Dissipative soliton generation in Yb-fiber laser with an invisible intracavity bandpass filter

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We report on dissipative soliton (DS) generation in an Yb-doped (YDF) fiber laser passively mode locked with the nonlinear polarization rotation (NPR) technique. We found that even without the insertion of a physical bandpass filter in the cavity, not only could DSs be automatically formed in the laser but also the formed DSs have a spectral bandwidth that is far narrower than the Yb-fiber gain bandwidth. Numerical simulations well reproduced the experimental observations. Our results suggest that a physical intracavity bandpass filter is not a crucial component for the generation of DSs in all-normal-dispersion YDF lasers mode locked with the NPR technique. © 2010 Optical Society of America

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It is a well-known fact that, owing to the natural balance between the dispersion effect and fiber nonlinearity, solitary waves can be formed in a mode-locked fiber laser with anomalous cavity dispersion. The formed solitons are known as nonlinear Schrödinger equation (NLSE) solitons [1,2]. In fiber lasers with normal cavity dispersion, no NLSE solitons can be formed. However, it was shown recently that dissipative solitons (DSs) could be formed in all-normal-dispersion fiber lasers [3,4]. Different from the solitons formed in anomalous dispersion fiber lasers, the dynamics of DSs is governed by the complex Ginzburg–Landau equation (GLE). Moreover, it has been shown that spectral filtering plays a crucial role in DS formation in a fiber laser [3–11]. For the erbium-doped fiber (EDF) lasers, as the narrow gain bandwidth functioned as a spectral filter in the lasers, the formed DSs were also called the "gain-guided solitons" [3]. For the Yb-doped fiber (YDF) lasers, due to the fact that the gain bandwidth of the YDF is large, about 40 nm, a bandpass filter or a bandwidth-limiting component was normally inserted in the cavity to limit the effective gain bandwidth for the benefit of DS formation [4–10]. This is particularly true for YDF lasers mode locked with the nonlinear polarization rotation (NPR) technique [4,7–10]. It was shown that a discrete bandpass filter in the laser cavity has the function of converting the frequency chirp to the self-amplitude modulation [7–9]. Therefore, almost all the previously reported DS operation YDF lasers mode locked with the NPR technique used an intracavity bandpass filter. It gave the impression that in the lasers, spectral filtering of the intracavity bandpass filter is necessary for DS formation. In this Letter, we show that DS operation can also be achieved in an YDF laser mode locked with the NPR technique even without inserting a discrete bandpass filter in the cavity. Any cavity component that has a narrow bandwidth could play that role. In particular, we showed that intrinsic to the NPR mode-locking technique, an artificial birefringence filter always exists in NPR mode-locked fiber lasers [12]. One can take advantage of the artificial birefringence filter to narrow down the effective gain bandwidth of YDF lasers and achieve self-started mode locking and DS operation in these lasers. Numerical simulations have also well supported our experimental observations.

We used an YDF laser, as schematically shown in Fig. 1. A segment of 33 cm YDF with absorption of 1020 dB/m at 977 nm (AD465-00, Fibercore) was used as the gain medium. All the other fibers used were the standard single-mode fiber (HI1060, Corning). The NPR mode-locking technique was adopted. To this end, a polarizer together with a fiber-type polarization controller (PC) was used to control the polarization of light in the cavity. A fiber-type polarization independent isolator was used to force the unidirectional operation of the laser. The polarizer was mounted on a 76-mm-long fiber bench, and the insertion loss of the fiber bench is about 1 dB. The laser was pumped by a 975 nm pump laser through a wavelength division multiplexer (WDM), and the output of the laser was via a 10% fiber coupler. The total cavity length was about 8.8 m. Different from the previously reported DS operation YDF lasers, no narrow bandpass spectral filter was inserted in the cavity.

Under an approximate PC orientation setting, self-started mode locking was achieved in the laser with a pump threshold of about 100 mW. Figure 2 shows a typical mode-locking state of the laser, measured at the pump power of 148 mW. The left inset of the figure shows the pulse train of the laser emission. The right inset shows the local rf spectrum around the fundamental

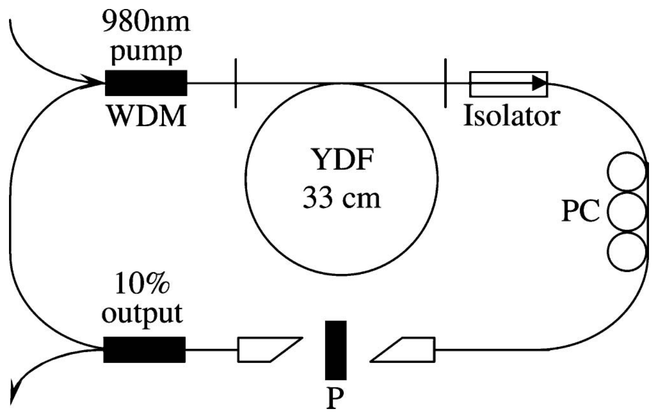

Fig. 1. Schematic of the fiber laser: P, polarizer.

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repetition frequency of 22.73 MHz; the signal-to-noise ratio is about 70 dB. The optical spectrum of the pulses has the characteristic steep spectral edges of DSs [3,4], indicating that the mode-locked pulses have been shaped to the DSs. The edge-to-edge bandwidth of the spectrum is about 10.8 nm, with the central wavelength at 1048.2 nm. The temporal profile of the DS was measured with a 45 GHz photodetector (New Focus, 1014) and a 50 GHz sampling oscilloscope (Agilent, 86100A). There was only one pulse in the cavity. The pulse width is about 51 ps. The average output power is about 0.72 mW, which corresponds to pulse energy of 31.7 pJ. The time-bandwidth product of the pulses is about 151, reflecting the strong chirped feature of the DSs. Experimentally we used a chirped mirror with group velocity dispersion of $-100\ \mathrm{fs}^2$ to compress the pulses. After the chirped mirror, the pulse width became about 48 ps, indicating that the pulse is compressible. The top of the optical spectrum as well as the edge-to-edge spectral width varied with the pump strength. The stronger the pump power, the broader is the edge-to-edge spectral width, e.g., as the pump power varied from 100 mW to 150 mW, the edge-to-edge bandwidth increased by 3 nm.

Under a fixed pump power, the central wavelength, the edge-to-edge spectral bandwidth, the pulse width, and the top of the spectrum of the DS varied with the rotation of the PC paddles, as shown in Fig. 3. When one of the paddles of the PC was continuously rotated by 4°, 8° from the state shown in Fig. 2, respectively, the central wavelength shifted from 1048.2 nm to 1048.6 nm and 1049.0 nm; the edge-to-edge spectral bandwidth changed from 10.8 nm to 10.6 nm and 10.1 nm; and the pulse width changed from 51.3 ps to 53.4 ps and 57.3 ps. The sideband peak near the short-wavelength side was strengthened, while that near the long-wavelength side was weakened, which suggests that the spectral limitation on the short-wavelength side is reduced, while that on the long-wavelength side is increased.

Obviously, without a concrete bandpass filter in the cavity, DS operation could still be obtained in the YDF laser. To get an insight on DS formation in the laser, we further numerically simulated the laser operation. We used exactly the same model and simulation technique as described in [3,11]. Briefly, we used the coupled complex GLEs to describe the light propagation in the cavity fibers. By circulating the light in the laser cavity

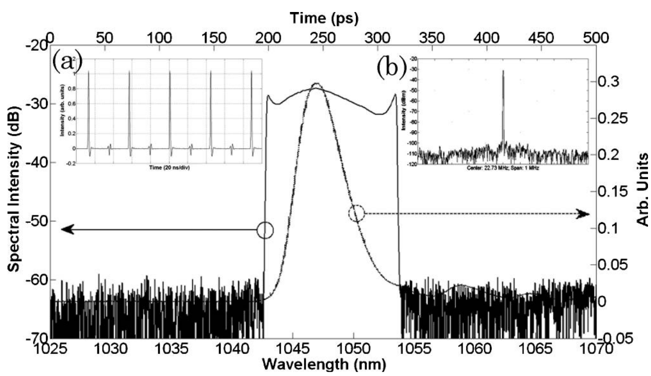

Fig. 2. (a) Typical optical spectrum and (b) corresponding pulse profile of the generated DSs (inset left, pulse train; inset right, rf spectrum).

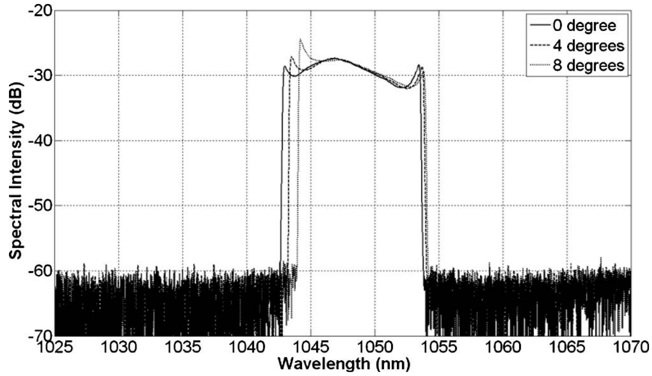

Fig. 3. Variation of the optical spectrum with cavity birefringence under fixed pump power.

and taking into account the action of each cavity component, we have also explicitly considered the laser cavity boundary effect, gain saturation, and pulse peak clamping effect. To get possibly close to our experimental conditions, we used the following simulation parameters [13]: the GVD parameter is $k''_{\mathrm{YDF}} = 20.0\ \mathrm{ps}^2/\mathrm{km}$, $k''_{\mathrm{SMF}} = 22.1\ \mathrm{ps}^2/\mathrm{km}$; the nonlinear parameter is $\gamma_{\mathrm{YDF}} = 3.95\ \mathrm{W/km}$, $\gamma_{\mathrm{SMF}} = 5.58\ \mathrm{W/km}$; the gain bandwidth of the YDF is 40 nm; the cavity length is $L = 1.9_{\mathrm{SMF}} + 10\%\mathrm{Output} + 1.2_{\mathrm{SMF}} + 0.3_{\mathrm{YDF}} + 5.4_{\mathrm{SMF}} = 8.8\ \mathrm{m}$; and the beat length is $L_b = L/20$. Figures 4(a) and 4(b) show the optical spectra and the pulse profiles of the calculated DSs when the small-signal gain was fixed as $6000\ \mathrm{km}^{-1}$ and the cavity linear phase delay bias (CLPDB) [11] was changed. This corresponds to the experimental condition of fixing the pump power but

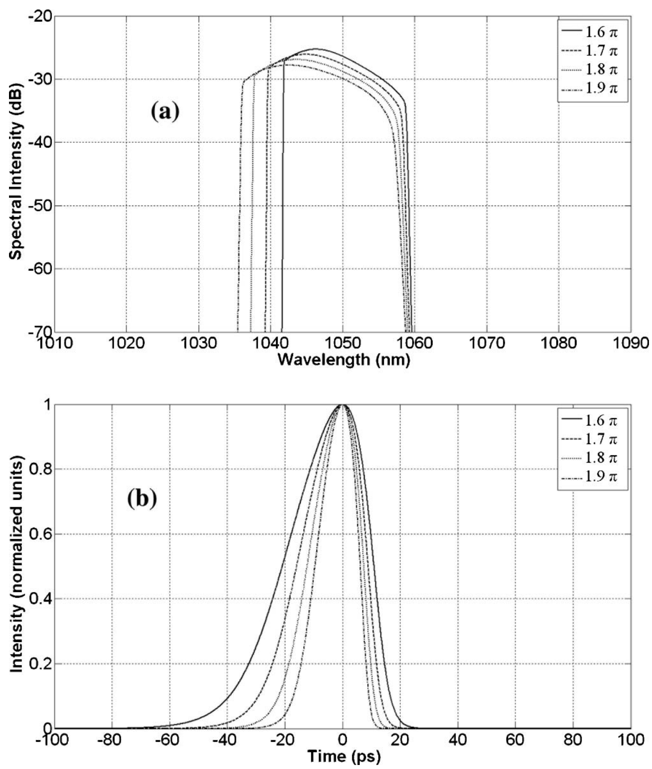

Fig. 4. (a) Numerically simulated optical spectrum and (b) corresponding pulse profile of the DSs versus the CLPDB change. Media 1 (2000 KB) shows the compressed pulse profiles versus compensation dispersion numerically calculated. The DS obtained at CLPDB $= 1.6\pi$ was used as the initial pulse.

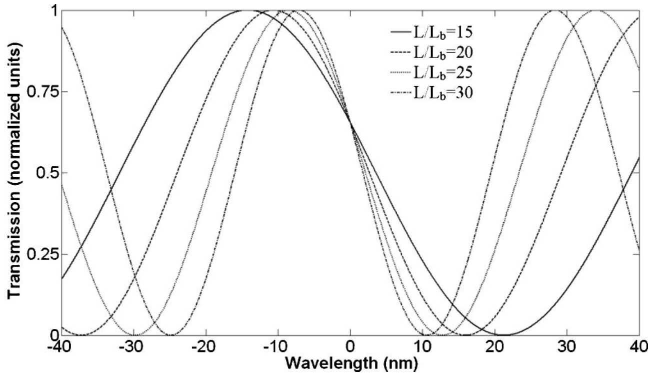

Fig. 5. Cavity transmission versus wavelength shift under different cavity birefringence. The central wavelength is at 1064 nm, and the CLPDB is 1.6π.

rotating the paddles of the PC. As observed in the experiment, strong spectral limitation occurred on the long-wavelength side, and the narrower the pulse width, the broader is the spectral bandwidth. In addition, our numerous simulations showed that the weaker the cavity birefringence, the stronger is the small-signal gain required for DS formation in the fiber laser. Numerically we also simulated the compression of the formed DSs through linear dechirping. It was found that the DSs could not be fully dechirped. Although pulses as narrow as about 687 fs could be obtained, wave breaking was always observed before the narrowest pulse was formed (Media 1 shows the compressed pulse profiles versus compensation dispersion numerically calculated. The DS obtained at $\text{CLPDB} = 1.6\pi$ was used as the initial pulse).

As the edge-to-edge spectral bandwidth of the formed DSs is far less than that of the gain bandwidth of the YDF, and all the other cavity components used also have much larger bandwidth than that of the generated DSs, it is suspected that an invisible bandpass filter with narrow bandwidth must have played a role. We point out that it was the birefringence filter of the laser [12]. It is well known that intrinsic to NPR mode-locking fiber lasers, the cavity transmission is a sinusoidal function of the linear and nonlinear phase shift of light in the cavity. To highlight it, we have shown in Fig. 5 the cavity transmission variation around a certain central wavelength. Depending on the linear cavity birefringence, the cavity transmission exhibits different transmission bandwidths, defined as $B_w = \lambda_c L_b / 2L$, where λ_c is the central wavelength [12]. In the experiment, rotating the paddles of the PC changes the cavity birefringence, which is equivalent to changing the effective cavity transmission bandwidth. Although the YDF has a broad gain profile, due to the bandpass limitation of the artificial cavity birefringence filter, the effective gain of the laser has a narrow bandwidth. Therefore, under the influence of the effective gain bandwidth limitation, DSs are still formed in the laser, even without the insertion of a bandpass filter. Note that the bandwidth of the artificial cavity birefringence filter decreases with the cavity birefringence; in case the cavity birefringence is very weak, the actual fiber gain bandwidth could eventually play the bandwidth-limiting role, leading to the formation of the "gain-guided solitons," but this would require that the pump power be sufficiently strong. We point out that the "gain-guided solitons" would be the largest energy soliton formable in the lasers.

In conclusion, we have achieved self-started DS operation in an all-normal-dispersion YDF laser with the NPR technique. It was shown that DS operation could still be obtained in the fiber laser even without inserting a bandpass filter in the cavity. It was shown that NPR mode locking could naturally introduce an artificial bandpass filter to the laser, and it consequently narrows down the effective gain bandwidth of the laser and results in DS formation. We have pointed out that the "gain-guided soliton," which is a special case of a DS being formed in the laser, would be the largest energy soliton formable in a fiber laser.

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