Dynamics of gain-guided solitons in an all-normal-dispersion fiber laser

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Received March 8, 2007; revised April 22, 2007; accepted April 30, 2007;
posted May 4, 2007 (Doc. ID 80827); published June 19, 2007

We report experimental and numerical results on the dynamics of gain-guided solitons in a passively mode-locked erbium-doped fiber laser made of purely normal dispersion fibers. We show that formation of the soliton in the laser is a result of mutual interaction and balance among the cavity transmission, fiber Kerr nonlinearity, gain saturation, and filtering over one cavity round trip. © 2007 Optical Society of America

OCIS codes: 060.4370, 060.5530, 140.3510.

Passively mode-locked fiber lasers have been extensively studied in the past for generating ultrashort pulses. Conventionally, the fiber lasers were operated in the anomalous cavity group-velocity dispersion (GVD) regime, where solitons are automatically generated as a result of the natural balance between the cavity dispersion and the fiber nonlinear Kerr effect. However, the soliton operation of the lasers limits the maximum achievable mode-locked pulse energy. To relax the limitation, the so-called stretched-pulse fiber laser was proposed [1]. Recently, it was shown that self-similar parabolic pulses could also be generated in a stretched-pulse laser with net positive GVD and in the absence of influence of the gain saturation and gain bandwidth limitation [2]. As a self-similar parabolic pulse has linear frequency chirp, such an optical pulse facilitates power scalability and linear pulse width compression. Nevertheless, for any laser as the mode-locked pulse energy increases, eventually the gain effects on the formed pulses can no longer be ignored. Kruglov *et al.* have shown that the self-similar scaling of a parabolic pulse in an amplifier is determined by the functional form of the gain profile [3]. Limpert *et al.* discussed the amplifier bandwidth limitation on the power scaling of a parabolic pulse [4]. In fact, the maximum achievable energy of a parabolic pulse is ultimately limited by the finite gain bandwidth of the amplifier [5,6].

It had been shown theoretically that solitary waves could still be formed in positive dispersion amplifiers as a result of the gain filtering effect [7]. In a previous paper, we have experimentally demonstrated that solitary pulses could indeed be generated in an erbium-doped fiber (EDF) laser made of purely normal dispersion fibers, and the formed solitons have a spectral width limited by the effective laser gain bandwidth [8]. Different from the Yb-doped fiber lasers that have superbroad gain and large gain saturation power, an EDF laser has less broad gain and low gain saturation intensity and therefore can easily show the gain limiting effects.

Strictly speaking, a pulse circulating in the laser cavity is different from that propagating in a positive dispersion gain medium. In lasers, a pulse is also subject to the action of the cavity components, cavity boundary condition, and the saturable absorption effect that is necessary for the self-started mode locking of a laser. To better understand the gain-guided soliton operation of the fiber lasers, we have further investigated the soliton evolution in the cavity. In this Letter, we report the results. We see that like the conventional soliton in a laser, the gain-guided soliton in a laser is also similar to the average soliton [9]. It is the mutual interaction among the cavity dispersion, fiber Kerr nonlinearity, laser gain effects, and their balance over a one cavity round trip that leads to the formation of the soliton. Moreover, we show that to form a chirped soliton, no cavity dispersion compensation is needed.

We used a fiber laser as shown in Fig. 1 for our studies. The EDF is 2.97 m long with a GVD of approximately −32 (ps/nm)/km. All other fibers used are dispersion-compensation fibers (DCFs) with a GVD of approximately −0.196 (ps/nm)/km at 1550 nm. The nonlinear polarization rotation (NPR) technique was used for achieving the self-started mode locking of the laser. To this end, a polarizer together with two polarization controllers, one consist-

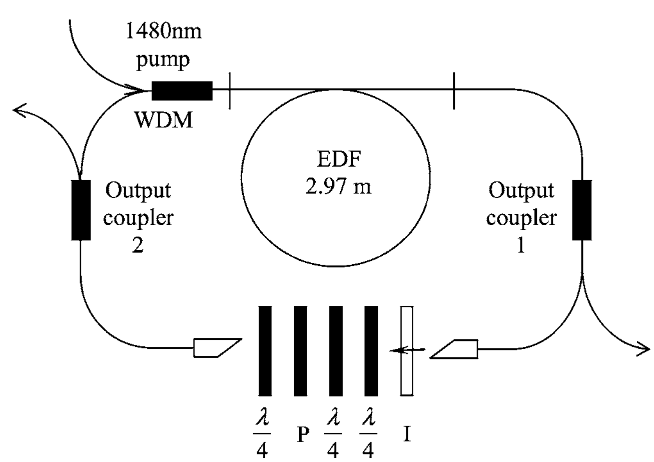

Fig. 1. Schematic of the fiber laser. I, polarization-independent isolator; P, polarizer; λ/4, quarter-wave plate; WDM, wavelength-division-multiplexing coupler; EDF, erbium-doped fiber.

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ing of two quarter-wave plates and the other consisting of one quarter-wave plate, was employed for adjusting the polarization of light in the cavity. The unidirectional operation of the laser was forced by a polarization-independent isolator. The wave plates, polarizer, and isolator are mounted on a 76 mm long fiber bench. Dispersion of the bulk components is estimated to be negligible. To study dynamics of the soliton evolution in the cavity, we purposely introduced two 10% fiber output couplers in the laser. One is located between the EDF and the bench, and the other one is located after the bench. The laser was pumped by a 1480 nm Raman fiber laser (KPS-BT2-RFL-1480-60-FA) through a fiber wavelength-division-multiplexing (WDM) coupler.

Although the total cavity dispersion is estimated at $\sim 0.122\ \mathrm{ps}^2$, self-started mode locking was obtained through appropriately selecting the wave-plate orientations. Figure 2 shows a typical mode-locked state obtained at a pump power of 1 W. The gain-guided soliton operation of the laser is supported by the features of the measured pulse spectra, as shown in Fig. 2(a). The 3 dB bandwidths of the pulse at the two output ports are 12.86 and 11.18 nm, respectively. Figure 2(b) shows the corresponding autocorrelation traces. If a Gaussian pulse profile is assumed, the pulse durations are 9.15 and 9.01 ps. The pulse width and spectrum profile changed only slightly as they moved from port 1 to port 2. However, the soliton intensity changed dramatically between the two output ports. It is from 14.760 dBm (29.9 mW) to 0.750 dBm (1.2 mW). We had measured the static insertion loss of the fiber bench, which is ~ 3 dB. This means that the polarizer on the fiber bench could have chopped away most of the pulse energy. With a 50 GHz sampling oscilloscope, we confirmed that there is only one gain-guided soliton in the cavity. The top of the measured spectral profiles is quite humped compared with those of the parabolic pulses [2,10,11]. Experimentally we found that the height of the hump varied with the wave-plate orientations and the pump power, which suggests that the cavity peak clamping effect could have played an important role in the formation of the pulse [12].

To get more information on the evolution of the pulse in the cavity, we further numerically simulated the laser based on the coupled Ginzburg–Landau equations (GLEs) and the round-trip model described in [13]. Our simulation considered the mutual interaction between the cavity dispersion, fiber nonlinear Kerr effect, the laser gain and gain dispersion, as well as the cavity boundary conditions and the cavity artificial saturable absorption. To make the simulation comparable with the experiment, we used the following parameters: nonlinear fiber coefficient $\gamma = 3\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, erbium fiber gain bandwidth $\Omega_g = 20$ nm, fiber dispersions $D''_{\mathrm{EDF}} = -32$ (ps/nm)/km, $D''_{\mathrm{DCF}} = -0.196$ (ps/nm)/km, and $D''' = 0.1$ (ps^2/nm)/km, beat length $L_b = L/2$, the orientation of the intracavity polarizer to the fiber fast birefringent axis $\Psi = 0.152\pi$, cavity length $L = 1.7_{\mathrm{DCF}} + 3.0_{\mathrm{EDF}} + 1.1_{\mathrm{DCF}} = 5.8$ m, and gain saturation energy $P_{\mathrm{sat}} = 1000$ pJ. We have also set two output ports for the laser as in the experiments and considered the effect of 3 dB bench loss.

Figure 3 shows a typical stable gain-guided soliton operation of the laser numerically obtained with the linear cavity phase delay bias set at 1.4π and the small-signal gain $g_0 = 5000$ [13]. Obviously, before and after the bench there is an ~ 6 dB peak spectral intensity jump, which is close to the experimental measurement (~ 6.56 dB) as shown in Fig. 2(a). The top of the numerically calculated pulse spectra is less humped than those experimentally observed. Whether this discrepancy is due to the absence of other effects in our model, such as the spectral bandwidth limitation caused by the cavity components and the simplified parabolic gain profile, needs to be investigated further.

Figure 4 shows the calculated pulse width variation along the cavity. Starting from the left of the fiber bench, the pulse keeps almost a constant pulse width of 9.13 ps propagating in the first piece of the DCF. In the gain fiber, the pulse width first narrows down from the 9.13 ps to a minimum of 8.93 ps and then monotonically broadens in the rest of the EDF. In the second DCF, the pulse propagates again with a nearly constant pulse width. A sudden pulse width drop of ~ 1 ps is incurred by passing through the intracavity polarizer, which completes the cavity round trip and enforces the linear and nonlinear cavity losses. We note that the pulse evolution in the cavity is very different from that of the parabolic pulses in a Yb-fiber laser, where a pulse broadens quasi-linearly in the single-mode fibers [11]. Figure 5 further shows the pulse frequency chirp along the cavity. We have plotted chirp profiles at different positions in one figure. The pulse profile drawn is at the position of output port 2 for reference. Since we used the coupled GLEs to simulate the pulse evolution in the cavity to consider the weak birefringence of the cavity, the chirp evolutions along each principal birefringence

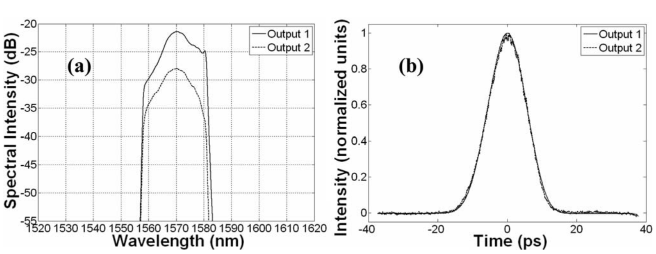

Fig. 2. (a) Optical spectra and (b) corresponding autocorrelation traces of a gain-guided soliton measured at the two output couplers.

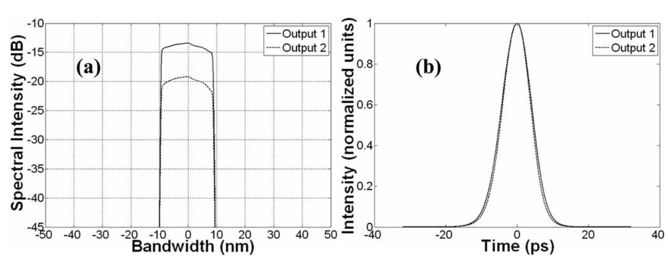

Fig. 3. (a) Optical spectra and (b) pulse profiles of a gain-guided soliton at two different cavity positions numerically calculated.

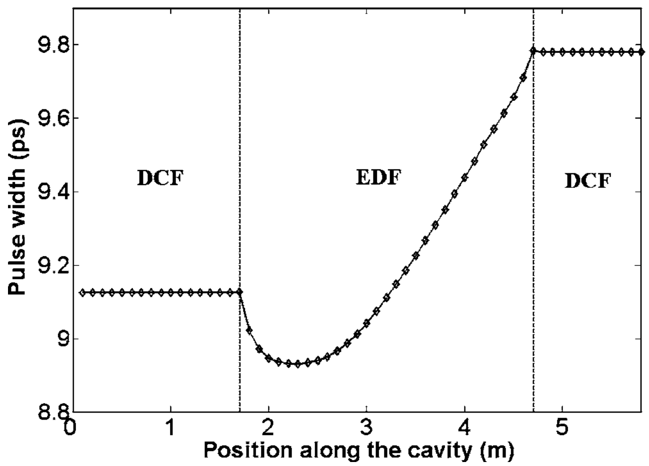

Fig. 4. Pulse width variation of a gain-guided soliton along the laser cavity numerically calculated.

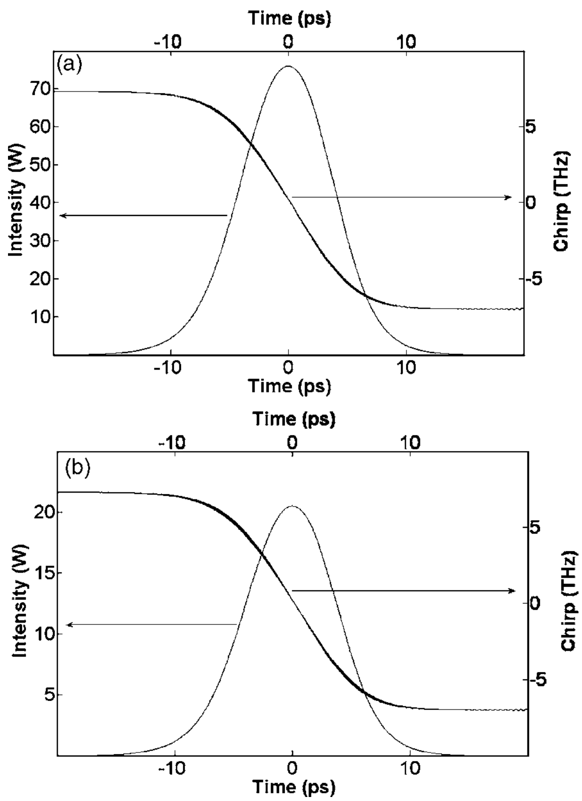

Fig. 5. Chirp profiles of the (a) horizontal and (b) vertical components of the gain-guided soliton at different cavity positions. The inserted pulse intensity profiles are the pulse components at the position of output coupler 2.

axis are plotted separately. It is surprising to see that not only the chirps of the pulses along the horizontal and vertical principal axes are the same, but also the chirps across the pulse profile at the different cavity positions have so small a difference that they are hardly distinguishable. The chirps of the pulses could be partly dechirped with linear anomalous dispersion, and the shortest pulse obtained was ~400 fs.

Although there is no dispersion compensation element in the laser to compensate the positive fiber dispersion, a stable chirped pulse could still be formed in the laser. In particular, as the pulse circulates in the cavity, the chirp of the pulse remains almost constant. Obviously, along the cavity, the pulse width varies; so does the pulse energy. However, at a fixed position, they have fixed values, which are invariant with time. From the pulse evolution in the cavity, effects of the gain and cavity transmission on the soliton shaping of the pulse become evident. It is the mutual interaction among the positive fiber dispersion, nonlinearity, gain filtering, and cavity transmission that leads to the formation of the pulse. Therefore, the formed pulse exhibits the general features of the gain-guided solitons. However, as the balance among the above effects is achieved not at every position in the cavity but over one cavity round trip, the parameters of the formed soliton vary periodically along the cavity with the cavity repetition rate.

In conclusion, we have both experimentally and numerically studied the dynamics of a gain-guided soliton in fiber lasers made of normal dispersion fibers. It was shown that like the conventional soliton in lasers, the gain-guided soliton formed is also similar to the average soliton. Its formation is a result of the mutual interaction and balance between the effects of cavity dispersion, fiber nonlinearity, and laser gain saturation, and spectral filtering within one cavity round trip.

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