Pulse-train nonuniformity in a fiber soliton ring laser mode-locked by using the nonlinear polarization rotation technique

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We report on the experimental observation of periodical intensity fluctuations on the output of a fiber soliton ring laser passively mode-locked by using the nonlinear polarization rotation technique. It is found that the appearance of such intensity fluctuations is independent of the orientation of the polarizer in the cavity, but closely related to the pump intensity. We have also numerically simulated the pulse dynamics of the laser. Our numerical simulations confirmed the experimental observations and showed that the soliton pulse nonuniformity is caused by the interaction between the nonlinear polarization rotation and the polarizer in the cavity.

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I. INTRODUCTION

Nonlinear polarization rotation (NPR) technique has been widely used to passively mode-lock the erbium-doped fiber lasers to generate ultrashort pulses [1–4]. The principle of the technique is quite simple. When a linearly polarized light is incident on a piece of weakly birefringent fiber, the polarization of the light will generally become elliptically polarized in the fiber. The orientation and ellipticity of the final light polarization is fully determined by the fiber length and its birefringence. However, if the intensity of the light is strong, the nonlinear optical Kerr effect in the fiber must be considered, which introduces extra changes to the light polarization [5,6]. As the polarization change introduced by the optical Kerr effect depends on the light intensity, if a polarizer is put behind the fiber, the light intensity transmission through the polarizer will become light intensity dependent. By appropriately selecting the orientation of the polarizer or the length of the fiber, an artificial saturable absorber effect with ultrafast response could then be achieved in such a system, where light of higher intensity experiences less absorption loss on the polarizer. The NPR technique makes use of this artificial saturable absorption to achieve the passive mode-locking in a fiber laser. Once a mode-locked pulse is formed, the nonlinearity of the fiber further shapes the pulse into an optical soliton and consequently the ultrashort soliton operation is obtained in the laser. Soliton operation is almost a generic feature of the fiber lasers mode-locked by this technique and has been intensively investigated [7–13]. Conventionally, the soliton operation of the fiber lasers is modeled by the extended nonlinear Schrödinger equation or the complex Ginzburg-Landau equation, and the formed solitons have a sech-form intensity profile. Although in a fiber laser due to the influence of the laser gain and output, a pulse circulating in the cavity periodically changes its intensity, it was theoretically demonstrated that at a fixed position in the cavity the pulse has a fixed pulse profile and pulse intensity, which is invariant of the time, namely, a soliton. This property of solitons formed in the fiber laser is known as the

average soliton [12]. Suggested by the average soliton theory of the laser, it was generally believed that the output of the lasers is uniform soliton pulses. Until very recently, Kim *et al.* theoretically analyzed the pulse dynamics of the lasers passively mode-locked by using the NPR technique [10,11]. They found that due to the interaction between the nonlinear polarization rotation and the passive polarizer inside the cavity, there exists an intrinsic intensity fluctuation of the output soliton pulses unless the polarizer is aligned with either the slow or the fast axis of the fiber. To our knowledge, so far this theoretical prediction has not been experimentally confirmed. In addition, we noticed that for the sake of simplicity, in their analysis Kim *et al.* have ignored the effect of resonant sideband generation of solitons in the laser. But in practice this effect always exists and significantly affects the properties of the solitons [14,15]. So to what extent their theoretical prediction describes the real soliton pulse dynamics in the lasers needs to be further studied.

In this paper we present the experimental observation of a kind of periodic soliton intensity variation in a passively mode-locked fiber soliton laser using the NPR technique. Our experimental results showed that the nonuniformity of the output pulses is another intrinsic feature of the laser, whose appearance is independent of the orientation of the polarizer in the cavity but closely related to the pump strength. With exactly the same polarizer orientation either stable uniform or strongly nonuniform soliton pulse output can be experimentally obtained by simply adjusting the pump power. To understand our experimental observations, we have further numerically simulated the soliton dynamics in our laser based on the coupled, extended, nonlinear Schrödinger equations. In particular, we have taken into account the effect of the resonant sideband generation of solitons in our simulations. Our numerical simulations have excellently reproduced all the details of the experimental results. Both of our experimental studies and numerical simulations suggested that the observed soliton pulse nonuniformity is a result of the interaction between the nonlinear polarization rotation of the soliton pulses and the passive
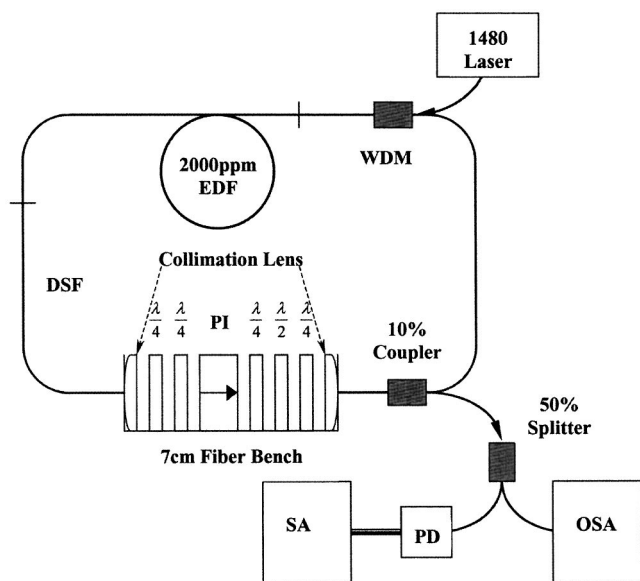
FIG. 1. A schematic of the experimental setup. $\lambda/4$, quarter-wave plate; $\lambda/2$, half-wave plate; PI, polarization-dependent isolator; WDM, wavelength division multiplexer; EDF, erbium-doped fiber; DSF, dispersion-shifted fiber; PD, photodetector; SA, spectrum analyzer; OSA, optical spectrum analyzer.

polarizer in the cavity, which is indeed an intrinsic feature of the fiber soliton laser.

II. EXPERIMENTAL RESULTS

Our experimental setup is shown in Fig. 1. The fiber laser has a ring cavity of about 5.5 m long. The cavity comprises a 3.5 m long 2000 ppm erbium-doped fiber with a group-velocity dispersion of about 10 ps/nm km, a piece of 1 m long single mode dispersion-shifted fiber, whose group-velocity dispersion is 2 ps/nm km and a piece of 1 m long standard single-mode fiber (SMF28). The nonlinear polarization rotation technique is used to achieve the self-started mode-locking in the laser. To this end a polarization-dependent isolator together with two polarization controllers is used to adjust the polarization of light in the cavity. The polarization-dependent isolator and the polarization controllers are mounted on a 7 cm long fiber bench to achieve accurate polarization adjustments. The laser is pumped by a pigtailed $In_xGaAs_{1-x}P$ semiconductor diode of wavelength 1480 nm. The output of the fiber laser is taken via a 10% fiber coupler and analyzed with an optical spectrum analyzer. A 10 GHz rf spectrum analyzer together with a 7 GHz photodetector is used to simultaneously monitor the intensity spectrum of the laser output. A commercial optical autocorrelator has also been used to measure the pulse width of the soliton pulses.

Provided that the orientations of the waveplates are appropriately set, soliton operation of the laser can be automatically obtained by increasing the pump power above the mode-locking threshold. As far as the artificial saturable absorber effect is attained, the soliton operation can be obtained in a wide range of the laser parameters, such as different

pump strength, different linear light polarization rotation bias, and orientations of the passive polarizer in the cavity. Depending on the pumping strength, multiple solitons can also coexist in the laser cavity. Due to the internal energy balance of each soliton, all the solitons have exactly the same properties: the same pulse width and pulse energy. This property was known as the soliton energy quantization effect [16]. In our laser the soliton has a pulse width (full width at half maximum) of about 340 fs.

A special property of the solitons formed in the laser is the sideband emission [15]. Since a soliton circulating in the cavity periodically experiences the laser gain and the output loss, its energy varies periodically, which results in that the soliton resonantly transfers its energy into dispersive waves of specific wavelengths. As an example Fig. 2 shows some typical soliton spectra observed in our laser, where the generated sidebands are clearly seen. The strength of the experimentally observed sidebands is normally asymmetric, which is a result of the asymmetric linear cavity loss of the laser [13]. The sideband emission resonantly drains away the soliton energy, which imposes another loss mechanism to the soliton. Gordon has theoretically studied the resonant interaction between a soliton and its sidebands [17]. He found that the energy flowing from the soliton to a sideband is proportional to the spectral intensity of the soliton at the sideband position. In order for a soliton to be stable in the cavity, apart from balancing the laser cavity losses, the laser gain must also balance the sideband emission loss. Therefore, changing the gain of the laser will change the soliton parameters such as the soliton pulse width and peak power, and ultimately this change is reflected on the variation of the sideband strength of the soliton. In a laser, a soliton with stronger sidebands has narrower pulse width and higher peak power. To explain this we note that a narrower soliton pulse means a broader spectral bandwidth, while the sideband positions on the soliton spectrum are fixed; based on Gordon's analysis it further means that more soliton energy will be transferred to the sidebands. Thus in the steady state, higher gain is required to maintain the soliton operation.

Experimentally we have investigated the uniformity of the soliton output of our laser by simultaneously monitoring the optical spectra of the solitons with an optical spectrum analyzer and the rf spectra of the laser output with a rf spectrum analyzer. Experimentally we found that independent of the orientation of the passive polarizer in the cavity and the linear light polarization rotation bias, we can always obtain either stable uniform or nonuniform soliton pulse output by changing the pump strength. For example, Fig. 2 shows the respective soliton spectra of our laser as the pump power is slightly increased from 97 mW in (a) to 100 mW in (b), 105 mW in (c), and 115 mW in (d). Associated with the pump power increase, the spectral strength of the dispersive waves increases from (a) to (d). Figure 3 presents the rf spectra of the laser output corresponding to the four states in Fig. 2, respectively. In the rf spectra only the fundamental rf component is displayed, which corresponds to the cavity repetition rate of 37.8 MHz. Except the pump power, all the other experimental parameters were fixed in obtaining the figures. Figure 2 shows that as the pump power is increased,
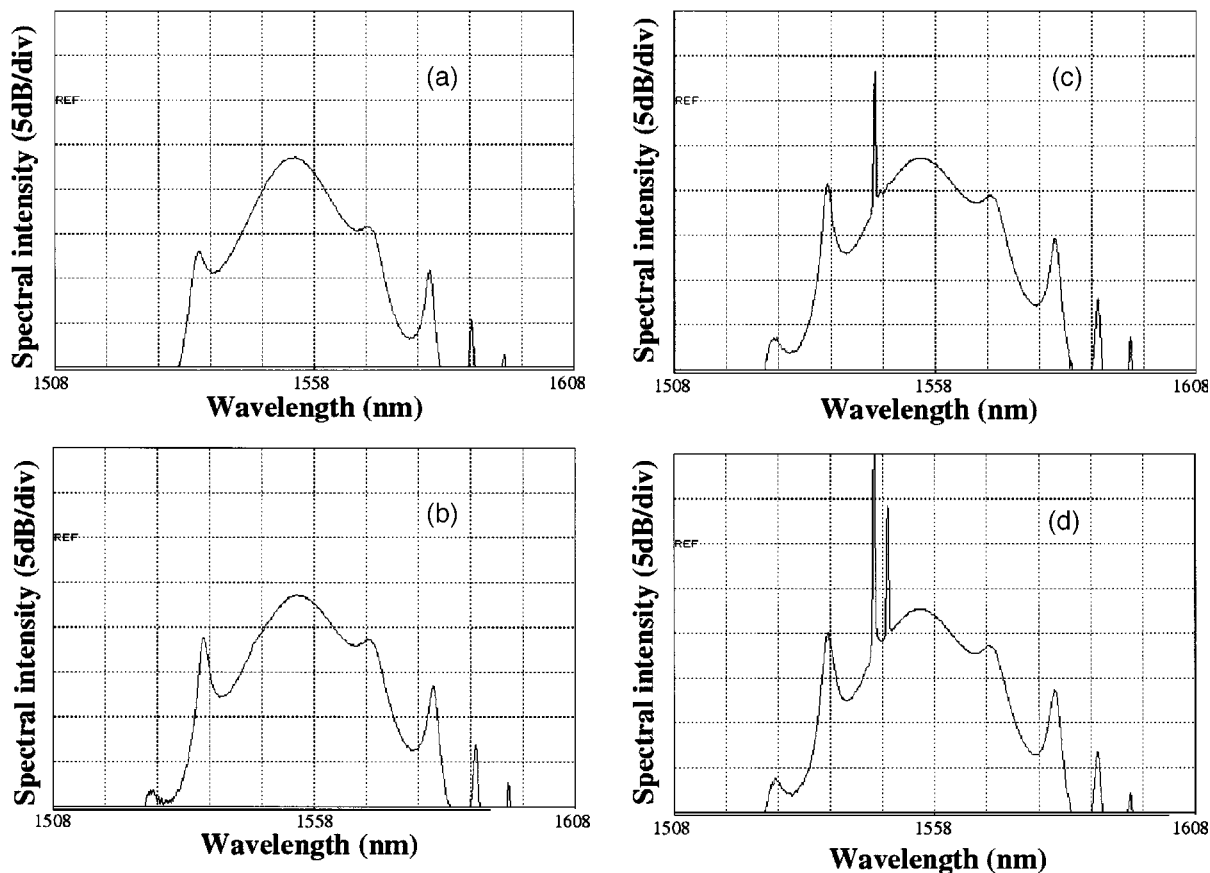
FIG. 2. Experimentally measured soliton spectra of the laser under different pump levels. From (a) to (d), the pump power is 97 mW, 100 mW, 105 mW and 115 mW, respectively.

the sideband strength also increases slightly. When the pump power is too strong, even the cw emissions had also appeared in our experiment as shown in Figs. 2(c) and 2(d). However, the cw components did not affect the soliton dynamics. From Fig. 3 we see that when the sidebands are weak, correspondingly, the soliton peak power is weak, there is only one peak located at 37.8 MHz in the rf spectrum of Fig. 3(a), which indicates that the laser has very uniform soliton output under the condition. However, as the pump power is increased to a certain level that depends on the settings of the wave plates in our experiment, two symmetric frequency sidebands appeared beside the main fundamental peak in Fig. 3(b), showing that the output soliton pulses are no longer uniform, but endure a periodic amplitude modulation. The modulation frequency is about 2.1 MHz, which is the frequency difference between the sidebands and the 37.8 MHz main peak. This modulation frequency corresponds to a period of 18 round trips. Slightly increasing the pump power further, we found that the modulation strength increases, as shown in Fig. 3(c), and even the harmonic sidebands appear as in Fig. 3(d). Increasing pump power the modulation frequency increases slightly as well. The modulation frequency in Fig. 3(c) is 2.5 MHz, corresponding to a period of 15 round trips, and the modulation frequency in Fig. 3(d) is 2.7 MHz, corresponding to a period of 14 round trips. Experimentally we found that independent of the orientation of the polarizer, as long as the pump power is appropriately adjusted, we can always obtain stable uniform soliton output. On the contrary, with all the other conditions fixed, when we increase the pump power the output pulses always become nonuniform, exhibiting a periodic-kind pulse amplitude variation.

III. NUMERICAL SIMULATIONS

To get an insight into the physical mechanism of the observed soliton pulse nonuniformity, we further conducted numerical simulations to study the soliton dynamics in our laser. Again our simulations are based on the coupled complex nonlinear Schrödinger equations describing the optical pulse propagation in weakly birefringent fibers:

$$\frac{\partial u}{\partial z} = i\beta v - \delta\frac{\partial v}{\partial t} - \frac{i}{2}\kappa''\frac{\partial^2 u}{\partial t^2} + i\gamma(|u|^2 + 2|v|^2)u$$
$$+ \frac{i\gamma}{3}v^2 u^* + \frac{g}{2}u + \frac{g}{2\Omega_g^2}\frac{\partial^2 u}{\partial t^2},$$

$$\frac{\partial v}{\partial z} = -i\beta u + \delta\frac{\partial u}{\partial t} - \frac{i}{2}\kappa''\frac{\partial^2 v}{\partial t^2} + i\gamma(2|u|^2 + |v|^2)v$$
$$+ \frac{i\gamma}{3}u^2 v^* + \frac{g}{2}v + \frac{g}{2\Omega_g^2}\frac{\partial^2 v}{\partial t^2},$$

(1)

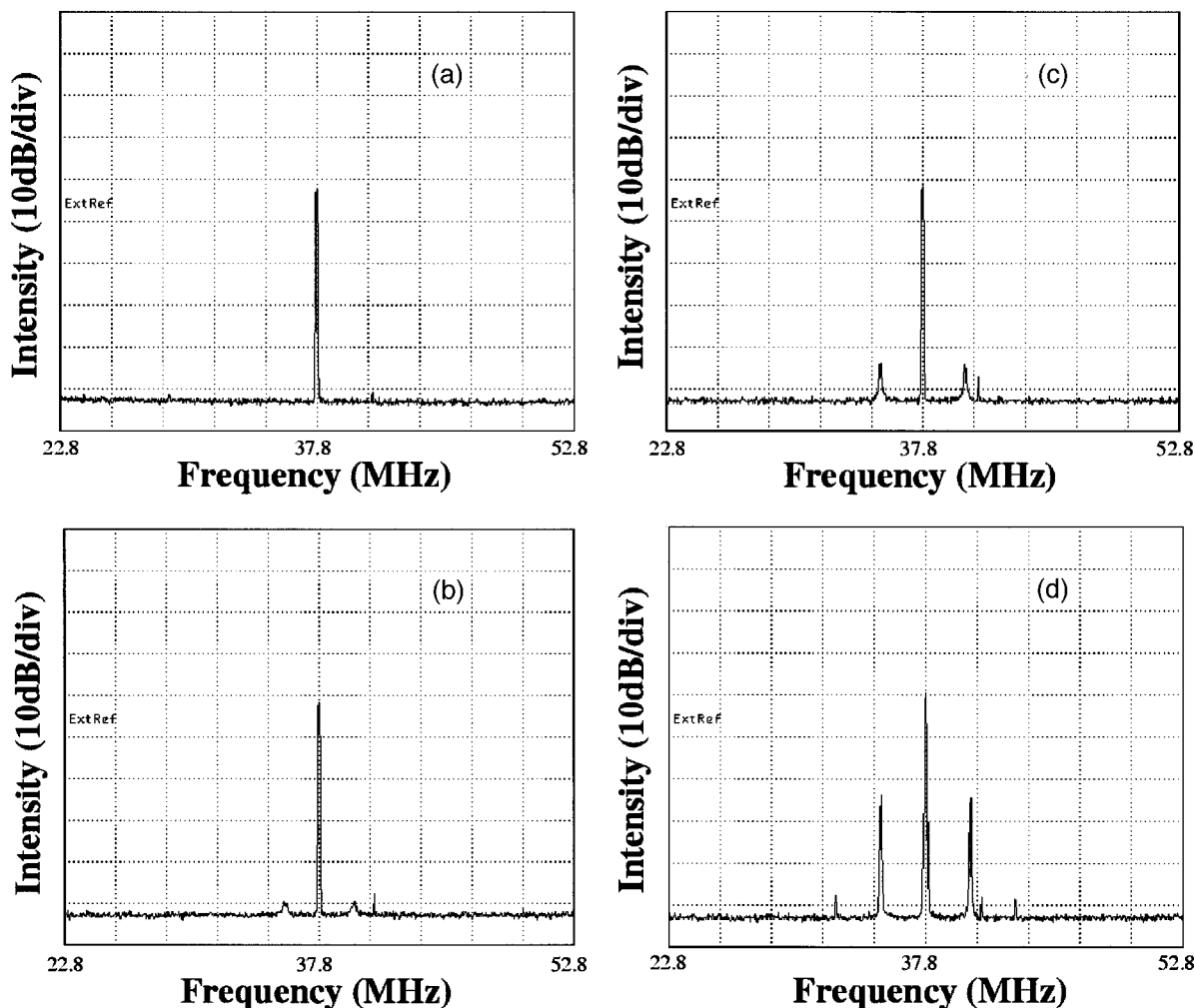where u and v are the two normalized slowly varying pulse

FIG. 3. rf spectra of the laser output corresponding, respectively, to the soliton operation states shown in Fig. 2.

envelopes along the slow and the fast axes of the optical fiber, respectively. $2\beta = 2\pi\Delta n/\lambda$ is the wave-number difference and $2\delta = 2\beta\lambda/2\pi c$ is the inverse group-velocity difference. κ'' is the dispersion parameter and γ is the nonlinearity of the fiber. g is the gain coefficient for EDF and Ω_g is the gain bandwidth.

The gain saturation is described by

$$g = g_0 \left/ \left[1 + \frac{\int (|u|^2 + |v|^2)dt}{E_s} \right], \right. \tag{2}$$

where g_0 is the small signal gain and E_s is the saturation energy. Whether the laser gain subjects to saturation depends on the total light energy in the laser cavity. For an undoped fiber, g is zero.

In the frequency domain, g has a spectral profile of

$$g(\omega) = g_p \left[1 - \left(\frac{\omega - \omega_0}{\Omega_g} \right)^2 \right], \tag{3}$$

where g_p is the peak gain and ω_0 is the peak gain frequency.

In accordance with our experimental condition we have used the following parameters for our simulations: $\gamma = 3$ W^{-1} km^{-1}, $\kappa'' = 2$ ps/nm km (for dispersion shifted fi-ber), $\kappa'' = 10$ ps/nm km (for erbium-doped fiber), $\kappa'' = 18$ ps/nm km (for standard single-mode fiber), $\Omega_g = 2\pi \times 10$ THz, gain saturation intensity $E_s = 120$, cavity length $L = 6$ m, beat length $L_b = L/4$, passive polarizer orientation to the fiber fast birefringent axis $\psi = 0.152\ \pi$, and linear polarization rotation phase bias $\varphi = 1.4\pi$.

A fundamental difference of our numerical model to those used by other groups is that we did not make the so-called master-equation simplification [18]. Therefore, there is no limitation on the action of cavity components to the soliton pulse when it circulates in the cavity. As in a practical fiber soliton laser, although after one round trip the overall pulse change may be small, the pulse change caused by a specific cavity component could still be very big. We have used a pulse tracing technique in our numerical simulations; namely, we start a numerical calculation with an arbitrary weak noise light and let it circulate in the cavity. According to our laser cavity configuration, within one round trip the noise light beam will first propagate in the three pieces of fibers with different group-velocity dispersions, where the light propagation is described by Eq. (1). Then it will pass through the polarization controllers and the polarization-dependent isolator. We modeled the action of the polarization controllers and the isolator by their corresponding transfor-

mation matrices. After one round trip of propagation in the cavity, the final state of the light is then used as the starting state for the next round of calculation. This process repeats until a stable state of light pulse is obtained. With this pulse tracing technique we have explicitly taken into account the effect of nonlinear coupling between the two orthogonal polarization components of the light in a birefringent fiber. The frequency-dependent linear cavity loss, and the nonlinear saturable absorber effect introduced by the combined effect of the nonlinear light polarization rotation and the passive polarizer, is also automatically included in the calculation. In addition, since every next round of numerical calculation starts with the calculation result of the previous round as the initial condition, effects of periodic gain and loss perturbation on the soliton pulses are also included. Furthermore, as in the numerical simulations apart from the optical pulse the dispersive waves within a calculation window are also traced, the effect of the resonant sideband emission by the soliton is then taken into account.

By properly setting the linear cavity phase bias, which corresponds in the experiment to appropriately selecting the orientations of the wave plates so as to ensure the laser is operating in the positive-feedback regime, soliton operation can be always obtained in the simulation. The exact soliton parameters, such as the pulse width and peak power, are determined by the laser parameter settings. However, in all our simulations we found that when the value of the gain is so selected that the generated soliton pulse peak power is weaker than that of the polarization switching power of the laser, we can always obtain the ideally uniform soliton pulse train as shown in Fig. 4(a). Figure 4(d) is the corresponding spectrum of Fig. 4(a). In this case the soliton pulses are very stable and uniform from round to round. In our simulations the orientation of the passive polarizer is not aligned with the principal axes of the optical fiber. But obviously we could still obtain stable uniform soliton pulse output from the laser. This result is very different from theoretical predictions of Kim *et al*. We have also checked laser output under different polarizer orientations; similar results have been observed. However, independent of the polarizer orientation and the linear cavity light polarization rotation bias, if the gain is set so large that the soliton peak power becomes larger than the polarization switching power, periodiclike amplitude variations always appear on the output soliton pulses as shown in Fig. 4(b). This can be more obviously observed on its corresponding spectrum shown in Fig. 4(e). The strength of the soliton sidebands changes with a period of around 20 round trips, showing that the amplitudes of the output soliton pulses are no longer uniform, but vary periodically. If the gain is further increased, the strength of the pulse intensity variation increases, and the modulation period reduces as shown in Fig. 4(c) and its corresponding spectrum, Fig. 4(f). In this case the amplitude modulation becomes quasiperiodic, as indicated by the appearance of the harmonic sidebands in the experiment as shown in Fig. 3(d). We note that only the gain parameter, which experimentally corresponds to the pump power, is increased in the calculation conditions of Fig. 4. We showed that by increasing the gain parameter, the strength of the sidebands increases and periodical intensity fluctuations are then observed, which is qualitatively

consistent with the experimental results. However, we noted that due to the average effect of the experimentally recorded optical spectra, the periodical change of the sideband strength could not be observed on the optical spectra recorded in the experiment. We could only observe the slight increase of the sideband strength as the pump power is increased in the experiment as shown in Fig. 2. Our numerical simulations reproduce well details of our experimental observations, which demonstrated that the observed periodic soliton pulse intensity fluctuation is indeed an intrinsic feature of the fiber soliton lasers.

IV. MECHANISM OF PULSE NONUNIFORMITY

We further investigated the physical origin of the observed soliton pulse nonuniformity based on our experimental results and numerical simulations. We found that it could still be explained as a result of interaction between the nonlinear polarization rotation of the soliton pulse and the polarizer in the cavity. We know that the laser is mode-locked by using the nonlinear polarization rotation effect. Through the combined action of the nonlinear light polarization rotation and a passive polarizer in the cavity, an artificial saturable absorption effect is generated in the laser, which results in the mode-locking of the laser and further stabilizes the solitons once they are formed. However, we should also bear in mind that the nonlinear polarization rotation is pulse peak power dependent. The latter is further related to the laser gain. Chen *et al*. have analytically derived the cavity transmission of such lasers [19]. With a fixed linear light polarization rotation bias, the actual cavity transmission is a sinusoidal function of the nonlinear light polarization rotation. This means that even when the laser cavity is initially biased to the positive feedback regime, if the pump power is so strong that the soliton peak power becomes too high, the nonlinear polarization rotation could drive the laser cavity transmission from the positive feedback regime to the negative feedback regime. This means when the soliton peak power increases beyond a certain value, which is determined by the linear cavity polarization rotation phase bias, it will then experience negative feedback. It is this negative feedback effect that makes the soliton pulse intensity in the laser to vary periodically. This process could also be understood phenomenally. Ideally the nonlinear polarization rotation should bias the polarization of the soliton pulse in such a way that when the soliton arrives at the position of the polarizer, its polarization is aligned with the polarizer. In this case the soliton will experience a positive feedback, and the soliton is stabilized in the cavity. However, if the laser gain is too strong, the pulse peak power could become too high and a big amount of nonlinear polarization rotation could be accumulated before it reaches the polarizer. Since the action of the polarizer on the soliton is discrete, in this case the nonlinear polarization rotation will bias over the polarization of the soliton such that it becomes no longer aligned with the polarizer, and thus the soliton pulse will endure loss and gradually will lose its energy every time it passes through the polarizer. This process will continue until the polarization of the soliton becomes realigned with the polarizer. Then start-
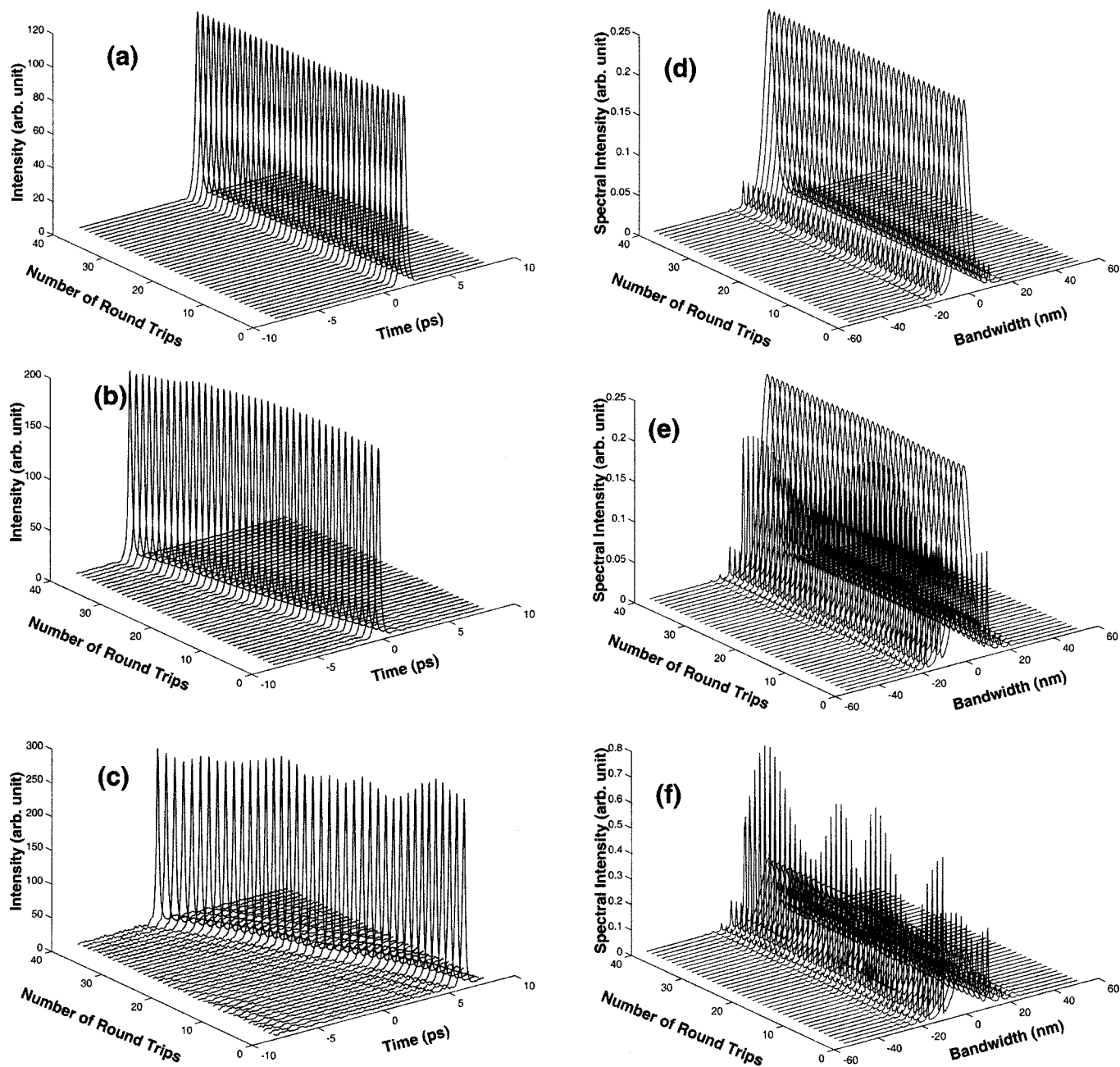
FIG. 4. Soliton pulses and the corresponding optical spectra numerically calculated under different pump strength. (a) and (d) Case of stable soliton operation, $g=300$; (b) and (e) case of periodic soliton intensity fluctuation, $g=360$; (c) and (f) case of strong soliton intensity fluctuation, $g=450$. All the other parameters are fixed.

ing from this point, the pulse peak power will increase again and the process repeats. Therefore, a periodiclike pulse peak power variation is obtained.

Based on the mechanism we discussed above, it is possible to see that to suppress the periodical intensity fluctuations, one needs to reduce the pump power with all the other conditions fixed so that the peak power of the solitons is below the polarization switching threshold. On the other side, as the polarization switching threshold is related to the linear polarization bias in the cavity, with a fixed pump power, one can also suppress the pulse nonuniformity by

appropriately adjusting the linear polarization bias to a position where the polarization switching power is higher. In this case as long as we increase the pump power, the pulse nonuniformity will always appear again. These two methods have been proved both feasible in our simulations. However, in practical experiment, since the accuracy of adjusting the linear polarization bias by rotating the wave plates is limited, and also the cavity operation is much more sensitive to the polarization change than to the pump power, it is very difficult to suppress the pulse intensity fluctuation by adjusting the linear polarization bias.

V. CONCLUSION

In conclusion, we have experimentally observed a periodic amplitude variation of the soliton pulses from a passively mode-locked fiber soliton laser, mode-locked by the nonlinear polarization rotation technique. Experimentally this periodic intensity fluctuation can be eliminated by appropriately reducing the pump power. We have also numerically simulated the laser operation and confirmed the experimental observations. Both of our experimental results and the numerical simulations suggested that the soliton pulse nonuniformity is caused by the interaction of the nonlinear soliton pulse polarization rotation and the passive polarizer in the cavity. When the peak intensity of the soliton pulse is too high, the generated nonlinear polarization rotation can bias over the polarization switching point, and consequently drive the laser cavity from the positive feedback regime to the negative feedback regime, which consequently causes the amplitude of the soliton pulses to periodically vary.

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