

Soliton collapse and bunched noise-like pulse generation in a passively mode-locked fiber ring laser

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Abstract: A passively mode-locked soliton fiber ring laser with dispersion managed cavity is reported. The laser emits intense bunched noise-like pulses including the transform limited pulses. The optical spectrum of the laser emission has a bandwidth as broad as 32.10 nm. It was found that purely depending on the linear cavity phase delay the laser could be switched between the soliton operation and the noise-like pulse emission. Numerical simulations showed that the laser emission was caused by the combined effect of soliton collapse and positive cavity feedback in the laser.

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Passively mode-locked fiber lasers as simple, inexpensive optical pulse source have been extensively investigated. By operating the lasers in the net negative cavity dispersion regime it has been shown that ultrastable soliton pulses with sub-picosecond pulse duration could be routinely generated [1-3]. Although the solitons formed in the lasers are still a result of the balanced action between the average cavity dispersion and the nonlinear self-phase modulation, as the solitons are circulating in the laser cavity, they are also subjected to the actions of the cavity components and the cavity. Therefore, features of the solitons were found fundamentally different to those of the solitons obtained in a single mode optical fiber, e.g. the

energy quantized multiple soliton emission [3], bound states of solitons [4], and multi-peak solitons [5] were experimentally observed in the lasers. Theoretically, soliton operation of a laser can be well described by the so-called round-trip model [5, 6], which takes into account both the nonlinear light propagation in laser cavity and the cavity properties such as the gain, loss and cavity feedback effect. In this paper we report on another novel effect of the soliton operation in a fiber laser passively mode-locked by using the nonlinear polarization rotation technique. We show experimentally that by simply shifting the linear cavity phase delay, the soliton operation of the laser can be tuned into a mode-locked state where the mode-locked pulse consists of a bunch of noise-like pulses while its optical spectrum has a super-broad bandwidth. Based on the numerical simulations we further show that this kind of laser emission is caused by the combined effect of soliton collapse and positive cavity feedback in the laser.

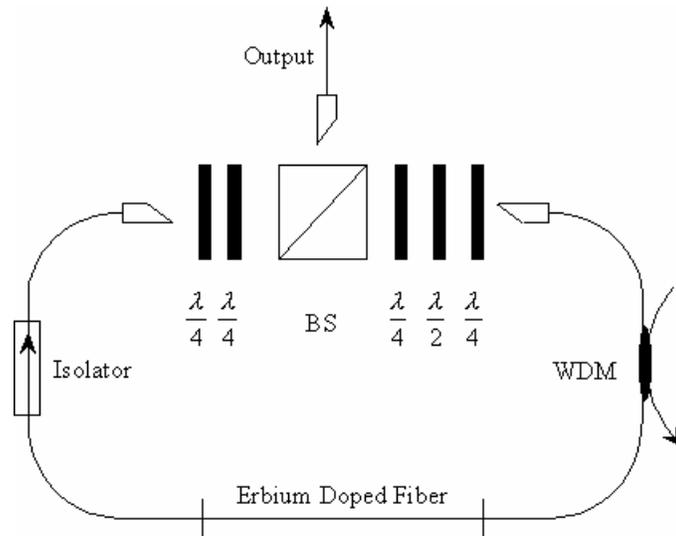


Fig. 1. Schematic of the fiber soliton laser setup. $\lambda/4$: quarter-wave plate; $\lambda/2$: half-wave plate; BS: beam splitter; WDM: wavelength-division multiplexer.

The fiber soliton laser used is schematically shown in Fig. 1. It has a ring cavity of about 12 meters. The cavity consists of 2-meter 8000 ppm erbium doped fiber (EDF) with a group velocity dispersion (GVD) of about +70 ps/nm/km, and 10-meter standard single mode fiber (SM28) with negative GVD of about -18 ps/nm/km. The nonlinear polarization rotation technique was used to mode-lock the laser. To this end two polarization controllers, one consists of two quarter-wave plates and the other two quarter-wave plates and one half-wave plate, together with a cubic polarization beam splitter were used to control the polarization of light in the cavity. The polarization beam splitter also functions as an output coupler in the laser. The polarization controllers and the cubic beam splitter were mounted on a 7-cm-long fiber bench to facilitate the adjustment. A fiber isolator was used to enforce the unidirectional operation of the ring cavity. The laser was pumped by a high power Fiber Raman Laser source (BWC-FL-1480-1) of wavelength 1480 nm. The output of the laser was detected simultaneously by an optical spectrum analyzer, a commercial autocorrelator, and a high-speed sampling oscilloscope.

As the total cavity GVD of the laser is in the negative dispersion regime, despite the fact that the cavity is dispersion managed, soliton operation could still be obtained. Experimentally we found that the overall soliton operation of the laser is similar to that of the non-dispersion managed soliton fiber lasers, e.g. effects such as the pump power hysteresis [7], multiple

soliton generation and various modes of the multiple soliton operation [1], bound states of solitons [4] were observed in the laser. Under normal conditions the single pulse soliton of the laser has a pulse width of about 300 fs and an optical spectral bandwidth of about 10 nm. The exact soliton parameters vary within a small range with the detailed laser operation conditions such as the orientations of the waveplates and the pump power strength.

A striking feature of the laser is that by simply changing the orientation of one of the waveplates, the soliton operation could be tuned into a mode-locked state whose optical spectrum has super broad bandwidth, while the corresponding pulse profile consists of a bunch of intense noise-like pulses. Figure 2 shows a typical result observed experimentally. Fig. 2(a) shows the optical spectrum and Fig. 2(b) and Fig. 2(c) the corresponding autocorrelation traces under different scan ranges. The optical spectrum is smooth. It has a 3-dB bandwidth of about 32.10 nm. The broadband spectrum suggests that the laser is still mode-locked. However, its spectral distribution is very different to that of a stable soliton of the laser. Once the state is obtained, decreasing the pump power does not reduce the spectral bandwidth. The autocorrelation trace of Fig. 2(b) has a profile of narrow pulse riding on a broad pedestal, which suggests that the actual mode-locked pulse consists of a series of coherent narrow random spikes. Changing the pump strength, the width of the pedestal could vary significantly, even extending beyond the scan range of the autocorrelator (50ps). However, the width of the narrow pulse has almost a constant value, indicating that the number of coherent spikes varies while the average pulse width of the spikes remains the same. By shortening the scan range of the autocorrelator we could obtain an autocorrelation trace as shown in Fig. 2(c), which shows that the narrow intensity modulation pulses have an averaged pulse width of about 75fs, which corresponds roughly to a transform-limited pulse determined by the measured spectral bandwidth. With the help of the high-speed oscilloscope it was further confirmed that independent of the pump power, there is always only one such mode-locked pulse circulating in the cavity. We note that a similar kind of fiber laser emission was also reported by M. Horowitz *et. al.* [8] and explained as caused by the polarization-dependent delay (PDD) effect as the laser used had a large cavity birefringence. However, our laser cavity has only weak birefringence, which obviously rules out the possibility of the PDD effect.

To find out the physical mechanism we have numerically simulated the laser operation by using the round-trip model [5, 6]. In our simulations we described the nonlinear pulse propagation in the cavity with the extended coupled nonlinear Schrödinger equations:

$$\begin{cases} \frac{\partial u}{\partial z} = i\beta u - \delta \frac{\partial u}{\partial t} - \frac{ik''}{2} \frac{\partial^2 u}{\partial t^2} + \frac{ik'''}{6} \frac{\partial^3 u}{\partial t^3} + i\gamma(|u|^2 + \frac{2}{3}|v|^2)u + \frac{i\gamma}{3}v^2u^* + \frac{g}{2}u + \frac{g}{2\Omega_g} \frac{\partial^2 u}{\partial t^2} \\ \frac{\partial v}{\partial z} = -i\beta v + \delta \frac{\partial v}{\partial t} - \frac{ik''}{2} \frac{\partial^2 v}{\partial t^2} + \frac{ik'''}{6} \frac{\partial^3 v}{\partial t^3} + i\gamma(|v|^2 + \frac{2}{3}|u|^2)v + \frac{i\gamma}{3}u^2v^* + \frac{g}{2}v + \frac{g}{2\Omega_g} \frac{\partial^2 v}{\partial t^2} \end{cases} \quad (1)$$

where u and v are the normalized envelopes of the optical pulses along the two orthogonal polarized modes. $2\beta = 2\pi\Delta n/\lambda$ is the wave-number difference between the modes and $2\delta = 2\beta\lambda/2\pi c$ is the inverse group velocity difference. k'' is the second order dispersion coefficient, k''' is the third order dispersion coefficient, and γ represents the nonlinearity of the fiber. g is the saturable gain coefficient of the erbium-doped fiber and Ω_g is the gain bandwidth. For undoped fibers $g = 0$.

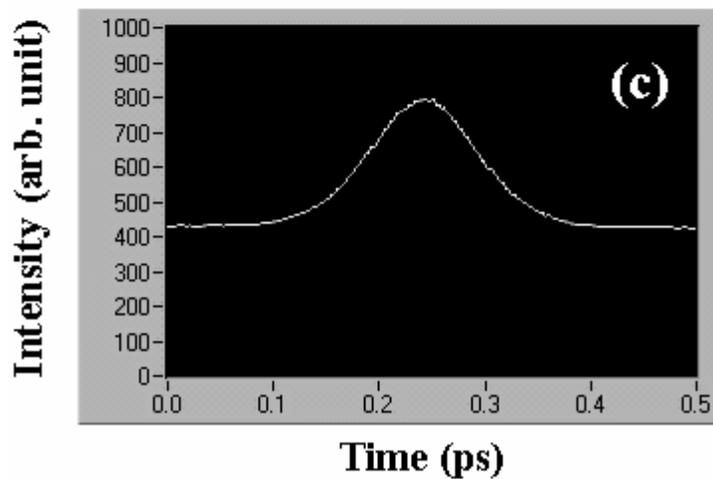
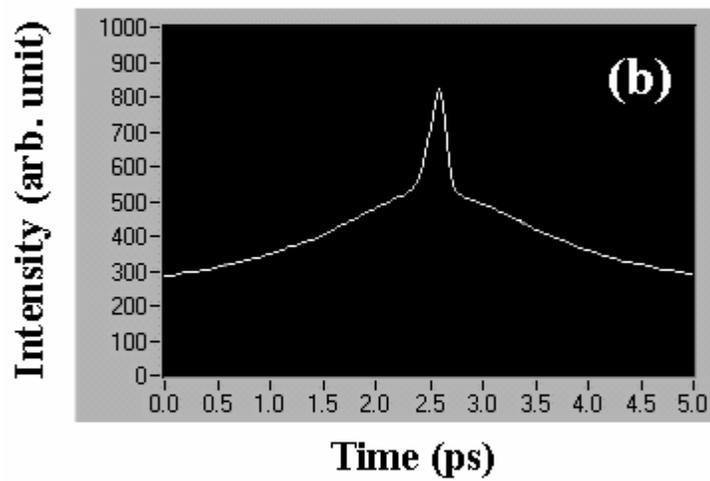
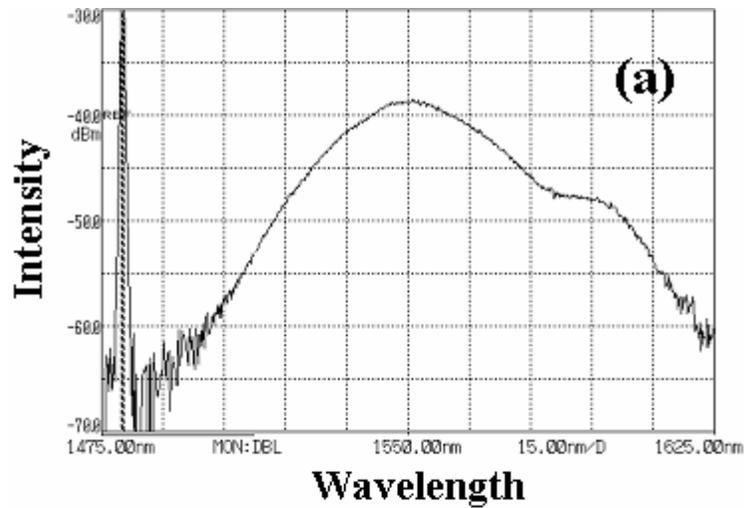


Fig. 2. A typical state of the bunched noise-like pulse emission. (a) Optical spectrum of the state; (b) Autocorrelation trace with a scan span of 5 ps; (c) Autocorrelation trace with a scan span of 0.5 ps.

The gain saturation is described by:

$$g = g_0 \exp\left[-\frac{\int (|u|^2 + |v|^2) dt}{P_{\text{sat}}}\right] \quad (2)$$

where g_0 is the small signal gain coefficient and P_{sat} is the saturation energy. We have used the following parameters for the simulations: $\gamma = 3 \text{ W}^{-1}\text{km}^{-1}$; $k'' = -20 \text{ ps}^2/\text{nm}/\text{km}$ (SMF); $k'' = +70 \text{ ps}^2/\text{nm}/\text{km}$ (EDF); $k''' = 0.1 \text{ ps}^3/\text{nm}/\text{km}$; $\Omega_g = 25 \text{ nm}$; gain saturation intensity $P_{\text{sat}}=1000$; cavity length $L = 5(\text{SMF})+2(\text{EDF})+5(\text{SMF})=12\text{m}$; cavity beat length $L_b=L/2$. The polarizer orientation to the fiber fast axis $\psi = 0.152\pi$.

We found numerically that the model could reproduce all the features of the soliton operation of the laser. In particular, by simply shifting the linear cavity phase delay the soliton operation of the laser can be tuned to a mode-locked state as described above. Fig. 3 shows for example a typical such mode-locked state numerically calculated. Figure 3(a) shows the time evolution of the mode-locked pulses with the cavity round trips and the pulse profiles in the cavity. The noise-like feature of the pulse profiles is clearly to see. Careful examination of the state shows that the laser emission actually is a bunch of pulses with random varying pulse width, peak power and pulse number. The average number of pulse within the bunch increases with the pump strength, which also determines the overall length of the bunch. A pulse in the bunch grows up and simultaneously its pulse width narrows down until it becomes a transform-limited pulse, and then the pulse collapses. Figure 3(b) is the calculated autocorrelation trace of the mode-locked pulse. Considering that the experimentally measured autocorrelation trace is actually time averaged, the result is then well in agreement with the experimental measurement. Based on the numerical simulations we further figured out that the state was actually formed by the combined effect of the soliton collapse and the positive cavity feedback in the laser. To explain it we note that depending on the linear cavity phase delay there exist two cavity feedback regimes in the laser, e.g. with our current laser parameter selection the cavity provides a positive feedback if the linear cavity phase delay φ is biased in the range of $\pi < \varphi < 2\pi$ and a negative feedback in the range of $0 < \varphi < \pi$. The $\varphi = \pi$ is the feedback switching point. The laser can always be mode-locked if the cavity provides a positive feedback. A generic property of solitons formed in gain media is the explosive increase in amplitude and decrease in pulse width. It eventually leads to soliton collapse [9, 10]. This property also applies for solitons formed in lasers. However, in the case of the current laser when the linear cavity phase delay φ is biased close to the cavity feedback switching point, the cavity feedback switching generates a soliton peak power limitation mechanism, which stabilizes the soliton operation. While when φ is biased far away from the cavity feedback switching point, a soliton collapses before its peak power reaches the feedback switching point. Consequently solitons in the laser are constantly destroyed and generated. Under strong pumping multiple of such process coexist unsynchronized, therefore, it forms the experimentally observed noise-like pulses. It is to note that as the linear cavity loss under such a linear cavity phase delay is very big, solitons can only be formed in the cavity at the position where a soliton was collapsed, which leads to the result that all the noise-like pulses are bunched in the cavity.

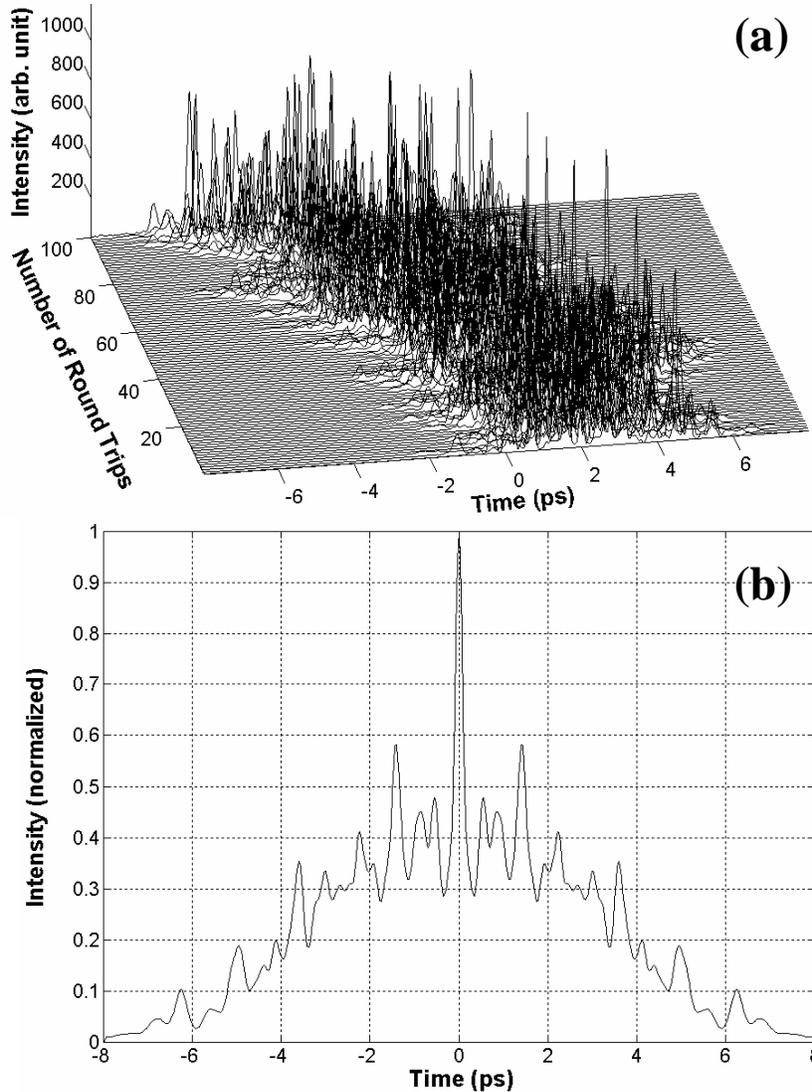


Fig. 3. A typical bunched noise-like pulse state numerically calculated. (a) Time evolution of the noise-like pulses; (b) Autocorrelation trace numerical calculated.

In conclusion, we have experimentally observed a kind of bunched noise-like pulse emission including the effective gain bandwidth limited pulses in a passively mode-locked fiber ring laser with dispersion managed cavity. The maximum 3-dB bandwidth of the bunched noise-like pulse emission has a bandwidth of about 32nm. Numerical simulations show that the bunched noise-like pulse emission is a natural state of the laser operation and it is caused by the combined effect of the soliton collapse and cavity positive feedback.