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Pulse-train nonuniformity in an all-fiber ring laser passively mode-locked by nonlinear polarization rotation*

Luo Zhi-Chao(罗智超)[a], Xu Wen-Cheng (徐文成)[a)†], Song Chuang-Xing (宋创兴)[a)], Luo Ai-Ping (罗爱平)[a)‡], and Chen Wei-Cheng (陈伟成)[b)]

[a)] *Laboratory of Photonic Information Technology, School of Information & Optoelectronic Science and Engineering, South China Normal University, Guangzhou* 510006, *China*

[b)] *Department of Physics, Foshan University, Foshan* 528000, *China*

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This paper reports the periodic power variation of the pulse-train in a passively mode-locked soliton fiber ring laser. It can obtain either the uniform or nonuniform pulse-train output by simply rotating the polarization controllers. The experimental results show that the pulse-train nonuniformity is caused by the interaction between the nonuniform polarization states of the soliton pulses and the passive polarizer in the cavity.

Keywords: fiber laser, soliton, mode locking
PACC: 4255N, 4265S

1. Introduction

A passively mode-locked erbium-doped fiber laser as an ideal ultra-short optical pulses source plays an important role in the high capacity optical fiber communication system and has been intensively investigated.[1−7] Soliton generation of a fiber laser is one characteristic of the nonlinear pulse propagation under some suitable operation conditions in the laser cavity. A soliton pulse propagates in the fiber ring laser with undistorted pulse spectrum and shape by balancing the anomalous group-velocity dispersion and self-phase modulation (SPM). In a soliton fiber laser, although the soliton pulses circulating in the cavity periodically experience gain and loss, it is always deemed that the output pulses have the same intensity and profile, which we called the average soliton.[8] The optical pulses propagated in a birefringent fiber with a polarizer could result in the nonuniform intensity of pulses by utilizing an intensity-dependent polarization rotation.[9−11] In recent years, Kim *et al*[12] analyzed that the intensity and polarization of output pulse-train in a fiber laser could be periodic fluctuations. They have shown that the periodic fluctuations relied on the birefringence of the fiber and the passive polarizer in the cavity. Zhao *et al*[13] investigated the periodic intensity fluctuations of output pulse-train experimentally and theoretically. They obtained the output nonuniform pulses by appropriately adjusting the pump power. They found that it was difficult to suppress the pulse intensity fluctuations by changing the linear cavity phase delay. However, in our experiment we could obtain or suppress the output nonuniform pulse-train by simply rotating the polarization controllers which alters the linear cavity phase delay. This means that the change of the linear cavity phase delay disturbs the balance of the pulse energy loss through the polarizer and recovered by the erbium-doped fiber.

Although we could obtain the pulse-train nonuniformity by either appropriately adjusting the pump power or rotating the polarization controllers, in this paper we concentrate on only an experimental study of pulse-train intensity periodic fluctuations via changing the linear cavity phase delay in an all-fiber ring laser. Once the fiber laser operated in a mode-locking state, it emitted uniform soliton pulses at first, then we rotated the polarization controllers slightly, the fiber

*Project supported by the Natural Science Foundation of Guangdong Province, China (Grant No 04010397).
†Corresponding author. E-mail: xuwch@scnu.edu.cn
‡E-mail: luoaiping@scnu.edu.cn

laser began to emit nonuniform soliton pulses. Furthermore, an obvious change of soliton optical spectrum was the phenomenon that the subsideband appeared. Our experimental results show that the periodic intensity fluctuations in the output pulse-train is a consequence of the interaction between an unstable polarization state induced by the intensity-dependent refractive index and passive polarizer in the cavity.

2. Experimental setup and results

The experimental setup is illustrated in figure 1. The fiber laser has a ring cavity of about 18.3 m long and its fundamental repetition is 11.02 MHz. A 5 m long erbium-doped fiber with a dispersion parameter of $D \approx -15$ ps/nm/km and about 13.3 m single mode fiber with a dispersion parameter of $D = 17$ ps/nm/km comprise the ring cavity. Two polarization controllers are employed to adjust the polarization states of the pulses in the cavity. Unidirectional operation and polarization selectivity are provided by the polarization-dependent isolator. The passive polarizer in the isolator is regarded as an attenuator of the soliton pulse circulating in the cavity. The attenuation is decided by the offset between the polarization state of soliton pulse and the orientation of polarizer. To increase the nonlinear phase delay in a single cavity round trip, a 1% output coupler is used. Since any perturbation on a fiber could change the pulse polarization state, all the fibers are fastened to the optical table to prevent any movement. To study the uniform/nonuniform output pulses and soliton pulse spectrum, we set a radio frequency spectrum analyzer (RFSA) and an optical spectrum analyzer (OSA) behind the output coupler. An oscillograph is used to observe the pulse-train. We also measure the pulse duration by using a commercial autocorrelator. The soliton has a pulse duration of about 500 fs in our laser.

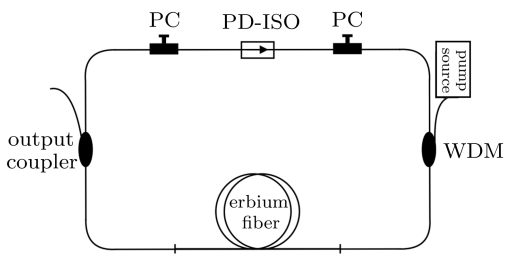


Fig.1. Schematic diagram of the fiber ring laser cavity. PC: polarization controller; PD-ISO: polarization-dependent isolator; WDM: wavelength division multiplexer.

The nonlinear polarization rotation technique was used to achieve the self-started mode-locking state of the fiber laser. The mode-locking threshold was ∼40 mW in our fiber laser. The soliton pulse circulating in the cavity periodically endures the gain provided by erbium-doped fiber and output loss. After each perturbation soliton pulses shed any excess energy into the so-called dispersive waves. The generation of sideband is well known as the dispersive waves which constructively interfere with the soliton pulses when the pulses propagate in the laser ring cavity. Although the spectral sidebands are symmetric in theory, they are generally asymmetric in the experimental observation due to the linear cavity loss of the fiber laser.[14] Increasing the pump power above the mode-locking threshold, we adjusted the polarization controllers properly such that the fiber laser achieved the mode-locking state. The mode-locked pulses could be observed in the oscillograph. Keeping the orientation of the polarization controllers, the self-started mode-locking operation could be attained again by simply increasing the pump power. We then selected an appropriate pump power and fixed it. By properly adjusting the orientation of the polarization controllers, we could easily observe either the output uniform or nonuniform soliton pulses. Correspondingly, there are two forms of soliton spectrum on the OSA: they are spectra with subsideband and without subsideband. The subsideband emission owing to the periodic power fluctuation has been demonstrated by Matera *et al* previously.[15]

Figure 2 shows the optical spectra measured under the conditions of setting different orientation of the polarization controllers. From figures 2(a) to 2(d), the polarization controllers were slightly rotated towards the unidirection, where $\Delta\alpha$ is equal to 0° in figure 2(a), 4° in figure 2(b), 10° in figure 2(c) and 20° in figure 2(d), respectively. The $\Delta\alpha$ is the rotational degrees of one polarization controller from which the fiber laser starts to output nonuniform pulse-train with all other cavity parameters fixed. In figure 2(a) the optical spectrum without subsideband corresponds to the output uniform soliton pulses, while the optical spectrum with subsideband generation corresponds to the output nonuniform soliton pulses. The intensity of CW presented in figures 2(a), 2(b), 2(c) and 2(d) in-

creases slightly. It is also shown that the subsideband intensity increases when the polarization controllers were rotated. As can be clearly seen from figure 2(d), the central wavelength of subsideband shifted from the sideband is 2.04 nm. However, the wavelength shifts of subsidebands changed slightly in the experiment.

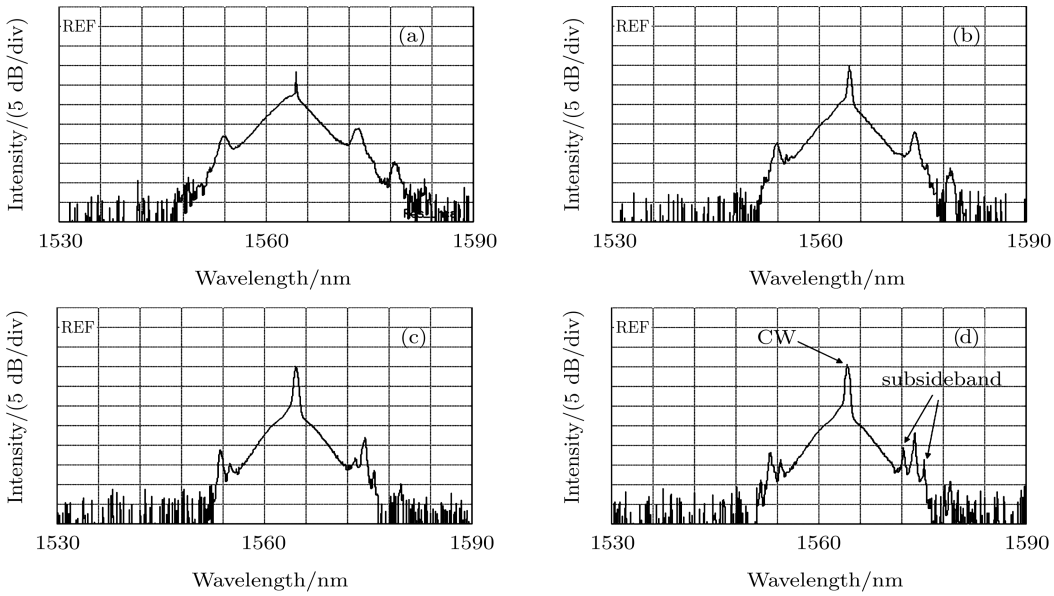
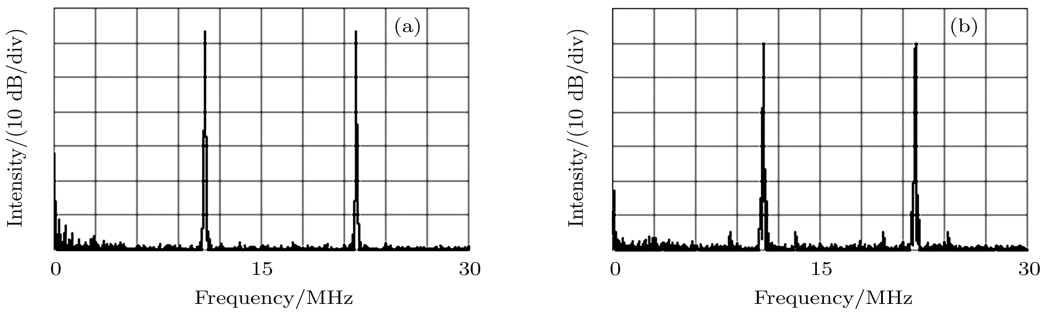


Fig.2. Experimental observation of optical spectra measured under different orientations of polarization controllers. From (a) to (d), $\Delta\alpha$ is equal to 0°, 4°, 10° and 20°, respectively.

Figure 3 illustrates the radio frequency (RF) spectra of the fiber laser corresponding to the four spectral states in figure 2. Figure 3(a) presents only the fundamental RF without any frequency sidebands on the RFSA, which is equal to the fundamental repetition frequency 11.02 MHz of the fiber laser. This indicates that the output pulse-train was uniform and its polarization state was stable at a fixed point in the laser cavity. With all other conditions fixed, we then did nothing except tuning the orientation of the polarization controllers. As a result, the linear cavity phase delay was changed. On the other hand, the polarization switching threshold changes which could lead to the nonuniform polarization states of the propagating pulses at a fixed point in the cavity. Provided that the polarization switching threshold is too low to support the uniform pulse, the pulse polarization is not a constant state at a fixed point in the laser cavity. If the pulse polarization state is nonuniform when it just arrives at the polarizer, the intensity of the soliton pulse is modulated by the passive polarizer. Figures 3(b), 3(c) and 3(d) show the modulation frequency of the pulse amplitude. The frequency sidebands were stable and symmetric on both sides of the main peak. However, the pulse-train shown on the oscillograph was unstable. It is mainly because the period of the power variation was not exactly equal to the multiples of the cavity round trips.



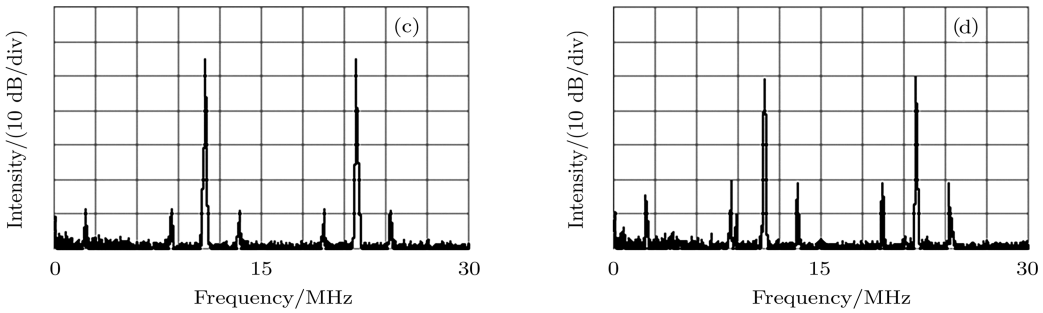


Fig.3. Correspondence of output RF spectra to the four states of optical spectrum in figure 2.

We can see clearly from figure 3 that the intensity of the main peak decreases when the frequency sidebands appear on the RFSA. The intensity of the main peak drops, this fact was due to the decreasing transmission rate of soliton pulses as we rotated the polarization controllers. We also found that the frequency between the main peak and the sideband is ∼2.7 MHz, this indicates that the soliton pulse periodically returns to its original intensity after about every four round trips in the laser cavity. The modulation frequency is invariable from figures 3(b) to 3(d), however, the modulation depth of pulse-train varies with $\Delta\alpha$. Figure 4 shows the modulation depth as a function of $\Delta\alpha$. We can see from figure 4 that the modulation depth increases monotonously with $\Delta\alpha$. It also shows that the modulation depth is directly proportional to the intensity of subsideband. In the experimental observation, when one polarization controller was fixed, the rotational range ($\Delta\alpha$) of the other one was wide and about 20° where the output pulses are nonuniform. Provided that we go on rotating one polarization controller towards the same direction while other cavity parameters are fixed, mode-locked pulse-train vanishes

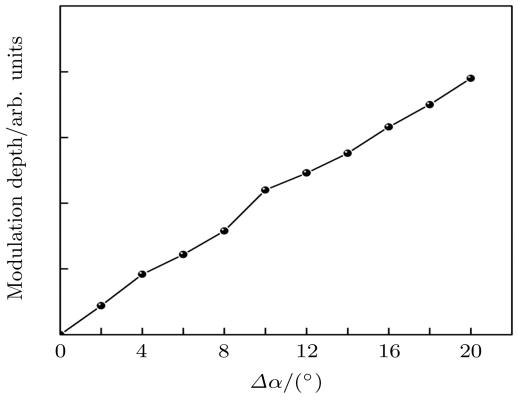


Fig.4. Modulation depth as a function of $\Delta\alpha$.

and the fiber laser is no longer mode locking. Nevertheless, if the polarization controllers were appropriately adjusted, we could always obtain either the output uniform or nonuniform pulse-train.

3. Analysis of pulse-train nonuniformity and discussion

The origin of the nonuniform polarization state is the intensity-dependent refractive index. The nonlinear rotation of the pulse polarization state generated by the Kerr nonlinearity of the birefringent fiber depends on the intensity of soliton pulse. Since the intensity of the soliton pulse is sufficiently strong, the nonlinear birefringence should be considered. The polarization of soliton pulses evolves nonlinearly because of the SPM- and XPM-induced phase shifts imposed on the orthogonally polarized components when they propagate along the birefringent fiber. If the pulse polarization state is no longer uniform at a fixed point, the amplitude of pulse is modulated by setting a polarizer behind the fixed point. It means that the interaction between the nonuniform polarization states of the soliton pulses and the polarizer could lead to output nonuniform pulse-train. Since the fiber laser has a ring structure, the fiber laser could be described as a length of birefringent fiber with two polarizers at both ends. In order to better explain the physical mechanism of pulse-train nonuniformity, we introduced a model[10] which is equivalent to fiber ring laser setup, as shown in figure 5.

The two polarizers illustrated in figure 5 correspond to the same passive polarizer in the laser cavity. Provided that a soliton pulse is launched into the system

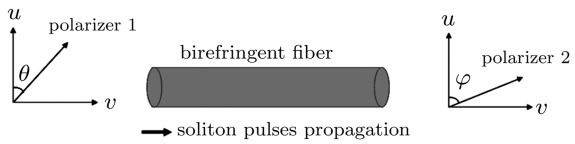


Fig.5. An equivalent setup for the fiber ring laser, which determines the intensity of pulse transmission in the laser cavity.

shown in figure 5, the initial soliton polarization state is forced into aligning with polarizer 1. Then the polarization state of pulse changes along the fiber from linear to elliptical due to the fiber birefringence. The angle between the fast axis (y) of the birefringent fiber and polarizer 1 is θ. The polarization state of the soliton pulse evolves nonlinearly in the birefringent fiber due to the cavity phase delay between the two orthogonal polarization components of the pulses. The total cavity phase delay consists of linear cavity phase delay and nonlinear cavity phase delay. The soliton pulse arrives at the passive polarizer after a round trip and the biased angle between the fast axis (y) of the birefringent fiber and the polarizer 2 is φ. The two orthogonal components of pulse interfere at the passive polarizer. The transmission coefficient of passive polarizer is

$$\begin{aligned} \Gamma \;=\; & \sin^2(\theta)\sin^2(\varphi) + \cos^2(\theta)\cos^2(\varphi) \\ & + \frac{1}{2}\sin(2\theta)\sin(2\varphi)\cos(\Phi_{\mathrm{l+nl}}), \end{aligned} \tag{1}$$

where the Φ_{l} is the linear cavity phase delay and the Φ_{nl} is the nonlinear cavity phase delay. Ideally, the total cavity phase delay is multiples of 2π. The pulse polarization state aligns with the polarizer at all times and the output pulse is uniform under this condition. This demonstrates that the pulse has a maximal transmission. Nevertheless, the output pulse-train can also be uniform, when the pulse polarization does not always align with the polarizer but has a fixed bias angle by balancing the pulse energy loss through the polarizer, this balance is recovered by the erbium-doped fiber. In this regime, the output pulse-train is uniform too.

In our experiment, we obtain the nonuniform pulses by changing the linear phase delay. The transmission coefficient has been changed. It disturbs the balance of pulse energy loss through the polarizer, this balance is recovered by the erbium-doped fiber. Since the nonlinear phase delay depends on the pulse intensity, the nonlinear phase delay has been changed when it is gained by the propagating pulse in a round trip. Of course, the pulse polarization state is not the original state after one round trip when it arrives at the polarizer. At the same time, the pulse polarization is forced into aligning with the polarizer. Therefore, the different polarization state when the pulse arrives at the polarizer experiences a different loss. As can be seen from equation (1), the transmission coefficient has a sinusoidal function of linear phase delay and nonlinear phase delay in the laser cavity. In order to more clearly explain the physical mechanism of pulse modulation, we show a schematic diagram of a pulse-train with 2.7 MHz modulation frequency in figure 6. The modulation is described as a sinusoidal function of nonlinear phase delay. The pulse-train has a repetition rate of 11.02 MHz. Figure 6(a) exhibits the pulses amplitude of different polarization states modulated by the polarizer. Figure 6(b) shows the frequency spectrum with sidebands due to the amplitude modulation in figure 6(a), which is well consistent with the experimental results.

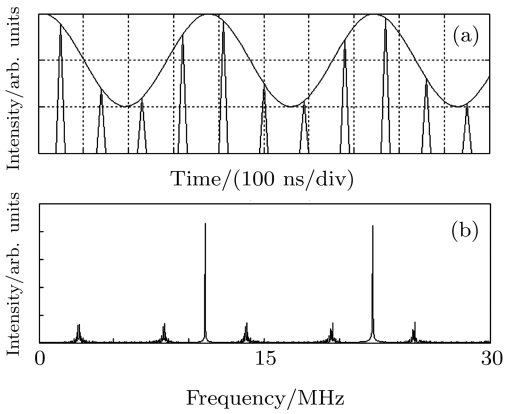


Fig.6. Schematic diagram of output nonuniform pulse-train. (a) Pulse-train modulated by a polarizer in time domain. (b) The frequency spectrum of (a) with frequency sidebands besides the repetition frequency due to amplitude modulation.

The process of pulse-train nonuniformity is dynamic. We assume that the laser emits uniform pulses at first. However, we alter the linear cavity phase delay via rotating the polarization controllers and the polarization switching threshold becomes lower. As a result, the pulse energy transmission through the polarizer gets stronger. Note that the action of polarizer on the soliton pulses is discrete. The circulating soliton pulse in the next round trip accumulates more nonlinear phase delay. The pulse polarization state changes when the pulse comes to the polarizer in the next round trip. The bias angle between the pulse polarization state and the polarizer becomes larger than

the offset of its original state. Then the pulse endures more loss at the polarizer. It results in the decrease of the pulse energy. In the next round trip, the pulse accumulates less nonlinear phase delay and the energy loss in the polarizer diminishes. This process continues until the polarization of the soliton pulse approximately realigns with its original polarization state. Then it repeats the process discussed above again and again. Consequently, the laser outputs the periodically nonuniform pulse-train. Nevertheless, the uniform pulse-train could be obtained again by rotating the polarization controllers in a contrary motion.

4. Conclusion

In conclusion, we have experimentally observed the pulse-train nonuniformity in a passively mode-locked fiber ring laser. The pulse-train nonuniformity is caused by the interaction of nonuniform polarization states caused by the intensity-dependent polarization rotation and the passive polarizer in the fiber ring laser cavity. The uniform or nonuniform pulse-train can be obtained by properly adjusting the polarization controllers. It is shown that a balance of gain and loss of the soliton pulse, such as the gain provided by erbium-doped fiber and loss at the polarizer, output coupler and fiber connector, can generate uniform pulse-train. We obtain nonuniform pulse-train by altering the linear phase delay which leads to the balance of gain and loss in the cavity being disturbed. In addition, the physical mechanism of pulse-train nonuniformity has also been analyzed and discussed.

References

[1] Tamura K, Ippen E P, Haus H A and Nelson L E 1993 *Opt. Lett.* **18** 1080

[2] Fermann M E, Andrejco M J, Silberberg Y and Weiner A M 1993 *Opt. Lett.* **18** 48

[3] Haus H A, Ippen E P and Tamura K 1994 *IEEE J. Quantum Electron.* **30** 200

[4] Liu D F, Chen G F and Wang X H 1999 *Sci. Chin.* (Series A) **29** 656

[5] Zhao W, Zhang W, Ma H Q, Liu C, Chen G F and Lu K Q 2007 *Chin. Phys.* **16** 1038

[6] Zhang S M, Lü F Y, Gong Y D and Yang X F 2007 *Chin. Phys.* **16** 1986

[7] Chen W C, Xu W C, Song F, Shen M C, Han D A and Chen L B 2008 *Eur. Phys. J.* D **48** 255

[8] Kelly S M J, Smith K, Blow K J and Doran K J 1991 *Opt. Lett.* **16** 1337

[9] Stolen R H, Botineau J and Ashkin A 1982 *Opt. Lett.* **7** 512

[10] Chen C J, Wai P K A and Menyuk C R 1992 *Opt. Lett.* **17** 417

[11] Horowitz M and Silberberg Y 1997 *Opt. Lett.* **22** 1760

[12] Kim A D, Kutz J N and Muraki D J 2000 *IEEE J. Quantum Electron.* **36** 465

[13] Zhao B, Tang D Y, Zhao L M and Shum P 2004 *Phys. Rev.* A **69** 043808

[14] Man W S, Tam H Y, Demokan M S, Wai P K A and Tang D Y 2000 *J. Opt. Soc. Am.* B **17** 28

[15] Matera F, Mecozzi A, Romagnoli M and Settembre M 1993 *Opt. Lett.* **18** 1499