that the pulse chirp can be tuned continuously from positive to negative by tuning the GVD of the cavity; the 0.04-ps² result is included because it yields a transform-limited output pulse.

3. Experimental results

The DMAS oscillator is designed and built as in Ref. [23], but with the addition of a grating pair for the dispersive delay line (Fig. 1). As in Ref. [23], a diffraction grating (300 lines per millimeter) along with the Gaussian dependence of the fiber collimator acceptance angle yield a 4-nm Gaussian spectral filter. The power, spectrum, and interferometric autocorrelation of pulses from output 1 (Fig. 1) are measured after dechirping the pulses with a grating pair. The pulse train is measured with a 30-GHz detector to ensure that only one pulse is in the cavity at a time. Mode-locking exists at many settings of the wave-plates, and is robust and self-starting at all values of the net GVD. In addition, the net GVD can be tuned continuously through zero without loss of mode-locking. At large anomalous net GVD, a typical example has 0.7-nJ output energy and 83-fs dechirped duration with 0.06-ps² chirp (Fig. 3). Although the cavity has large anomalous dispersion, there are no spectral sidebands (Fig. 3 inset), which clearly distinguishes these pulses from the only other known mode-locking regime with this net GVD, the soliton. Other distinguishing features include the temporal and spectral shapes, the short pulse duration (considering the high magnitude of net GVD) and the fact that the pulse has chirp. The ability to produce short pulses at any net dispersion can facilitate laser designs at 1550-nm, for example. Standard single-mode fibers have anomalous dispersion, and can still be used to generate ultrashort and high-energy pulses.

To find a transform-limited output pulse, we set the net GVD to the value predicted by simulations (Fig. 2) and varied the intra-cavity grating spacing while monitoring the autocorrelation from output 2 (Fig. 1) until the pulse duration was minimized. A typical example, found with net GVD of 0.03 ps², has 1.9-nJ pulse energy, 61-fs dechirped pulse duration, and 0.06-ps² chirp from output 1 (Fig. 4(a,b)). 250-pJ and 77-fs pulses are emitted directly from output 2 (Fig. 4(c,d)). In this example the transform-limited output pulse has lower energy, but this energy can be increased simply by swapping the output coupler with the dispersive delay, and taking the transform-limited output from the beam splitter (see Fig. 1). It should be noted that the system is very stable and the intra-cavity grating separation can be varied smoothly without loss of mode-locking.

Recent work shows a large reduction in the free-running carrier-envelope offset-frequency linewidth, and frequency noise power spectral density, of a fiber laser operating near zero GVD [28]. These results motivate the design of new fiber lasers that can be mode-locked with net zero
GVD. When tuned to zero net GVD, the DMAS laser emits 0.8-nJ pulses with 67-fs dechirped duration and 0.06-ps² chirp (Fig. 5). We note that the main features (bandwidth, chirp, spectral shape, and energy) of the three operating regimes are similar. With further tuning of the waveplates and the pump power aimed at optimizing performance, 3.5-nJ pulses with 56-fs pulse duration can be achieved (data not shown).

4. Conclusion

In conclusion, amplifier similaritons are generated in a fiber laser with a dispersion map. The pulse evolution is stabilized by a narrow-band spectral filter, which leads to a strong nonlinear attraction in the gain segment of the fiber laser. The output pulse parameters only change slightly as a function of the net GVD, which demonstrates the power of the local nonlinear attraction in the gain fiber. This freedom from global parameters allows for several practical advantages. At large net anomalous GVD, the DMAS laser can free up length design restrictions when designing oscillators at 1550-nm wavelengths. At large normal dispersion, the DMAS laser can be designed with a transform-limited output. Finally, at zero GVD, where the timing jitter is predicted to be minimal, the DMAS laser can be useful as a route to low-noise frequency combs. All modes of operation produce sub-100 fs pulses with nanojoule energies and should readily scale to greater than 200-kW peak power even with single-mode fiber designs.

Acknowledgments

The authors would like to thank Brandon Bale for useful discussions about numerical simulations. Portions of this work were supported by the National Science Foundation (Grant No. ECS-0701680) and the National Institutes of Health (Grant No. EB002019).