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Experimental studies of noise-like pulses in a dispersion-managed fiber laser

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Abstract Based on an erbium-doped dispersion-managed fiber laser, the characteristics of noise-like pulses under different net cavity group velocity dispersions (GVDs) are experimentally investigated. Results show that the spectral bandwidth of noise-like pulse will increase as the net cavity GVD increases and attains maximum when the GVD is slightly positive. The effect of Raman scattering is enhanced due to the temporal width attains minimum. When the net cavity GVD increases continually and further into the positive region, the spectral width begins to decrease and the effect of Raman scattering is suppressed due to the positive dispersion. Our experimental results are in good agreement with the previous prediction of numerical simulation.

Key words fiber optics; noise-like pulse; broadband spectrum; fiber laser
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1 Introduction

Passively mode-locking fiber lasers have attracted great attention as potential applications in ultrafast optical communication, or as compact and economical sources for fundamental research[1~5]. Conventionally, the mode-locking pulses operation of a fiber laser is described by the Ginzburg - Landau equation (GLE), which takes into account the mutual interaction among cavity dispersion, fiber nonlinearity, and laser gain medium[6]. One of the operation states of the fiber laser is the emission of solitons. When the cavity dispersion is negative, the interaction between the fiber dispersion and fiber nonlinearity leads to the formation of the soliton, characterized by the pronounced sidebands in the soliton spectrum. Generally speaking, due to that the spectral bandwidth of the formed soliton is much narrower than the laser gain bandwidth, which is caused by the pulse peak clamping effect[2,7] of the cavity and the soliton nature of the pulse[6], the influence of the laser gain bandwidth on the formed solitons is very weak. Therefore, conventional soliton fiber lasers predominately exhibit the conventional soliton features. However, when the cavity dispersion is positive, due to the laser gain saturation and gain dispersion, soliton can still be formed, which is known as gain-guided soliton[8,9]. The gain-guided soliton has different properties to the conventional soliton as a result of the different soliton formation mechanisms. Obviously, there exist two completely different soliton formation mechanisms and therefore two different types of solitons in the mode-locked fiber lasers, although both of them are governed by the GLE.

Apart from the soliton operation in the fiber lasers, a kind of noise-like pulse state of operation was observed experimentally and investigated numerically in passively mode-locked fiber lasers[10~12], because its temporal pulse behavior resembles noise burst[10]. Noise-like pulses attract the researchers' interest due to their broad bandwidth and high power. However, previous research about noise-like pulse in fiber lasers is limited to a local dispersion regime. Although, Kang *et al.* has studied the dependence of the spectral bandwidth of the noise-like pulses on the net laser cavity dispersion[10], the difference in behaviors between their experimental results and the predictions of numerical simulation still need to be inspected again. In this paper, the characteristics of noise-like pulses under different net cavity group velocity dispersions

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(GVDs) in the dispersion managed mode-locking fiber laser based on the nonlinear polarization rotation technology are systematically investigated by experiments. The experimental results and the analysis provide useful information that helps to optimize and tune the properties of the noise-like pulse in the fiber laser.

2 Experimental setup

A schematic of the fiber laser used in our experiments is shown in Fig. 1. It has a cavity structure that consists of two segments of single mode fiber (SMF) with negative GVD of about $-23\ \mathrm{ps}^2/\mathrm{km}$ and a segment of 3-m EDF with positive GVD of about $43\ \mathrm{ps}^2/\mathrm{km}$. The wavelength-division-multiplexer (WDM) is made of the standard SMF. The initial loop length of the laser cavity is 31 m and different net cavity GVDs of the laser are achieved by varying the length of the SMF.

The nonlinear polarization rotation technique is used to mode lock the laser[13]. So a polarization dependent isolator is inserted in the cavity to assure the unidirectional operation of the laser. Two polarization controllers, of which one is a quarter-wave plate and the other consists of a quarter-wave plate and a half-wave plate, are used to adjust the polarization of the light. The polarization controllers, polarization dependent isolator, and polarizer are mounted on a 7-cm-long fiber bench, with which accurate polarization adjustment can be easily achieved. The laser is pumped by a 1480-nm pigtailed InGaAsP semiconductor diode. The pump power can be continuously adjusted. The output of the laser is taken by a beam splitter and analyzed by an optical spectrum analyzer and a commercial optical autocorrelator.

The transmission coefficient of the setup or the laser cavity is[14]

$$T = \sin^2\theta \sin^2\varphi + \cos^2\theta \cos^2\varphi + \frac{1}{2}\sin 2\theta \sin 2\varphi \cos[\Delta\Phi_l + \Delta\Phi_{nl}], \qquad (1)$$

where θ and φ are the angles of the polarizer and analyzer orientation with respect to the fast axis of the fiber, respectively, and $\Delta\Phi_l$ and $\Delta\Phi_{nl}$ are the phase delays between the two orthogonal polarization components caused by the linear and nonlinear fiber birefringence, respectively. Man *et al.*[15] have shown that the linear cavity transmission of the laser is a sinusoidal function of $\Delta\Phi_l$ with a period of 2π. As will be shown below, the transmission coefficient plays an important role in deciding the features of the output pulse. It is worth noting that within one period of the linear cavity phase delay change, the laser cavity can provide positive feedback only in half of the period, and in the other half of the period, it actually has negative feedback.

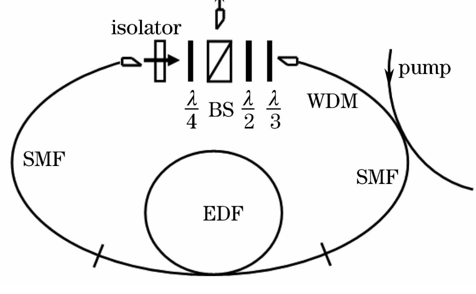

Fig. 1 Schematic of the dispersion management fiber laser setup. $\lambda/4$: quarter-wave plate; $\lambda/2$: half-wave plate; EDF: erbium-doped fiber; SMF: single mode fiber; BS: beam splitter; WDM: wavelength-division multiplexer.

3 Experimental results

Depending on the selection of the linear phase delay bias, the mode-locking pulses in the fiber lasers can be operated in the soliton mode or noise-like pulse mode. We present some of the typical experimental results for the purpose of better understanding of the characteristics of noise-like pulse in dispersion-managed fiber lasers. Soliton operation of the laser can be easily obtained by increasing the pump power above the self-start threshold, provided that the polarization controllers are appropriately set. When the linear cavity phase delay bias is small, further increasing the pump power will make the intensity of soliton reach a certain value and then do not increase any more because the pulse peak power is clamped by the cavity peak clamping effect[2,7]. As a result, new solitons could be generated one by one in the cavity. Because the solitons share the same laser gain, gain competition between them combined with the cavity feedback feature results the solitons having exactly identical pulse parameters in the steady state. This is the so called multiple-soliton generation and pulse-energy quantization[2]. However, when the linear cavity phase delay bias is larger, pulse will undergo collapse before they reach the peak power limitation. The collapsed low intensity pulses will be amplified again. After rounds of circulation, noise-like pulses are obtained[12].

Firstly consider the case in which the laser operation with large negative net cavity GVD. Initially, the cavity length is about 31 m, corresponding to a net cavity GVD of about $-0.525\ \mathrm{ps}^2$ at 1550 nm. Due to the large negative net cavity GVD, the maximal peak intensity of pulse is clamped and we cannot obtain the operation mode of noise-like pulse. We then gradually decrease the length of the SMF. When the cavity length is 18 m corresponding to a net dispersion of about $-0.219\ \mathrm{ps}^2$, noise-like pulses are obtained, just as those shown in Fig. 2 (a). We note that the 3 dB bandwidth is only about 8.10 nm. The autocorrelation trace of Fig.2(b) has a profile of narrow spike riding on a broad pedestal, which suggests that the actual mode-locked pulse consists of a series of coherent narrow random pulses[13]. When the net cavity GVD is larger negative, the maximal intensity is limited and the temporal width is broad, therefore, the effect of Raman scattering is nonsignificant.

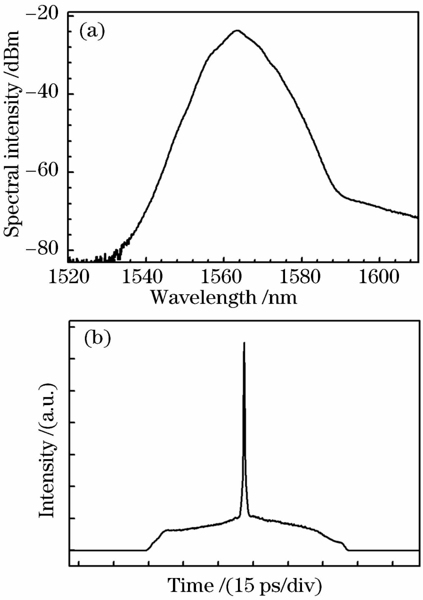

Fig.2 Optical spectrum (a) and autocorrelation trace (b) of noise-like pulse operation

The spectral bandwidth and pulse energy increase as the cavity length decreases gradually. This can be seen clearly form Fig.3 with the cavity length of 10.5 m. The maximal 3 dB spectral bandwidth of noise-like pulses is 55.9 nm. The obtained spectral bandwidth is much larger than the gain bandwidth of EDF and it is also larger than the bandwidth obtained in the soliton state. In addition, the peak intensity of the pulse is increased and the temporal width becomes narrow, hence the effect of Raman scattering is enhanced. The pronounced characteristic is that the intensity on the red components is stronger than that on the blue components. The autocorrelation trace has a profile similar to that shown in Fig. 2(b) due to the identical mechanism of noise-like pulse generation. However, the intensity of the pedestal is stronger and the width is narrower than that in Fig.2(b).

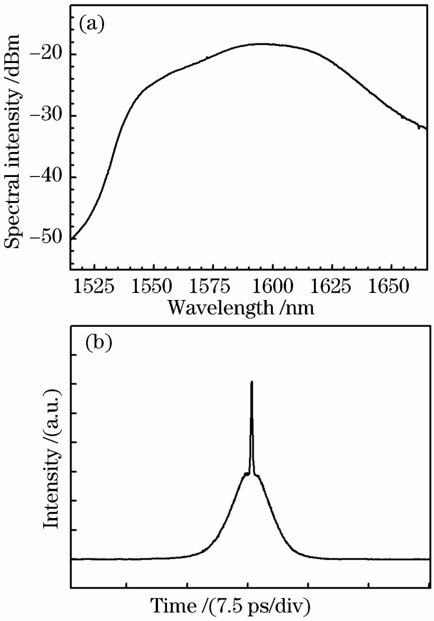

Fig.3 Typical optical spectrum (a) and autocorrelation trace (b) of noise-like pulse with the laser cavity length of 10.5 m

If the fiber laser cavity length continues to decrease, the features of mode-locking pulse will differ from that when the net GVD is large negative since the dispersion plays an important role. For the net cavity GVD is negative and close to zero, the sideband characteristic of soliton is eliminated and the spectra of mode-locking pulse have the typical characteristic of parabolic. We continue carefully to cut back the length of the SMF until that the net cavity GVD is near zero. At the same time, we find that noise-like pulses are easier to be obtained when the net GVD of laser cavity is small. If the state of soliton operation is obtained, the fiber lasers could be switched to the states of the noise-like pulse emission by simply rotating the orientations of the wave plate, which corresponds to the setting change of the linear cavity phase delay bias[2].

Consider the case in which the laser operation with slightly positive net cavity GVD and the cavity length of 7.6 m, corresponding to a net GVD of about $0.017\ \mathrm{ps}^2$. Pulse formation and evolution in the cavity become more complex as the net cavity GVD approaches zero. The characteristics of noise-like pulse spectrum in the small positive net cavity GVD are quite different to those of in the negative net cavity GVD. Figure 4 shows the noise-like pulse spectrum and autocorrelation trace. A noteworthy feature is that the spectrum of pulse is broadened extremely. Under this condition, the maximal 3 dB spectral bandwidth obtained is 66.6 nm. This is related to the narrow spike in the autocorrelation trace of Fig.4(b). It shows that the spike is about 194 fs. The other notable feature is that the spectrum is nearly symmetrical. In the negative net GVD case, the spectrum on the red side is enhanced by the effect of Raman scattering. However, in the positive net GVD case, the spectrum is symmetrical, which shows that the effect of Raman scattering is weakened. Moreover, the width of the pedestal in the autocorrelation trace attains its minimum.

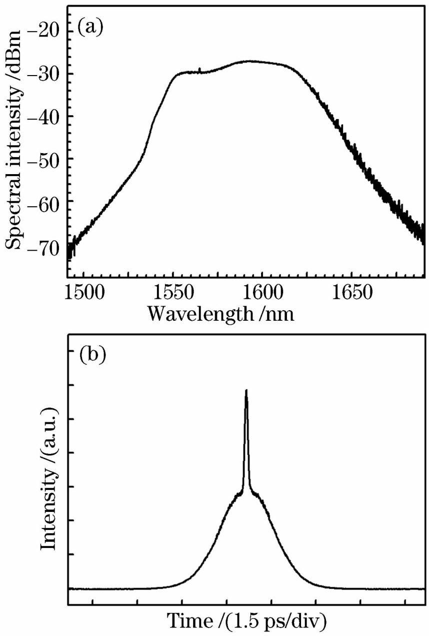

Fig.4 Noise-like Pulse spectrum (a) and autocorrelation trace (b) with the laser cavity length of 7.6 m

However, when the dispersion-managed fiber laser operation with large positive net cavity GVD, the cavity length is 6.6 m, corresponding to a net GVD of about 0.040 ps^2. Figure 5 shows that the 3 dB spectral bandwidth of the pulse is 60.65 nm. In order to decrease the potential effects of experimental error, we further decrease the length of SMF. When the cavity length is 4.87 m, corresponding to a net GVD of about 0.079 ps^2, the maximal spectral bandwidth of the noise-like pulse is only 13.6 nm. It suggests that when the net GVD of laser cavity in the positive regime increases, the spectral bandwidth of noise-like pulse will decrease. On the other hand, the spectrum is symmetrical due to that the effect of Raman scattering is nonsignificant.

Figure 5 shows the noise-like pulse spectral 3 dB width as a function of the net cavity GVD. From the figure, we can clearly see that as the amount of the SMF in the cavity is cut-back, the net cavity GVD and the spectral width increases. Moreover, when the net cavity GVD is slightly positive, the spectral width reaches its maximal value. When the net cavity GVD increases continually and further into the positive region, the spectral width begins to decrease. Our results indicate that the dependence of the obtained optical spectrum is similar to that obtained in the stretched-pulsed lasers. For example, the output spectral bandwidth of the stretched-pulsed lasers attains the maximum when the net dispersion is slightly positive[16]. In addition, our experimental results are indeed in good agreement with the numerically solving of the full nonlinear Schrödinger's equations in Ref. [10]. The reason why the dependence of the obtained optical spectrum on the net cavity GVD in Ref. [10] is somewhat different from the numerical simulation, is possible the use of polarization-maintaining fiber, which changes the dispersion properties of the two orthogonal axes. However, our laser cavity has only weak birefringence, which obviously rules out the possibility of this effect.

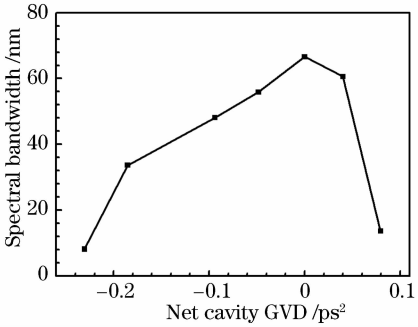

Fig.5 Output spectral width as a function of net cavity GVD

4 Conclusions

The generic characteristics of noise-like pulse in dispersion-managed fiber laser are experimentally investigated. Depending on the laser cavity design, various features can be obtained in the dispersion-managed fiber laser. When the net cavity GVD is large negative, the bandwidth is narrow. The effect of Raman scattering is not prominent due to the low intensity and broad temporal width. However, the spectral bandwidth will increase as the net cavity GVD increases and attains the maximum when the GVD is slightly positive. At the same time, the temporal width attain the minimum and the effect of Raman scattering is enhanced. When the net cavity GVD increases continually and further into the positive region, the spectral width begins to decrease and the effect of Raman scattering is weakened due to the positive dispersion. The various features of mode-locked pulse depend on the interaction and competition of cavity dispersion, fiber nonlinearity, and laser gain saturation.

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