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Interactions of chirped femtosecond soliton-like pulses*

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This paper studies the interactions between two and more adjacent chirped soliton-like pulses, respectively. The results show that the pulses present strong interactions when the separations between them are smaller than a certain value, and their behaviour is very distinct under different conditions, such as a different number of pulses or different initial separations between them. Furthermore, we also study the suppression of these interactions and obtain very good effects by using different initial amplitude ratios.

Keywords: chirped pulses, adjacent interaction, suppression
PACC: 4265, 4265S, 4200

High-repetition-rate femtosecond lasers are interesting for a variety of applications, in particular, for optical communication systems. Over the past decade, dense-wavelength-division-multiplexing systems have enabled the transmission capacity of single-mode fibres to increase from 2.5 Gb/s to more than 10 Tb/s.[1−3] This remarkable growth in system capacity has been accomplished mainly by simultaneously increasing the number of wavelength channels and the transmission rate per wavelength channel. The bit rate of communication systems depends mostly on the repetitive frequency of the signal pulse, the separation between two adjacent pulses decreases with the increase of the pulse repetitive frequency. But small separation between two adjacent pulses may lead to strong interaction, and cause pulse distortion, which is disadvantageous to the information regarding undistorted transmission. Therefore, interactions between two adjacent solitons are not favourable factors for the transmission of the information. Therefore it is important to search for methods to keep the pulse form unchanged during the transmission.

Interaction between adjacent pulses is one of the hottest topics in the optical fibre communication field.[4−8] Up to now, three restrained methods have been proposed:[9,10] (i) phase alteration between adjacent pulses; (ii) unequal amplitudes between adjacent pulses; (iii) inclusion of third-order dispersion. In this paper, we study the interactions between two or more adjacent chirped femtosecond soliton-like pulses[11] of the high-order nonlinear Schrödinger equation (HNLSE). It is found that the pulses present strong interactions when the distance between them is smaller than a certain value and the behaviour of them is very distinct under different conditions, such as a different number of pulses or different initial separation between them. Since the interactions of adjacent pulses will cause pulse sequence distortion and then lead to serious false codes or missing information during the communications, the suppression of them becomes very important and arouses extensive attention among the research field.

As is well-known, the symmetry of the soliton will be destroyed when one of the high-order effects, such as third-order dispersion, nonlinear dispersion, nonlinear gradient term and nonlinear absorption etc, acts separately. But the balance between them can keep the shape of soliton, this has been verified both experimentally[12,13] and theoretically.[11,14−16] For an optical system, including bandwidth-limited gain and higher order effects, a so-called distributed model can be used when the period of the perturbation is small

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in comparison with the amplifiers spacing. The equation for the propagation of pulses can be written in the form:[11]

$$\begin{aligned} & E_z - \mathrm{i}\frac{D}{2}E_{tt} - \mathrm{i}\left|E\right|^2 E \\ = & \delta E + \mathrm{i}\sigma E_t + \varepsilon E_{tt} \\ & + \chi\left|E\right|^2 E + \lambda E_{ttt} \\ & + \mu(\left|E\right|^2 E)_t + \nu E(\left|E\right|^2)_t, \end{aligned} \tag{1}$$

where $E(z,t)$ is the complex envelope of the electric field, z is the normalized propagation distance, and t is the retarded time. The model parameters δ, σ, ε, and χ are real constants; λ, μ, and ν can be complex. The coefficient $D = +1\,(-1)$ corresponds to anomalous (normal) dispersion. Furthermore, $\delta > 0\,(< 0)$ is the linear excess gain (loss) at the carrier frequency ω_0 and the gain-centre frequency ω_a, ε describes the effect of spectral limitation due to gain bandwidth-limited amplification and/or spectral filtering; χ characterizes nonlinear gain and/or other absorption processes. The real part of λ represents the net third-order dispersion introduced by material. The real part of μ is the nonlinear dispersion term, it is responsible for self-steepening at the pulse edge, the imaginary part of μ describes the combined effect of nonlinear gain and/or absorption processes. The ν is the nonlinear gradient term which results from the time-retarded induced Raman process. In fact, the imaginary part of ν is usually responsible for the soliton SFS, and its real part could be zero. The HNLSE has the soliton-like solution as[11,14–16]

$$E(t,z) = A_0\,\mathrm{sech}[\eta(t-\rho z)]^{1+\mathrm{i}\beta}\exp[\mathrm{i}(\Omega t - Kz)]. \tag{2}$$

Here A_0, η, ρ, β, Ω and K describe the characteristics of the soliton-like pulses, where the parameters A_0, η, Ω, ρ and K are given by

$$\mathrm{A}_0 = \sqrt{\frac{\eta^2(6b_1\lambda_\mathrm{r} - \beta b_5\lambda_\mathrm{i})}{3\mu_\mathrm{r}}}, \tag{3}$$

$$\eta = \sqrt{\frac{\sigma + \Omega b_9}{-b_1\lambda_\mathrm{i} - 2\beta\lambda_\mathrm{r}}}, \tag{4}$$

$$\Omega = \frac{2\beta b_5\lambda_\mathrm{i} - 12b_1\lambda_\mathrm{r} + 3(Db_2 + 6\beta\varepsilon)\mu_\mathrm{r}}{2(\beta b_6\lambda_\mathrm{i} - 3b_4\lambda_\mathrm{r})\mu_\mathrm{r}}, \tag{5}$$

$$\rho = \frac{\eta^2[(2-3b_1)\lambda_\mathrm{i} - \beta b_3\lambda_\mathrm{r}] - \sigma - \Omega b_9 + \beta\Omega b_{11}}{\beta}, \tag{6}$$

$$K = \frac{1}{2}(\Omega^2 b_{10} - 4\beta\eta^2 b_8 - b_1\eta^2 b_{12}), \tag{7}$$

and the chirp parameter β together with model parameters δ, σ, ε, χ, λ, μ and ν satisfy the compatibility conditions as follows

$$\delta - \beta\eta^2 b_{12} = b_1\eta^2 b_8 - \Omega(\sigma + \Omega b_7), \tag{8}$$

$$2\chi(6b_1\lambda_\mathrm{r} - \beta b_5\lambda_\mathrm{i}) = 3\mu_\mathrm{r}(2b_2 b_8 - 3b_{12}\beta) \tag{9}$$

with the notations $b_1 = 1-\beta^2$, $b_2 = 2-\beta^2$, $b_3 = 3-\beta^2$, $b_4 = 4-\beta^2$, $b_5 = 11-\beta^2$, $b_6 = 16+\beta^2$, $b_7 = \varepsilon - \lambda_\mathrm{i}\Omega$, $b_8 = \varepsilon - 3\lambda_\mathrm{i}\Omega$, $b_9 = 2\varepsilon - 3\lambda_\mathrm{i}\Omega$, $b_{10} = D + 2\lambda_\mathrm{r}\Omega$, $b_{11} = D + 3\lambda_\mathrm{r}\Omega$, $b_{12} = D + 6\lambda_\mathrm{r}\Omega$.

In order to investigate numerically the interactions between adjacent soliton-like pulses, the initial condition is given by

$$\begin{aligned} \psi(t,0) = & r_1 A_0\,\mathrm{sech}\left[\eta\left(t-q_0\right)\right]^{1+\mathrm{i}\beta}\exp\left[\mathrm{i}\Omega\left(t-q_0\right)\right] \\ & + r_2 A_0\,\mathrm{sech}\left[\eta\left(t+q_0\right)\right]^{1+\mathrm{i}\beta}\exp\left[\mathrm{i}\Omega\left(t+q_0\right)\right], \end{aligned} \tag{10}$$

in which r_1, r_2 and $2q_0$ are the amplitude coefficient and the initial separation between adjacent pulses respectively. At first we consider the interaction between two adjacent soliton-like pulses. To search for the interaction regularity, we take $r_1 = r_2 = 1$ in Eq.(10) and other parameters are fixed as those in Ref.[11]. From Fig.1(a), we can see that there is no interaction between two adjacent pulses when the separation is equal to 12. A lot of numerical simulations show that when the separation is smaller, there exists strong attraction between two adjacent pulses along with the total energy changed in the process of propagation, as shown in Fig.1(b)–1(d). It is clear that the two adjacent pulses present obvious interaction when the separation is equal to 10, first they attract, and then repel weakly during their propagation, as shown in Fig.1(b). From Fig.1(c), we can see that the two pulses fuse into one when the initial separation is equal to 8, namely $q_0 = 4$. The interaction between two adjacent chirped soliton-like pulses is very different from that of solitons. And as shown in Fig.1(d), the total energy of the former varied acutely at anterior transmission distance when the separation is equal to or less than 10. After a distance of evolution, the total energy becomes unchanged. When the separation between two adjacent pulses is larger, as the dashed line shown in Fig.1(d) for $q_0 = 6$, the total energy variation is smaller.

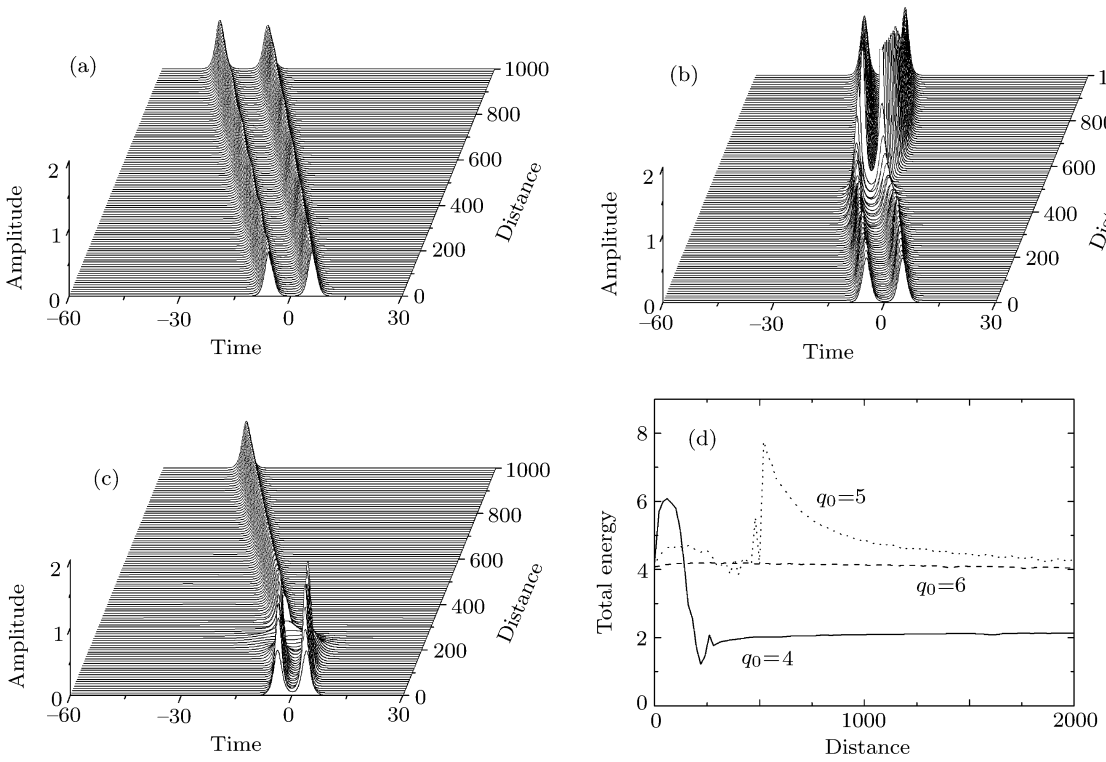


Fig.1. Space–time plot of two adjacent pulses: (a) $q_0 = 6$ and $r_1 = r_2 = 1$; (b) $q_0 = 5$; (c) $q_0 = 4$. (d) total energy for (a) (b) (c).

Because of the distortion caused by the interaction, serious false codes or missing information will occur during the communications. So the distortion caused by the interaction is not a favourable factor for the transmission of the pulses. Therefore, it is very important to suppress the interaction and keep the pulse separation during the transmission. A lot of numerical simulations show that the traditional method of initial unequal amplitudes works well here and the corresponding results are shown in Fig.2. From Fig.2, one can see that the interaction is restrained effectively when the initial amplitude ratio is selected properly. When the separation between two adjacent pulses is equal to 10, the initial amplitude ratio of 1.1 can suppress the interaction effectively. For the case of $q_0 = 4$, the amplitude ratio of $r_1 : r_2 = 1.1 : 1$ cannot work yet, the ratio of $r_1 : r_2 = 1 : 1.1$ can restrain the strong attraction between the two pulses instead, as shown in Fig.2(b).

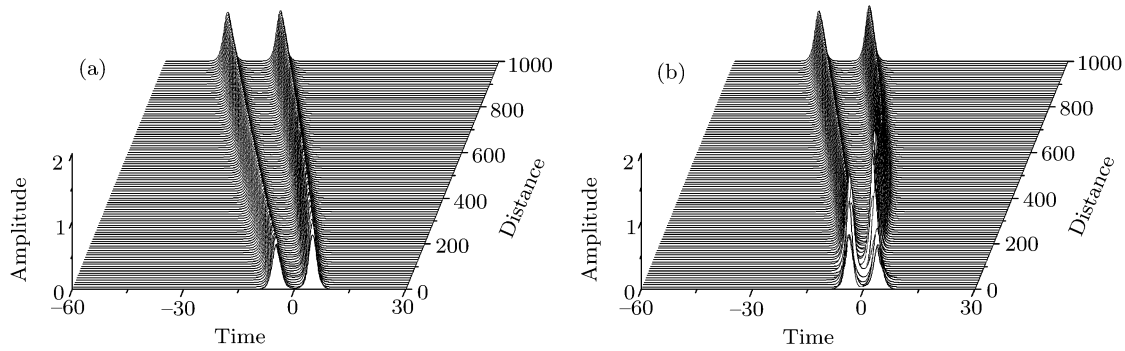


Fig.2. (a) Space–time plot for $q_0 = 5$ and $r_1 : r_2 = 1.1 : 1$; (b) Space–time plot for $q_0 = 4$ and $r_1 : r_2 = 1 : 1.1$.

For the general cases, we carry out a lot of numerical simulations and try to find the minimum of the amplitude ratio for different relative distance. But the results show that only some definite value of amplitude ratio can restrain their interaction for certain relative distance and there is no regularity between them. For example, when the separation is equal to 10, the amplitude ratio of 1.07 and 1.09 can restrain the interaction very well, but the value of 1.08 cannot work yet. However, when the amplitude ratio varies from 1.1 to 1.2, all of them can suppress the interaction effectively, as shown in Fig.3. Furthermore, we also study how the noises affect the interaction of the adjacent pulses. The results show that a definite range of noises will have no effect on the interaction and suppression of the adjacent pulses, as shown in Fig.4. We can see that the white noise, whose maximal value is 0.02, does not affect the interaction and suppression of two adjacent pulses with the separation of 10.

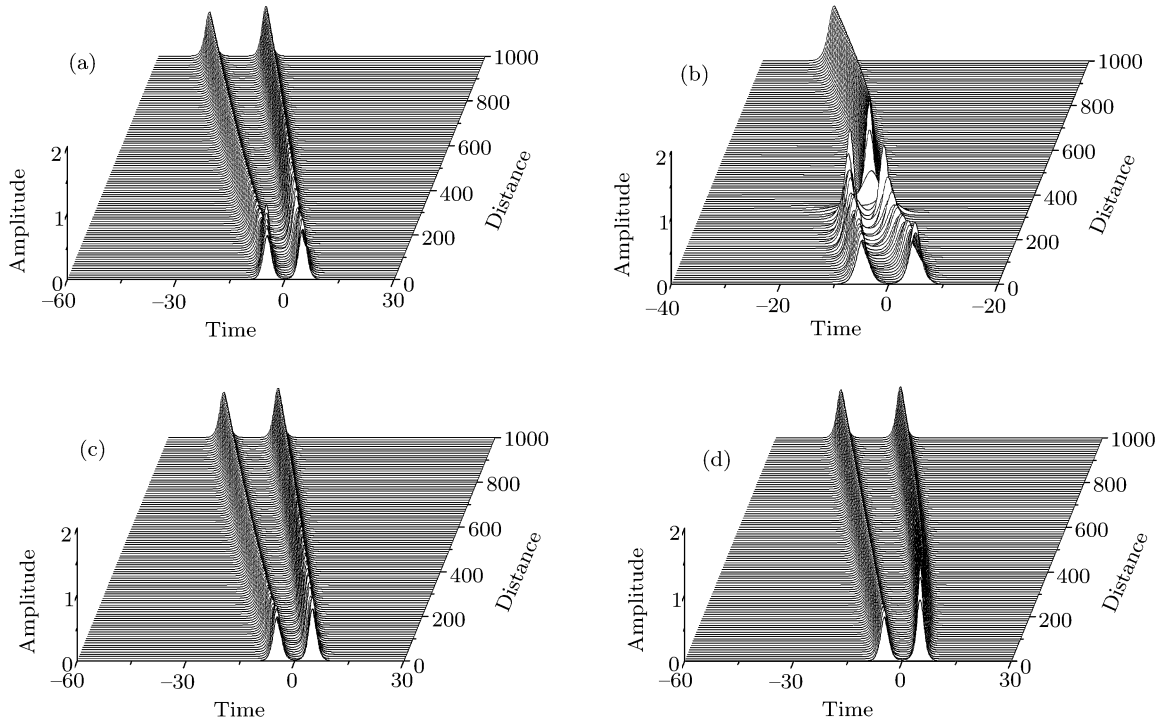


Fig.3. Space–time plot for $q_0 = 5$: (a) $r_1 : r_2 = 1.07 : 1$; (b) $r_1 : r_2 = 1.08 : 1$; (c) $r_1 : r_2 = 1.09 : 1$; (d) $r_1 : r_2 = 1.18 : 1$.

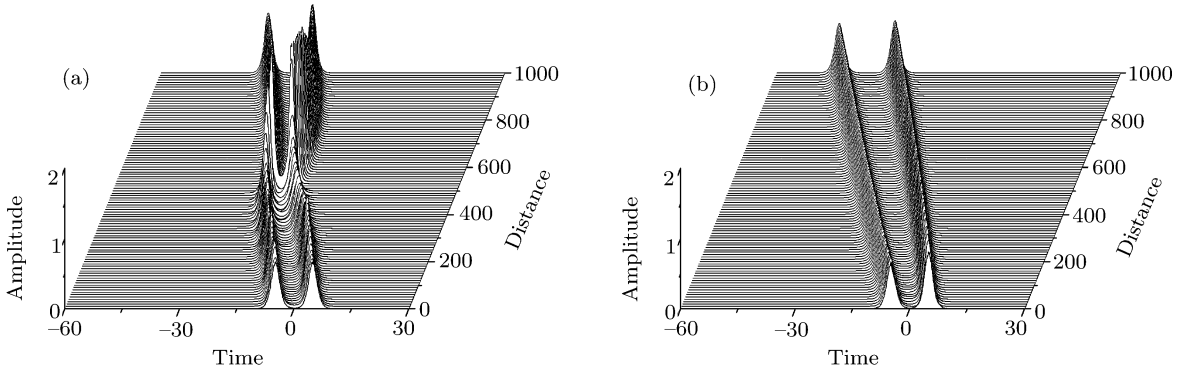


Fig.4. Space–time plot for the cases: (a) $q_0 = 5$ and $r_1 = r_2 = 1$; (b) $q_0 = 5$ and $r_1 : r_2 = 1.1 : 1$, when the maximal value of white noise is 0.02.

Finally, we consider the interactions between three or more adjacent pulses. The results show that the interactions are more complex than that of two pulses. As shown in Fig.5(a), the three pulses finally combined into one when the initial separation between them is equal to 10. For restraining the interactions, we select the initial amplitude ratio as $r_1 : r_2 : r_3 = 1.1 : 1.1 : 1$, as shown in Fig.5(b), the interactions between them can be suppressed effectively. For four pulses, the interactions between them are more complex than those of two or three pulses. When the initial separations are equal to or less than 10, there exist strong interactions between them, as shown in Fig.6. Figure 6(a) shows the space–time plot of the interaction of four adjacent pulses when the separation between them is equal to 10. We can see clearly that the pulses present more complex interaction behaviour than that shown above. Two of them disappeared after a distance of transmission and the other two present an interaction similar to that shown in Fig.1(b). When the separation between them decreases more, the interactions are not similar to the results shown above any more. They present the combination of three pulses and the other one keeps transmitting solely, as shown in Fig.6(b) when the initial separation between pulses is equal to 9. For the suppression of four pulses interaction, we also used the method of initial unequal amplitude. The results are shown in Fig.7, from which we can see that the interactions presented in Fig.6 are restrained effectively for definite amplitude ratio. Figure 7(a) shows the suppression of interaction between four pulses when the separations between them are equal to 10 and the amplitude ratio is $1.1 : 1 : 1.1 : 1$. And Fig.7(b) shows the case of $q_0 = 4.5$ and $r_1 : r_2 : r_3 : r_4 = 1.1 : 1.1 : 1 : 1.1$.

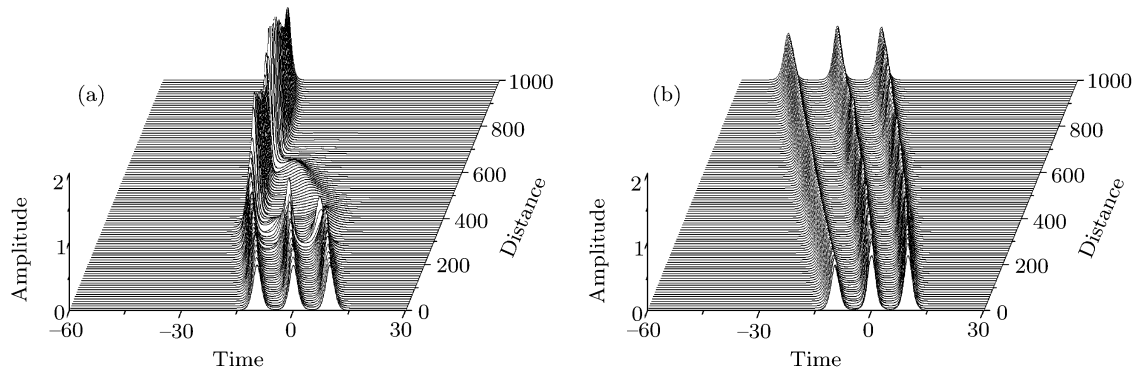


Fig.5. (a) Space–time plot for three pulses when the initial separation is equal to 10. (b) Space–time plot for three pulses when the initial separation is equal to 10 and $r_1 : r_2 : r_3 = 1.1 : 1.1 : 1$.

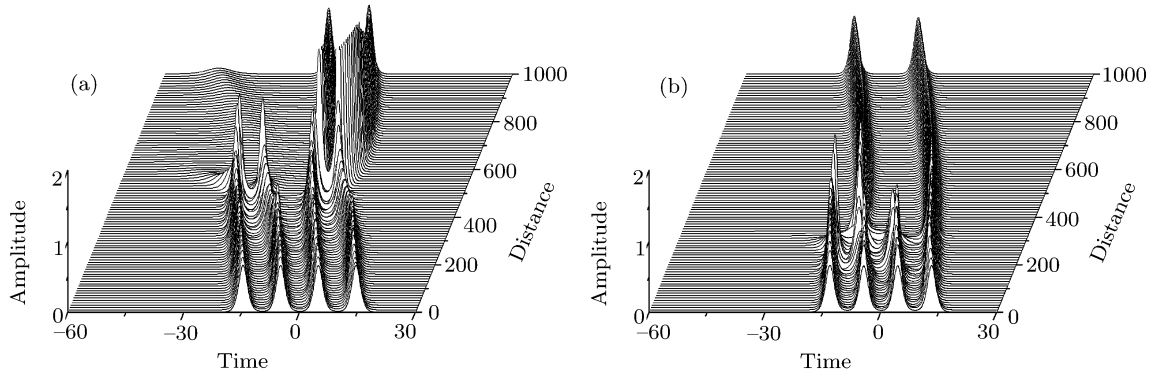


Fig.6. (a) Space–time plot for four pulses when the initial separation is equal to 10. (b) Space–time plot for four pulses when the initial separation is equal to 9.

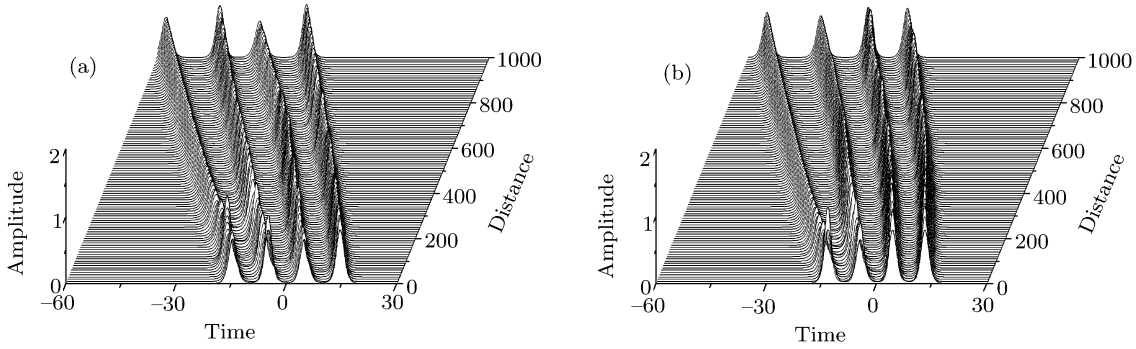


Fig.7. (a) Space–time plot for four pulses when the initial separation is equal to 10 and $r_1 : r_2 : r_3 : r_4 = 1.1 : 1 : 1.1 : 1$. (b) Space–time plot for four pulses when the initial separation is equal to 9 and $r_1 : r_2 : r_3 : r_4 = 1.1 : 1.1 : 1 : 1.1$.

In conclusion, we have studied the interactions between two or more adjacent chirped soliton-like pulses. The results show that the pulses present strong interactions when the separations between them are smaller than a certain value and the behaviours of them are very different for different cases. For the sake of reducing the serious false codes or the information missing during the communications, the suppression of the interactions between adjacent pulses becomes very important and will offer theoretical foundation for real communication systems. Therefore, we have also studied the suppression of these interactions and obtained very good results by using different initial amplitude ratios. Based on these results, we predict that they will be helpful for information communication in fact or offer some useful reference for the design of communication systems.

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