Article ID: 1004-4213(2011)09-1328-5

Propagation of Optical Wave with Phase Perturbed by Continuous Spectrum and Generation of Pulse Trains in Optical Fibers with Quintic Nonlinearity

ZHONG Xian-qiong, XIANG An-ping, CHENG Ke

(*College of Optoelectronic Technology, Chengdu University of Information Technology, Chengdu* 610225, *China*)

Abstract: According to the extended nonlinear Schrödinger equation including quintic nonlinearity in optical fibers, modulation instability (MI) based generation of high-repetition-rate optical pulse trains is numerically demonstrated by using the optical wave with its phase perturbed by Gaussian-typed continuous spectrum instead of conventional monochromatic one. The results show that, the pulse trains can also be generated due to MI effect like the conventional case. However, being different from the conventional case, the generated pulse trains here consist of limited number of pulses which are generally not equal in width, intensity, and interval. And the pulse number increases with the propagation distance. Moreover, when the other parameters are the same, the positive quintic nonlinearity can make the pulse width and interval shorten, which means that the positive quintic nonlinearity is beneficial to generate higher repetition rate pulse trains. While the negative one takes the opposite. The numerically calculated chirps developed during the generation process of pulse trains indicate that, both the chirps and their variations with the distance are highly nonmonotonic, and the quintic nonlinearity will change both the chirp range and the chirp amount.

Key words: Quintic nonlinearity; Modulation instability; Pulse trains

CLCN: O437 **Document Code**: A **doi**: 10.3788/gzxb20114009.1328

0 Introduction

Modulation instability (MI) is an important nonlinear phenomenon which has been found in many fields such as plasmas, hydromechanics, and nonlinear optics, etc. Even only in nonlinear optics, MI has been extensively studied in temporal-[1-2], spatial-[3], or spatial-temporal[4] domain. Among them, the temporal-domain MI originates from the interaction of self-phase or cross-phase modulation and dispersion effect and it occurs in ordinary optical fibers, photonic crystal fibers[5], fiber lasers[6], fiber Bragg grating[7], and etc. For its important theoretical significance itself and applications in generation of high-repetition rate soliton-like pulse trains[8], generation of super-continuum spectra[9], optical switching[10], measurement of the nonlinear and dispersion parameters of fibers[11], and etc., MI in optical fibers has attracted special interests and has been extensively studied experimentally, theoretically, and numerically. And influence of various low-order and high-order physical effects on MI has also been studied. Particularly, MI based generation of high-repetition rate soliton-like pulse trains can be applied in high-speed long haul optical communication systems. Moreover, in comparison with other approaches such as various actively or passively mode-locked fiber lasers, MI is an all-optical technology, which has many desirable advantages such as simple, convenient, and flexible to achieve higher repetition rate[12], etc. Therefore, many researchers have investigated MI based generation of pulse trains numerically or experimentally. In numerical simulations[8, 13], one usually imposes weak sinusoidal modulation on the amplitude of the initial stationary continuous-wave to demonstrate MI based generation of pulse trains. Under these circumstances, the corresponding frequency spectrum of the initial optical perturbation has been assumed to be discrete. However, the practical initial optical

Foundation item: The Key Project of Chinese Ministry of Education (No. 210186) and the Scientific Research Foundation of CUIT (No. 2010d1)

First author: ZHONG Xian-qiong (1969—), female, professor, Ph.D. degree, mainly focuses on nonlinear fiber optics and metamaterials. Email: zxqlxh@yeah.net

Received date: 2011-04-21 **Revised date**: 2011-05-06

perturbation is generally continuous. Thus, In Ref. [14], after superimposing an initial time-localized perturbation (a Gaussian shape, for instance) on the input continuous-wave, MI has been reconsidered and then some unexpected results have been found. In this case, the frequency spectrum of the perturbation is continuous. In Ref. [12], we numerically demonstrated MI based generation of pulse trains with initial Gaussian-typed perturbation imposed on the amplitude of the continuous-wave.

On the other hand, previous researches have revealed that, for high incident optical power, or for some high nonlinear materials such as semiconductor-doped fibers, quintic nonlinearity will take effect and influence MI[8,15], soliton formation[16], and other propagation characteristics. In this case, quintic nonlinearity can not be neglected and must be taken into account. Accordingly, in this paper, by superimposing a Gaussian-typed perturbation on the phase of the input continuous-wave propagating in an optical fiber with quintic nonlinearity, we numerically calculated evolutions of the time-domain shapes, spectra, and frequency chirps of this perturbed optical wave and demonstrated MI based generation of pulse trains.

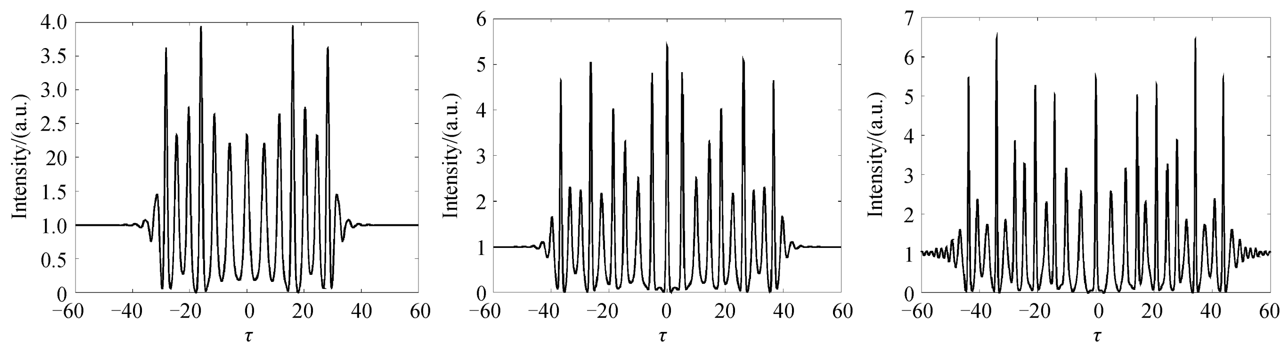
1 Calculations and discussions

When taking into account the quintic nonlinearity, the extended nonlinear Schrödinger equation is of the following form

$$\mathrm{i}\frac{\partial U}{\partial \xi}-\frac{1}{2}\mathrm{sgn}\ (\beta_2)\frac{\partial^2 U}{\partial \tau^2}+a_1|U|^2U+ a_2|U|^4U=0 \tag{1}$$

Where U, $\xi=z/L_D$, and $\tau=T/T_0$ are normalized amplitude of optical wave, normalized propagation distance, and normalized time, respectively. They are all dimensionless. And z is the propagation distance. T is the time coordinate frame moving at the group velocity. β_2 is second-order group-velocity dispersion coefficient. Sgn stands for the signal function. $a_1=L_D/L_{NL_1}$ and $a_2=\mathrm{sgn}(\gamma_2)L_D/L_{NL_2}$ are the cubic and quintic nonlinear parameters, respectively. $L_D=T_0^2/|\beta_2|$, $L_{NL_1}=1/(\gamma_1 P_0)$, and $L_{NL_2}=1/(|\gamma_2|P_0^2)$ are the dispersion length, cubic nonlinear length, and quintic nonlinear length, respectively. T_0, γ_1, γ_2, and P_0 are the pulse width, cubic nonlinear coefficient, quintic nonlinear coefficient, and incident optical power, respectively. Assuming the initial input to be the continuous-wave with its phase imposed by a Gaussian-typed perturbation and adopting the split-step Fourier method, one can numerically calculate the shapes, spectra of the incident optical wave. The parameters $a_1=1$, $\beta_2<0$, and perturbation amplitude $A_m=0.000\,1$ have been set during the following calculations.

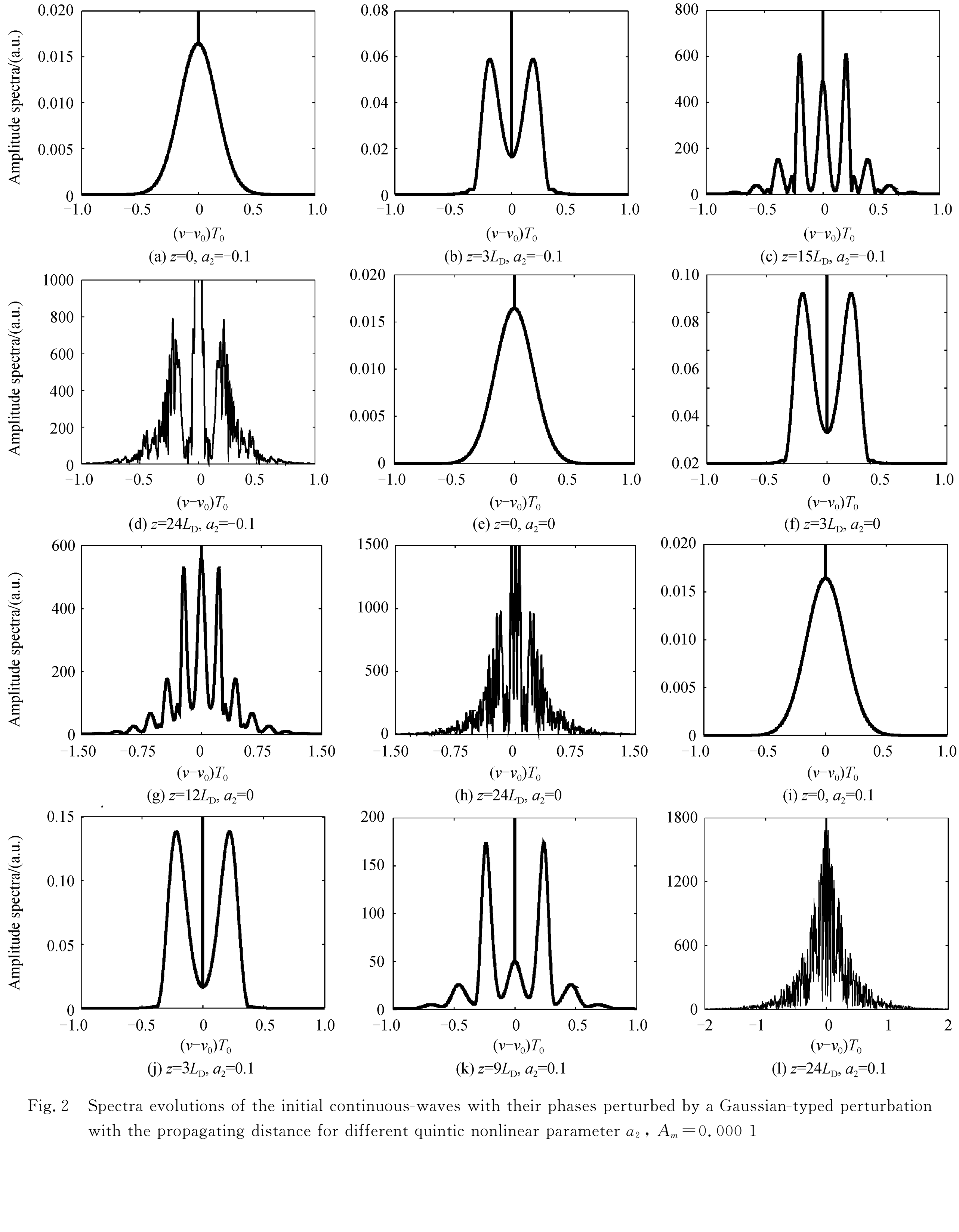
It can be seen from Fig. 1 that, the pulse trains can also be generated gradually with increase of the propagation distance. However, the generated pulse trains consist of limited number of pulses which are generally not equal in width, intensity, and interval. And the pulse number increases with the propagation distance. The most important thing is that, when the other parameters are the same, the positive quintic nonlinearity can make the pulse width and interval shorten which thus means the positive quintic nonlinearity is beneficial to generate higher repetition rate pulse trains. While the negative one takes the opposite. However, the positive quintic nonlinearity can not be increased unlimitedly. Furthermore, when the repetition rate is high and pulse width is short enough, Eq. (1) becomes invalid and must be modified by taking into account the high-order dispersion effects. Accordingly, the repetition rate can not be raised unlimitedly.



(a) A_m=0.0001, a_2=−0.1, z=24L_D　(b) A_m=0.0001, a_2=0, z=24L_D　(c) A_m=0.0001, a_2=0.1, z=24L_D

Fig. 1　Generated pulse trains for different quintic nonlinear parameter a_2

In addition, being similar to the gain spectra of MI, the amplitude frequency spectra as shown in Fig. 2 develop from the initial smooth profiles to the two-peak, multi-peak, and then continuous structure, which indicates that the generation of pulse trains results from MI effect. The corresponding evolutions of normalized frequency chirps $-T_0\ (\partial\Phi/\partial T) = -\ (\partial\Phi/\partial\tau)$ are also numerically simulated in Fig. 3. Where Φ is the phase shift which is developed during propagation. Obviously, the chirps and their variations with the distance are both highly nonmonotonic. That is to say, with increase of the distance, the chirps will increase and achieve a maximum value, then decrease. Ten they increase once again and achieve a new maximum value, and then decrease again, and so on. Meanwhile, the time range of the chirp will broaden. Besides, the quintic nonlinearity will change both the chirp range and the chirp amount. The interaction between the nonmonotonic chirp



(a) $z=0,\ a_2=-0.1$ (b) $z=3L_D,\ a_2=-0.1$ (c) $z=15L_D,\ a_2=-0.1$

(d) $z=24L_D,\ a_2=-0.1$ (e) $z=0,\ a_2=0$ (f) $z=3L_D,\ a_2=0$

(g) $z=12L_D,\ a_2=0$ (h) $z=24L_D,\ a_2=0$ (i) $z=0,\ a_2=0.1$

(j) $z=3L_D,\ a_2=0.1$ (k) $z=9L_D,\ a_2=0.1$ (l) $z=24L_D,\ a_2=0.1$

Fig. 2 Spectra evolutions of the initial continuous-waves with their phases perturbed by a Gaussian-typed perturbation with the propagating distance for different quintic nonlinear parameter a_2, $A_m=0.000\ 1$

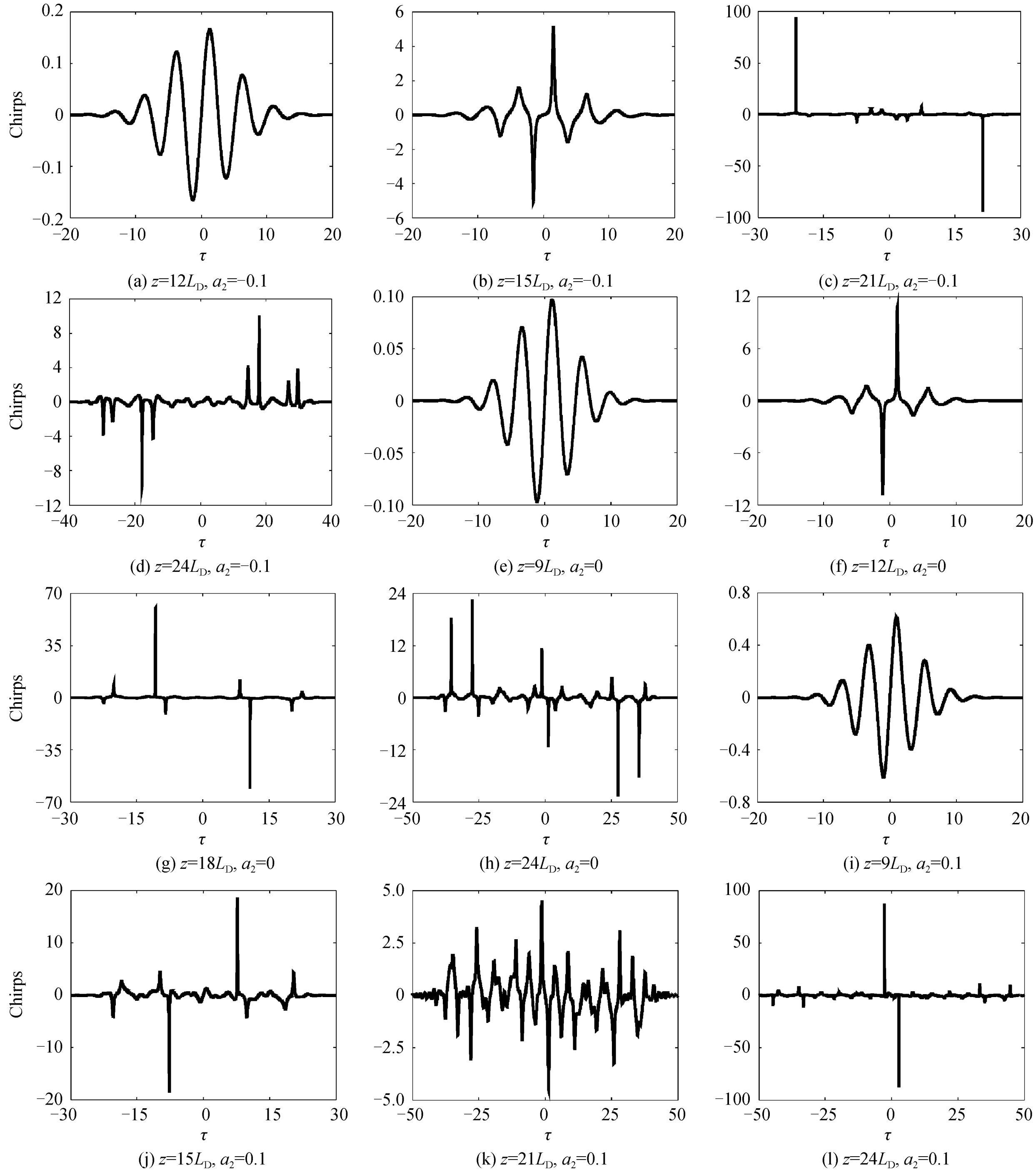


Fig. 3 Chirps evolutions of the initial continuous-waves with their phases perturbed by a Gaussian-typed perturbation with the propagating distance for different quintic nonlinear parameter a_2, $A_m = 0.000\ 1$

and the anomalous dispersion gradually breaks the input optical wave up into pulse trains.

2 Conclusions

On the basis of the extended nonlinear Schrödinger equation in an optical fiber with quintic nonlinearity, evolutions of the shapes, frequency spectra, and developed frequency chirps of the optical wave with its phase perturbed by Gaussian-typed continuous spectrum instead of conventional monochromatic one are numerically calculated. The results show that, the generated pulse trains consist of limited number of pulses which are generally not equal in width, intensity, and interval. And the pulse number increases with the propagation distance. Moreover, when the other parameters are the same, the positive quintic nonlinearity can make the pulse width and interval shorten which thus means the positive quintic nonlinearity is beneficial to generate higher repetition rate pulse trains. While the negative one takes the opposite. Being similar to the gain spectra of MI, the amplitude frequency spectra will develop from the initial smooth profiles to the two-peak, multi-peak, and then continuous structure, which indicates that the generation of pulse trains results from MI effect. The numerically calculated chirps developed during the generation process of pulse trains indicate that, both the chirps and their variations with the distance are highly nonmonotonic, and the quintic nonlinearity will change both the chirp range and the chirp amount. Due to the interaction between this nonmonotonic chirp and the anomalous dispersion, the optical wave whose phase initially perturbed by Gaussian-typed continuous spectrum can gradually evolve into high-repetition-rate optical pulse trains.

References

[1] TCHOFO DINDA P, PORSEZIAN K. Impact of fourth-order dispersion in the modulational instability spectra of wave propagation in glass fibers with saturable nonlinearity[J]. *JOSA B*, 2010, **27**(6): 1143-1152.

[2] ZHONG X Q, XIANG A P. Cross-phase modulation induced modulation instability in single-mode optical fibers with saturable nonlinearity[J]. *Optical Fiber Technology*, 2007, **13**(3): 271-279.

[3] ZHANG KY, HOU C F. One-dimensional modulational instability of broad optical beams in biased centrosymmetric photorefractive crystals[J]. *Physics Letters A*, 2009, **374**(2): 169-172.

[4] SALERNO D, JEDRKIEWICZ O, TRULL J, *et al*. Noise-seeded spatiotemporal modulation instability in normal dispersion[J]. *Physical Review E*, 2004, **70**(6): 5603-5606.

[5] CHEN J S Y, WONG G K L, MURDOCH S G, *et al*. Cross-phase modulation instability in photonic crystal fibers[J]. *Optics Letters*, 2006, **31**(7): 873-875.

[6] GONG Y D, SHUM P, TANG D Y, *et al*. 660GHz solitons source based on modulation instability in a short cavity[J]. *Optics Express*, 2003, **11**(20): 2480-2485.

[7] SHI P M, YU S, LIU T, *et al*. Analytical investigation of modulation instability in a fiber Bragg grating[J]. *Optics Letters*, 2009, **34**(9): 1339-1341.

[8] HONG W P. Modulation instability of optical waves in the high dispersive cubic-quintic nonlinear Schrödinger equation [J]. *Optics Communications*, 2002, **213**(1-3): 173-182.

[9] DEMIRCAN A, BANDELOW U. Analysis of the interplay between soliton fission and modulation instability in supercontinuum generation[J]. *Applied Physics B*, 2007, **86**(1): 31-39.

[10] da DALT N, de ANGELIS C, NALESSO G F, *et al*. Dynamics of induced modulational instability in waveguides with saturable nonlinearity[J]. *Optics Communications*, 1995, **121**(1-3): 69-72.

[11] FATOME J, PITOIS S, MILLOT G. Measurement of nonlinear and chromatic dispersion parameters of optical fibers using modulation instability [J]. *Optical Fiber Technology*, 2006, **12**(3): 243-250.

[12] ZHONG X Q, XIANG A P. Generation of high-repetition-rate pulse trains through the continuous-wave perturbed by a weak pulse in an optical fibre[J]. *Chinese Physics Letters*, 2010, **27**(1): 4203-4207.

[13] ZHANG Hua, HAN Wen, WEN Shuang-chun, *et al*. Influence of stimulated raman scattering on modulation instability in single-mode fibers[J]. *Acta Photonica Sinica*, 2005, **34**(1): 32-37.

[14] MUSSOT A, KUDLINSKI A, LOUVERGNEAUX E, *et al*. Impact of the third-order dispersion on themodulation instability gain of pulsed signals[J]. *Optics Letters*, 2010, **35**(8): 1194-1196.

[15] ZHONG X Q, XIANG A P. Effects group-velocity mismatch an cubic-quintic nonlinearity on cross-phase modulation instability in optical fibers[J]. *Chinese Optics Letters*, 2007, **5**(9): 534-537.

[16] HAO R Y, LI L, LI Z H, *et al*. A new way to exact quasi-soliton solutions and soliton interaction for the cubic-quintic nonlinear Schrödinger equation with variable coefficients[J]. *Optics Communications*, 2005, **245**(1-6): 384-390.

五阶非线性光纤中连续谱相位扰动下的光传输与脉冲串产生

钟先琼,向安平,程科

(成都信息工程学院 光电技术学院,成都 610225)

摘　要:根据包含五阶非线性的扩展非线性薛定谔方程,数值研究了高斯型连续谱相位扰动而不是传统单色扰动下基于调制不稳定性的高重复率脉冲串产生.结果表明:脉冲串也能像传统情形那样形成,但却呈现出不同的特性.如脉冲数目有限,且各脉冲的高度、强度及间距不等.脉冲数目随传输距离增加而增加.而五阶非线性能使脉冲宽度和间距变小因而有利于高重复率脉冲串产生,负五阶非线性则相反.对脉冲串形成过程中演变啁啾的数值计算表明,啁啾及其随距离的变化都是高度非单调的,五阶非线性将改变啁啾的范围和量值.

关键词:五阶非线性;调制不稳定性;脉冲串