Generation of multiple gain-guided solitons in a fiber laser

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We report the experimental observation of multiple gain-guided solitons in an erbium-doped fiber laser made of all normal-dispersion fibers. Numerical simulations show that, in the case of a narrow gain bandwidth, under the action of the cavity pulse peak clamping effect multiple gain-guided solitons can indeed be formed in a laser. © 2007 Optical Society of America

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Recently we experimentally demonstrated gain-guided soliton (GGS) operation in a passively mode-locked fiber laser made of all normal-dispersion fibers [1]. Unlike the conventional solitons observed in fiber lasers made of all negative-dispersion fibers or dispersion-managed fiber lasers with net negative cavity dispersion, where the soliton formation is a result of the balanced interaction between the cavity dispersion and the fiber nonlinear optical Kerr effect, the GGS formation in the laser of Ref. [1] is due mainly to the laser gain effect. It is the nonlinear mutual interaction among the fiber nonlinearity, cavity dispersion, laser gain saturation, and dispersion that leads to the formation of the stable nonlinear pulse in the laser.

Apart from the GGS, a stable noiselike-pulse emission state was also observed, whose formation can be traced back to the cavity pulse peak clamping effect and the interference between the linear and nonlinear waves in the cavity [2]. Under all experimentally accessible laser operation conditions, no multiple GGSs were observed. The stable laser operation of the laser is either the single-pulse GGS state or the noiselike-pulse emission state. By inserting a spectral filter into the cavity, Chong *et al.* [3] also achieved mode locking in an ytterbium-fiber laser without any dispersion compensation element in the cavity. In their laser, again, only a single chirped picosecond pulse could be generated, and no multiple pulses were observed.

It is well known that the soliton operation of fiber lasers with net negative cavity group-velocity dispersion (GVD) is prone to multisoliton formation [4]. The mechanism of multiple soliton formation in these lasers is due to the cavity pulse peak clamping effect [5]. A soliton formed in the laser has fixed energy. Once its peak is clamped, its pulse width is also fixed. Therefore increasing the gain of the laser cannot change the soliton parameters but increases the gain for the dispersive waves. When the dispersive waves become strong, they are shaped into a new soliton [5]. In fact, independent of the sign of the cavity GVD, in the lasers that are mode locked with the nonlinear polarization rotation technique the cavity pulse peak clamp effect always exists. It is unexpected that multiple GGSs were not observed in the lasers. Recently, Ortaç *et al.* [6] reported the experimental observation of bound states of parabolic pulses in an ytterbium-fiber laser operating in the normal-dispersion region. Although their fiber laser has a dispersion-managed cavity, their results suggest that under appropriate conditions multiple GGS formation should still be possible in a laser.

In this Letter we report the experimental observation of multiple GGS formation in a fiber laser made of purely normal-dispersion fibers. We show, based on numerical simulations, that the observed multiple GGS is caused by the cavity pulse peak clamping effect under the condition of narrow gain bandwidth. The gain bandwidth determines the formed GGS spectral width. The smaller the gain bandwidth, the narrower is the soliton spectral width, and the easier it is for a GGS to separate spatially from the dispersive waves in the laser cavity. This result not only shows the influence of the gain property on the formed GGS, but also demonstrates the close similarity in soliton features between the GGS and the conventional soliton in a laser.

The fiber laser is shown in Fig. 1. The erbium-doped fiber (EDF) has a length of 2.97 m with a GVD of about −52 (ps/nm)/km; all other fibers are dispersion-shifted fiber (DSF) with a GVD of about −0.196 (ps/nm)/km at 1550 nm. The nonlinear polarization rotation technique is used for mode locking the laser. To this end a polarizer together with two polarization controllers, one consisting of two quarter-wave plates and the other of one quarter-wave plate, was used to adjust the polarization of light in the cavity. The unidirectional operation of the laser is forced by a polarization-independent isolator. The wave plates, the polarizer, and the isolator are mounted on the 76 mm long fiber bench. Dispersion of these bulk components was estimated to be negligible. Two 10% output couplers, one located before and one after the fiber bench, were used to monitor the laser operation and the pulse dynamics in the

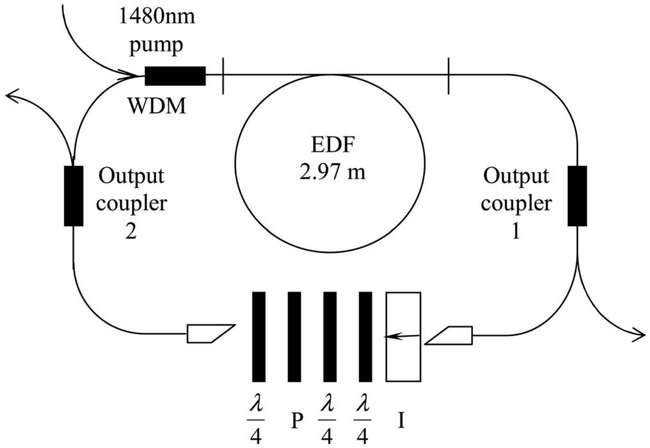

Fig. 1. Schematic of the fiber laser. I, polarization independent isolator; P, polarizer; λ/4, quarter-wave plate; WDM, wavelength-division-multiplexing coupler; EDF, erbium-doped fiber.

cavity. The laser was pumped by a 1480 nm Raman fiber laser (KPS-BT2-RFL-1480-60-FA) through a fiber WDM coupler. The WDM and the fiber output couplers were specially made with the dispersion-shifted fiber.

The total cavity dispersion is estimated at about $0.122\,\text{ps}^2$. With appropriate orientation settings of the wave plates, self-started mode locking was obtained, and the laser mode-locking threshold varied with the orientations of the wave plates. As the laser is made of all normal-dispersion fiber, the stable mode-locked pulses exhibited typical GGS features. However, unlike with the previous laser [1], multiple GGSs have been observed in the current experiment. Figure 2 shows an example of such a typical state observed. The optical spectrum of the pulses has the characteristic of steep spectral edges, suggesting that it is a gain-guided soliton. Figure 2(b) shows the corresponding autocorrelation trace. If a Gaussian pulse profile is assumed, the pulse width is about 9.28 ps. Figure 2(c) is the oscilloscope trace simultaneously measured. Obviously, two pulses coexist in the cavity.

The separation between the pulses is about 2.2 ns, which is 237 times the pulse duration. Therefore no direct interaction exists between the solitons. Nevertheless, the separation between the pulses remained unchanged as the solitons circulate in the cavity. However, slightly changing the orientation of any one of the quarter-wave plates would alter the soliton spacing. In our experiment even a second-harmonic mode-locking state was observed, where the separation between the GGSs is exactly half of the cavity round-trip time. The two solitons have identical pulse heights on the oscilloscope trace, indicating that they have the same pulse energy. With varying pump strength the energy of both pulses varied simultaneously and always maintained the same height, which resembles the feature of soliton energy quantization of conventional solitons in fiber lasers. The state shown in Fig. 2 was measured at output coupler 1. We have also confirmed the result at output port 2; except that the pulse width is slightly narrower and the intensity is weaker, the pulse separation is the same as that measured at port 1. Experimentally we limited the pump power below 1.5 W to avoid damage to the WDM coupler. Consequently only two GGSs could be formed. We believe that with even higher pump power more GGSs could be generated.

To understand the multiple-soliton-formation mechanism of the laser, we further numerically simulated the influence of various laser parameters on the formed GGS. Again, we used the same model as described in [1] and the following parameters to possibly match our experimental conditions: nonlinear fiber coefficient $\gamma = 3\ \text{W}^{-1}\,\text{km}^{-1}$; fiber dispersions $D''_{\text{EDF}} = -32\ (\text{ps/nm})/\text{km}$, $D''_{\text{DSF}} = -0.196\ (\text{ps/nm})/\text{km}$, and $D''' = 0.1\ (\text{ps}^2/\text{nm})/\text{km}$; beat length $L_b = \text{L}/2$; orientation of the intracavity polarizer to the fiber fast birefringent axis $\Psi = 0.152\pi$; cavity length $L = 1.7_{\text{DCF}} + 3.0_{\text{EDF}} + 1.1_{\text{DCF}} = 5.8\ \text{m}$; and gain saturation energy $P_{\text{sat}} = 1000$. We also considered the insertion loss of

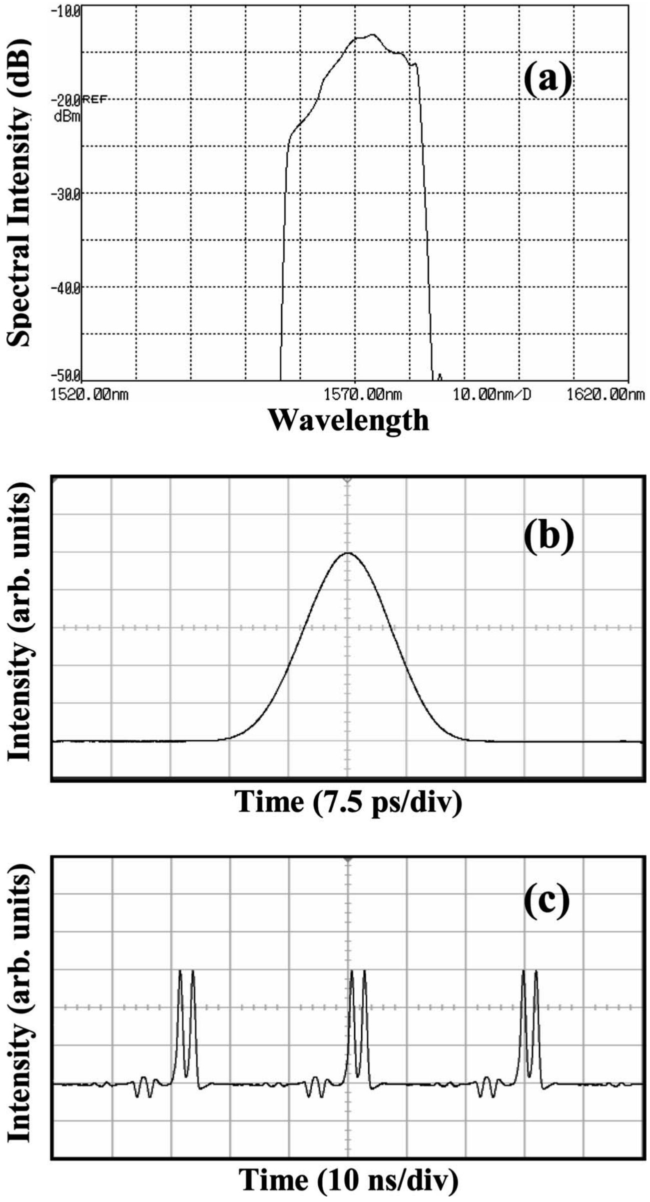

Fig. 2. Typical multiple gain-guided soliton state of the laser. (a) Optical spectrum, (b) autocorrelation trace, (c) oscilloscope trace.

the fiber bench to be 3 dB. Except that we have changed the erbium fiber gain bandwidth from $\Omega_g = 20$ nm to $\Omega_g = 16$ nm, the other fiber parameters are actually the same as those used in [1]. Numerically we found that with a gain bandwidth larger than 20 nm, no multiple GGSs could be formed in our laser.

With a narrow gain bandwidth ($\Omega_g = 16$ nm), multiple GGS can indeed be formed in the laser. Figure 3 shows, for example, a calculated numerical result. A GGS is initially circulating in the cavity. As the pump strength is increased, the soliton peak intensity increases. Eventually the soliton peak is clamped by the cavity. Further increasing the pump amplifies not the soliton but the background dispersive waves. Thus that the spectral bandwidth of the GGS is limited by the gain bandwidth, and in the current case it is narrow; the formed GGS is spatially well separated from the dispersive waves. Therefore, instead of a noiselike wave's being formed, the background dispersive waves are quickly shaped into a new GGS. Because of the gain competition and the cavity feedback, in the initial phase of the new pulse formation strong antiphase soliton peak variation exists. However, both solitons quickly approach the steady state, where they have identical soliton parameters. The separation between the two GGSs is randomly determined by the initial condition and the pump strength. Once the two-soliton state is obtained, the pump strength can then be decreased to a much lower value until one of the solitons is destroyed. There is a strong pump hysteresis of soliton formation and annihilation. Numerically we found that as the pump strength varied, parameters of both solitons varied accordingly; nevertheless, in the steady state they always remained identical.

Our numerical simulations clearly show that the multiple GGS formation is caused by the cavity pulse peak clamping effect. However, the cavity dispersive property also played an important role. Numerically we found that only when the gain bandwidth is narrower than a certain value could multiple GGS be obtained; otherwise the noiselike pulse emission as reported in [2] was always observed. The larger the total linear cavity GVD, the narrower the gain bandwidth required for multiple GGS formation. To explain the phenomenon, we note that a GGS formed in the laser is a result of the interaction among the cavity dispersion, fiber nonlinear effect, gain dispersion, and saturation [1,7], and its spectral bandwidth is determined mainly by the gain bandwidth. A soliton with a narrower spectral bandwidth is easier to separate spatially from the linear waves than a soliton with broader spectrum.

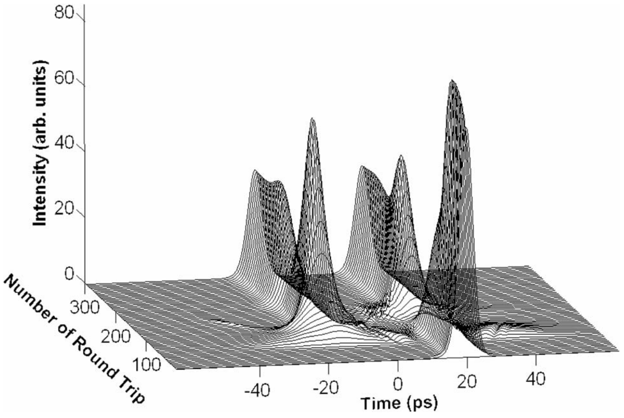

Fig. 3. Numerically calculated multiple gain-guided soliton formation process in the laser.

Note also that although in our simulation we have explicitly reduced the erbium gain bandwidth, this is actually not necessary. In fact, any spectral bandwidth limiting element, such as a bandwidth limiting filter in the cavity, would have the same effect. We believe this could be exactly what happened in our laser, e.g., although the same erbium-doped fiber has been used in our experiment as in [1]; because of the cummulative effect of the extra output coupler in the cavity, the cavity birefringence can be increased. Consequently, the bandwidth of the cavity birefringent filtering becomes smaller, which reduces the effective gain bandwidth.

In conclusion, we have experimentally observed multiple GGS generation in a fiber laser made of purely normal-dispersion fibers. Numerical simulations suggest that the formation of the multiple GGS is still a result of the cavity pulse peak clamping effect. Under the condition of narrow gain bandwidth or small linear cavity GVD, the formed GGS and the dispersive waves can efficiently spatially separate, and soliton shaping of the strong dispersive waves leads to the formation of multiple GGSs. Our experimental and numerical results show again that the GGSs have properties similar to those of solitons formed in lasers with net negative cavity GVD.

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