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Higher-order effects on self-similar parabolic pulse in the microstructured fibre amplifier*

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By considering higher-order effects, the properties of self-similar parabolic pulses propagating in the microstructured fibre amplifier with a normal group-velocity dispersion have been investigated. The numerical results indicate that the higher-order effects can badly distort self-similar parabolic pulse shape and optical spectrum, and at the same time the peak shift and oscillation appear, while the pulse still reveals highly linear chirp but grows into asymmetry. The influence of different higher-order effects on self-similar parabolic pulse propagation has been analysed. It shows that the self-steepening plays a more important role. We can manipulate the geometrical parameters of the microstructured fibre amplifier to gain a suitable dispersion and nonlinearity coefficient which will keep high-quality self-similar parabolic pulse propagation. These results are significant for the further study of self-similar parabolic pulse propagation.

Keywords: self-similar parabolic pulse, microstructured fibre amplifier, higher-order dispersion, nonlinear effect
PACC: 4281, 4281D

1. Introduction

Recently, a chirped pulse with a parabolic intensity profile has been generated in a nonlinear optical fibre amplifier with normal group-velocity dispersion (GVD). The parabolic pulse has unique attractive features such as resistance to optical wave breaking, self-similarity in shape, and enhanced linearity of chirp.[1−10] The remarkable properties of self-similar parabolic pulse lead to a number of applications such as highly efficient pulse compression,[5,8,11] pulse synthesis,[12] high-power ultrashort fibre laser,[13] and the optical amplifier.[14]

To date, these studies of self-similar parabolic pulse generation and propagation have been represented in conventional fibre amplifiers.[4,9,12,14,15] However, microstructured fibre amplifier (MFA) exhibits a novel structure that can easily control the normal GVD and nonlinearity coefficient, which are responsible for self-similar parabolic pulse generation and propagation.[16−18] As ultra-short pulses propagate in MFA, higher-order effects on pulse propagation become obvious. According to investigations, no paper, which is related to theoretical and experimental studies of higher-order effects, has been reported. In this paper, based on generalized nonlinear Schrödinger (GNLS) equation, higher-order effects on self-similar parabolic pulse propagation are discussed in a MFA with normal GVD. Numerical results show that the higher-order effects greatly change the self-similar parabolic pulse shape and distort the optical spectrum and damage the linearity of chirp. Different higher-order effects on self-similar parabolic pulse propagation are also analysed. When the geometrical parameters of the MFA are changed suitably, higher-order effects can be controlled and high-quality self-similar parabolic pulse propagation is kept.

2. Theoretical model

The special geometrical structure of MFA allows us to establish a well-defined procedure to design specific predetermined dispersion and nonlinearity.[17−21] The definition of the dispersion coefficient is $D = -\frac{\lambda}{c}\frac{\mathrm{d}^2 n_{\mathrm{eff}}}{\mathrm{d}\lambda^2}$, $n_{\mathrm{eff}} = n_{\mathrm{eff}}\left(\frac{r}{\lambda}, \frac{\Lambda}{\lambda}\right)$ is the effective refractive index of the mode, with r being air-hole radius, and Λ the hole to hole spacing; the nonlinearity co-

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efficient is $\gamma = 2\pi n_2/\lambda A_{\rm eff}$, with n_2 (2.2×10^{-20}–$3.4\times10^{-20}{\rm m}^2\cdot{\rm W}^{-1}$) being the nonlinear refractive index, $A_{\rm eff}$ the effective cross section area. Therefore, we can manipulate the geometrical parameters of the fibre and design a proper geometry to attain suitable dispersion and nonlinearity coefficients which are fit for self-similar parabolic pulse propagation.

Considering the characteristic of the MFA and ultra-short input pulse, the theoretical model must include all higher-order effects: third-order dispersion (TOD), self-steepening (SS), and intrapulse Raman scattering (IRS), so our simulations are based on the GNLS equation[22]

$$\frac{\partial A(z,t)}{\partial z} + {\rm i}\frac{\beta_2\partial^2 A(z,t)}{2\partial t^2} - \frac{\beta_3\partial^3 A(z,t)}{6\partial t^3} - \frac{g_0}{2}A(z,t)$$
$$= {\rm i}\gamma\left[|A(z,t)|^2A(z,t) + \frac{\rm i}{\omega_0}\frac{\partial}{\partial t}(|A(z,t)|^2A(z,t)) - \tau_{\rm R}A(z,t)\frac{\partial|A(z,t)|^2}{\partial t}\right]. \quad (1)$$

Here, $A(z,t) = |A(z,t)|\exp({\rm i}\phi(z,t))$ is the pulse envelope in a co-moving frame. Chirp[22,23] is $\delta\omega(t) = -\dfrac{\partial\phi(z,t)}{\partial t}$, β_2 is normal GVD, β_3 is TOD, g_0 is gain coefficient. SS is correlative to ω_0 (carrier frequency) and T_0 (pulse width), $\tau_{\rm R}$ governs IRS, when the geometrical parameters are varied, dispersion and nonlinearity coefficients change accordingly.

3. Numerical simulation results

The GNLS equation is solved by split-step Fourier method, with normalized length (L)=10, g_0=0.48 ${\rm m}^{-1}$, $T_{\rm R}$=2.8fs; for the input field a Gaussian pulse with λ_0=1550nm, T_0 =0.18ps, E_0=90pJ, representative dispersion and nonlinearity parameters are listed in Table 1.

Table 1. Dispersion and nonlinearity parameters.[20,21]

fibre	r/μm	Λ/μm	$\beta_2/({\rm ps}^2\cdot{\rm m}^{-1})$	$\beta_3/({\rm ps}^3\cdot{\rm m}^{-1})$	$\gamma/({\rm W}^{-1}\cdot{\rm m}^{-1})$
F_1	0.27	1.98	0.044	0.00154	0.0056
F_2	0.26	1.82	0.057	0.0008	0.0023

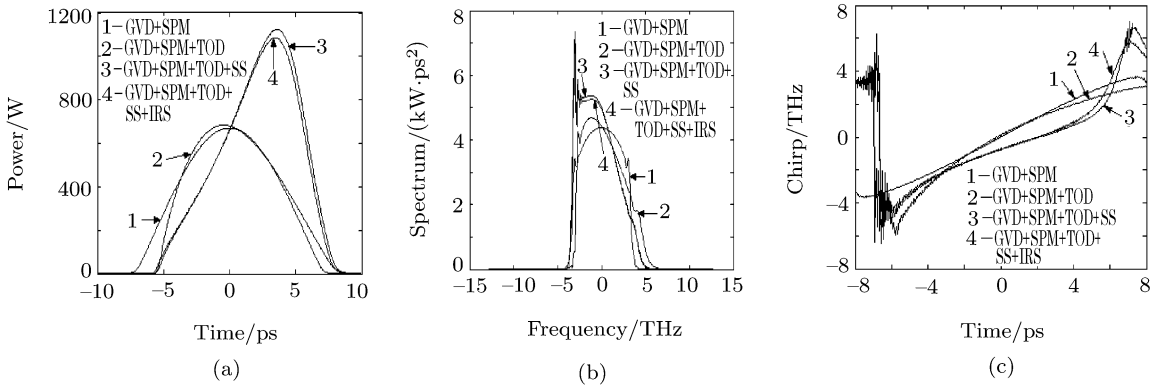


Fig.1. Waveform (a), frequency (b) and chirp (c) evolution of self-similar parabolic pulse in MFA (F_1) for different higher-order effects.

Figure 1 depicts the waveform (a), frequency (b) and chirp (c) evolution of self-similar parabolic pulse in MFA (F_1) as there exist different higher-order effects. They all lead to pulse distortion compared with curve 1, which ignores higher-order effects. Figure 1(a) shows that TOD (curve 2) steepens the pulse-front and shifts the position of the peak a little left. In the case of SS (curve 3), it tilts pulse-front and steepens the back edge markedly. The peak occurs to right shift about 4 ps and the power sharply increases

about 500W. In view of IRS (curve 4), it reduces the peak energy and the position of the peak turns to a little left. Figure 1(b) shows that they all make spectrum asymmetric obviously; peak shift and oscillation appear. Considering SS (curve 3), the spectrum is very asymmetric and a sharp peak appears.

These phenomena can be explained from the point of view of chirp. As pulse intensity changes and peak power shifts, the pulse front is negative (red shift), while the back edge is positive (blue shift). Figure 1(c) indicates that higher-order effects cause chirp asymmetry and linearity to be lost. The chirp induced by GVD and self-phase modulation (SPM) is linear in a wide range, as shown in Fig.1(c) (curve 1). In view of TOD (curve 2), since its red shift is faster, the negative chirp is bigger, and the pulse front is steeper. Considering SS (curve 3), which results from GVD and pulse intensity, since the edge's speed is much faster than the peak's and blue shift is also much faster, the linearity is destroyed remarkably. The central chirp mainly shifts to the trailing edge and the positive chirp becomes much bigger and steeper according to the pulse distortion in Fig.1(a) (curve 3). In the case of IRS (curve 4), it reduces the value of positive chirp but turns to linearity for the red shift plays a more part. The Stokes components increase and the anti-Stokes decrease: that is, they continuously transfer energy from the blue part to the red part of the pulse spectrum. The energy transfer results in the centre frequency shift, thus the spectrum is asymmetric.

Since the higher-order effects destroy remarkably the self-similar parabolic pulse shape and the linear chirp, we must adjust the geometrical parameters and design a proper geometry to obtain suitable dispersion and nonlinearity coefficients for MFA (F_2). The simulation results are shown in Fig.2.

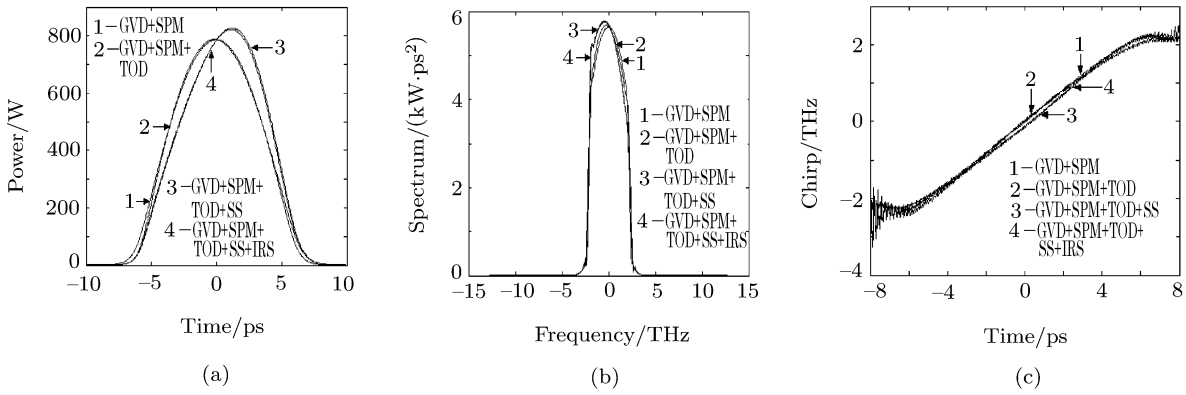


Fig.2. Waveform (a), frequency (b) and chirp (c) evolution of self-similar parabolic pulse in MFA(F_2) for different higher-order effects.

Comparing Fig.2 with Fig.1, we see that the higher-order effects have influence less on the pulse. Pulse shape turns out to be symmetric; optical spectrum is almost the same and highly linear chirp is achieved. SS still steepens the back edge a little for an input ultra-short pulse. This indicates that feasible normal GVD and nonlinearity can be attained to hold high-quality self-similar parabolic pulse propagation.

Then we change the normal GVD and nonlinearity coefficients in MFA (F_2). Figure 3 indicates that

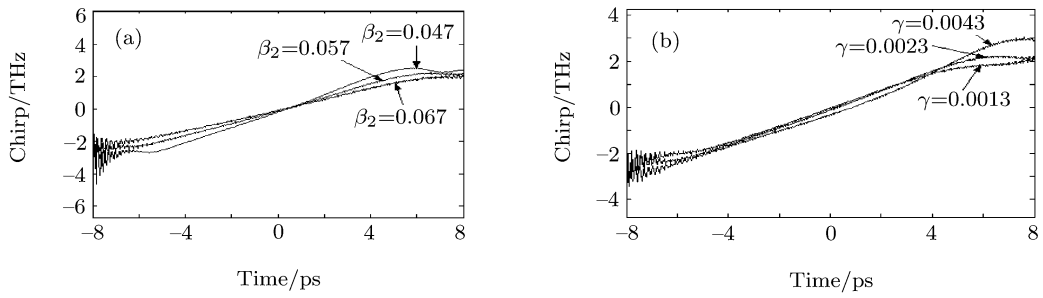


Fig.3. Chirp evolution of self-similar parabolic pulse for different normal GVDs (a) and different nonlinearity coefficients (b).

increasing normal GVD and decreasing nonlinearity coefficient can lead to high linear chirp. That is, relative high normal GVD and low nonlinearity coefficients are beneficial to high-quality self-similar parabolic pulse propagation, thus we can design a proper geometry to gain suitable dispersion and nonlinearity parameters.

4. Conclusion

In conclusion, we have considered higher-order effects on self-similar parabolic pulse propagation in MFA, and studied their influence on the waveform, the frequency and the chirp. Different higher-order effects on the pulse and chirp shape are different, while SS influences more strongly. Relative high normal GVD and low nonlinearity coefficients are helpful for obtaining high-quality self-similar parabolic pulse propagation. Suitable dispersion and nonlinearity coefficients can be gained by varying the MFA arrangement and symmetry. Our results are important for the future experimental and practical studies, such as highly efficient pulse compression, pulse synthesis, high-power ultra-short pulse fibre lasers and transmission systems.

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