Gain-guided solitons in dispersion-managed fiber lasers with large net cavity dispersion

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Gain-guided solitons are experimentally observed in dispersion-managed fiber lasers with large net positive group-velocity dispersion. It is shown that formation of the soliton is a robust feature of the lasers. Numerical simulations also confirmed the experimental results. © 2006 Optical Society of America

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Passively mode-locked fiber lasers operating in the anomalous group-velocity dispersion (GVD) regime have been intensively investigated.[1–4] It was shown that, because of the natural balance between the cavity GVD and the fiber nonlinear optical Kerr effect, optical solitons are routinely produced in the lasers. Soliton operation of a laser could not only significantly narrow the mode-locking pulse width but also enhance the stability of the mode-locked pulses. Soliton fiber lasers with quantum-noise-limited pulse jitter have been demonstrated.[5] Unlike optical pulse propagation in lossless fibers, a laser is a dissipative system, where gain and losses coexist and play an important role in laser operation. It was predicted that in such a system a soliton can even be formed in the normal GVD regime.[6] As soliton formation is induced purely by the existence of gain and gain dispersion, the soliton is known as a gain-guided soliton. In a very recent experiment we have demonstrated the gain-guided soliton operation of a mode-locked fiber laser.[7] Compared with the solitons obtained in lasers of negative cavity GVD, gain-guided solitons have a large frequency chirp and a laser gain–bandwidth limited spectrum with steep spectral edges.

Solitary waves in essence are a kind of localized nonlinear wave. Soliton formation is robust in nonlinear systems. Smith *et al.*[8] have shown that, even in a fiber system with periodically varying positive and negative GVD, optical solitons can still be formed. Although the pulse width of a soliton formed in the system is periodically stretched and compressed, on average it follows the soliton theory well. Such a soliton was named a dispersion-managed soliton. It was also found that dispersion management could suppress dispersive wave emission and enhance soliton stability. Dispersion-managed soliton fiber lasers were also extensively investigated for achieving solitons with large pulse energies.[2,9–11] However, all the previous research on dispersion-managed fiber lasers is limited to the regime in which the net cavity dispersion is close to zero or has small positive dispersion. For example, the maximum net cavity dispersion is $+0.016\ \mathrm{ps}^2$ in Ref. 10 and $+0.032\ \mathrm{ps}^2$ in Ref. 11. Is mode locking still possible with larger net cavity dispersion? What is the nature of the mode-locked pulse? In this Letter we report the gain-guided soliton operation of a dispersion-managed fiber laser. We show that, like the conventional soliton, the gain-guided soliton can also exist in dispersion-managed systems with relatively large positive net cavity dispersion.

The fiber laser used has a cavity configuration similar to that reported in Ref. 7. Briefly, the cavity is a fiber ring comprising 1.8 m 2880 parts in 10^6 erbium-doped fiber (EDF) with a GVD of about 50 (ps/nm)/km and standard single-mode fiber (SMF) whose GVD is about −18 (ps/nm)/km. Dispersion management is achieved by changing the length of the SMF in the cavity. The nonlinear polarization rotation technique was used to achieve the self-started mode locking of the laser. Therefore a polarization-dependent isolator and two polarization controllers, one consisting of two quarter-wave plates and the other two quarter-wave plates and one half-wave plate, were incorporated into the cavity. The laser is pumped by a 1480 nm pump source, and the generated pulses were output via a 10% fiber coupler.

The fiber laser has a typical dispersion-managed cavity configuration as reported by other authors.[2,9–12] However, in contrast to conventional dispersion-managed fiber lasers, we have operated the laser in the large net positive cavity GVD regime. The bulk wave plates used in our laser have almost negligible GVD. Therefore we estimate that with 5 m of SMF the net cavity GVD should be roughly zero. Indeed, with this SMF length we have obtained conventional dispersion-managed soliton operation in the laser.[10,11] The soliton spectrum obtained has a characteristic Gaussian profile without any spectral sidebands, which suggests that the net cavity GVD is near zero. This state of laser operation continued until the SMF length was reduced to 4 m. On our further cutting the length of the SMF, the optical spectrum of the mode-locked pulse gradually changed into that of gain-guided solitons. Figure 1 shows, for example, the typical operation of the laser obtained

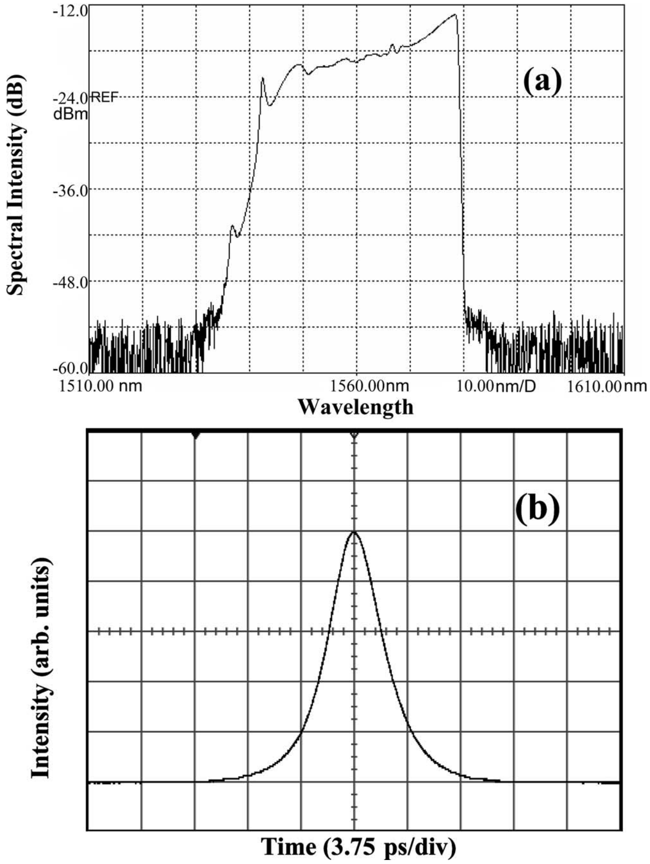

Fig. 1. Typical state of mode-locked operation of the dispersion managed fiber laser. (a) Optical spectrum of the mode-locked pulse. (b) Corresponding autocorrelation trace.

when the length of the SMF is about 2 m (net cavity dispersion is about 0.069 ps^2, more than two times the maximum in Ref. 11). The gain-guided soliton nature of the mode-locked pulse is indicated by its pump-dependent spectral bandwidth and the characteristic steep spectral edge. Nevertheless, unlike the gain-guided soliton of a non-dispersion-managed fiber laser,[7] several spectral spikes, resembling the soliton sidebands of conventional fiber laser solitons, appeared on the short-wavelength side of the optical spectrum as shown in Fig. 1(a).

Spectral spike generation seems an inherent feature of the soliton. In our experiments with a shorter SMF of about 1.5 m (yielding a larger net cavity dispersion than that of Fig. 1) we also obtained the optical spectrum shown in Fig. 2, where the spikes appear on both edges of the spectrum. Thus far we have not fully understood the physical mechanism of the spectral spike generation. Experimental studies show that they have properties different from those of the soliton sidebands. The soliton sidebands are formed as a result of constructive interference between the soliton and dispersive waves, and the sideband positions are fully determined by the cavity length and dispersion.[13] Changing the pump strength will change only the sidebands' strength rather than their positions. However, the spectral spikes observed are tunable with the pump power as shown. Since the spectral spikes appear only on the spectral edges, we believe that they could be related to the strong pulse width stretching and compressing in the laser cavity.

Figure 1(b) shows the autocorrelation trace of the mode-locked pulses of Fig. 1(a). It has a FWHM width of 3.245 ps if a Gaussian pulse profile is assumed. Autocorrelation traces of the solitons obtained in our lasers have commonly a pulse width of several picoseconds. When the output pulse is transmitted through a piece of standard SMF fiber, under optimized conditions the pulse width can be further compressed to about 1 ps. However, no transform-limited pulses were obtained with the pulse compression method, which is different from the traditional dispersion-managed solitons generated at near-zero cavity dispersion, where the pulse could be compressed to several tens of femtoseconds.

Under our experimental conditions the length of the SMF can only be reduced to about 1.5 m. Further shortening the length of the SMF would continuously increase the total positive cavity dispersion. However, self-started mode locking became difficult to achieve because of the short cavity. Under gain-guided soliton operation we also simultaneously monitored the oscilloscope trace of the laser, which confirmed that there is only one pulse circulating in the cavity.

The gain-guided soliton operation of the laser is again confirmed by numerically solving the coupled laser Ginzburg–Landau equations describing soliton propagation in optical fibers and simultaneously considering the laser cavity effects. Details of the numerical simulation technique were reported in Refs. 4 and 7. In comparison with the simulations reported previously, the parameters we changed are the cavity length, which is now $L=0.5_{\mathrm{SMF}}+1.8_{\mathrm{EDF}}+0.6_{\mathrm{SMF}}=2.9$ m, and the fiber dispersion for the SMF and the EDF, as in the experiments. Figure 3 shows a typical simulation result when the linear cavity phase delay bias is set as $\mathrm{Ph}=1.4\pi$ and the pump strength G is varied. Figure 3(a) shows the soliton pulse train at the pump strength $G=2500$. The calculated pulse width is about 8.2 ps. Figure 3(b) is the soliton spectra. With a dispersion-managed cavity of such a posi-

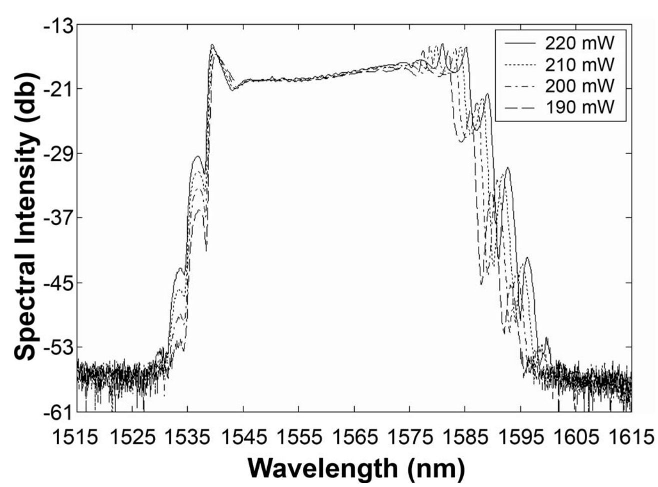

Fig. 2. Optical spectra of the mode-locked pulses under various pump strengths.

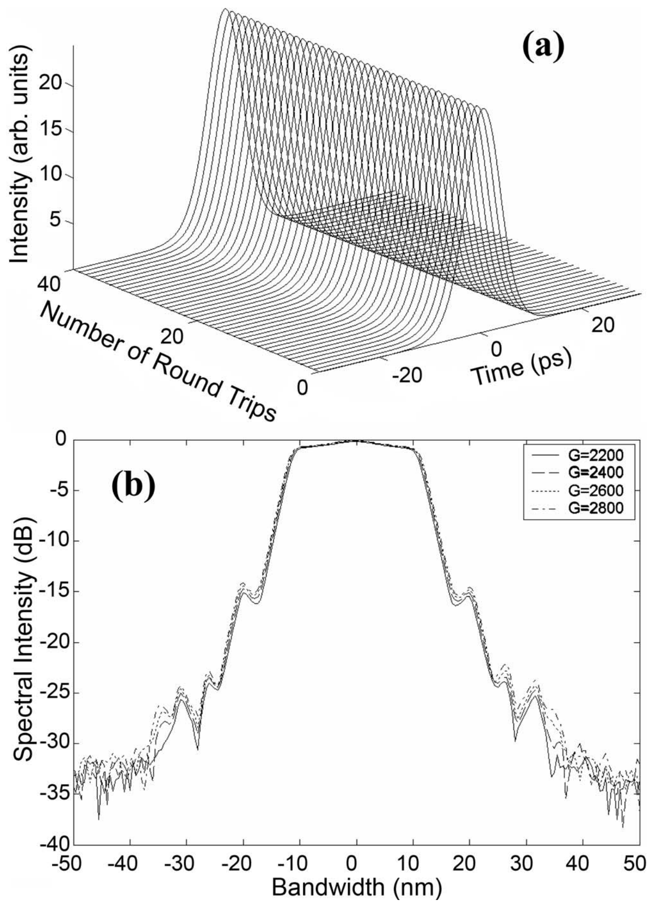

Fig. 3. Numerically simulated (a) soliton pulse train at $G=2500$ and (b) soliton spectra of the laser under various pump strengths.

tive net cavity GVD, self-started mode-locking can still be achieved in the laser with the nonlinear polarization rotation technique. Determined by the net cavity GVD, the mode-locked pulse shows clear gain-guided soliton features, e.g., a stable nonlinear pulse with gain-limited spectrum width and large frequency chirp. In particular, the pulse spectrum exhibits spectral spikes, whose position is pump strength dependent.

In conclusion, we have both experimentally and numerically demonstrated gain-guided soliton operation of dispersion-managed fiber lasers. It was shown that, despite the existence of a piece of negative GVD fiber in the cavity, which supports the generation of a conventional soliton, to the degree that the total cavity GVD is large and positive, the mode-locked pulse still exhibits gain-guided soliton features. Nevertheless, dispersion management results in the generation of pump-power-dependent spectral spikes on the steep edges of the spectrum, which is distinctive of the soliton spectrum of non-dispersion-managed fiber lasers and that of conventional dispersion-managed solitons generated in the near-zero net cavity dispersion regime.[9–13]

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