# Interaction of a parabolic-shaped pulse pair in a passively mode-locked Yb-doped fiber laser*

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We numerically investigate the formation and interaction of a parabolic-shaped pulse pair in a passively mode-locked Yb-doped fiber laser. Based on a lumped model, the parabolic-shaped pulse pair is obtained by controlling the inter-cavity average dispersion and gain saturation energy, Moreover, pulse repulsive and attractive motion are also achieved with different pulse separations. Simulation results show that the phase shift plays an important role in pulse interaction, and the interaction is determined by the inter-cavity average dispersion and gain saturation energy, i.e., the strength of the interaction is proportional to the gain saturation energy, a stronger gain saturation energy will result in a higher interaction intensity. On the contrary, the increase of the inter-cavity dispersion will counterbalance some interaction force. The results also show that the interaction of a parabolic-shaped pulse pair has a larger interaction distance compared to conventional solitons.

**Keywords:** passively mode-locked fiber laser, parabolic-shaped pulse pair, pulses interaction

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## 1. Introduction

Passively mode-locked fiber lasers that generate multiple solitons have always been investigated when the pump power exceeds a certain threshold.[1–6] Extensive experimental and theoretical studies have shown that the multiple solitons state is an intrinsic character of passively mode-locked fiber lasers. This character makes them good candidates for optical sources in high rate transmission optical communications. Depending on different operation regimes, three types of multiple solitons states would be generated in a laser cavity referred to as soliton bunching, harmonic mode locking (PML) and the bound state of solitons (BSs).[3] The bound state of solitons attracts a great deal of interest for their ability to tolerant perturbation and keeps equilibrium separation, and the formation of a bound soliton is verified as a result of the direct interaction between solitons.[4]

However, soliton interaction is also a major problem in limiting high speed data transmission when solitons evolve in optical fibers, since it would result in collision or separation between neighboring solitons and destroy the transferred information. Interaction forces among solitons were first theoretically studied by Gordon,[7] he pointed out that the strength of the forces is a function of the soliton separation distance and the relative phase difference between the solitons determine either attractive or repulsive interactions. Mitschke and Mollenaue experimentally verified the interaction soon after.[8] Recently, various numerically simulated and experimentally observed studies on multipulse interaction in a PML laser were reported.[1,9–16] Tang *et al*. has proved that the soliton interaction in a nonlinear polarization rotation (NPR) passively mode-locked fiber laser is the consequence of the dispersive waves or the continuous-wave components.[1] Liu has argued that the dispersion-induced phase shift plays a key role in the relative motion of solitons in a PML laser operating in the anomalous dispersion regimes using the NPR technique.[11,12] He has also investigated the generation and propagation of robust bound state pulses emitted from a passively mode-locked figure-eight laser with net-anomalous dispersion.[13] Ou-Yang *et al.* numerically studied the bound states of dark soliton formation and motion in a nonlocal media.[14] Moreover, the solitons interaction in the fiber laser with newly developed mode-locking materials, such as a graphene-based ultrafast mode locker, has also been experimentally investigated.[15,16]

Bound states of solitons have been observed in a passively mode-locked fiber laser with various types of mode-locking mechanisms, such as the traditional soliton and dispersion managed soliton regimes,[1–5,17] the self-similarly evolving pulse and the all-normal-dispersion regimes.[6,18] Aiming to improve the single soliton energy, researchers have put forward a passively mode-locked Yb-doped fiber laser working in a wave-break-free regime which supports a parabolic-shaped pulse. In our early work,[6] we have noticed that bound soliton

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pairs are attainable under certain initial conditions in this kind of laser. However, few attempts have been made on the interaction of parabolic-shaped pulse pair. In this paper, we further report on the theoretical study of a parabolic-shaped pulse interaction in a net-normal dispersion Yb-fiber laser mode-locking with a fast saturable absorber. In addition, the interaction mechanism in the cavity is also revealed.

## 2. Model

The cavity design of the passively mode-locked Yb-doped all-fiber laser is illustrated in Fig. 1. The cavity consists of a 0.25-m-long doped fiber, a 5-m-long single mode fiber (SMF), a length variable dispersion compensation (DC) fiber, a saturable absorber (SA), and an output coupler (OC). To analyse its operation, the laser is numerically simulated as a lumped model. This model treats the oscillator cavity as a concatenation of some separated elements and optical pulses circulating in the laser cavity will pass through them successively.

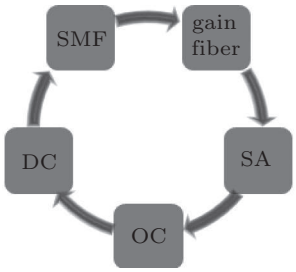



**Fig. 1.** Schematic of the passively mode-locked Yb-doped fiber laser.

We simulate the propagation of the light field in fiber by solving the nonlinear Schrödinger equation (NLSE) using the split-step algorithm. The pulses evolution in fiber is under the cooperation of the intra-cavity losses, bandwidth limited saturable gain, dispersive, and nonlinear effect. Their balance preserves the formation of solitons

$$\frac{\partial A(z,T)}{\partial z} = \frac{g}{2}A(z,T) + \frac{\mathrm{i}}{2}\beta^2\frac{\partial^2}{\partial T^2}A(z,T) + \mathrm{i}\gamma|A(z,T)|^2A(z,T), \quad (1)$$

where $A(z,T)$ is the slowly varying temporal envelope of the light field, $\beta_2$ is the dispersion of the group velocity dispersion coefficient, $\gamma$ is the Kerr nonlinearity coefficient, and $g$ is the doped fiber gain. For a single-mode fiber (SMF), $g$ is taken as zero. Here, $g$ is a spectrum-dependent parameter and has a parabolic shape, which is determined by its small signal gain $g_0$, full width at half maximum of the gain spectrum $\Omega_g$, pulse energy$E$, and the gain saturation energy $E_{sat}$. The parameter $g$ is defined as

$$g(\omega) = \frac{g_0}{1+(\omega/\Omega_g)^2 + E/E_{sat}}, \quad (2)$$

Other effects of cavity components we employed in the simulation, such as SA and OC, are taken into account by multiplying their transform functions when pulses pass through them. The saturation absorber is expressed as

$$R = R_{unsat} + R_{sat}[1 - 1/(1+P/P_{sat})], \quad (3)$$

where $R_{unsat} = 60\%$ and $R_{sat} = 30\%$ represent unsaturated reflectance and saturated reflectance, respectively, $P$ is the instantaneous power, and $P_{sat}$ is the saturation power. After the SA, pulses pass through the OC, which would reduce some energy by a factor of 10, and also take into account the losses in the cavity. The inter-cavity net group velocity dispersion $\beta_2^{net}$ is equal to the summation of $\beta_2^{gain}L^{gain}$, $\beta_2^{SMF}L^{SMF}$, and $\beta_2^{DC}L^{DC}$. We can change $\beta_2^{DC}L^{DC}$ to adjust $\beta_2^{net}$ since

$$\beta_2^{net} = \beta_2^{gain}L^{gain} + \beta_2^{SMF}L^{SMF} + \beta_2^{DC}L^{DC}. \quad (4)$$

## 3. Results and discussion

We first consider a noise signal, which evolves into steady pulses under the interaction of the inter-cavity effects. The following parameters are used in our simulations: $\beta_2^{Gain} = 0.025\ \mathrm{ps^2\cdot m^{-1}}$, $\beta_2^{SMF} = 0.025\ \mathrm{ps^2\cdot m^{-1}}$, $\gamma^{Gain} = 0.005\ \mathrm{W^{-1}\cdot m^{-1}}$, $\gamma^{SMF} = 0.0013\ \mathrm{W^{-1}\cdot m^{-1}}$, $g_0 = 20\ \mathrm{m^{-1}}$, $P_{sat} = 150$ W, and $\Omega_g = 40$ nm. The above parameters are from the data sheets of fiber products. For the DC fiber, we use the parameters used in Ref. [19], that is, $\beta_2^{DC} = -0.082\ \mathrm{ps^2\cdot m^{-1}}$, and $\gamma^{DC} = 0.079\ \mathrm{W^{-1}\cdot m^{-1}}$. We can change $L^{DC}$ to adjust $\beta_2^{net}$.

We varied the values of the inter-average group dispersion $\beta_2^{net}$ and the gain saturation energy $E_{sat}$. The former determine the operation regime of the laser, and the latter is determined by the pump power, the increase of $E_{sat}$ corresponds to the increase of pump power in the experiments.

A stable single pulse is generated when $E_{sat}$ is higher than 15 nJ. To guarantee the laser operates in a linearly chirped parabolic regime, we utilize the method we have used previously, where $E_{sat} = 150$ nJ, and $\beta_2^{net}$ increases linearly and slightly. The parabolic shape pulse is obtained when $\beta_2^{net}$ exceeds $0.0016\ \mathrm{ps^2\cdot m^{-1}}$. The result is shown in Fig. 2 in the case of $\beta_2^{net} = 0.004\ \mathrm{ps^2\cdot m^{-1}}$. The stable pulse train is formed after about 200 roundtrips. The pulse duration is about 1 ps, and the peak power is about 30 W, corresponding to a pulse energy of about 30 pJ.

With appropriate net group dispersion, we changed the gain saturation energy. The simulation results show that the pulse energy and duration are proportional to $E_{sat}$. The increasing saturation energy results in the increase of pulse duration and energy, except the pulse shape. These results prove that the pulse shape is only determined by the inter-cavity dispersion. When $E_{sat}$ exceeds 260 nJ, the pulse will split into two

pulses. The two pulses have the profile similar to the single pulse operation regime shown in Fig. 2(b), and have exactly the same parameters such as pulse duration and peak power, as shown in Fig. 3. The single pulse energy is about 30 pJ. The parameters in Fig. 3 are the same as those in Fig. 2, except for $E_{\rm sat} = 300$ nJ. The increase of gain saturation energy results in the increase of the single pulse energy.

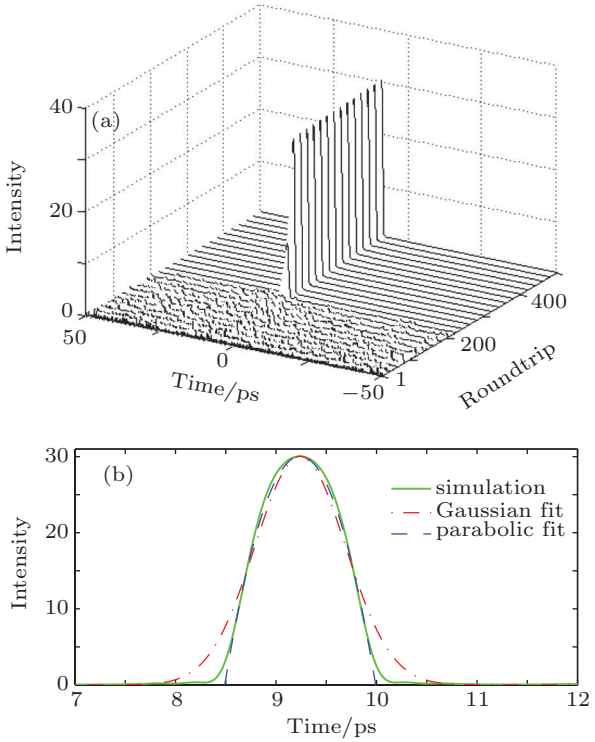



**Fig. 2.** (color online) (a) Formation and evolution of a parabolic-shaped pulse. (b) Temporal profile of the output pulse.

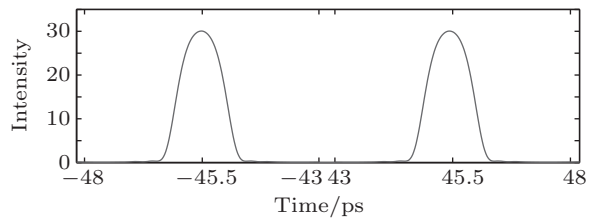



**Fig. 3.** Temporal profile of the output pulse. The parameters are the same as those in Fig. 2, except for $E_{\rm sat} = 300$ nJ.

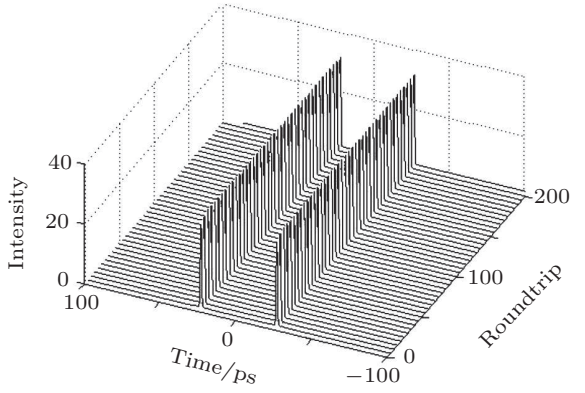



**Fig. 4.** Pulses evolution in the cavity when the pulse separation equals 50 ps.

To simulate the soliton interaction in the laser, we input two arbitrary weak lights in the cavity firstly and let them evolve into stable pulses with a desired separation. We then change the laser operation condition to study their interaction. The simulation results show that the two weak lights finally evolve into stable pulses with the same parameters. Figure 4 shows a case of a pulses interaction, where the separation is 50 ps, which is fairly large compared with their pulse duration of 1 ps. By changing the gain saturation energy in the range of a two pulse operation regime, the two pulses respond identically, indicating that in condition of the large separation, there is no interaction between them.

By keeping the gain saturation energy unchanged, the separation between the pulses decreases gradually. When the separation is reduced to 20 ps, the interaction between pulses is observed. The simulation result shows that an interaction force exists which depends on the gain saturation energy and is also influenced by the pulse separation. We can see from Fig. 5 that after a few roundtrips with the initial separation, the two pulses begin to repel each other after about 60 roundtrips, and finally come to a stable distance. Further simulations show that the interaction is also influenced by the inter-cavity average dispersion, and the increase of the path average dispersion will counterbalance the repel force, weaken the separation progress, and reduce the separation distance. However, it cannot eliminate the force completely. With the separation decreasing continuously, when the separation is below 7 ps, the soliton collision is observed. We can see from Fig. 6(a) that at the initial stages of pulse evolution, the two pulses obviously evolve with amplitude oscillations, and collide with each other at nearly 70 roundtrips. The collision also depends on the gain saturation energy and inter-cavity dispersion, and we can control the collision distance by adjusting the two parameters. Figure 6 shows some different collision distance conditions with different parameters, showing that the position of the collision is a little different.

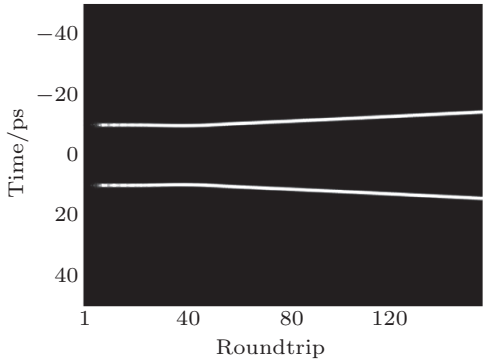



**Fig. 5.** Pulse evolution trajectory in the cavity when the pulse separation equals 20 ps, and the gain saturation energy equals 300 nJ.

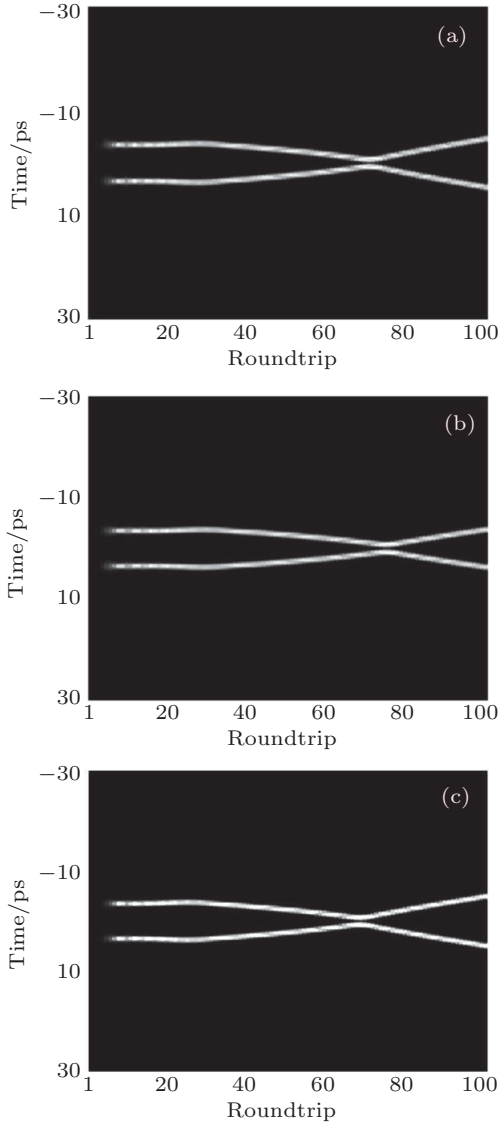



**Fig. 6.** Pulse evolution trajectory in the cavity when the pulse separation equals 7 ps. (a) $\beta_2^{\text{net}} = 0.004$ ps$^2$·m$^{-1}$, $E_{\text{sat}} = 300$ nJ; (b) $\beta_2^{\text{net}} = 0.008$ ps$^2$·m$^{-1}$, $E_{\text{sat}} = 300$ nJ; (c) $\beta_2^{\text{net}} = 0.004$ ps$^2$·m$^{-1}$, $E_{\text{sat}} = 280$ nJ.

The simulation results above indicate that the soliton interaction of a linearly chirped parabolic pulse pair is clearly observed by using our laser. Based on the numerical results, we can see that the coexisting pulses have several kinds of gain saturation energy and pulse-separation-dependent repulsive or attractive interactions. Theoretically, when the separation of the pulses exceeds ten times the pulse duration, those kinds of interaction are weak enough to be ignored. On the contrary, we could see from Fig. 5 that the interaction also exists when the separation is 20 ps.

The cases of pulse interaction with a large pulse separation have been studied in Ref. [9], which attributes the interaction to the phase shift. The pulse evolution trajectory of Fig. 1 is shown in Fig. 7(a). Compared with soliton 1 in Fig. 9 in Ref. [9], the pulse evolution in Fig. 1 exhibits a similar motion, suggesting that the phase shift plays a critical role in producing the interaction in parabolic pulse pairs. Figure 7 shows some results of the pulse phase shift with different pump energies or net average dispersion. We note that with different operational conditions, the motions in every roundtrip of pulse are different, indicating that those pulses experience different phase shifts. The pump energy and net-average-dispersion-dependent phase shift may be the source of different phenomena in Fig. 6. When we adjust the inter-cavity condition to eliminate the phase shift, the interaction also disappears (compare Fig. 8 with Fig. 5). These results reveal that the presence of the phase shift affected by the pump energy and net average dispersion are the reason why the interaction distance of the parabolic-shaped pulse pair is large.

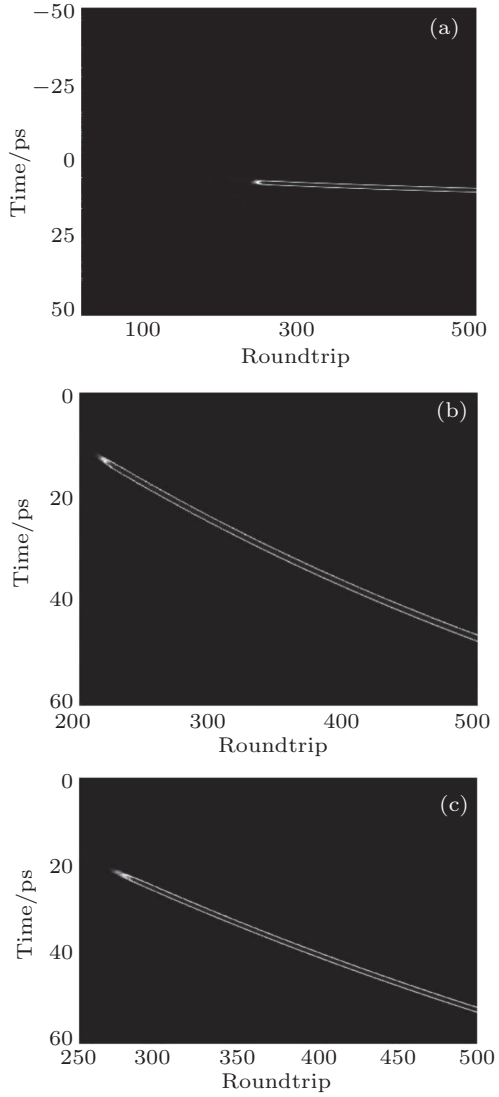



**Fig. 7.** (a) Pulse evolution motion of Fig. 1. (b) Pulse motion with the same parameters as those in Fig. 1, except for $E_{\text{sat}} = 200$ nJ. (c) Pulse motion with the same parameters as those in Fig. 1, except for $\beta_2^{\text{net}} = 0.006$ ps$^2$·m$^{-1}$.

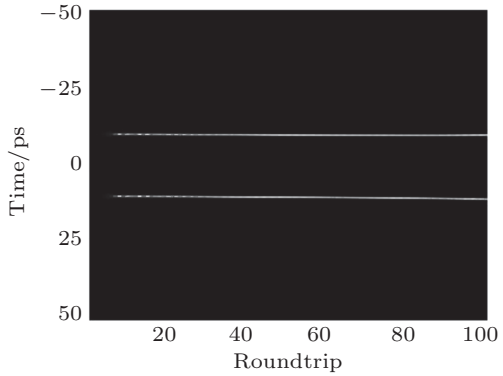



**Fig. 8.** Pulse evolution with a separation of 20 ps. No phase shift is imposed on the pulses.

## 4. Conclusion

In summary, we have numerically studied the interaction of parabolic-shaped pulse propagation in a passively mode-locked Yd-doped fiber laser operated in a wave-breaking-free regime. It is shown that there is a mutual separation and gain saturation energy dependent interaction in the laser. These results show that the interaction between parabolic-shaped pulses is stronger than conventional soliton interaction, and occurs when the separation is about 30 times the soliton duration. Furthermore, the numerical simulations also show that the interaction of parabolic-shaped pulses is the result of a phase shift. These results suggest that there are more practical differences between the parabolic-shaped pulse pair and conventional ones.

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