

# Dispersion management in a harmonically mode-locked fiber soliton laser

Thomas F. Carruthers and Irl N. Duling III

Optical Sciences Division, Naval Research Laboratory, Washington, D.C. 20375

Moshe Horowitz

Department of Computer Science and Electrical Engineering, University of Maryland–Baltimore County, Baltimore, Maryland 21250, and  
Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel

Curtis R. Menyuk

Department of Computer Science and Electrical Engineering, University of Maryland–Baltimore County, Baltimore, Maryland 21250, and  
Laboratory for Telecommunications Sciences, c/o U.S. Army Research Laboratory, Building 601, Room 131,  
2800 Powder Mill Road, Adelphi, Maryland 20783-1197

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Harmonically mode-locked Er-fiber soliton lasers have become a reliable source of high-repetition-rate picosecond pulses in high-speed communications and photonic analog-to-digital conversion systems because of their low-noise, dropout-free operation. We have fabricated such a laser with a strongly dispersion-managed cavity and modeled its operation, and we have found that dispersion management significantly extends the power range over which uninterrupted single-pulse production is attained and dramatically decreases the effects of amplified spontaneous emission on the phase noise of the laser.

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The harmonically mode-locked and dispersion-managed (DM) sigma soliton laser<sup>1</sup> exhibits remarkably stable operation in spite of the fact that nearly  $10^4$  ~1-ps pulses circulate in its cavity. Its pulse dropout ratio has been measured to be less than  $10^{-14}$  in bit-error-ratio measurements,<sup>2</sup> and it has been shown to exhibit less than 10 fs of timing jitter in a 100-Hz–1-MHz frequency range when driven by a quiet synthesizer.<sup>3</sup> A similar pulse-dropout ratio has been reported in a regeneratively mode-locked DM ring laser developed by Bakhshi *et al.*<sup>4</sup> Ellis *et al.* have developed a DM fiber soliton ring laser that is highly harmonically mode locked at 40 GHz, with a reported timing jitter of less than 460 fs.<sup>5</sup>

We have studied the stability of a harmonically mode-locked DM sigma laser experimentally and theoretically. We use a split-step model and an innovative superpulse technique that allows us to model pulse interactions through the slow gain medium with a reduced number of pulses. This technique allows the observation of supermode competition, pulse dropouts, pulse-pair generation, and noise,<sup>6</sup> whereas in traditional analyses researchers have effectively studied isolated pulses or have assumed that all pulses in the laser cavity are identical.<sup>7</sup> The simulation identifies several distinct regimes of operation; one of these regimes, in which the laser generates an uninterrupted train of single pulses, is the desirable mode of operation of a telecommunications optical source.

We find both experimentally and theoretically that the stable regime in DM lasers exists over a much broader range of intracavity power than in an equivalent uniform-dispersion laser and that the amplified

spontaneous emission (ASE) noise of the DM laser is ~10 dB lower than that of the uniform-dispersion laser.

The sigma soliton laser, which is functionally equivalent to a unidirectional fiber ring laser, is illustrated in Fig. 1. A polarization-maintaining fiber loop contains an isolator, an output coupler, and a Mach–Zehnder amplitude modulator that is driven at 10 GHz by a frequency synthesizer. The loop is connected to a non-polarization-maintaining branch by a polarizing beam splitter; the branch contains a 16-nm optical bandpass filter, an Er-doped gain fiber, 60 m of payout fiber, and 13.5 m of dispersion-compensating fiber. The dispersion-compensating fiber nearly completely cancels the total dispersion of the others; the average dispersion of the laser is 0.1 ps/(nm km) at its operating wavelength of 1560.5 nm. A 45° Faraday rotator and mirror return light in a polarization state orthogonal

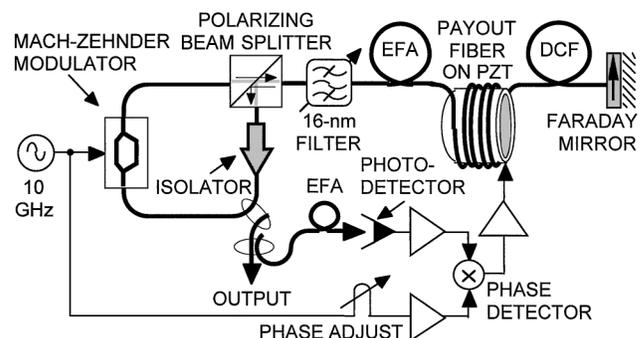


Fig. 1. Actively mode-locked soliton sigma laser: EFA's, Er-fiber amplifiers; DCF, dispersion-compensating fiber; PZT, piezoelectric transducer.

to its incident state so that birefringence variations are compensated for at every point in the branch. A phase-detector-based stabilization system maintains an appropriate length of the laser with respect to the modulation frequency by adjusting the voltage driving a piezoelectric cylinder around which the payout fiber is wound<sup>8</sup>; an Er-fiber amplifier in the feedback loop allows active length stabilization even at pulse energies of less than 50 fJ. The effective length of the laser is 192 m, and, when it is driven at 10 GHz, the laser operates at nearly its 10,000th harmonic.

In a DM system a pulse spends much of its time in a stretched state and experiences a lower effective nonlinearity than a pulse in a comparable uniform-dispersion fiber.<sup>9</sup> The energy of the stable nonlinear pulse in a DM system is therefore greater than that of an equivalent uniform-dispersion soliton.<sup>10</sup> The dispersion-map strength factor,<sup>11</sup>  $\gamma = \sum_n |D_n L_n| / \tau_{1/2}^2$ , where  $D_n$  and  $L_n$  are the dispersion and the length, respectively, of the  $n$ th fiber segment in the laser cavity and  $\tau_{1/2}$  is the FWHM pulse duration, has a value in the sigma laser of approximately 6.4 for 1.4-ps pulses. The corresponding maximum degree of energy enhancement of the DM soliton in the laser cavity over the comparable uniform-dispersion soliton is roughly a factor of 6 at the highest intracavity power.<sup>11</sup>

The laser that we modeled has a ring cavity rather than the sigma configuration; we found that this simplification does not cause significant error. The dispersion map of the model was matched to that of the sigma laser. It is impossible to model the propagation of all the pulses in the cavity; we therefore modeled the propagation of a small number of individual pulses and a superpulse that represents the pulses that are not simulated individually, allowing us to model accurately the gain saturation of the amplifier. The model enables us to calculate the induced energy variations in the available time slots, to study the dynamics of pulse dropout, and to find accurately the limits of the stable operating regime.

The simulations predict, and the experiment confirms, that distinct regimes of operation of the laser are encountered as the average optical power in the cavity,  $P_{\text{cav}}$ , measured at the output coupler, is varied (by variation of the pump power).<sup>2,3</sup> These regimes are indicated schematically in Fig. 2 as a series of sampling oscilloscope density contour plots of the optical pulses, detected with a fast photodetector, and autocorrelation traces. In Fig. 3 we plot measurements of the pulse duration and the optical bandwidth, and the figure indicates the boundaries between the observed regimes of operation. The four regimes are described below:

(1) At the lowest power, the pulse durations are close to the Kuizenga–Siegman limit of  $\sim 5$  ps for this laser, and the pulses are very noisy. This state corresponds to the first regime, in which nonlinear effects are absent.

(2) As the cavity power is increased to  $\sim 0.5$  mW, nonlinear processes overcome coherence-disrupting processes in the laser. The laser has enough available power to generate solitonlike pulses, which experience

less loss in the time window of the amplitude modulator than do longer linear pulses, but not enough power is available to fill the pulse train. The pulse duration drops to 3.3 ps, and the oscilloscope traces display a superposition of pulses and dropouts. The proportion of dropouts decreases as  $P_{\text{cav}}$  increases, and the pulse duration drops smoothly to 2.6 ps at  $P_{\text{cav}} = 5$  mW. The duration–bandwidth product of the pulses is very nearly equal to the transform limit of 0.44 for Gaussian pulses throughout this regime, and it rises above this value in regimes 1 and 3.

(3) When  $P_{\text{cav}} = 5.5$  mW, the laser begins to generate an uninterrupted stream of solitonlike pulses, and the pulse duration increases to 3.3 ps. The simulations predict that this boundary will occur at  $P_{\text{cav}} = 5$  mW, in excellent agreement with observations. As  $P_{\text{cav}}$  increases to its maximum value of 34 mW, the pulse duration smoothly decreases to 1.4 ps. This is the desirable operating regime as an optical pulse source for data transmission, and this regime exists over an intracavity power range of at least a factor of 6, up to the maximum intracavity power that is possible for this laser.

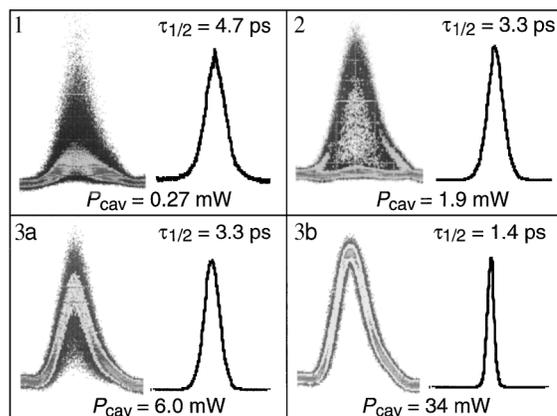


Fig. 2. Representative sampling oscilloscope density contour plots (left) and autocorrelation curves (right) of the pulses from the three observed regimes of operation. The pulses are labeled in the top left-hand corner by the regime into which they fall: The intracavity power  $P_{\text{cav}}$  is given in each box. Two sets of curves from the power extremes of regime 3 are shown.

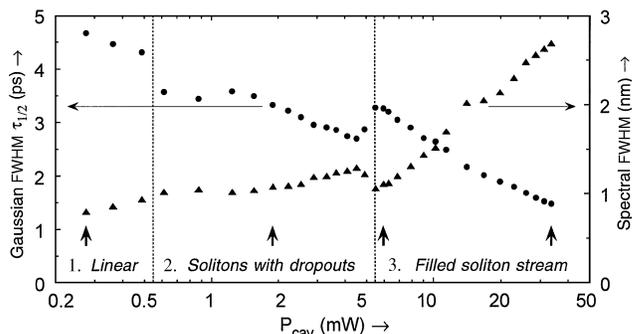


Fig. 3. Pulse duration  $\tau_{1/2}$  (circles) and the optical bandwidth  $\Delta\lambda$  (triangles) of the pulses generated by the laser as a function of intracavity optical power  $P_{\text{cav}}$ . The three observed regimes of operation are indicated. The positions of the four plots from Fig. 2 are indicated by the arrows.

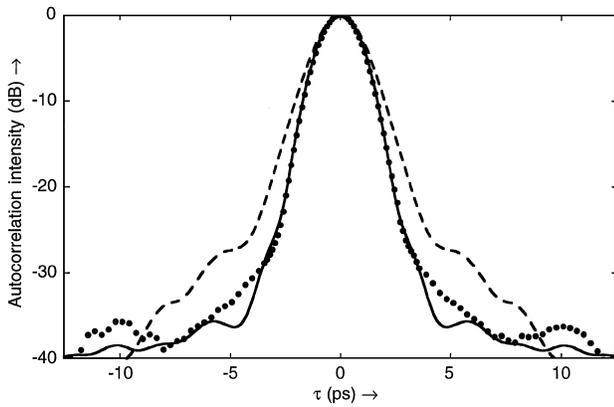


Fig. 4. Simulations of the pulse autocorrelation functions generated by the DM sigma laser (solid curve) and by a uniform-dispersion laser with a cavity dispersion of 2 ps/(nm km) (dashed curve). The experimental data are represented by the circles. The pulse duration is 1.4 ps and the intracavity power is 34 mW in all cases.

(4) In a uniform-dispersion laser cavity, the pulse duration would continue to decrease—and the optical bandwidth to increase—as  $P_{\text{cav}}$  increases, until losses in the optical filter and nonlinear effects forced the laser to generate multiple pulses in some time slots and thereby lower the average pulse energy and bandwidth.<sup>6</sup> This regime was not observed experimentally, nor was it observed in the simulation of the DM sigma laser even at the highest studied power of 150 mW. The pulse duration of a uniform-dispersion soliton depends inversely on its energy. In contrast, the duration of a DM soliton depends only slightly on its energy.<sup>10,11</sup> The upper boundary for the regime of uninterrupted single-pulse production is therefore greatly extended.

In Fig. 4 we compare simulated pulse autocorrelation functions generated by the DM laser with those generated in a uniform-dispersion laser with a dispersion of 2 ps/(nm km); this value was chosen because the pulses in each case have a duration of 1.4 ps when  $P_{\text{cav}} = 34$  mW. The experimental autocorrelation function for the DM sigma laser agrees well with the DM simulation. The ASE noise in the DM laser is more than 5 dB below that of the uniform-dispersion laser.

The phase noise of the DM sigma laser is low for several reasons. As Fig. 4 demonstrates, ASE noise generation is suppressed in a DM laser. The nearly complete dispersion compensation of the laser cavity minimizes ASE-to-phase-noise conversion.<sup>12</sup> Dispersion management allows the circulating pulses to possess higher energies than those in an equivalent uniform-dispersion laser. Finally, the extension of the threshold for multiple-pulse generation allows stable operation at intracavity powers that are much higher than those possible in a uniform-dispersion laser.

Amplitude noise is suppressed because of the Kerr nonlinearity in the cavity: Pulse energies are stabilized by the increased loss that higher-energy (and therefore broader-bandwidth) pulses experience in the

finite cavity bandwidth<sup>13</sup> and, in the sigma laser, also by the increased loss of nonlinearly polarization-rotated light in the polarizing beam splitter.<sup>1</sup> In Fig. 2 we demonstrate that amplitude noise is lower for higher intracavity powers. Because of the suppression of the dependence of pulse duration on energy, simulations show that amplitude-noise suppression is less in the DM laser than in an equivalent uniform-dispersion laser.<sup>6</sup> However, supermode competition is sufficiently discouraged that longitudinal-mode noise levels are typically suppressed by at least 80 dB, according to single-sideband amplitude-noise measurements, and extremely low bit-error ratios are attained in transmission experiments.

We have obtained good quantitative agreement among the theoretical and the experimental autocorrelation traces, the optical spectra, the dependence of the pulse duration on laser power, and the minimum laser power that is needed to avoid dropout. A detailed comparison between the experimental and the theoretical results will be published elsewhere.<sup>14</sup>

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