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Generation of time-dependent ultra-short optical pulse trains in the presence of self-steepening effect*

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Starting from the extended nonlinear Schrödinger equation in which the self-steepening effect is included, the evolution and the splitting processes of continuous optical wave whose amplitude is perturbed into time related ultra-short optical pulse trains in an optical fibre are numerically simulated by adopting the split-step Fourier algorithm. The results show that the self-steepening effect can cause the characteristic of the pulse trains to vary with time, which is different from the self-steepening-free case where the generated pulse trains consist of single pulses which are identical in width, intensity, and interval, namely when pulses move a certain distance, they turn into the pulse trains within a certain time range. Moreover, each single pulse may split into several sub-pulses. And as time goes on, the number of the sub-pulses will decrease gradually and the pulse width and the pulse intensity will change too. With the increase of the self-steepening parameter, the distance needed to generate time-dependent pulse trains will shorten. In addition, for a large self-steepening parameter and at the distance where more sub-pulses appear, the corresponding frequency spectra of pulse trains are also wider.

Keywords: nonlinear optics, self-steepening effect, ultra-short optical pulse trains, split-step Fourier algorithm, optical perturbation

PACC: 4265, 4265T, 4281D

1. Introduction

As is well known, owing to the interplay between the dispersion (including temporal domain, spatial domain or spatiotemporal domain) and the nonlinear effect of the optical material, many phenomena such as modulation instability,[1−26] optical solitons,[27−31] pulse compression,[30−35] and supercontinuum spectrum[6,36,37] may appear. Among them, modulation instability is actually a universal phenomenon which can be observed in many nonlinear systems. In nonlinear optics, modulation instability has received much special attention either in the temporal domain[1−17] and spatial domain[18−21] or spatiotemporal domain,[22−25] for its widespread applications in the areas: generating supercontinuum spectrum,[6] producing high-repetition-rate soliton-like pulse trains,[7] modulation instability lasers,[8] optical switching,[9] optical bullets,[24] etc. On the other hand, however, as the previous studies indicated, the temporal domain modulation instability which is generally believed to occur in optical fibres is detrimental to wavelength-division multiplexing (WDM) optical fibre communication system.[10] In the spatial domain, modulation instability can lead to optical filaments and then cause great damage to the laser materials in high power laser systems.[21]

As a typical application of modulation instability in optical fibres, the generation of high-repetition-rate soliton-like pulse trains is of special importance due to its potential application in high speed and large capacity optical fibre communication systems. Of course, many other approaches such as actively and passively mode-locking laser,[38−40] optical parametric oscillator,[41] and a variety of multiplexing technologies[42,43] have already been developed to achieve this objective. In comparison, however, as an all-optical technology, utilizing modulation instability to produce pulse trains has many desirable merits such as simple, convenient, and easy to achieve higher repetition rate, etc. Furthermore, its configuration is very cheap due to the fact that no expensive modulator is required. Besides, it is very convenient

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to adjust the repetition rate by varying the modulation frequency.[44] Accordingly, many efforts have been made to investigate modulation instability induced pulse trains experimentally[44] or numerically.[45,46] In the case of no self-steepening effect, the previous numerical investigations show that when perturbed by an externally sine modulated optical wave, the continuous background optical wave can evolve and develop into pulse chains which consist of a series of single pulses that are identical in width, intensity, and interval, due to induced modulation instability in optical fibres.[46] Generally, however, the self-steepening effect should be taken into account for subpicosecond pulse propagation. This effect can restrict the regime of modulation instability but enlarge the regime for the existence of a bright soliton.[47] Thus, it may modify greatly the evolution of the perturbed continuous background optical wave propagating in optical fibres. And the generated pulse trains may exhibit new features.

In the present paper, with the self-steepening effect taken into account, the evolution and the splitting processes of continuous optical wave whose amplitude is perturbed into time-dependent ultra-short optical pulse trains in the anomalous region of an optical fibre are numerically simulated in detail by adopting the split-step Fourier algorithm.

2. Theoretical analysis

With the self-steepening effect taken into account, the slowly time varying envelopes A of the optical field satisfies the following extended nonlinear Schrödinger equations:[47]

$$\frac{\partial A}{\partial z}+\frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 A}{\partial T^2}=\mathrm{i}\gamma\left|A\right|^2A-\frac{\gamma}{\omega_0}\frac{\partial}{\partial T}\left(\left|A\right|^2A\right), \quad (1)$$

where β_2 is the second-order group velocity dispersion coefficient, γ is the nonlinear coefficient, z is the propagating distance, T is the time coordinate frame moving at the group velocity, and ω_0 is the angle frequency of the optical field. Taking the following transform:

$$U=\frac{A}{\sqrt{P_0}},\quad \xi=\frac{z}{L_{\mathrm{D}}}=\frac{z\left|\beta_2\right|}{T_0^2},\quad \tau=\frac{T}{T_0}, \quad (2)$$

where P_0 is the peak power of the incident optical pulse, T_0 is the width of the incident pulse, L_{D} is the dispersion length of the optical fibre, and U, ξ, and τ are normalized envelope, distance, and time, respectively. Inserting expressions (2) in Eq.(1), then equation (1) will reduce to the following dimensionless form:

$$\frac{\partial U}{\partial\xi}-\mathrm{i}\alpha_1\frac{\partial^2U}{\partial\tau^2}=\mathrm{i}\alpha_2\left|U\right|^2U+\alpha_3\frac{\partial}{\partial\tau}\left(\left|U\right|^2U\right). \quad (3)$$

The parameters concerned here are respectively defined as

$$\alpha_1=-\frac{1}{2}\mathrm{sgn}(\beta_2),\quad \alpha_2=\frac{L_{\mathrm{D}}}{L_{\mathrm{NL}}}=N^2,\quad \alpha_3=-\frac{N^2}{T_0\omega_0},$$
$$L_{\mathrm{D}}=\frac{T_0^2}{\left|\beta_2\right|},\quad \text{and}\quad L_{\mathrm{NL}}=\frac{1}{\gamma P_0}. \quad (4)$$

For the modulation instability that generally occurs in the anomalous dispersion regime of an optical fibre where a fundamental-state optical soliton exists, the dispersion parameter α_1 and nonlinear parameter α_2 can be respectively set as α_1=0.5 and α_2=1 in the following numerical simulation.

3. Numerically simulation and discussions

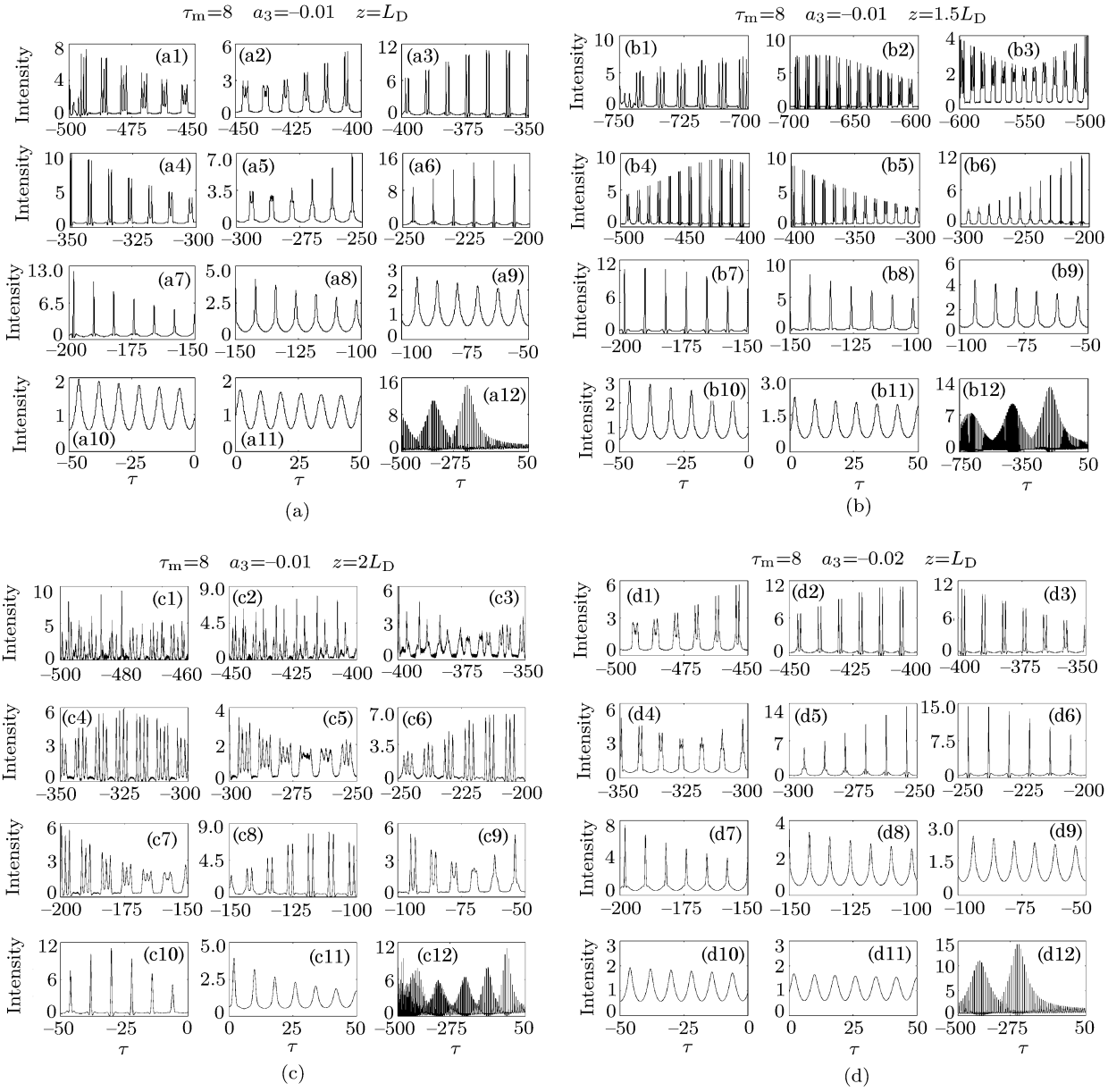
It is well known that the continuous optical wave exhibits inherent instability for a small perturbation in amplitude and splits into soliton-like pulse trains when propagating in the anomalous dispersion regime of an optical fibre. To demonstrate this modulation instability induced generation of ultra-short pulse trains, equation (3) can be solved numerically by adopting the split-step Fourier algorithm with the following initial condition:[46]

$$U\left(0,\ \tau\right)=1+A_{\mathrm{m}}\sin\left(\frac{2\pi\tau}{\tau_{\mathrm{m}}}\right), \quad (5)$$

where A_{m} and τ_{m} are the modulation depth (or perturbation amplitude) and modulation period (or perturbation period), respectively. The shape evolution of amplitude-perturbed continuous optical wave in the anomalous dispersion regime of an optical fibre for different values of self-steepening coefficient α_3 and propagation distance z is shown in Fig.1. The common parameters used in calculations are A_{m}=0.2 and τ_{m}=8. Other parameters are also shown in the figure.

To observe more clearly, each figure is divided into eleven sub-figures according to different time ranges, while the twelfth one is the whole figure which combines the preceding eleven sub-figures. Our simulation result shows that, with the increase of the propagating distance, the leading edge of the optical wave first narrows gradually and pulse trains come into being. However, the existence of self-steepening effect can cause the characteristic of the pulse trains to vary

with time, which is quite different from the case of no self-steepening effect, where the generated pulse trains consist of single pulses which are identical in width, intensity, and interval, that is to say, when pulses move a certain distance, they turn into the ultra-short pulse trains within a certain time range as shown in Fig.1. Moreover, each single pulse may split into several sub-pulses. And as time goes on, the number of the sub-pulses will decrease gradually and the pulse width and the pulse intensity will change correspondingly. The maximum number of the sub-pulses will actually increase with the propagation distance and the value of self-steepening parameter increasing. For the given parameters above, one can see from Fig.1 that the maximum number of the sub-pulses can be up to five as shown in Fig.1(e). As for the pulse intensity, one can see more obviously from the twelfth figures that the most powerful pulse appears at the position where the pulse trains consist of single pulses and the pulse is narrowest in width. One can also realize from the figure that no pulse trains emerge at the trailing edge of the optical wave and only the initial sine modulated continuous optical wave exists. In addition, with the increase of the self-steepening parameter, the distance needed to generate time-dependent pulse trains will shorten.



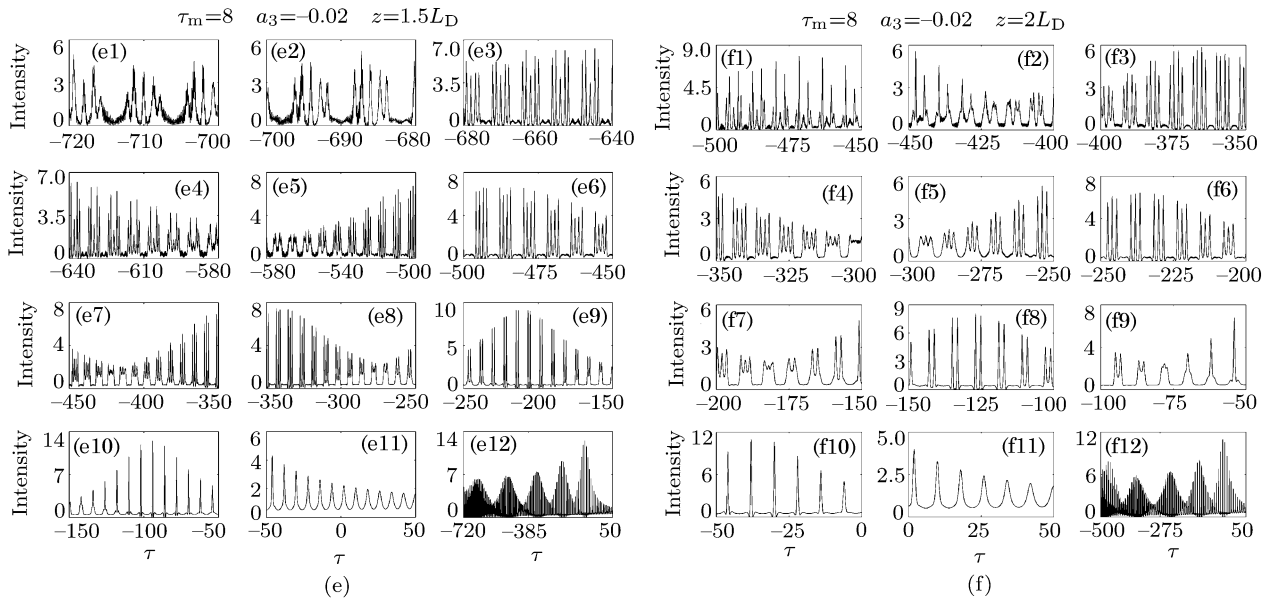
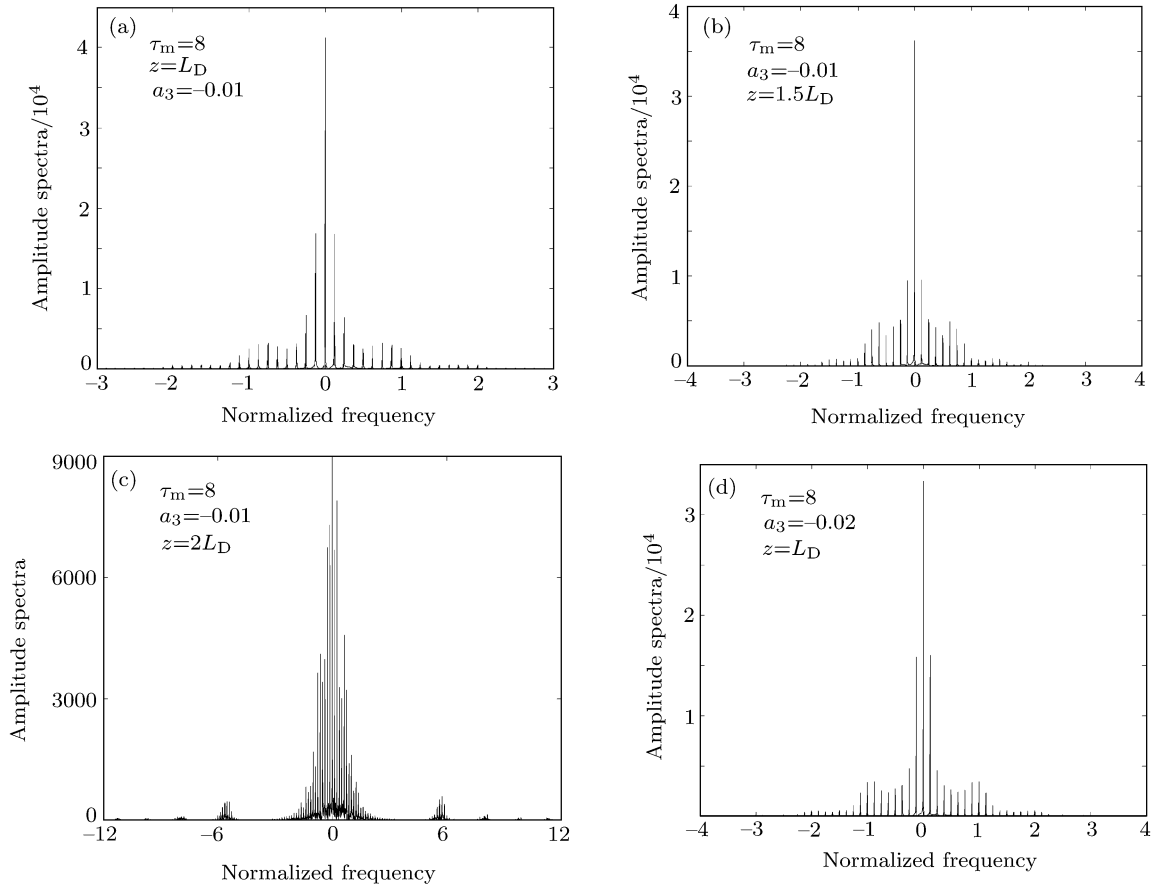


Fig.1. The shape evolutions of amplitude-perturbed continuous optical wave for different values of self-steepening parameter α_3 and propagation distance z.

It should be noted that from the viewpoint of the frequency domain, the generation of ultra-short pulse trains should be closely related to the corresponding frequency spectrum of the optical wave. Thus, the frequency spectra have also been given in Fig.2 where the parameters used correspond to those in Fig.1.



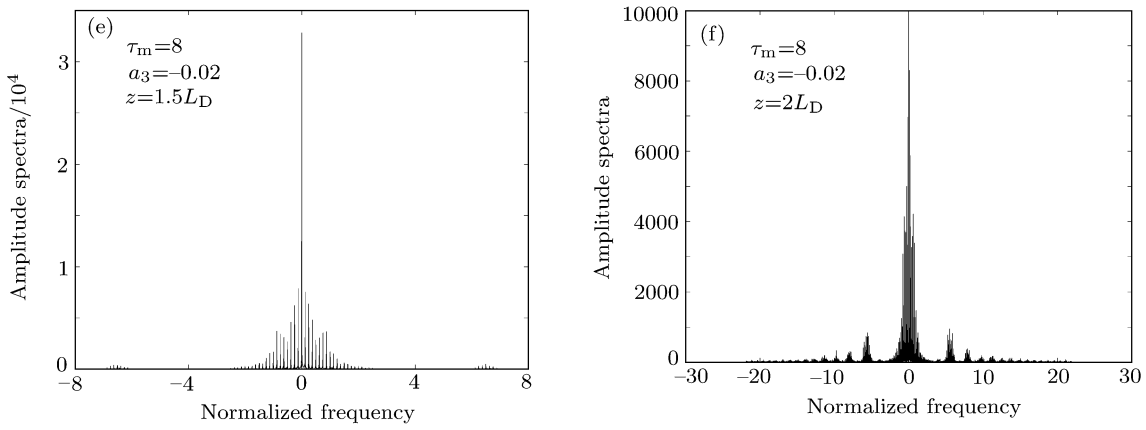


Fig.2. The spectrum evolution of amplitude-perturbed continuous optical wave for different values of self-steepening parameter α_3 and propagation distance z.

It can be observed from Fig.2 that the corresponding frequency spectra are discrete. And with the increase of distance, more and more Stokes and anti-Stokes spectral lines appear gradually and the spectra broaden. Moreover, at the distance where more sub-pulses appear, the spectra are also wider and may exhibit multi-peak structure. Furthermore, the spectral width generally increases with the self-steepening parameter increasing.

Our simulations also show that the modulation period will affect the repetition rate of pulse trains. As previous studies have indicated,[46] the shorter the modulation period is, the higher the repetition rate will be. Moreover, the large modulation depth can shorten the distance needed to generate the pulse trains. In addition, with the self-steepening effect neglected, our simulation results accord with those of Ref.[46] completely.

4. Conclusions

The influence of self-steepening effect on the generation of ultra-short optical pulse trains has been numerically investigated in optical fibres by adopting the split-step Fourier algorithm. The results show that the existence of self-steepening effect can cause the characteristic of the pulse trains to vary with time, which is different from the self-steepening-free case where the generated pulse trains consist of single pulses which are identical in width, intensity, and interval, that is to say, when pulses move a certain distance, they turn into ultra-short pulse trains within a certain time range. What the most interesting thing is that each single pulse may split into several sub-pulses. And as time goes on, the number of the sub-pulses will decrease gradually and the pulse width and intensity will change too. The maximum number of the sub-pulses will increase with the propagation distance and self-steepening parameter increasing. For the parameters given in the present paper, the maximum number of the sub-pulses can be up to five. And the most powerful pulse appears at the position where the pulse trains consist of single pulses and the pulse is narrowest in width. On the trailing edge of the optical wave, however, no pulse trains come into being and only the initial sine modulated continuous optical wave exists. With the increase of the self-steepening parameter, the distance needed to generate time related pulse trains will shorten. In addition, for a large value of self-steepening parameter and at the distance where more sub-pulses appear, the corresponding frequency spectra of pulse trains are also wider.

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