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Parabolic pulse generation in short fiber amplifiers

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Abstract

The evolution of a laser pulse in a normal dispersion fiber amplifier is studied numerically. The cases of amplification with ideal spectrally flat gain and amplification with spectrally parabolic gain are considered. It is shown that the transformation of the input pulse envelope into parabolic form is possible, not only for spectrally flat but also for spectrally limited gain. In the last case, the important parameter is the optimal length of the amplifier. The results show that for a sufficiently broadband gain, it is always possible to find the optimal amplifier length, which provides the output pulse with envelope close to the parabola.

Keywords: fiber amplifiers, similaritons, parabolic pulses

(Some figures may appear in colour only in the online journal)

1. Introduction

The technology of pulsed fiber lasers and amplifiers is currently in demand for a wide range of applications: optical communication, material processing, medicine, etc [1, 2]. Urgent industrial needs in fiber systems delivering pulses of higher energy, peak power, and shorter pulse duration stimulate elaboration of new approaches to amplification and generation of laser pulses. Among the methods enthusiastically developed in recent decades, the concept of similariton (self-similar) parabolic laser pulses with linear frequency modulation is of particular interest [3]. Parabolic linear chirped pulses are very suitable for optical processing. They could be effectively compressed in temporal [4, 5] and spectral [6, 7] domains enabling pulses of high peak power and high spectral density.

A parabolic similariton is an asymptotic solution of the nonlinear Schrödinger equation (NSE) with a constant gain and positive dispersion coefficient [8]. Therefore, the parabolic pulses could be naturally generated in fiber amplifiers with normal dispersion, thus acquiring high energy without a critical wave-breaking causing the pulse destruction [9]. However, in contrast to the ideal case described by the NSE, in real amplifiers, the gain is not constant either along the spectrum (since the broadband of gain is limited) or along the length (due to the gain saturation). Although, the gain saturation has been shown not to destroy parabolic similariton generation [10], the spectral limitation of the gain line is always a critical factor. Indeed, the similariton spectrum width is proportional to $\sim E^{1/3}$ (E is the pulse energy) [3] and therefore, generation of high-quality and high power parabolic similariton pulses with the spectrum width comparable with the width of the gain spectrum is rather impossible.

A promising method of parabolic similariton generation in passive fibers with decreased normal dispersion [11] is not able to solve the problem. It is mainly due to the fact that generation of a parabolic envelope requires a long length of the passive fiber, where effects of higher order dispersions (mainly, third order dispersion (TOD)) on the pulse evolution are rather significant [12]. Important results on parabolic pulse generation in long (~1 km) Raman amplifiers based on nonuniform fibers have been reported [13] demonstrating that even in the case of a low and sufficiently broadband Raman amplification, limitations associated with TOD and finite gain line do not allow us to form high-quality parabolic pulses with energies higher than 1 nJ.

Generation of parabolic pulses has been intensively studied in recent years. In particular, generation of parabolic pulses in long (hundreds of meters long) nonuniform fiber amplifiers with compensation of TOD has been theoretically investigated in [14, 15]. However, the limited width of the gain spectrum has not been taken into account in these studies.

Here, in contrast to the previous works, we consider generation of parabolic similaritons in relatively short (no more than several meters long) fiber amplifiers. Practically, they could be thought of as amplifiers built from Yb or Er doped fibers with normal dispersion and strong pumping. In particular, we report on the method and algorithm of searching for the optimal amplifier parameters providing the maximal match of the output pulse to the parabolic similariton.

2. Basic equations

Let us consider an optic amplifier built from a fiber with normal group velocity dispersion (GVD). Signal propagation in such an amplifier is governed by the generalized Ginzburg–Landau equation [16] that describes evolution of the complex amplitude of the signal $A(z, t)$:

$$\frac{\partial A}{\partial z} - i\frac{\beta_2 - ig/\Omega_g^2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3} = i\gamma\left[|A|^2 A + \frac{2i}{\omega_0}\frac{\partial}{\partial t}(|A|^2 A) - T_R A\frac{\partial |A|^2}{\partial t}\right] + gA, \quad (1)$$

where z is the longitudinal coordinate, t is the time in the running reference frame, $\beta_2 > 0$ is the normal GVD coefficient, β_3 is the TOD, γ is the Kerr nonlinearity parameter, T_R is the Raman constant, g is the gain, and ω_0 is the carrier frequency. Equation (1) differs from the classical nonlinear Schrödinger equation (NSE) by the terms describing the gain spectrum in parabolic approximation with the gain line width Ω_g and the gain g that is assumed to depend on the fiber length through the gain saturation effect:

$$g = g_0\left(1 + \frac{\int |A(z, t)|^2 dt}{E_{sat}}\right)^{-1}. \quad (2)$$

Here, g_0 is the low signal gain, and E_{sat} is the saturation energy. The used fiber amplifier parameters are listed in table 1. The initial pulse is transform limited Gaussian pulse with the duration of $\tau = 0.3$ ps and peak power of $P = 100$ W. Numerical simulations of equation (1) have been performed with the use of split step Fourier method [16]. The root-mean square error of this method is proportional to Δl^2 (Δl is step size). For the value of $\Delta l = 10^{-3}$ m used in the work the root-mean square error is less than 0.01% for the amplifier length of less than 5 m. In the following sections, we consider a few limiting cases of the pulse evolution governed by equation (1).

3. Nonsaturated gain with flat spectrum

It is very helpful to compare our simulation results with theoretical predictions that could be derived from a simplified version of equation (1). We should note that the short amplifier length and relatively high second-order dispersion at the given amplified pulse parameters make contributions of TOD and higher nonlinearities negligible. Thus, equation (1) could be analyzed in the next shortened form

Table 1. Fiber amplifier parameters.

Parameter	Value
Nonlinearity coefficient γ, $W^{-1} \times km^{-1}$	6
GVD coefficient β_2, $ps^2\ km^{-1}$	50
TOD coefficient β_3, $ps^3\ km^{-1}$	0.2
Raman constant T_R, fs	3
Low signal gain g_0, m^{-1}	0.88

$$\frac{\partial A}{\partial z} - i\frac{\beta_2 - ig/\Omega_g^2}{2}\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A = gA. \quad (3)$$

The case of nonsaturated gain with flat spectrum corresponds to nonlinear Schrödinger equation with a constant gain (equation (3) with the limits $E_{sat} \to \infty$, $\Omega_g \to \infty$). It is well known that under these conditions the initial pulse of the energy E_{in} (in our case, $E_{in} \approx 75$ pJ) and of an arbitrary shape, asymptotically ($z \to \infty$), converges to a parabolic similariton form [3, 5, 8]:

$$A(z, t) = |A(z, t)|\exp(i\Phi(z, t)),$$
$$|A(z, t)| = A_0 \exp\left(\frac{2g}{3}z\right)\sqrt{1 - \frac{t^2}{t_p{}^2(z)}}, \quad |t| < t_p,$$
$$|A(z, t)| = 0, \quad |t| > t_p,$$
$$t_p = \frac{3\sqrt{\gamma\beta_2/2}}{g}A_0\exp\left(\frac{2g}{3}z\right), \quad A_0 = \frac{1}{2}\left(\frac{2gE_{in}}{\sqrt{\gamma\beta_2/2}}\right)^{\frac{1}{3}},$$
$$\Phi(z, t) = \varphi_0 + \frac{3\gamma A_0{}^2}{4g}\exp\left(\frac{4}{3}gz\right) - \frac{g}{3\beta_2}t^2. \quad (4)$$

The chirp of the asymptotic pulse is proportional to the gain and inversely proportional to the GVD: $\alpha = 2g/(3\beta_2)$. The similariton duration t_p increases exponentially with the length z. The spectrum width of the chirped pulse can be approximately estimated through the pulse duration at half of maximum τ_{FWHM} as $\Delta\Omega = \sqrt{(2\ln 2/\tau_{FWHM})^2 + (\alpha\tau_{FWHM})^2}$, so the spectrum width $\Delta\Omega \approx \alpha\tau_{FWHM} \propto \alpha t_p$ also enlarges exponentially with the amplifier length.

Figure 1 compares the simulation results (equation (1)) with the asymptotic solutions (equation (4)). At the beginning of the pulse amplification, the pulse shape significantly differs from the asymptotic parabolic pulse shape (figure 1(a)). However, after the pulse propagation over several meters of the amplifying fiber its further evolution follows expression (4) that is, in fact, a nonlinear attractor of the dynamic system (figure 1(b)). The misfit (MF) parameter M^2 [13, 17] shown in figure 1(c)

$$M^2 = \frac{\int [|\tilde{A}|^2 - |A|^2]^2 dt}{\int |\tilde{A}|^4 dt} \quad (5)$$

describes the difference between the simulated pulse shape $|\tilde{A}|^2$ and the analytical asymptotic shape $|A|^2$ (4). As can be

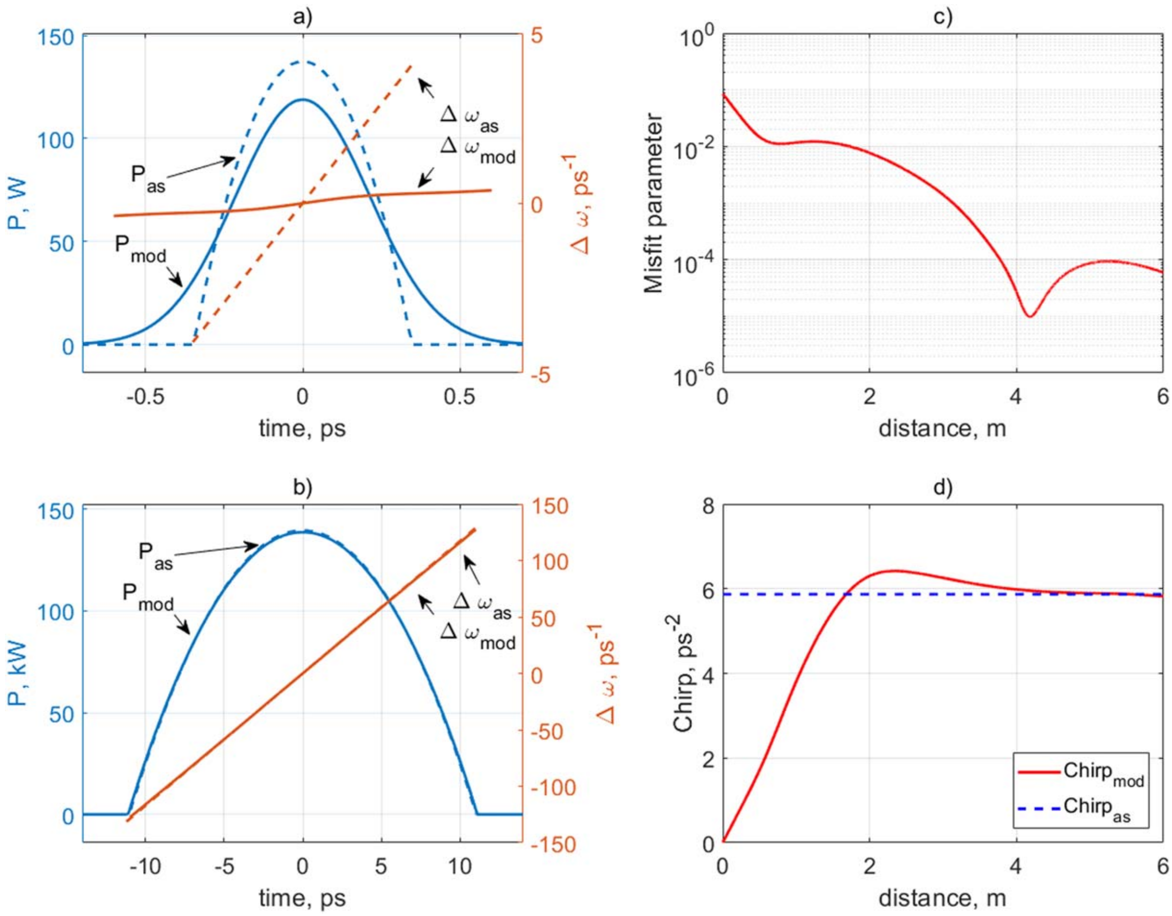

Figure 1. Nonsaturated gain with flat spectrum. The pulse shape ($P_{\rm as}$, $P_{\rm mod}$) and the pulse instantaneous frequency ($\Delta\omega_{\rm as}$, $\Delta\omega_{\rm mod}$) in the amplifier output. The amplifier length $L = 0.1$ m (a) and 6 m (b). The simulations of equation (1) ($P_{\rm mod}$, $\Delta\omega_{\rm mod}$) are solid lines, and calculations by equation (4) ($P_{\rm as}$, $\Delta\omega_{\rm as}$) are dashed lines. Evolution of MF parameter (c) and the pulse chirp (d) with the amplifier length, the simulation of equation (1) is solid line, the asymptotic limit $\alpha = 2g/(3\beta_2)$ is a dashed line.

seen in figures 1(c) and (d), the MF parameter tends to zero and the pulse chirp approaches the asymptotic limit with the amplifier length.

4. Saturated gain with flat spectrum

To analyze this case, we have to put the limit $\Omega_g \to \infty$ in equation (3). Then, an analytical solution could be obtained by the variational method [18, 19]. In terms of this method, the trial pulse has the form of a parabolic similariton

$$u(z, t) = u_0(z)\sqrt{1 - \left(\frac{t}{t_p(z)}\right)^2}\exp\left(i\left(\frac{\alpha(z)t^2}{2} + \varphi(z)\right)\right),\quad |t| < t_p, \tag{6}$$

where t_p and α are duration and chirp of the trial pulse, and φ is its phase.

The dynamical system is described by the equations for the time-averaged NSE Lagrangian $\mathbf{L} = \frac{i}{2}\left(u\frac{\partial u^*}{\partial z} - u^*\frac{\partial u}{\partial z}\right) + \frac{\beta_2}{2}\left|\frac{\partial u}{\partial t}\right|^2 + \frac{\gamma}{2}|u|^4$

$$\frac{\partial\langle\mathbf{L}\rangle}{\partial\alpha} = 0,\quad \frac{\partial\langle\mathbf{L}\rangle}{\partial u_0} = 0,\quad \frac{\partial\langle\mathbf{L}\rangle}{\partial t_p} = 0,$$

which could be reduced to a set of equations describing evolution of the pulse parameters during its propagation through the amplifier:

$$\frac{du_0}{dz} = \frac{g_0 u_0}{1 + \frac{4}{3}\frac{u_0{}^2 t_p}{E_{sat}}} - \alpha\beta_2 u_0,$$
$$\frac{dt_p}{dz} = 2\beta_2\alpha t_p,$$
$$\frac{d\alpha}{dz} = -2\alpha^2\beta_2 + \frac{u_0^2\gamma}{t_p^2}. \tag{7}$$

The pulse saturation energy used in numerical simulations is $E_{sat} = 10$ nJ (that approximately is 135 times more than initial pulse energy $E_{in} \approx 75$ pJ). This value has been selected to provide an increase of the initial pulse energy by more than 30 dB over the amplifier length of 10 m. A similar gain level is typical for high-power Yb fiber amplifiers of similar length. The initial parameters of equation (7) are: $u_0^2(0) = P = 100$ W, $\alpha(0) = 0$, $t_p(0) = \tau_p = 3\pi\tau/4$, where τ is the duration of initial Gaussian pulse so $\tau_p = 0.7$ ps, i.e.

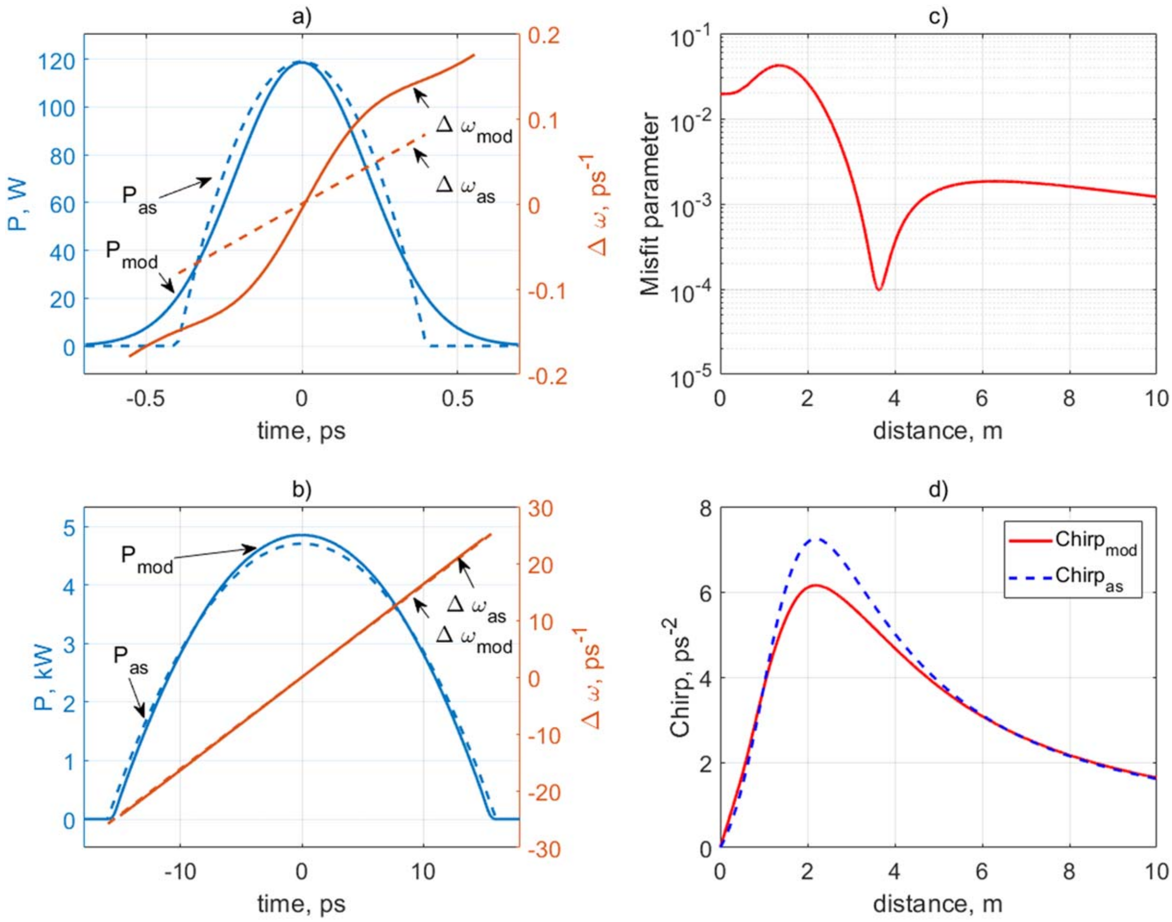

Figure 2. Saturated gain with flat spectrum. Evolution of the pulse and its instantaneous frequency along the amplifier length $L = 0.1$ m (a) and 10 m (b). The simulations of equation (1) (P_{mod}, $\Delta\omega_{\text{mod}}$) are solid lines, calculations by equation (7) (P_{as}, $\Delta\omega_{\text{as}}$) are dashed lines. Evolution of the MF parameter (c) and pulse chirp (d) along the amplifier length, the simulation of equation (1) is a solid line, the calculation by equation (7) is a dashed line.

the energies and peak powers of the initial Gaussian pulse used in simulations (equation (1)) and the initial parabolic pulse in equation (7) are equal. Figure 2 compares the results obtained through simulation of equation (1) and calculations of equation (7). Similar to the previous case, equation (7) describes a nonlinear attractor that makes a main contribution to the formation of the pulse parabolic envelope and its linear chirp. It might be expected that for the same fiber length, the pulse energy and the pulse chirp are substantially lower in the case of the saturated gain rather than nonsaturated gain. Importantly, one can observe a pronounced local minimum of the MF parameter (near amplifier length $z \approx 3.8$ m) that highlights the maximal match of the pulse shape and parabola achieved in this point (figure 2(c)). However, in this point the pulse chirp differs from its theoretical value (figure 2(d)).

5. Saturated gain with limited spectrum

Let us consider the case that suits most the real fiber amplifiers. Now, a finite gain linewidth is taken into account. To simulate equation (1), we use the parameter $\Omega_g = 20$ ps^{-1} that corresponds to the gain linewidth of ~40 nm in an ytterbium fiber amplifier operating at $\lambda \approx 1050$ nm. The saturation energy is still $E_{sat} = 10$ nJ.

We have to compare the simulated evolution of the initial Gaussian pulse in a fiber amplifier described by equation (1) (in shortened form (3)) with the evolution of the parabolic pulse described by equation (7). However, a direct comparison of these features is impossible, since the Lagrangian $\mathbf{L}$ does not describe a spectrally limited gain, whereas equations (1) and (3) do. Therefore, with the other parameters being equal, a pulse evolution described by equation (3) always acquires less energy than the parabolic pulse described by equation (7).

However, to avoid this contradiction, we can reformulate the problem. Let us now find such amplifier parameters governed by equation (3) that correspond to the maximal match of the amplified pulse shape to the parabolic pulse obtained in the system with a spectrally flat saturated gain. Equality of the initial energies is not more required, since the pulse, in the case of spectrally flat gain, always has to be of a lower initial energy. In this way, the problem of the optimal amplifier parameters is reduced to minimization of the MF

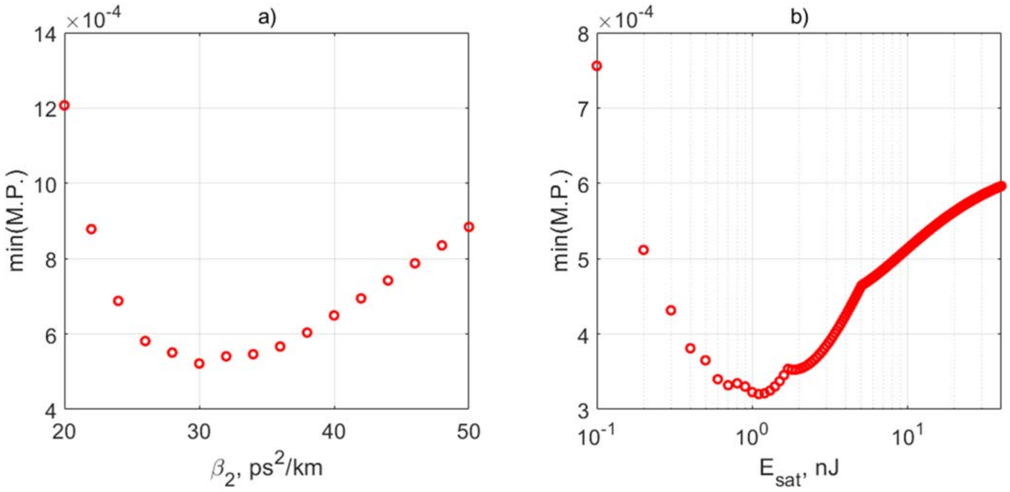

Figure 3. Saturated gain with limited spectrum. The minimal MF parameter (8) as dependences on GVD ($E_{sat} = 10$ nJ) (a) and the amplifier saturation energy $\beta_2 = 30\ \mathrm{ps}^2\ \mathrm{km}^{-1}$ (b).

functional that is similar to (4)

$$M^2 = \frac{\int [|A|^2 - |u|^2]^2 dt}{\int |A|^4 dt}. \quad (8)$$

For a real fiber amplifier of length L, the optimization could be performed not only by a proper choice of parameters in equation (3) determining the pulse $|A|^2$. Varying the initial values of $t_p(0)$ and $u_0(0)$ within a certain range, we could determine a parabolic pulse described by equation (6) (evolving in an amplifier with a spectrally flat saturated gain) that corresponds to the minimal MF parameter.

For example, at the given amplifier parameters, the minimum value of functional (8) is $M^2 \approx 9 \cdot 10^{-4}$ ($\beta_2 = 50\ \mathrm{ps}^2\ \mathrm{km}^{-1}$, the right point in plot 3(a)). This minimal value is achieved at the amplifier length of $L = 2.03$ m and with initial parabolic variational solution parameters $u_0(0) = P$, $t_p(0) = 0.86 \cdot \tau_p$. Then, the minimum MF parameters are calculated for decreasing GVD values. For each point, the values of L, $u_0(0)$ and $t_p(0)$ match the MF functional minimum. The results are presented in figure 3(a). To find the minimum of MF parameter, the amplifier length and the values $u_0(0)$ and $t_p(0)$ are altered within the ranges of $L \in [1.5..2.5]$ m and $u_0(0) \in [0.9..1] \cdot P$, $t_p(0) \in [0.8..0.95] \cdot \tau_p$, respectively. At GVD $\beta_2 = 30\ \mathrm{ps}^2\ \mathrm{km}^{-1}$, the minimum value of MF parameter is as low as $M^2 \approx 5 \cdot 10^{-4}$. Further, the dependence of the minimal MF parameter on the saturation energy E_{sat} is considered at this GVD value (figure 3(b)). These results show that the absolute minimum of the MF parameter $M^2 \approx 3 \cdot 10^{-4}$ is achieved at the value of $E_{sat} = 1$ nJ. This value ($\sim 10^{-4}$) is rather close to the misfit parameter observed in the case of a spectrally flat gain. However, in this case, the reduced saturation energy corresponds to the lower output pulse energy.

Figure 4 shows the evolution of the initial pulse in the case of spectrally limited gain with $E_{sat} = 10$ nJ, $\beta_2 = 30\ \mathrm{ps}^2\ \mathrm{km}^{-1}$. With the optimal amplifier length of $L = 1.97$ m, the pulse envelope is very close to the parabola (figure 4(a)). Figure 4(b) shows that the optimal length is determined quite definitely. If the amplifier length just slightly differs from the optimal value, the MF parameter significantly increases. Unfortunately, in the case of spectrally limited gain, it is impossible to get an absolutely linear chirp because of gain decreasing on spectral wings of the pulse. Nevertheless, though the pulse chirp is not perfectly linear (nonlinear frequency modulation is observed on the pulse wings), in the central part of the pulse its value is high enough and the pulse is suitable for an effective temporal pulse compression. A strong increase of the pulse peak power occurs after its propagation through an external dispersive element. Figure 4(c) compares the envelopes of the output pulse and output pulse passed through a linear dispersion element (diffraction gratings with $\beta_2 d = -0.07\ \mathrm{ps}^2$, where d is the distance between the gratings). A more than sixfold increase of the peak power indicates a rather sufficient linearity of the output pulse chirp. Figure 4(d) compares the envelope shapes of the output pulse propagating through an amplifier of different lengths. The results show that for the amplifier length shorter than the optimal length, the envelope maintains a Gaussian-like shape, while for longer amplifier lengths, the pulse envelope gets a triangular shape.

6. Conclusion

We have studied the laser pulse evolution in a nonlinear amplifier. The well-known normal GVD amplifying system with a flat gain spectrum and a parabolic similariton as a nonlinear attractor is supplemented by new important observations. The pulse asymptotic convergence is non-monotonic and has a number of local minima (figures 1(c) and 2(c)) associated with a gradual linearization of the pulse chirp. The first local minimum of asymptotic pulse convergence to a parabolic shape is still maintained in the case of a limited gain spectrum. In other words, if the gain spectrum is broad enough, there is an optimal fiber length at which the pulse shape becomes close to a parabola (figure 4). Deviation from a parabolic shape can be minimized by optimizing GVD and

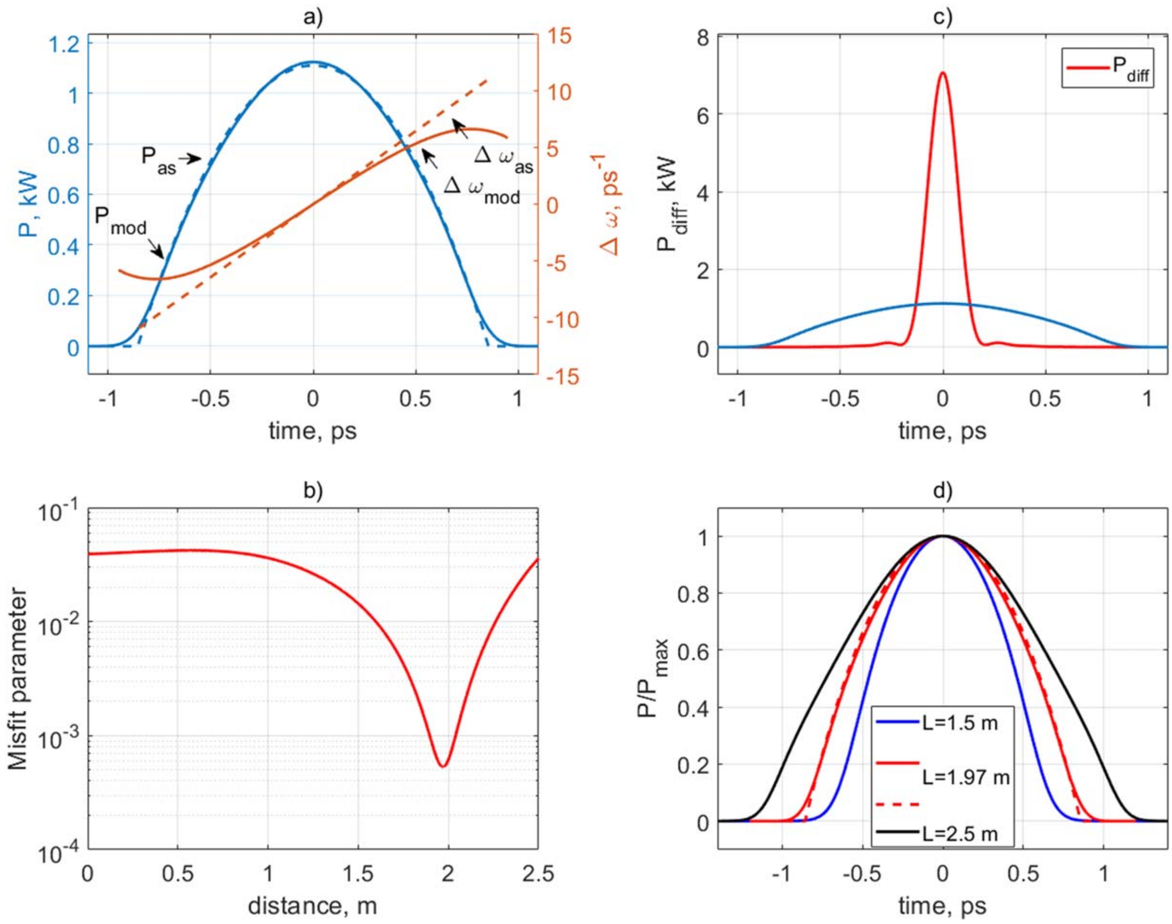

Figure 4. Saturated gain with limited spectrum. Evolution of the pulse and its instantaneous frequency along the amplifier length of $L = 1.97$ m. The simulations of equation (1) (P_{mod}, $\Delta\omega_{mod}$) are solid lines, calculations by equation (7) (P_{as}, $\Delta\omega_{as}$) are dashed lines (a). MF parameter evolution along the amplifier length (b). The pulse at the amplifier output (the length $L = 1.97$ m, blue line) and after compression with an external linear dispersion element (c). The normalized pulse shapes after pulse amplification in the amplifiers of different lengths. Dashed line is a parabolic envelope (d).

pumping values (figure 3). The above conclusions are made for short amplifiers, when higher order dispersion coefficients (third- and higher order dispersions), Raman scattering and nonlinear dispersion are negligible. The proposed method allows optimization of the amplifier length for generation of parabolic pulses in real fiber amplifiers. The proposed parabolic pulse generators can be used in conjugation with the temporal and spectral compression systems [20, 21], optical processors [22] and for cascade amplification of the pulses up to extreme energies [23, 24].

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