doi:10.3788/gzxb20164505.0506002

光纤中短间距脉冲串的非线性传输特性与混沌孤子波包产生

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摘 要:采用分步傅里叶算法,在基元脉冲数分别为9、17和25及相邻基元脉冲时间间隔分别为1、2及3的情况下,对短间隔脉冲串在光纤负色散区的非线性传输特性进行数值研究.研究结果表明,尽管脉冲数、脉冲位置、脉冲强度和相邻两脉冲间的时间间隔随距离变化,且在传输过程中弱脉冲基座会扩展到很宽的时间范围,但是整个主脉冲波包始终保持局域即其时间间隔几乎不变,展宽速度不明显.同时,主脉冲波包永不重复前面的轮廓,即波包演化出现混沌行为.短间隔脉冲串的非线性演化可以形成混沌孤子波包,基元脉冲间的时间间隔及脉冲串的脉冲数都会影响混沌孤子波包的子脉冲数和它的持续时间.

关键词:混沌孤子波包;短间距脉冲串;非线性传输特性;混沌;孤子
中图分类号:O437 **文献标识码**:A **文章编号**:1004-4213(2016)05-0506002-10

Nonlinear Propagation Characteristic of the Short-Interval Pulse Trains and Chaotic Soliton Wavepacket Generation in Optical Fibers

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Abstract: The nonlinear propagation characteristic of the short-interval pulse trains in the anomalous dispersion regions of optical fibers was investigated numerically by adopting split-step Fourier algorithm for time intervals between two adjacent elementary pulses respectively being 1, 2, and 3, and number of elementary pulses being 9, 17, and 25. The results indicate that, although the pulse number, pulse position, pulse intensities, and the time interval between two adjacent pulses, may vary with distance, and although the weak pulse pedestal may extend to very wide temporal range during propagation, the whole main wavepacket all along maintains localized with their temporal duration being nearly unchanged instead of broadening obviously and rapidly. What is more, the main pulse wavepacket never repeats its previous profile, which means that the wavepacket evolution exhibits chaotic behavior. Thus, in this sense, the nonlinear evolution of short-interval pulse trains can cause the chaotic soliton wavepacket generation. Both the elementary pulse time interval and pulse number of the pulse trains affect the chaotic soliton wavepacket in terms of its sub-pulse number and especially its temporal duration.

Key words: Chaotic soliton wavepackets; Short-interval pulse trains; Nonlinear propagation characteristics; Chaotic; Soliton
OCIS Codes: 060.0060; 190.4370; 190.5530; 290.5910

Foundation item: The Key Project of Science and Technology of the Ministry of Education (No. 210186) and the Major Project of Natural Science Supported by the Educational Department of Sichuan Province (Nos. 13ZA0081, 12ZB09)

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Received: Nov. 6, 2015; **Accepted**: Feb. 2, 2016

0 Introduction

As is well known, optical solitons[1-2] or optical solitary[3-4] waves are optical localized structures which result from the balance among nonlinearity and dispersion in temporal domain, nonlinearity and diffraction in spatial domain, or nonlinearity, dispersion, and diffraction in spatiotemporal domain, which respectively corresponds to temporal-domain solitons[5-6], spatial-domain solitons[7-10], and spatiotemporal domain solitons (or light bullets)[11-13]. It is worth mentioning that, in the strict sense, optical solitons should all along maintain their profiles in terms of their pulse shapes, pulse durations, and pulse spectra during propagation. Obviously, only minority of optical solitons can rigorously satisfy this hard condition. For instance, typical strict optical solitons are the familiar fundamental bright fiber solitons with hyperbolic-secant shapes or dark fiber solitons with hyperbolic tangent shapes. Up to now, however, solitons have gone far beyond their initial meanings and been extended considerably. More and more generalized solitons have been revealed analytically, numerically, or experimentally. For instance, the higher-order bright fiber solitons exhibit breather behavior, which means that they will periodically evolve with original shapes recovery at every soliton period. Another interesting category of solitons called similaritons can maintain their overall shapes but with their widths and amplitudes changing with the distance, which are reported to be able to occur in dispersion-managed optical fibers[14], fiber lasers and fiber amplifiers[15-16], or nonlinear planar waveguide amplifiers[16-17]. Moreover, similaritons may be asymptotic[14, 16, 18] or exact[16, 19], temporal[14-16] or spatial[16], bright[15-16] or dark[14]. Besides similaritons, previous reports have revealed that there still exist a rich variety of dissipative optical solitons in mode-locked lasers[20-23], some of which are beneficial to generate high-energy high-quality laser pulses without wave breaking. Of course, the dissipative optical solitons may be similaritons.

So far, the nonlinear optical propagation in optical fibers has been extensively studied for different contexts. As different initial conditions, a variety of initial temporal light profiles typically including Gaussian, super-Gaussian, hyperbolic-secant, hyperbolic tangent, sine modulated continuous optical wave, soliton trains, and etc., are adopted to investigate their nonlinear propagation evolutions[24-25]. In terms of soliton trains, however, people pay much more attention to the nonlinear propagation of soliton pairs. Only minority of reports involve the three-, four-, five-, and six-solitons[25]. In optical soliton communication systems, however, there are generally pulse trains consisting of multi-solitons. Thus, it is of practical importance for investigation on the nonlinear propagation of pulse trains consisting of multi-pulses. So far, it is generally thought that the short-interval pulses consisted pulse trains will cause intense interaction among adjacent elementary pulses and result in detrimental effects on the communication performance. However, our study in this work indicates that, the short-interval pulse trains can evolve into chaotic soliton wavepacket, which manifests as maintaining localized during propagation with their temporal duration being nearly unchanged instead of broadening obviously and rapidly despite the fact that the pulse number, pulse position, pulse intensities, and the time interval between two adjacent pulses, may vary with distance. And the main pulse wavepacket never repeats its previous profile. This interesting chaotic evolution behavior of the short-interval pulse trains may be of potential application in chaotic soliton communication.

1 Theory model

The well-known standard nonlinear Schrödinger equation governing the optical pulse propagation in the anomalous dispersion region of the ordinary single-mode optical fiber with circular waveguide is of the following normalized form

$$\mathrm{i}\frac{\partial U}{\partial \xi}+\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2}+N^2|U|^2U=0 \tag{1}$$

where U, τ, and $\xi = z / L_{\mathrm{D}}$ are respectively the normalized amplitude of the optical field, normalized time, and normalized distance. L_{D}, z, and N, are respectively dispersion length of the fiber, propagation distance, and soliton order number.

The incident short-interval pulse trains are assumed to be written as

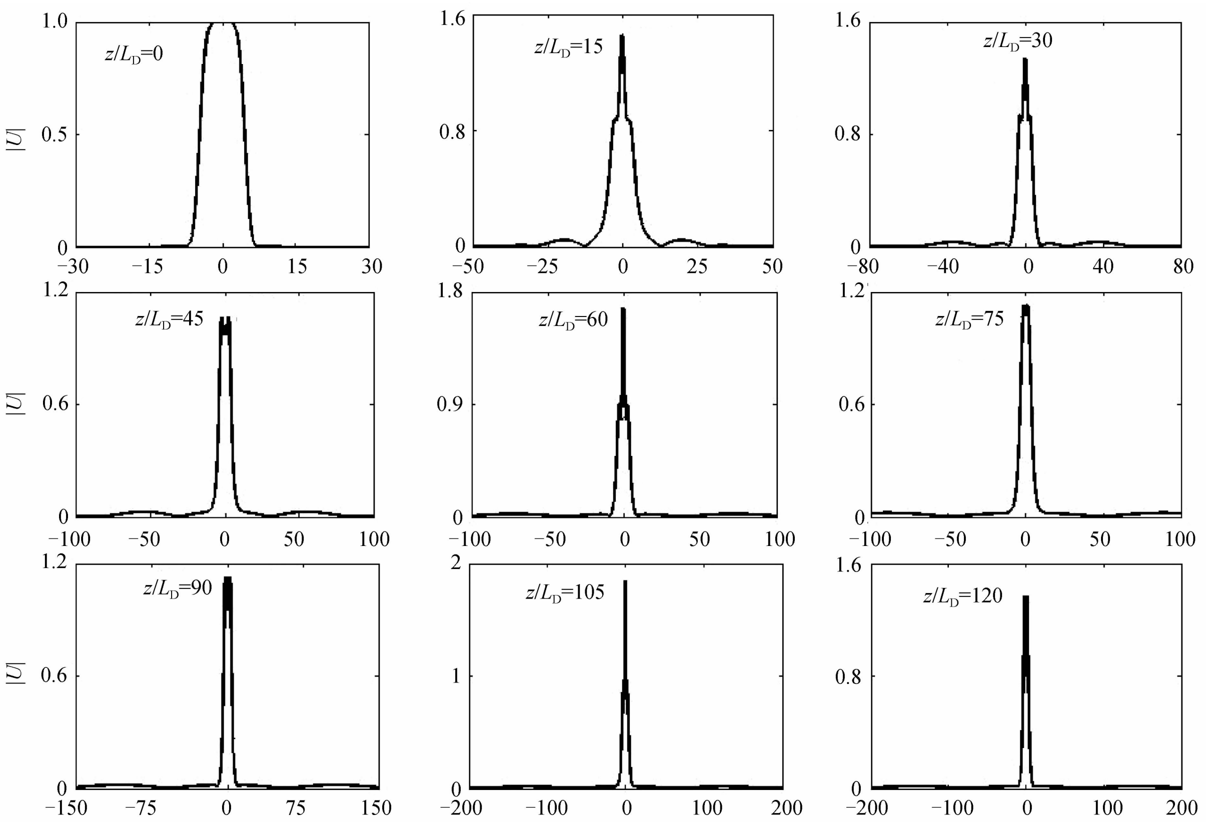
$$U(\tau,\xi=0)=u(\tau)/\mathrm{Max}\{u(\tau)\} \tag{2}$$

$$u(\tau)=\sum_{m=-n}^{n}\exp\left[-\frac{(\tau-m\tau_0)^2}{2}\right] \tag{3}$$

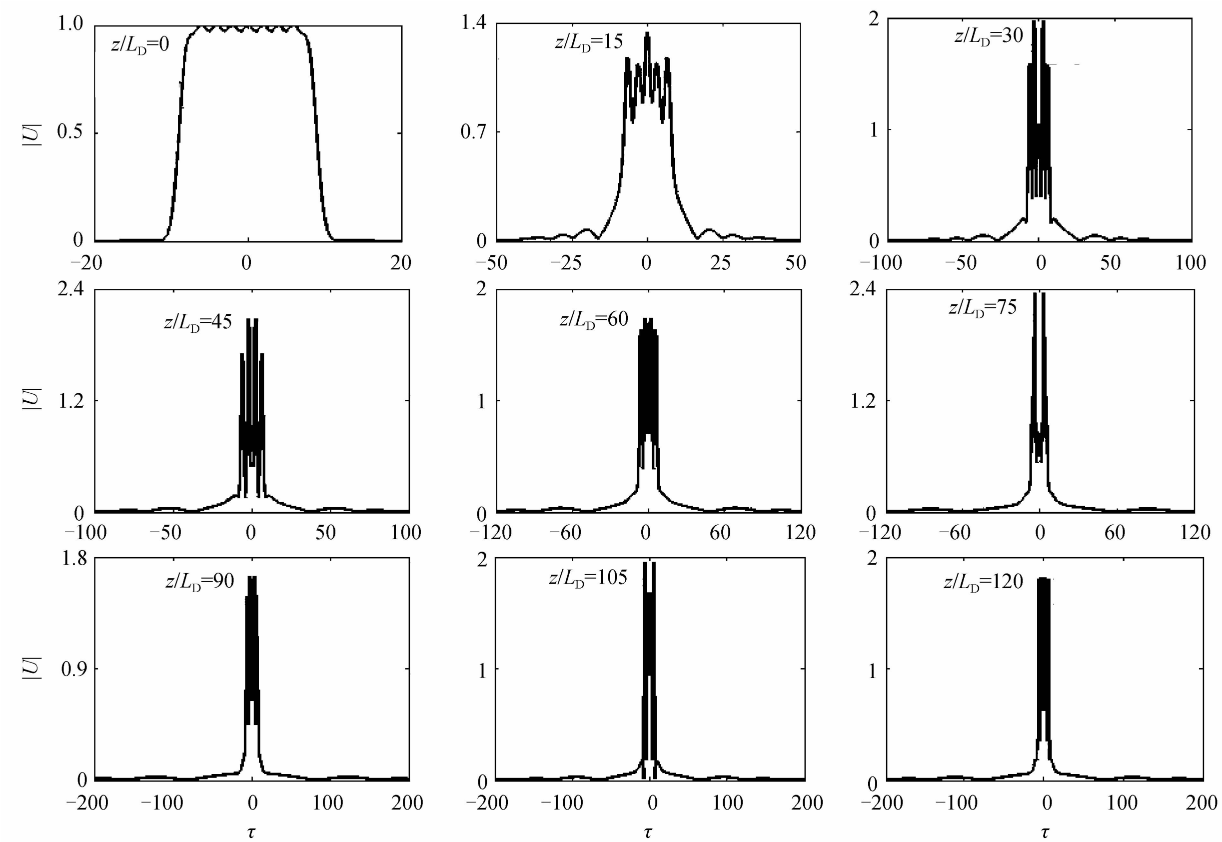
Namely, the incident pulse trains here is constructed by combining $2n+1$ elementary Gaussian pulses. Where m is the sequence number of the elementary pulse and τ_0 the time interval between two adjacent elementary pulses. The function Max represents taking the maximal value. The expression of Eq. (2) is quite similar to but different from those of the stacking pulses[26-28]. For the general stacking pulses, there exist frequency chirps and relative phase delays among elementary pulses. Previous reports investigated the nonlinear propagation of these general stacking pulses but only limited to the short-distance case. Here, we will study the long-distance nonlinear propagation of short-interval pulse trains which are simply combined by elementary Gaussian pulses and have no frequency chirps and relative phase delays among elementary pulses. According to Eq. (2), Eq. (1) can be numerically solved to investigate the evolution dynamics of the short-interval pulse trains by utilizing the split-step Fourier algorithm.

2 Calculations and discussions

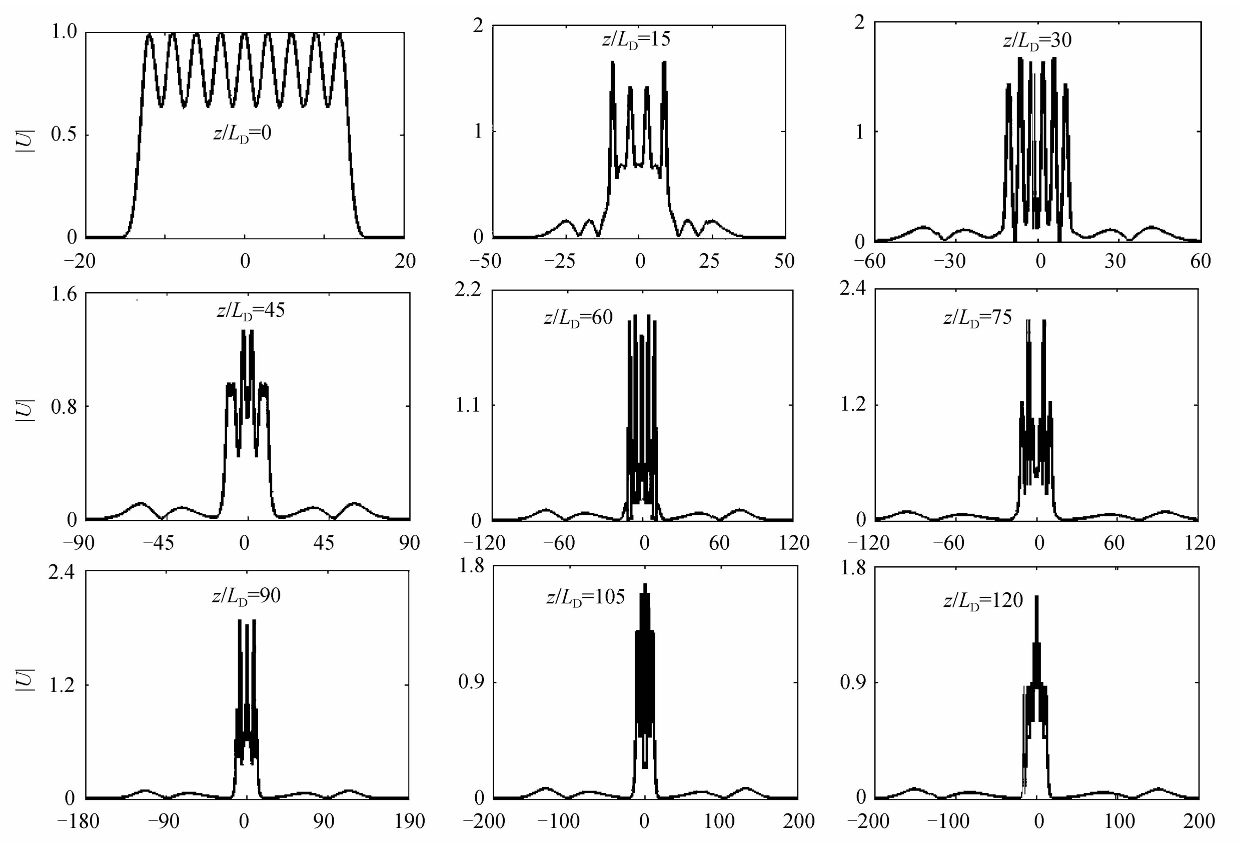
The typical optical fiber parameters in our calculation are set as the following. The group-velocity dispersion coefficient, the third-order nonlinear coefficient, the effective mode field area, the effective nonlinear refractive coefficient, and the wavelength of the optical carrier wave, are respectively $\beta_2=-20\ \mathrm{ps}^2\cdot\mathrm{km}^{-1}$, $\gamma=2\ \mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$, $A_{\mathrm{eff}}=60\ \mu\mathrm{m}^2$, $n_{2\mathrm{eff}}=2.96\times10^{-20}\ \mathrm{m}^2\cdot\mathrm{W}^{-1}$, and $\lambda_0=1.55\ \mu\mathrm{m}$. Numerical calculated temporal evolutions of short-interval pulse trains for different parameters n and τ_0 are displayed in Fig. 1. It is easy to infer that, when the parameter n is fixed, small τ_0 corresponds to smooth or flat pulse top and narrow temporal duration. Conversely, larger τ_0 corresponds to modulated peak structures appearing on the pulse top and wider pulse temporal duration. When the parameter τ_0 is fixed, larger n corresponds to more elementary pulses and naturally results in wider pulse temporal duration. These characteristics can be clearly seen in every first sub-figure in Fig. 1. Thus, changing parameters n and τ_0 can construct different short-interval pulse trains with different shaped pulse top and pulse temporal duration. Fig. 1 still indicates that, during propagation, the initial short-interval pulse trains may distort, break, combine, and generate weak pedestals on both sides of the pulse. With increase of distance, the evolved pulse wavepacket may vary in terms of the number, positions, intensities, and durations of the formed sub-pulses. For most cases, these formed sub-pulses are not separated completely but manifest as modulational multiple-peak structures superimposing on a higher intensity background. This is the reason why we call the evolved pulse profile the wavepacket. Besides, on the leading and trailing edges of the pulse, the pedestal may appear. It will stretch with the distance and make the pulse wavepacket extend to wide temporal range. However, in comparison with the central main wavepacket, the pedestal is very weak and can be ignored. In addition, larger n or τ_0 corresponds to resulting in more sub-pulses generations and wider temporal range.



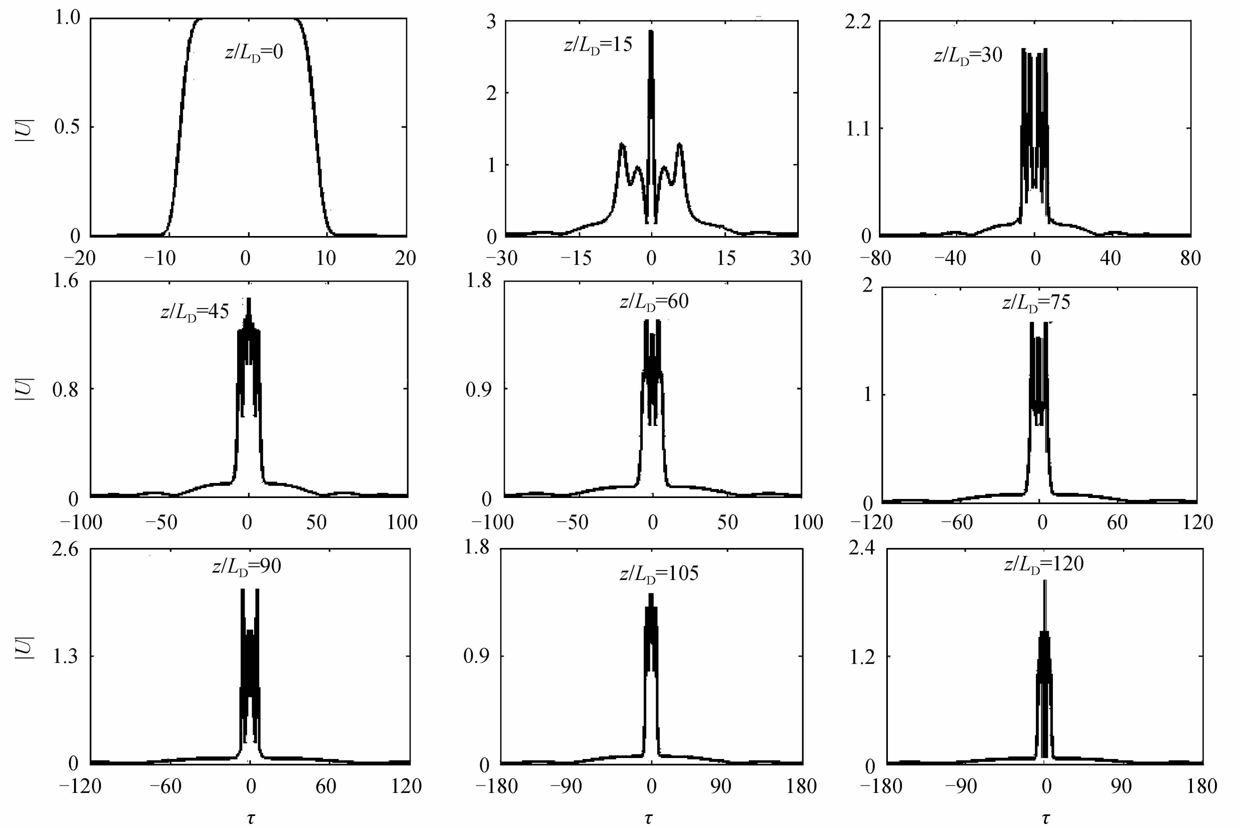
(a) $n=4$ $\tau_0=1$



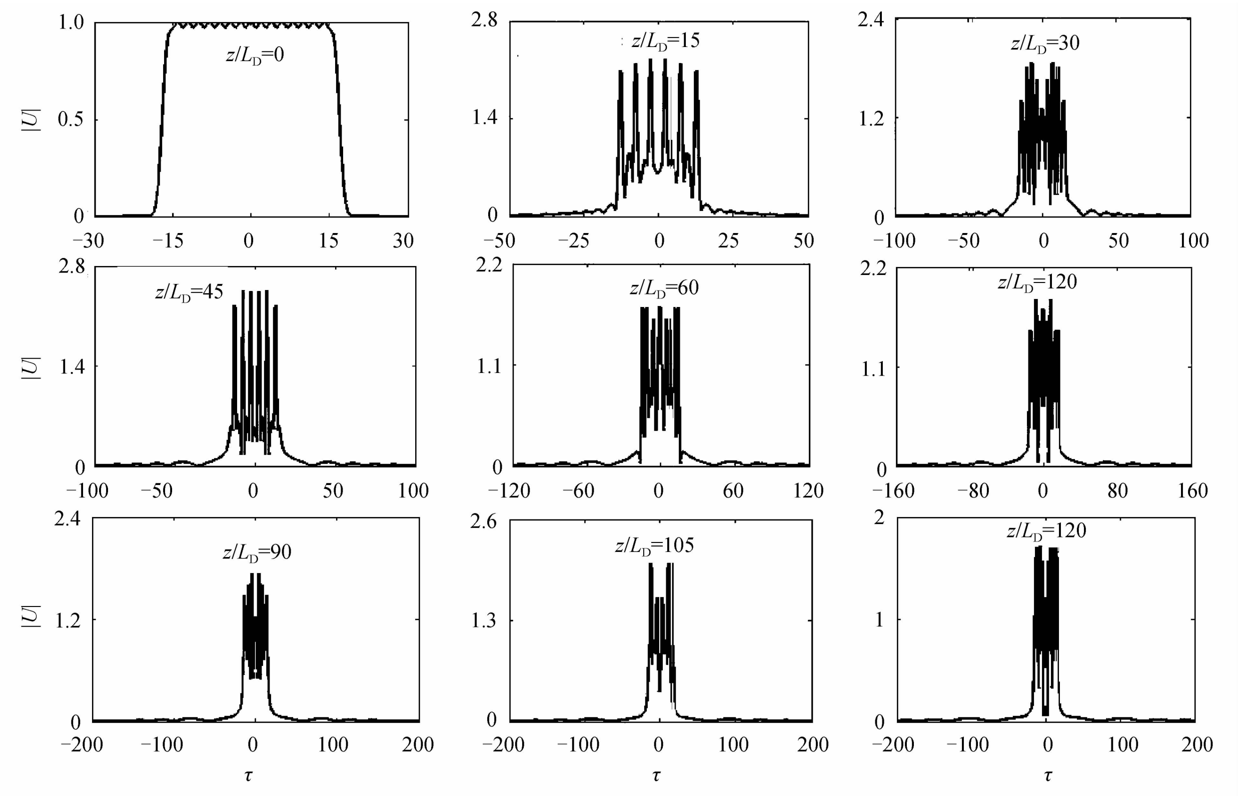
(b) n=4　　τ_0=2



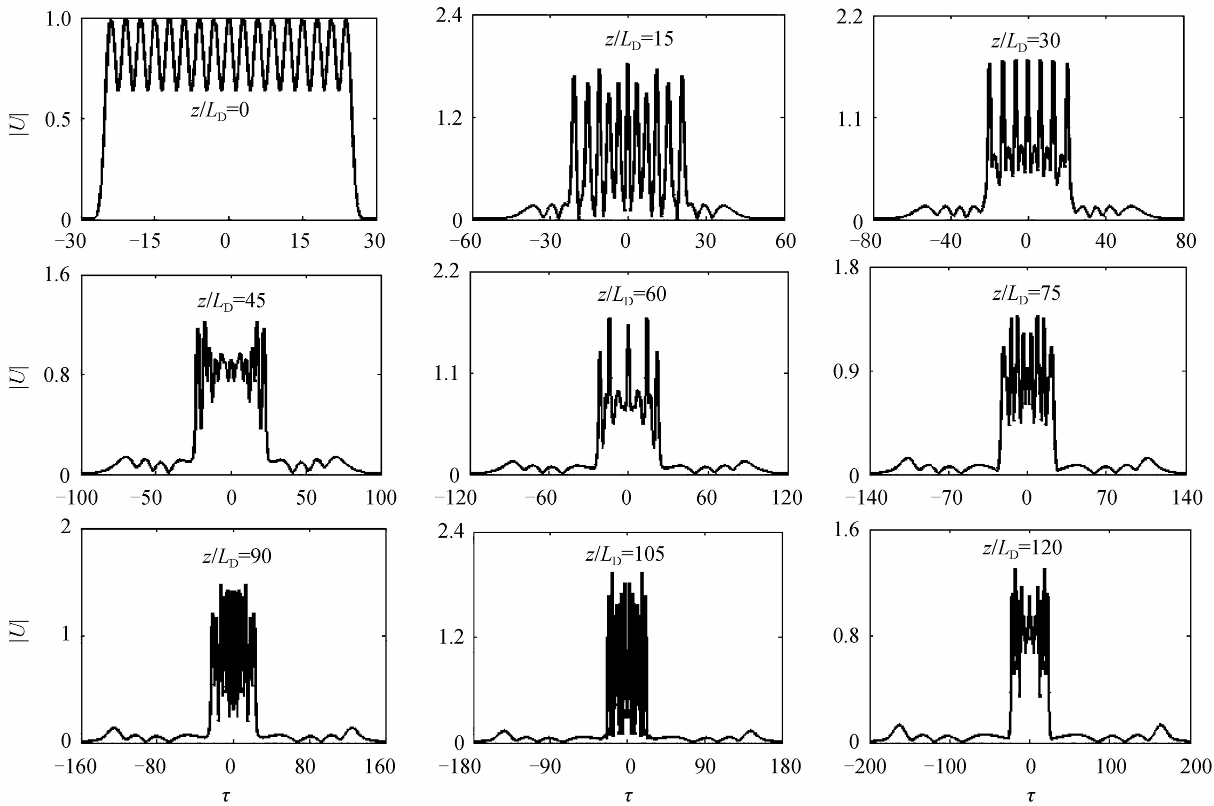
(c) n=4　　τ_0=3



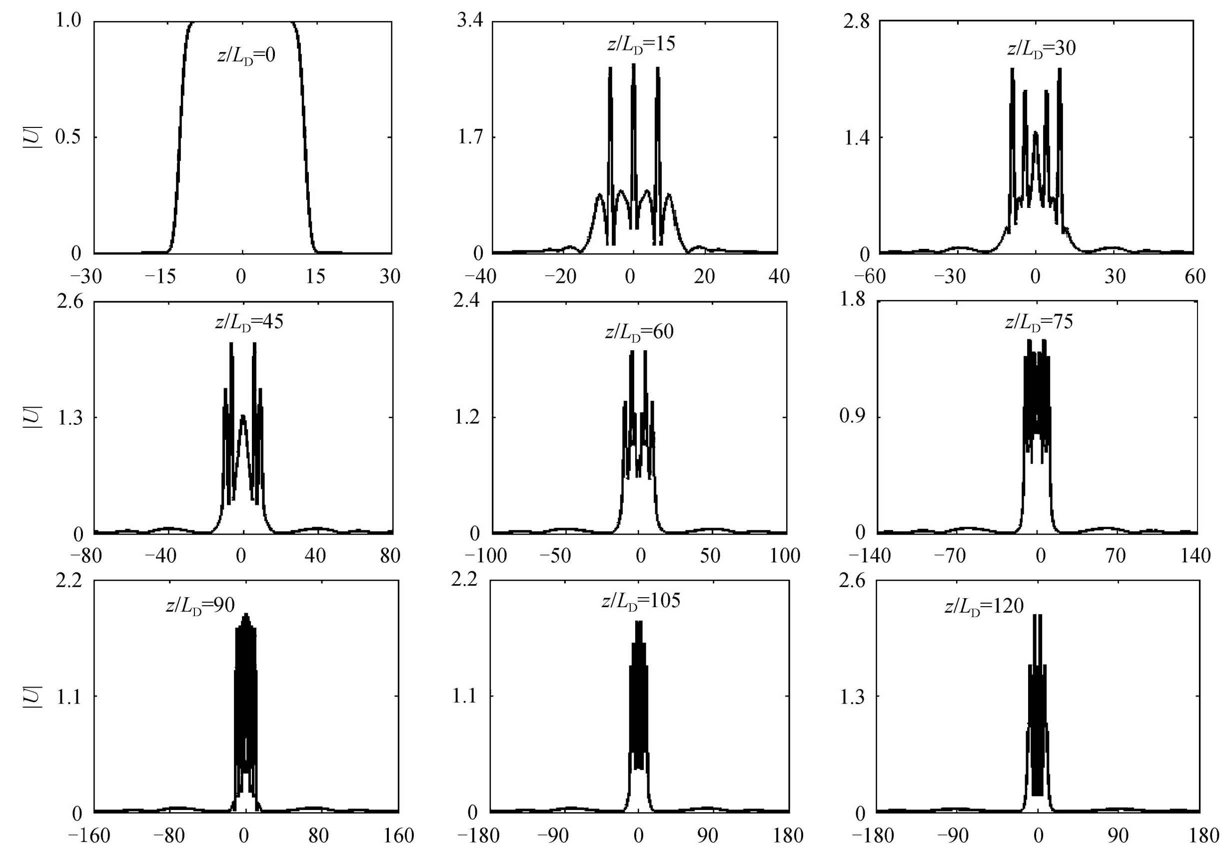
(d) n=8 τ_0=1



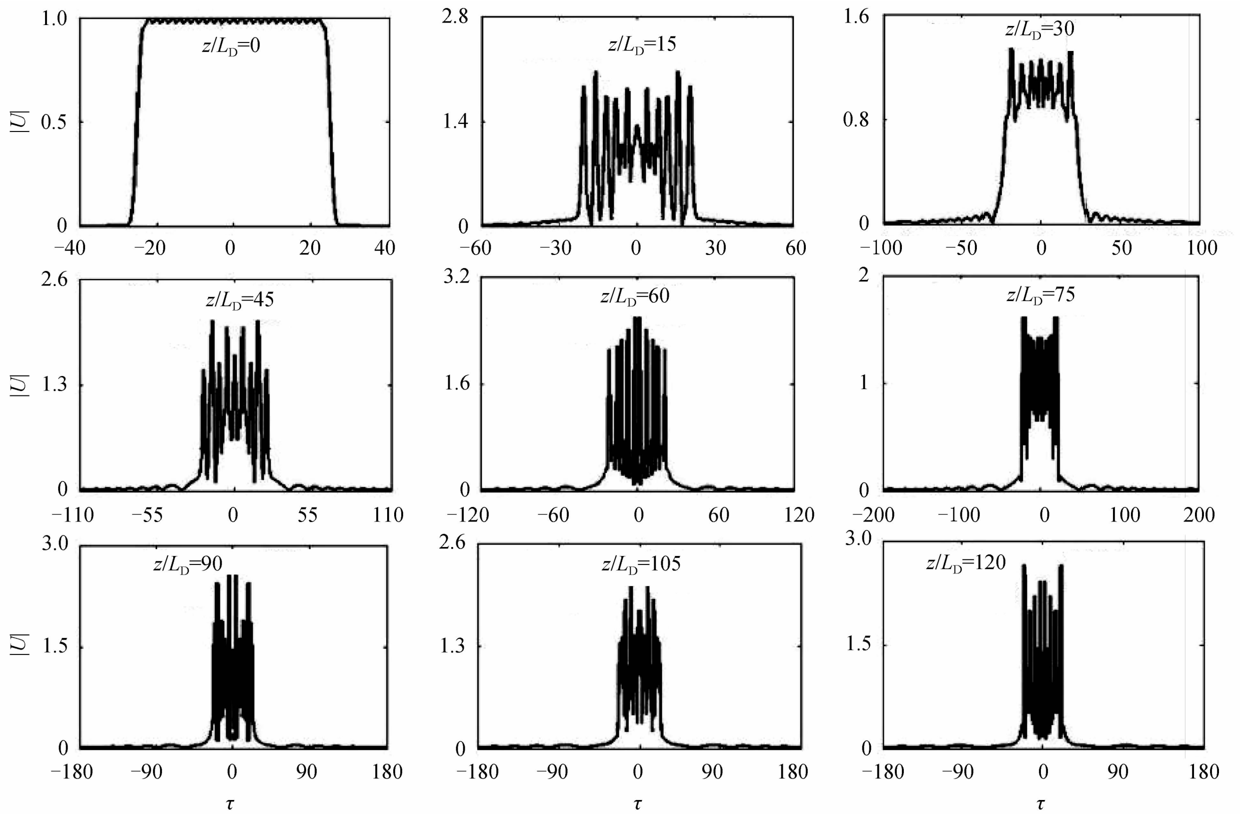
(e) n=8 τ_0=2



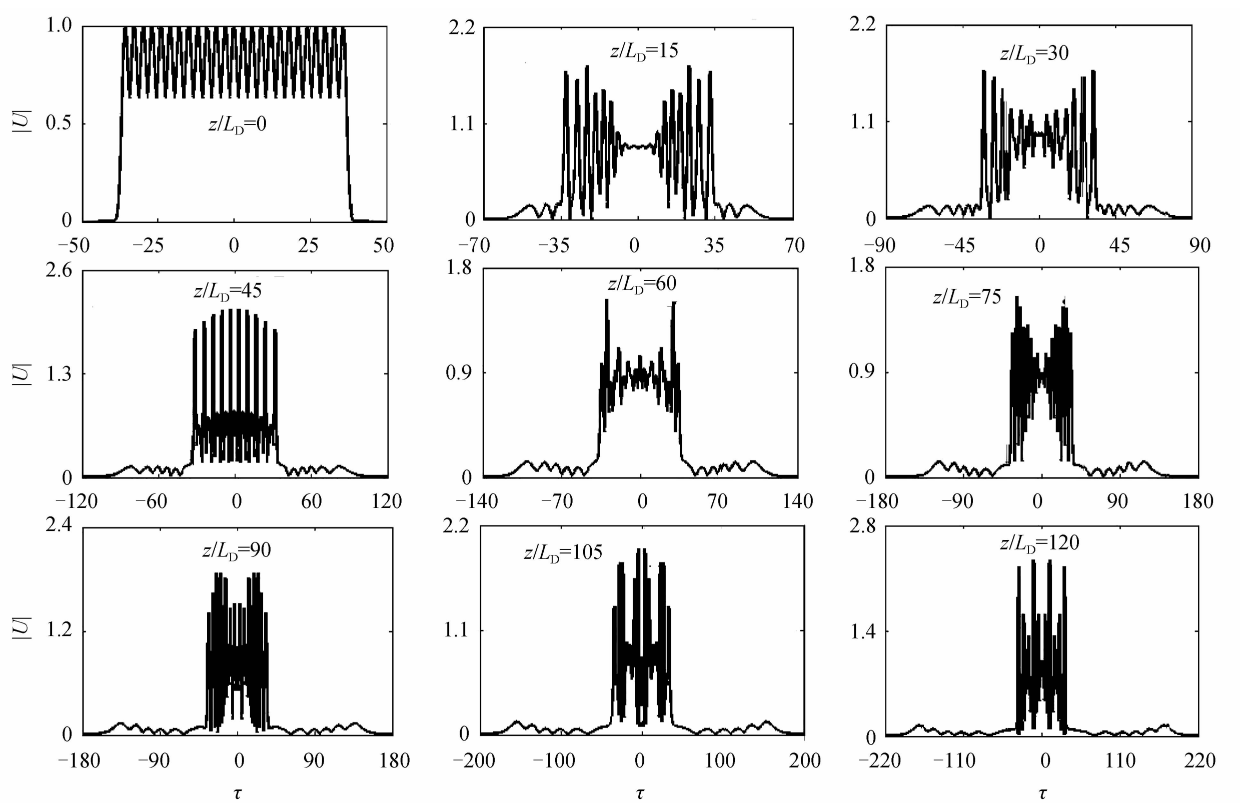
(f) n=8　　τ_0=3



(g) n=12　　τ_0=1



(h) n=12 τ_0=2



(i) n=12 τ_0=3

Fig. 1 Two dimensional temporal evolutions of the short-interval pulse trains for different parameters n and τ_0

In order to observe more clearly the total evolution tendencies of the short-interval pulse trains, the contour maps of temporal evolutions of the short-interval pulse trains for different parameters n and τ_0 are further presented in Fig. 2. From Fig. 2, those characteristics just mentioned above can be seen once

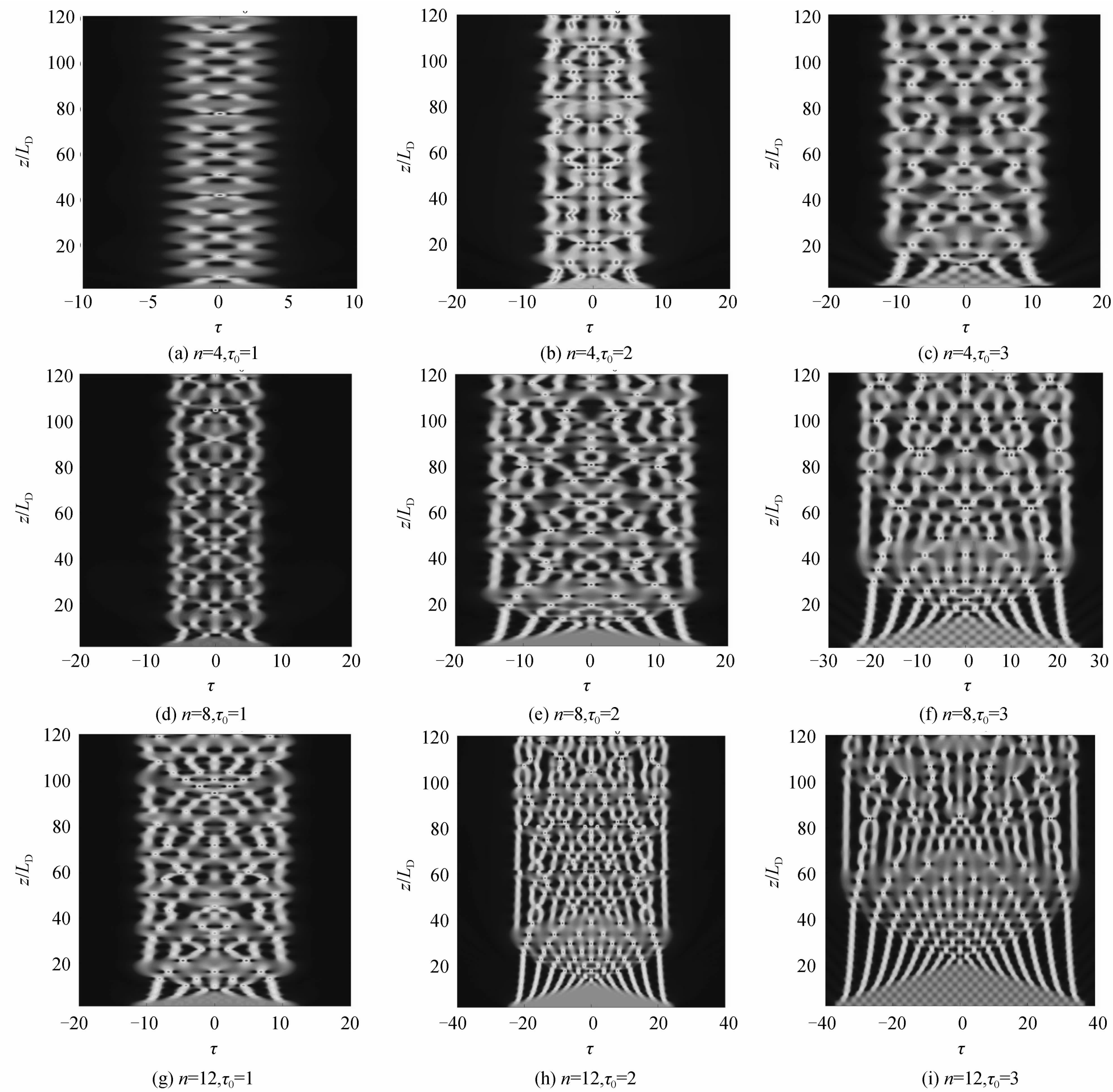


Fig. 2 Contour maps of temporal evolutions of the short-interval pulse trains for different parameters n and τ_0

more. Moreover, Fig. 2 still indicates that, the main pulse wavepackets obviously exhibit quasi-breather behaviors. Being different from the familiar higher-order bright fiber solitons, however, the evolved main pulse wavepackets here never repeat their previous profiles. This important characteristic means that the evolved main pulse wavepackets have become chaotic. Despite this, the main wavepackets all along maintain localized instead of broadening obviously and rapidly. In this sense, we thus say that the chaotic soliton wavepacket generates. Depending on different propagation distance and different parameters n and τ_0, the chaotic soliton wavepacket may contain one, two, or even more sub-pulses. These propagation characteristics and chaotic soliton wavepacket generation also apply to those pulse trains with more elementary pulses.

The physical mechanism of the chaotic soliton wavepacket generation can be interpreted by utilizing phenomenological method to some extent. The chaotic soliton wavepacket generation may reflect the intrinsic certain randomness of Eq. (1) described nonlinear dynamic system. Owing to the case that the initial short-interval pulse trains are not the solutions of the nonlinear dynamic equation, the system becomes very sensitive to the initial condition. Hence the initial pulse trains will adjust their shape profiles continuously during propagation. Through the interaction of anomalous dispersion and positive nonlinearity, the elementary pulses mutually attract and merge one moment but break and repel the next. However, owing to the large deviation of the initial pulse trains from the solution of Eq. (1), the adjusted pulse profile still deviates the equation solution. Then, as the new initial input, it adjusts itself during propagation and evolves to another adjusted but still deviated new shape profile. Every new shape profile never repeats its previous one. Moreover, instead of broadening continuously and rapidly, it all along remains localized. This adjustment and evolution process continues and ultimately leads to chaotic soliton wavepacket generation after long-distance propagation. However, it is worth mentioning that, not all of the initial pulses which deviate the equation solution can successfully evolve to chaotic soliton wavepackets. Taking Gaussian pulse for example, through continuously adjusting its pulse profile, it can approach the equation solution step by step and ultimately evolve to the hyperbolic secant soliton pulse. It may be because it has small deviation from the latter. Both of them have similar single-peak bell-shaped profiles. While the short-interval pulse trains here have quite different multiple-peak profiles and therefore deviate from the hyperbolic secant soliton profile too much.

3 Conclusions

Utilizing the split-step Fourier algorithm to solve the standard nonlinear Schrödinger equation, we have numerically calculated and obtained the long-distance nonlinear propagation evolution characteristics of the short-interval pulse trains in the anomalous dispersion regimes of optical fibers, for different time intervals between two adjacent elementary pulses and different number of elementary pulses. The results show that, the short-interval pulse trains do not broaden obviously and rapidly during propagation, they evolve into so-called chaotic soliton wavepackets instead. These chaotic soliton wavepackets manifest as never repeating their previous profiles but all along maintaining localized although they may vary in terms of the number, positions, intensities, and durations of their sub-pulses. Moreover, they may contain two or even more sub-pulses. Besides, it is worth mentioning that, varying the parameters n and τ_0 can effectively manipulate the chaotic soliton wavepackets in terms of their sub-pulse number and temporal ranges. This work may be of significance in enriching study on new types of chaotic optical solitons and of potential application in chaotic soliton communication.

References

[1] COLMAN P, HUSKO C, COMBRIÉS, *et al*. Temporal solitons and pulse compression in photonic crystal waveguides [J]. *Nature Photonics*, 2010, **4**(12): 862-868.

[2] LI J H, ROGERS C, CHOW K W, *et al*. Propagation of solitary pulses in optical fibers with both self-steepening and quintic nonlinear effects[J]. *Communications in Theoretical Physics*, 2014, **61**(6): 735-741.

[3] HAN M M, ZHANG S M, LIN X L, *et al*. Polarization dynamic patterns of vector solitons in a graphene mode-locked fiber laser[J]. *Optics Express*, 2015, **23**(3): 2424-2435.

[4] ZHAO L M, TANG D Y, ZHANG H, *et al*. Bunch of restless vector solitons in a fiber laser with SESAM[J]. *Optics Express*, 2009, **17**(10): 8103-8108.

[5] HASEGAWA A, TAPPERT F. Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. anomalous dispersion[J]. *Applied Physics Letters*, 1973, **23**(3): 142-144.

[6] ZHANG H, TANG D Y, ZHAO L M, *et al*. Vector dark domain wall solitons in a fiber ring laser[J]. *Optics Express*, 2010, **18**(5): 4428-4433.

[7] OUYANG S G, GUO Q. Dark and gray spatial optical solitons in Kerr-type nonlocal media[J]. *Optics Express*, 2009, **17**(7): 5170-5175.

[8] STEGEMAN G I, SEGEV M. Optical spatial solitons and their interactions: universality and diversity [J]. *Science*, 1999, **286**(5444): 1518-1523.

[9] ITURBE CASTILLO M D, CHAVEZ CERDA S, RAMIREZ MARTINEZ D. Splitting after collision of high-order bright spatial solitons in Kerr media[J]. *Optics Express*, 2014, **22**(25): 30769-30776.

[10] OUYANG S G, GUO Q, LAN S, *et al*. Conservation laws of the generalized nonlocal nonlinear Schrödinger equation [J]. *Chinese Physics*, 2007, **16**(8): 2331-2337.

[11] GURGOV H C, COHEN O. Spatiotemporal pulse-train solitons[J]. *Optics Express*, 2009, **17**(9): 7052-7058.

[12] GRELU P, SOTO-CRESPO J M, NAIL A. Light bullets and dynamic pattern formation in nonlinear dissipative systems [J]. *Optics Express*, 2005, **13**(23): 9352-9630.

[13] SOTO-CRESPO J M, GRELU P, AKHMEDIEV N. Optical bullets and "rockets" in nonlinear dissipative systems and their transformations and interactions[J]. *Optics Express*, 2006, **14**(9): 4013-4025.

[14] WU L, ZHANG J F, FINOT C, *et al*. Propagation of dark similaritons on the compact parabolic background in dispersion-managed optical fibers[J]. *Optics Express*, 2009, **17**(10): 8278-8286.

[15] KRUGLOV V I, AGUERGARAY C, HARVEY J D. Parabolic and hyper-Gaussian similaritons in fiber amplifiers and lasers with gain saturation[J]. *Optics Express*, 2012, **20**(8): 8741-8754.

[16] WU L, ZHANG J F, LI L, *et al*. Similaritons in nonlinear optical systems[J]. *Optics Express*, 2008, **16**(9): 6352-6360.

[17] CHEN S, YI L, GUO D, *et al*. Self-similar evolutions of parabolic, Hermite-Gaussian, and hybrid optical pulses: Universality and diversity[J]. *Physics Review E*, 2005, **72**(1): 016622.

[18] CHANG G, WINFUL H G, GALVANAUSLAS A, *et al*. Self-similar parabolic beam generation and propagation[J]. *Physics Review E*, 2005, **72**(1): 016609.

[19] PONOMARENKO S A, AGRAWAL G P. Optical similaritons in nonlinear waveguides [J]. *Optics Letters*, 2007, **32**(12): 1659-1661.

[20] LIU X M, WANG L R, LI X H, *et al*. Multistability evolution and hysteresis phenomena of dissipative solitons in a passively mode-locked fiber laser with large normal cavity dispersion[J]. *Optics Express*, 2009, **17**(10): 8506-8512.

[21] LIU X M. Numerical and experimental investigation of

dissipative solitons in passively mode-locked fiber lasers with large net-normal-dispersion and high nonlinearity[J]. *Optics Express*, 2009, **17**(25): 22401-22416.

[22] KALASHNIKOV V L. Chirped dissipative solitons of the complex cubic-quintic nonlinear Ginzburg-Landau equation [J]. *Physics Review E*, 2009, **80**(4): 046606.

[23] ZHU W L, HE Y J. Stability conditions for moving dissipative solitons in one- and multidimensional systems with a linear potential[J]. *Optics Express*, 2010, **18**(16): 17053-17058.

[24] AGRAWAL G P. Nonlinear Fiber Optics (3rd ed.)[M]. New York: Academic Press, 2001.

[25] WEI J P, JIANG X F, WANG J, *et al*. Characteristics of transmission for the solitons string based on simpson algorithm of modified symmetric split-step Fourier method [J]. *Acta Photonica Sinica*, 2015, **44**(1): 0119002.

[26] WANG Wen-long, TAN Chao, FU Xi-quan. Nonlinear propagation for stacked pulses by cross-phase modulation[J]. *Acta Photonica Sinica*, 2014, **43**(8): 0819003

[27] ZHOU Xiao-jun, ZHANG Zhi-yao, SUI Zhan, *et al*. Characteristics of nonlinear transmission of stacking chirped pulses in single-mode fiber[J]. *Acta Optica Sinica*, 2008, **28**(s): 159-163.

[28] WANG You-wen, CHEN Lie-zun, ZHANG Li-fu, *et al*. Characteristics of temporal modulation in nonlinear propagation of broad-band lases stacked by chirped pulses[J]. *High Power Laser and Particle Beams*, 2010, **22**(8): 1823-1828.