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Generation of 15-nJ bunched noise-like pulses with 93-nm bandwidth in an erbium-doped fiber ring laser

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ABSTRACT We report on the generation of high power superbroad spectrum bunched noise-like pulses from a passively mode-locked erbium-doped fiber ring laser without using the stretched-pulse technique. The maximum 3-dB spectral bandwidth of the noise-like pulses is about 93 nm with an energy of about 15 nJ. We further show numerically that the superbroad spectrum of the pulses is caused by the transform-limited feature of the pulses together with the Raman self-frequency shift effect.

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1 Introduction

Passively mode-locked erbium-doped fiber lasers (PMEFLs) using either the figure-of-eight configuration or the nonlinear polarization rotation (NPR) technique for mode-locking have been intensively investigated in the past decade [1–4]. As the lasers operate at around 1.55 μm, where the optical fibers have anomalous group velocity dispersion (GVD), under the mutual effect of the fiber GVD and Kerr nonlinearity, solitons with ultrashort pulse duration were routinely generated. However, it was experimentally observed that the solitons formed have only low peak power. Increasing the laser gain could only increase the number of solitons in the cavity rather than their peak power. Traditionally it was believed that soliton instability could have limited the peak power of the mode-locked pulses, and to overcome the problem, a stretched-pulse mode-locking technique was introduced [5]. Instead of constructing the laser cavity by exclusively using the fibers of anomalous GVD, the fiber of normal GVD is also incorporated. Such a laser is also known as a dispersion-managed laser [6, 7]. Using dispersion-management has the advantage that the pulse is temporally stretched in the positive GVD fiber, therefore, the average pulse peak power in the cavity is low so that soliton breaking caused by the high peak power could be avoided. Depending on the operation conditions and the position of the laser output port, the pulses from a dispersion-managed fiber laser could be strongly frequency chirped. Nevertheless, this frequency chirp can be de-chirped outside the cavity and consequently pulses with large energy and narrow duration can be obtained. K. Tamura et al. have demonstrated a dispersion-managed fiber laser whose mode-locked pulse energy and spectral bandwidth are about 0.5 nJ and 53 nm, respectively [7]. With an appropriately designed dispersion map, F.Ö. Ilday et al. have generated pulses with 5 nJ pulse energy and 50 fs pulse width [6].

Apart from the large energy chirped pulse emission, a dispersion managed fiber laser can also emit so-called noise-like pulses with broad spectral bandwidth [8–10]. M. Horowitz et al. firstly reported the experimental observation of the laser emission and attributed it to the combined effect of polarization modal walk-off and cavity nonlinear transmission [8]. J.U. Kang experimentally studied the dependence of the spectral bandwidth of the noise-like pulses on the net laser cavity dispersion, and obtained a maximum spectral bandwidth of 80 nm in a net positively dispersive cavity [9]. In a recent experiment we have also observed noise-like pulse emission in a passively mode-locked fiber ring laser with a dispersion-managed cavity [10]. However, contrary to the previous explanation, we found that the laser emission could be caused by the soliton collapse effect in the lasers. Soliton collapse is a general property of the gain guided solitons. In fact solitary waves also exist in amplified nonlinear dispersive media independent of the medium dispersion [11]. However, these solitons were found to be unstable. After initial undistorted soliton propagation they experience a sudden explosive temporal compression and then collapse [12]. Provided that our understanding is correct, it would suggest that solitons observed in the lasers are essentially gain guided solitons. Therefore, the formation of the noise-like pulses should also be a generic property of all PMEFLs, whose appearance is independent of the cavity dispersion management. To confirm this, we report further on the experimental observation of the noise-like pulse generation in a conventional PMEFL. In particular, we show that by taking advantage of the soliton collapse effect and the soliton self-frequency shift (SSFS), high power superbroad spectral bandwidth noise-like pulses can be generated, and the spectral bandwidth of the laser emission is practically only limited by the effective laser gain available.

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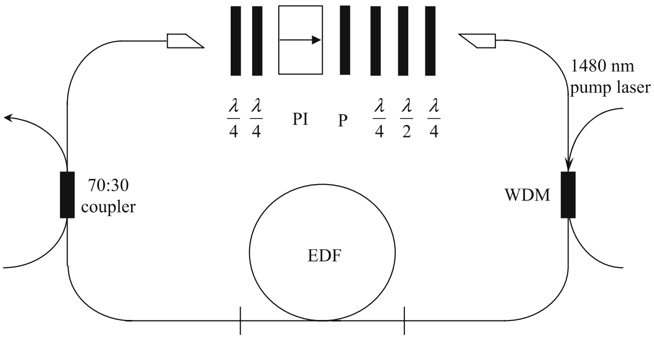

FIGURE 1 Schematic setup of the fiber laser: λ/4: quarter-wave plate; λ/2: half-wave plate; PI: polarization-dependent isolator; P: polarizer; WDM: wavelength-division multiplexer; EDF: erbium doped fiber

2 Experimental setup

The fiber soliton laser used is schematically shown in Fig. 1. It has a ring cavity of about 21 m. The cavity comprises a 17.6-m-long erbium doped fiber (EDF-1480-T6) with negative GVD, a segment of dispersion-shifted fiber of about 2.5 m, and another segment of standard single mode fiber (SM28) of about 1 m. The NPR technique is used to achieve the self-started mode locking in the laser. A polarization-dependent isolator is inserted into the cavity to force the unidirectional operation of the laser. Two polarization controllers, one consisting of two quarter-wave plates and the other two, quarter-wave plates and one half-wave plate, are used to adjust the polarization of the light. The polarization controllers, polarization-dependent isolator, and a polarizer are mounted on a 7 cm-long fiber bench. The laser is pumped by a high power fiber Raman laser source (BWC-FL-1480-1) of wavelength 1480 nm. The laser emission is emitted through a 70% fiber output coupler. The signal is analyzed with an optical spectrum analyzer (Ando AQ-6315B), a 26.5 GHz rf spectrum analyzer (Agilent E4407B ESA-E SERIES) and a 500 MHz oscilloscope (Agilent infiniium). A commercial optical autocorrelator (Autocorrelator Pulsescope) has also been used to measure the pulse profile of the soliton pulses.

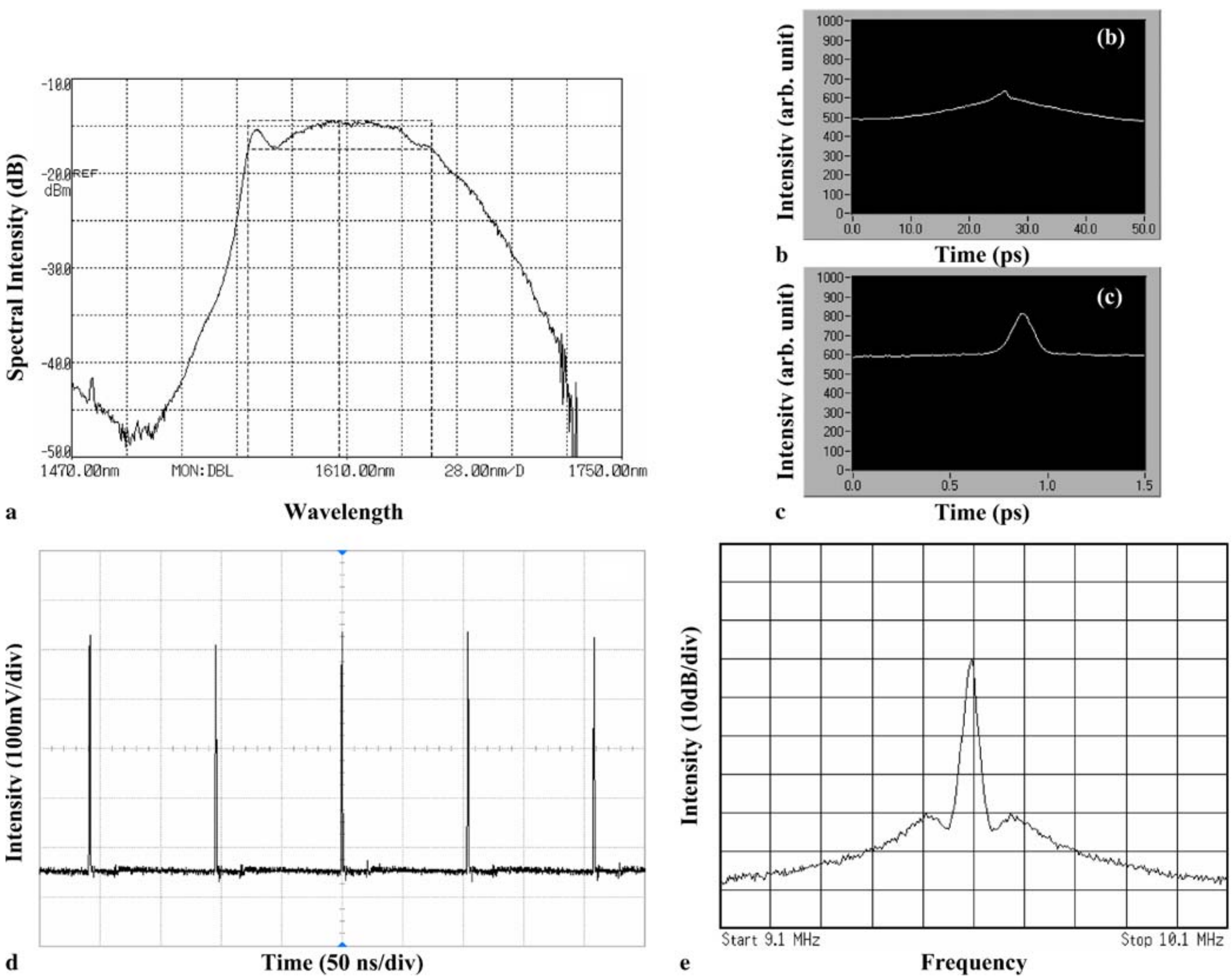

FIGURE 2 Bunched noise-like pulse emission. (**a**) optical spectrum; (**b**) autocorrelation trace under large scan range; (**c**) autocorrelation trace under small scan range; (**d**) oscilloscope trace; (**e**) rf spectrum around the fundamental cavity repetition rate

3 Results and discussion

Stable soliton operation could be easily obtained in the laser provided that the orientations of the polarization controllers are appropriately set. Under normal conditions the single-pulse soliton of the laser has a pulse width of about 316 fs and a 3-dB optical spectral bandwidth of about 10 nm. After the single-pulse soliton is obtained, tuning one of the wave plates while holding all the other experimental conditions unchanged will shift the laser operation from the conventional soliton emission into the noise-like pulse emission, the same as that reported in [10]. Figure 2 shows the optimized noise-like pulse emission state observed. The optical spectrum is smooth. It has a 3-dB bandwidth of about 93.180 nm, far broader than the EDF gain bandwidth. Figure 2b and c show the corresponding autocorrelation traces measured under different scan ranges of the autocorrelator. Again, the autocorrelation trace consists of a narrow spike riding on a broad and smooth shoulder that extended over the entire width of the measurement window of 50 ps. The exact width of the shoulder varies with the pump power, which could be as broad as several hundred of picoseconds under strong pumping. We note that if a small scan range of the autocorrelator is used, the autocorrelation trace obtained is shown in Fig. 2c. In this case the overall structure of the autocorrelation trace is lost. The narrow spike on top of the broad shoulder of the autocorrelation trace gives the average pulse width of the fine structures within the mode-locked pulses. In our laser this corresponds to an average pulse width of about 80 fs ($sech^2$ profile assumed). Figure 2d further shows the measured oscilloscope trace and Fig. 2e the rf spectrum of the laser emission. Under the noise-like pulse operation there is always one mode-locked pulse in the cavity, and it circulates with the fundamental cavity repetition rate. Based on the combined information provided by the autocorrelation trace and the oscilloscope trace, we confirmed that the mode-locked pulse consists of a bunch of pulses with randomly varying pulse widths and peak powers, namely the "noise-like" pulse [8]. The noise-like feature is also represented by its rf spectrum as shown in Fig. 2e. Around the fundamental cavity repetition frequency, there are also two broad symmetrical spectral sidebands, which indicate the existence of random peak mod-

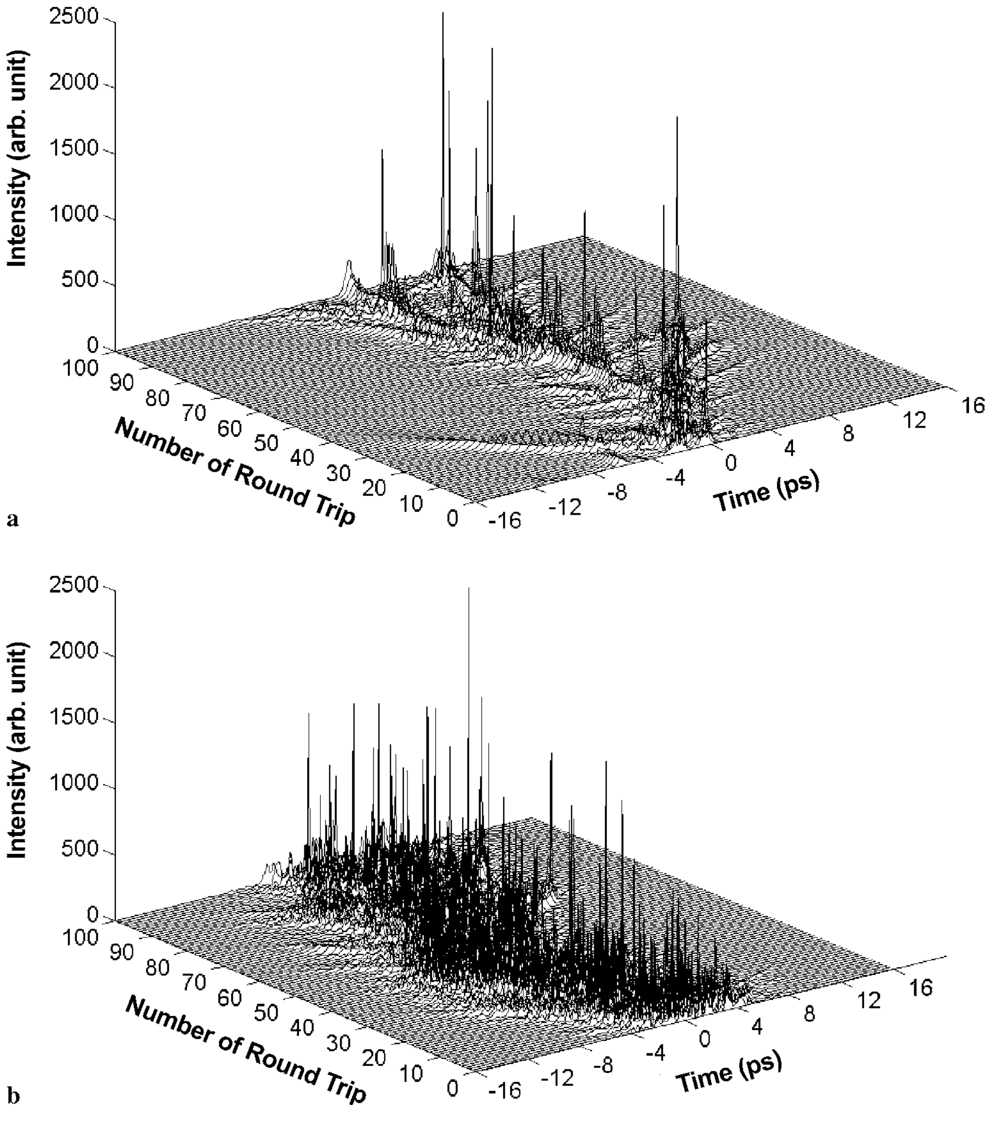

FIGURE 3 Typical bunched noise-like pulse emission numerically calculated. (**a**) $g_0 = 850$. (**b**) $g_0 = 1200$

ulation of the mode-locked pulses. The output power of the laser emission is about 21.6 dBm, which gives that the energy of the mode-locked pulse to be about 15 nJ.

The state of noise-like emission is stable. With a fixed laser cavity configuration, the exact duration of the overall bunch, the 3-dB optical spectral bandwidth and energy vary with the pump strength. Detailed experimental investigations show that the maximum achievable spectral bandwidth is closely related to the EDF length. Provided that the pump strength is strong enough, the longer the EDF the broader the spectral bandwidth that can be obtained. With the pump power available in our laser (~ 1 W), the optimized EDF length is 17.6 m, which generates the maximum 3-dB bandwidth of 93.180 nm as shown in Fig. 2. This optimized EDF length corresponds to the length for which the pump power is just fully absorbed by the EDF. With shorter EDF we found that even under the maximum available pump power, only noise-like pulses with narrower 3-dB bandwidth could be obtained. For example, when the EDF length is equal to 5 m, the maximum 3-dB bandwidth achievable is only 58.269 nm.

Using the technique reported in [10], we have also numerically simulated the laser operation and confirmed the noise-like pulse emission. Differently from previous work, we have also included the Raman self-frequency shift effect in our model to take into account the effect introduced by the long laser cavity of the current laser. The Raman soliton self-frequency shift is essentially a propagation effect. Its strength is dependent on the cavity length and the pulse peak power. The longer the fiber laser cavity, the stronger the effect when the laser is operating in the noise-like pulse mode. With the inclusion of the Raman self-frequency shift effect, the coupled extended Ginzburg–Landau equations used in our simulations are

$$\begin{cases} \dfrac{\partial u}{\partial z} = \mathrm{i}\beta u - \delta\dfrac{\partial u}{\partial t} - \dfrac{\mathrm{i}k''}{2}\dfrac{\partial^2 u}{\partial t^2} + \dfrac{\mathrm{i}k'''}{6}\dfrac{\partial^3 u}{\partial t^3} - \mathrm{i}T_\mathrm{R} u\dfrac{\partial |u|^2}{\partial t} \\ \qquad + \mathrm{i}\gamma\left(|u|^2 + \dfrac{2}{3}|v|^2\right)u + \dfrac{\mathrm{i}\gamma}{3}v^2u^* + \dfrac{g}{2}u + \dfrac{g}{2\Omega_\mathrm{g}}\dfrac{\partial^2 u}{\partial t^2} \\ \dfrac{\partial v}{\partial z} = -\mathrm{i}\beta v + \delta\dfrac{\partial v}{\partial t} - \dfrac{\mathrm{i}k''}{2}\dfrac{\partial^2 v}{\partial t^2} + \dfrac{\mathrm{i}k'''}{6}\dfrac{\partial^3 v}{\partial t^3} - \mathrm{i}T_\mathrm{R} v\dfrac{\partial |v|^2}{\partial t} \\ \qquad + \mathrm{i}\gamma\left(|v|^2 + \dfrac{2}{3}|u|^2\right)v + \dfrac{\mathrm{i}\gamma}{3}u^2v^* + \dfrac{g}{2}v + \dfrac{g}{2\Omega_\mathrm{g}}\dfrac{\partial^2 v}{\partial t^2}, \end{cases} \quad (1)$$

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. T_R is the Raman term, g is the saturable gain coefficient of the erbium-doped fiber and Ω_g is the gain bandwidth. For undoped fibers $g = 0$.

The gain saturation is described by:

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

where g_0 is the small signal gain coefficient and P_sat is the saturation energy.

Typical numerical results are shown in Figs. 3 and 4. We used the following parameters for the simulations: $T_\mathrm{R} = 6$ fs; $\gamma = 3\,\mathrm{W^{-1}km^{-1}}$; $k'' = -18$ ps/nm/km (SMF); $k'' = -18$ ps/nm/km (EDF); $k'' = -2$ ps/nm/km (DSF); $k''' = 0.1\,\mathrm{ps^2/nm/km}$; $\Omega_\mathrm{g} = 25$ nm; gain saturation intensity $P_\mathrm{sat} = 500$; cavity length is $L = 1_\mathrm{SMF} + 5_\mathrm{EDF} + 11.5_\mathrm{DSF} = 17.5$ m; cavity beat length $L_\mathrm{b} = L/2$. The polarizer orientation to the fiber fast axis $\psi = 0.125\pi$. The linear cavity phase delay is chosen as 1.7π.

Our numerical simulations show again, that depending on the linear cavity phase delay bias setting, the laser can either operate in the conventional soliton emission state or the noise-like pulse emission state in agreement with the experimental observations. In particular, numerical simulations show that the solitons formed in the lasers have the intrinsic feature of soliton collapse due to the existence of saturable absorption. Stable solitons can only be observed in the lasers when the soliton peak power is clamped, e.g. in the current laser by the cavity nonlinear polarization switching effect, which could occur before the soliton collapse depending on the linear cavity phase delay bias setting [10]. If the

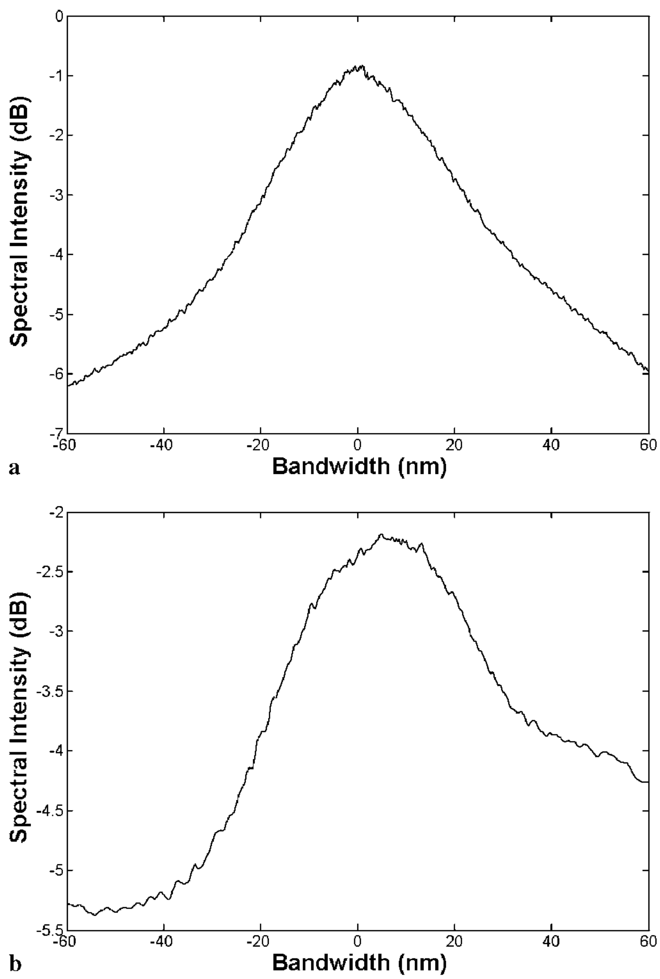

FIGURE 4 Optical spectra of bunched noise-like pulse emission numerically calculated. (**a**) Without Raman effect. (**b**) With Raman effect

pulse peak power is unclamped, the soliton peak will continuously increase, the soliton pulse width decreases, and the spectral bandwidth broadens. When the soliton pulse width becomes so broad that it is comparable to the gain bandwidth of the EDF, the gain dispersion then imposes a loss mechanism on the soliton, consequently the soliton collapses. However, due to the self-starting property of the laser, a new soliton will build up slowly from the collapsed soliton, and evolves eventually into collapse again, and the whole process repeats as shown in Fig. 3a. Depending on the laser gain, much of this soliton collapse and generation process coexists in the cavity, and under the gain competition, they are always unsynchronized. Therefore, at any instance pulses of randomly varying amplitudes and pulse widths coexist in the cavity. As new pulses are always generated from the collapsed solitons, they are correlated to each other and form the so-called bunched noise-like pulses in the cavity as shown in Fig. 3b.

We note that just before a soliton collapses, it has not only an optical spectrum comparable to the EDF gain bandwidth, but also a very high peak power. In this case the soliton self-frequency shift effect can no longer be ignored [13]. The soliton self-frequency shift further broadens the spectral bandwidth of the noise-like pulses, and results in the noise-like pulse emission having an optical spectrum broader than the EDF gain bandwidth. Figure 4b shows the optical spectrum of the noise-like pulses numerically calculated when $g_0 = 2000$, to simulate the effect of the long EDF amplification. For the purpose of comparison, we have also shown in Fig. 4a the optical spectrum of the noise-like pulses calculated without the Raman self-frequency shift effect. Obviously, the existence of the Raman self-frequency shift could not only broaden the optical spectrum of the noise-like pulses, but also shift the average central wavelength of the pulses to the longer wavelength. Nevertheless, we note that as the existence of the Raman self-frequency shift does not change the noise-like nature of the pulses, it will therefore cause no obvious change in the autocorrelation traces of the lasers with and without the existence of the Raman self-frequency shift effect. Again, our numerical simulation qualitatively reproduced the experimental observations accurately.

4 Conclusions

In conclusion, we have experimentally observed a kind of high power superbroad spectrum noise-like pulse emission in a conventional PMEFL, and pointed out that it is caused by the soliton collapse effect and the associated soliton self-frequency shift in the laser. Our experimental results not only confirmed that noise-like pulse emission is a generic property of all PMEFLs, but also suggests that even higher power and broader spectral bandwidth noise-like pulse emission is in principle, possible to achieve, provided that even stronger pump sources and larger nonlinearity fibers are available.

We believe such a superbroad spectrum light source could have applications in optical systems, such as optical coherence tomography, optical coherence radar and fiber optical sensing systems where high power super broadband optical sources are required. It is however worth bearing in mind that the nature of the light source is a bunch of pulses with randomly varying pulse widths, peak powers, and central wavelengths. Although the spectral bandwidth of the light is broad, it could be difficult to obtain narrow pulses with constant pulse width by spectrally slicing the spectrum. Therefore, it is not be suitable for applications where a stable and narrow pulse width is important.

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