Self-similar propagation and compression of chirped self-similar waves in asymmetric twin-core fibers with nonlinear gain

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Ultrashort-pulse propagation in asymmetric twin-core fiber amplifiers is studied with the aid of self-similarity analysis of the nonlinear Schrödinger-type equation interacting with a source, variable dispersion, variable Kerr nonlinearity, variable gain or loss, and nonlinear gain. Exact chirped pulses that can propagate self-similarly subject to simple scaling rules of this model have been found. It is reported that the pulse position of these chirped pulses can be precisely piloted by appropriately tailoring the dispersion profile. This fact is profitably exploited to achieve optimal pulse compression of these chirped self-similar solutions.

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I. INTRODUCTION

The study of self-similar solutions of the relevant nonlinear differential equations has become a topic of growing interest, because of their ubiquity in the description of complicated phenomena, including the scaling properties of turbulent flow [1], the formation of fractals in nonlinear system [2], and the wave collapse in hydrodynamics [3]. The concept of self-similarity arises after the influences of initial conditions have faded away, but the system is still far from the ultimate state. In the context of nonlinear optics, only a limited number of self-similar phenomena have been reported. To name a few, the self-similar behaviors in stimulated Raman scattering [4], the evolution of self-written wave guides [5], the formation of Cantor set fractals in materials that support spatial solitons [6], and the nonlinear propagation of pulses in optical fibers [7] were investigated. Recently, this concept has been extended to an optical fiber amplifier [8] and a laser resonator [9]. In both cases, parabolic pulses were shown to propagate self-similarly and the predicted evolution was verified experimentally. As reported, these self-similar pulses or solitary waves possess a strictly linear chirp that leads to efficient compression or amplification and thus are particularly useful in the design of optical fiber amplifiers, optical pulse compressors, and soliton-based communication links.

Today, optical solitons are regarded as the natural data bits and an important alternative for the next generation of ultrahigh-speed optical communication systems [10,11]. In the case of exact soliton pulse propagation, the pulse evolution is governed by the nonlinear Schrödinger equation (NLSE). In addition, much effort has also been devoted to optical pulse compression techniques because of their practical utility, for shortening the durations of pulses generated by oscillators and amplifiers. Most of these techniques rely on chirping obtained either by self-phase-modulation in the normal dispersion regime or by combining phase modulation with amplification [12,13]. Soliton effects can also be utilized for compression where the problem of residual pedestals can be reduced through appropriate intensity of nonlinearity. Based on the nonlinear effects in optical fibers, we can classify the pulse compressors into two broad categories, referred to as fiber-grating compressors [14] and the usual soliton-effect compressors [15]. In a fiber-grating compressor, nonlinear pulse compression is achieved through the self-phase-modulation associated with the Kerr effect, when combined with external dispersive elements such as diffraction grating. The resulting compression is intensity dependent and due to a combination of the artificial negative dispersion associated with the grating and the phase shift associated with the Kerr nonlinearity, whereas the usual soliton-effect compressor makes use of higher-order solitons supported by fiber as a result of the interplay between self-phase-modulation and anomalous group-velocity dispersion. It is interesting to note that these two types of compressors are complimentary to each other and generally operate at different regions of the pulse spectrum. Thus, the fiber-grating compressor is useful to compress pulses in the visible and near-infrared regimes while the soliton-effect compressor is useful in the range 1.3–1.6 μm. However, the latter procedure has the drawback of wastage of energy [16]. Of all these techniques, adiabatic soliton compression, through the decrease of dispersion along the length of the fiber, provides a better pulse quality [17], albeit in a less rapid manner. Exact solutions have played a crucial role in demonstrating the above-mentioned pulse compression techniques in an amplifying medium. The fact that the NLSE or modifications of the same is known to possess soliton solutions has come in handy to find exact solutions of the above modified equation. All the aforementioned methods for pulse compression were restricted to pulse propagation through single-core fibers. Although it is more easy to fabricate twin-core fibers with some built-in asymmetry, the nonlinear pulse compression in these types of couplers has not received much attention in the literature. The existence of the solitary-wave solutions in twin-core fibers (TCF's) has been reported in Refs. [18,19]. Soliton solutions, when the nonlinearity for one

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component can be neglected, have been studied perturbatively [20]. In this context, the relevant equation is the NLSE driven by a source, originating from the coupling term. Soliton bound states in the TCF's have also been reported [21].

In this paper we describe ultrashort-pulse propagation in asymmetric twin-core fiber amplifiers with the aid of self-similarity analysis of the nonlinear Schrödinger-type equation interacting with a source, variable dispersion, variable Kerr nonlinearity, variable gain or loss, and nonlinear gain. This equation is not integrable by the inverse scattering method, and, therefore, this does not have soliton solutions; however, it possesses solitary-wave solutions which have often been called solitons. Exact chirped pulses that can propagate self-similarly subject to simple scaling rules of this model have been found. Furthermore, we have delineated pulse compression of these exact chirped self-similar solutions by piloting, precisely, the pulse position through appropriate tailoring of the dispersion profile. Apart from using the exact solutions of the NLSE with a source, recently obtained by two of the present authors [22], we take recourse to recent works [23–26] in the context of the NLSE with variable dispersion, variable Kerr nonlinearity, and variable gain or loss and nonlinear gain.

II. SELF-SIMILAR PROPAGATION IN ASYMMETRIC TCF's

As detailed in Refs. [20,25], the origin of source in the generalized NLSE can be attributed to the built-in asymmetry of the TCF. In the realistic situation in fiber, there will always be some nonuniformity due to two factors. It may arise from a variation in the lattice parameters of the fiber medium, so that the distance between two neighboring atoms is not constant throughout the fiber. It may also arise due to the variation of the fiber geometry—e.g., diameter fluctuation. These nonuniformities influence various effects such as loss (or gain), phase modulation, etc. Thus, these effects can be aptly modeled by making the dispersion, gain, and other parameters space dependent. In this case, the generalized NLSE with a source can be written as

$$i\psi_z - \frac{\beta(z)}{2}\psi_{\tau\tau} + \gamma(z)|\psi|^2\psi = i\frac{g(z)}{2}\psi + i\chi(z)|\psi|^2\psi + \eta e^{i\Phi(\tau,z)}, \tag{1}$$

where $g(z)$ is the linear gain and $\chi(z)$ is nonlinear gain, respectively. The above equation is deliberately cast into a form similar to that of Refs. [23,24], where the solutions of this equation without a source have been recently analyzed. However, in our recent work [25], we have demonstrated that the presence of the source is vital for supporting pulse propagation in asymmetric twin-core fibers without a nonlinear gain term in Eq. (1). Under certain parameter conditions, exact chirped self-similar solutions of Eq. (1) are found for the first time, and they exhibit explicitly a nonlinear chirp arising from the nonlinear gain. The phase Φ in the source term contains the phase part of the pulse propagating via second core, whose amplitude part is contained in η. Equation (1) describes the amplification or attenuation [for negative $g(z)$] of pulses propagating in a single-mode nonlinear fiber where $\psi(\tau,z)$ is the complex envelope of the electric field in a comoving frame, τ is the retarded time, $\beta(z)$ is the group velocity dispersion (GVD) parameter, $\gamma(z)$ is the nonlinearity parameter, $g(z)$ is the distributed gain function, and $\chi(z)$ is the nonlinear gain function.

In recent times, various forms of inhomogeneities have been discussed in the literature. A nonlinear compression of chirped solitary waves has been discussed by Moores [27] and Kumar and Hasegawa [28]. A deformed NLSE has been discussed by Burstev *et al.* in Ref. [29], wherein the Lax pair for the system has been presented. The soliton solution and the possibility of amplification of soliton pulses using a rapidly increasing distributed amplification with scale lengths comparable to the characteristic dispersion length have been reported by Quiroga-Teixeiro *et al.* [30]. For the propagation of two orthogonally polarized optical fields in a nonuniform fiber media, the coupled inhomogeneous NLSE, under a suitable variable transformation, has been reduced to the coupled NLSE [31]. Similarity reduction for the variable-coefficient coupled NLS equation of different form has been studied in [32]. Numerically, it was shown that, in the case where the gain due to the nonlinearity and linear dispersion balance with each other, equilibrium solitons will be formed [33]. As mentioned earlier, Kruglov *et al.* have reported exact self-similar solutions of Eq. (1), without a source, and nonlinear gain, characterized by a linear chirp and demonstrated pulse compression taking into account nonlinear soliton effects [23,27,34]. More recently, an important technology referred to as dispersion management (DM) has been developed by researchers [11,35]. Serkin and Hasegawa have formulated the effect of varying dispersion with an external harmonic oscillator potential on the soliton dynamics and have explained the concept of amplification of the soliton [26]. Motivated by these works, we have analyzed solutions of Eq. (1) for pulse compression, which may find application particularly in soliton-based communication links [36] via asymmetric TCF's. We show that it is possible to control the compression of the pulse propagating in the first core of the TCF's through the control of the pulse propagating through the asymmetric second core.

For finding solutions of Eq. (1), one writes the complex function $\psi(z,\tau)$ as

$$\psi(z,\tau) = P(z,\tau)\exp\{im_0 \ln[P(z,\tau)] + i\Phi(z,\tau)\}, \tag{2}$$

where P and Φ are real functions of z and τ; we look for rational solutions of the NLSE assuming that the phase has the following quadratic form:

$$\Phi(z,\tau) = a(z) + b(z)[\tau - \tau_p(z)] + c(z)(\tau - \tau_p)^2, \tag{3}$$

where the pulse position τ_p is a function of z. Then Eqs. (1)–(3) yield a self-similar form of the amplitude:

$$P(z,\tau) = \frac{Q(T)}{\sqrt{1 - 2c_0 R(z)}}\exp[S(z) - m_0\Theta(z)], \tag{4}$$

where the scaling variable T is given by

$$T = \frac{\tau - \tau_p(z)}{1 - 2c_0 R(z)}. \quad (5)$$

And the other functions $R(z)$, $\Theta(z)$, $S(z)$, and $\tau_p(z)$ in Eqs. (4) and (5) take the forms

$$R(z) = \int_0^z \beta(z')dz', \quad (6)$$

$$\Theta(z) = -\lambda \int_0^z \frac{\beta(z')}{1 - 2c_0 R(z')^2} dz', \quad (7)$$

$$S(z) = \frac{1}{2} \ln\left(\frac{m_0^2 - 2}{2} \rho(0)\right) + \int_0^z g(z')dz', \quad (8)$$

$$\tau_p(z) = \tau_c - b_0 R(z), \quad (9)$$

where b_0, λ, c_0, and τ_c are the integration constants and $\rho(z) = \beta(z)/\gamma(z)$. In terms of the above functions (6)–(9), the phase parameters are found to be

$$a(z) = a_0 + \frac{1 + m_0^2}{2}\Theta(z) - \frac{b_0^2}{2}R(z) - \frac{m_0}{2} \ln[|c(z)|] - m_0 S(z), \quad (10)$$

$$b(z) = b_0, \quad (11)$$

$$c(z) = \frac{c_0}{1 - 2c_0 R(z)}. \quad (12)$$

For the existence of self-similar solutions, the following relationship between gain profile and distributed parameters should be maintained:

$$g(z) = \frac{1}{2\rho(z)} \frac{d}{dz}\rho(z) + \frac{c_0 \beta(z)}{1 - 2c_0 R(z)} - \frac{\mu \lambda m_0 \beta(z)}{[1 - 2c_0 R(z)]^2}, \quad (13)$$

$$\frac{\chi(z)}{\gamma(z)} = \frac{3m_0}{m_0^2 - 2}, \quad (14)$$

where $\mu = 1$ or $\frac{3}{4}$. And the source should be of the form $\eta = \beta(z)/2[1 - c_0 D(z)]^{3/2}\varepsilon$. Here, ε is a constant characterizing the strength of the source. The condition in Eq. (13) describes that the parameter functions in Eq. (1) cannot be chosen independently, while the latter condition [Eq. (14)] implies that the nonlinear chirp parameter m_0 in fact can be determined by the ratio $\chi(z)/\gamma(z)$. In this paper, it is required that this ratio be a constant. From the physical cases we have considered, we come to the conclusion that $m_0^2 \neq 2$ for arbitrary nonlinear materials.

In view of the above, for $\mu = 1$, the function $Q(T)$ which satisfies

$$Q'' - \lambda Q + 2\kappa Q^3 - \varepsilon = 0, \quad (15)$$

where the prime indicates the derivative with respect to T and $\kappa = -\gamma(0)/\beta(0)$.

III. EXACT SELF-SIMILAR SOLUTIONS

As shown in Ref. [22], the solutions of the above equation can be obtained through a fractional transform

$$Q(T) = \frac{A + Bf^2(T)}{1 + Df^2(T)}, \quad (16)$$

which connects the solutions of the damped NLSE with a source to the elliptic equation $f'' \pm af \pm \lambda f^3 = 0$. As is well known, f can be taken as any of the three Jacobi elliptic functions with an appropriate modulus parameter: $\text{cn}(T,m)$, $\text{dn}(T,m)$, and $\text{sn}(T,m)$, with amplitude and width, appropriately, depending on m. Using the limiting conditions of the modulus parameter, one can obtain both localized and trigonometric solutions. We list below a few interesting solutions, ranging from trigonometric and hyperbolic to pure cnoidal.

For explicitness, we consider Eq. (15), with all the parameters, and illustrate below various type of solutions, taking $f = \text{cn}(T,m)$. Other cases can be similarly worked out. The consistency conditions are given by

$$A\lambda - 2(AD - B)(1 - m) + 2\kappa A^3 - \varepsilon = 0, \quad (17)$$

$$-2mD(AD - B) - \lambda BD^2 + 2\kappa B^3 - \varepsilon D^3 = 0, \quad (18)$$

$$2(AD - B)(3m + 4mD - 2D) - \lambda AD^2 - 2\lambda BD + 6\kappa AB^2 - 3\varepsilon D^2 = 0, \quad (19)$$

$$2(AD - B)(3D - 3mD - 4m + 2) - \lambda AD - \lambda B + 6\kappa A^2 B - 3\varepsilon D = 0. \quad (20)$$

The above equations clearly indicate that the solutions, for $m=1$, $m=0$ and other values of m, have distinct properties. For example, when $m=1$, A is obtained as the solution of the cubic equation [Eq. (17)], containing the source strength ε. Before elaborating on the general solution, we list below a few localized as well as periodic solitary wave solutions.

A. Trigonometric solution

For $A=0$, $\lambda=4$, and $m=0$, we find that

$$\psi(z,\tau) = (\varepsilon/2) \frac{\sqrt{(m_0^2 - 2)\rho(z)}}{\sqrt{2}[1 - 2c_0 R(z)]} \frac{\cos^2(T)}{1 - (2/3)\cos^2(T)}, \quad (21)$$

subject to the condition on the strength of the source with the strength of the nonlinearity: $\varepsilon = \sqrt{(64/27\kappa)}$, and $m_0 \neq 2$.

B. Pure cnoidal solutions

For $\kappa = \mp|\kappa|$, $m = 1/2$, and $A=0$, it is found that another specific value of $\lambda = \pm 2\sqrt{3}$ yields yet another pure cnoidal solution

$$Q(T) = \varepsilon \frac{\text{cn}^2(T,m)}{1 \pm \frac{1}{\sqrt{3}}\text{cn}^2(T,m)}, \quad (22)$$

subject to the condition $\varepsilon = \sqrt{(4/3\sqrt{3}|\kappa|)}$.

At this point it is worth mentioning that no solutions are obtained for $m=0$, $B=0$ and for $m=1$, $A=0$. Although we have not noted here, more general solutions with A, B, and D nonzero are also possible.

C. Dark solitary wave

In order to obtain a dark-solitary-wave solution, which is *nonsingular*, we first solve the cubic equation [Eq. (17)], which is already in the Vieta form by using Cardano's formula. Thus

$$A^3 + (-\lambda/2\kappa)A = \varepsilon/2\kappa,$$

which can be written as

$$A^3 + pA = q.$$

The discriminant D_1 is identified as

$$D_1 = Q_1^3 + R_1^2,$$

where $Q_1=p/3$ and $R_1=q/2$. For $D_1<0$, i.e., $\varepsilon^2<\lambda^2/27\kappa^3$, there are three unequal real roots. By defining $\theta=\cos^{-1}(R_1/\sqrt{-Q_1^3})$, then the real roots are $A_1=2\sqrt{-Q_1}\cos(\theta/3)$, $A_2=2\sqrt{-Q_1}\cos[(\theta+2\pi)/3]$, and $A_3=2\sqrt{-Q_1}\cos[(\theta+4\pi)/3]$.

Thus A is determined in terms of ε, κ, and λ. From Eq. (20) we determine the value of B in terms of D as

$$B = \Gamma D,$$

where

$$\Gamma = \frac{6\kappa A^2 - \lambda + 4}{3\varepsilon + 4A + \lambda A}.$$

More explicitly, from Eq. (19), B is determined to be

$$B = \frac{3(1-A\Gamma)}{2\Gamma(A\Gamma-1) - \lambda\Gamma^2 - 2\lambda\Gamma + 6\kappa A - 3\varepsilon\Gamma^2}. \tag{23}$$

Hence, the nonsingular solitary wave solution can be written as

$$Q(T) = \frac{A + B\,\mathrm{sech}^2(T)}{1 + D\,\mathrm{sech}^2(T)}. \tag{24}$$

We emphasize that this dark-solitary-wave solution is the general solution of this model and is valid for all values of the amplitude parameter values A, B, and D subject to the condition $AD-B\neq 0$.

IV. NONLINEAR CHIRPING

Here, we cite an example corresponding to the trigonometric solution, illustrative of the fascinating features of chirping by considering the system in which the GVD and the nonlinearity are distributed according to

$$\beta(z) = \beta_0\cos(\sigma z), \quad \gamma(z) = \gamma_0\cos(\sigma z), \tag{25}$$

where β_0, γ_0, and $\sigma(\neq 0)$ are arbitrary constants. In this case, the corresponding gain and the nonlinear gain of the fiber amplifier are given by

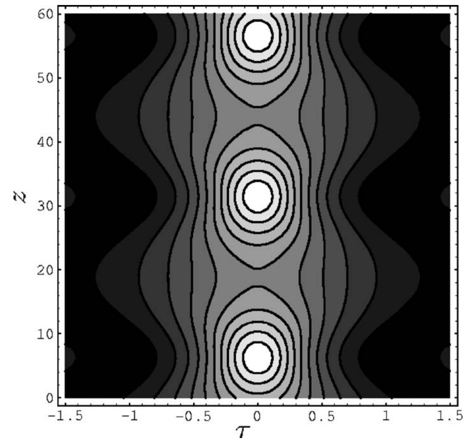

FIG. 1. Contour plot depicting the nonlinear chirping of the trigonometric solution in the regime of $\beta(z)\gamma(z)>0$.

$$g(z) = \frac{\sigma\nu\cos(\sigma z)}{2-2\nu\sin(\sigma z)} - \frac{\mu\lambda m_0\cos(\sigma z)}{[1-\nu\sin(\sigma z)]^2}, \tag{26}$$

$$\chi(z) = \frac{3m_0\gamma_0}{m_0^2-2}\cos(\sigma z), \tag{27}$$

where the parameter $\nu=2c_0b_0/\sigma$ has been introduced for brevity.

Hence the amplitude of the self-similar wave is

$$P(z,\tau) = A(z)\frac{\cos^2[T/W(z)]}{1-(2/3)\cos^2[T/W(z)]}, \tag{28}$$

where

$$A(z) = (\varepsilon/2)\frac{\sqrt{|\beta_0|}}{\gamma_0\sqrt{|\gamma_0|}}\left(\frac{1}{1-\nu\sin(\sigma z)}\right)$$

and

$$W(z) = \tau_0[1-\nu\sin(\sigma z)],$$

and the pulse position τ_p varies with $\tau_p=\tau_c-(b_0\beta_0/\sigma)\sin(\sigma z)$. The resultant chirps consisting of linear and nonlinear contributions are derived as [8]

$$\delta\omega(\tau) = \frac{m_0}{W(z)}\frac{\tan\left(\dfrac{\tau-\tau_p}{W(z)}\right)}{1-(2/3)\cos^2\left(\dfrac{\tau-\tau_p}{W(z)}\right)} - b_0 - \frac{2c_0\tau_0}{W(z)}(\tau-\tau_p). \tag{29}$$

We notice that the first term in Eq. (29) denotes the nonlinear chirp that results from the nonlinear gain, while the last two terms account for the linear chirp.

The propagation of this chirped pulse has been depicted in Fig. 1 for various parameter values of τ_0 and $\nu=1$.

V. NONLINEAR COMPRESSION

Now, we elucidate the compression problem of the pulse in a dispersion decreasing optical fiber. For the purpose of

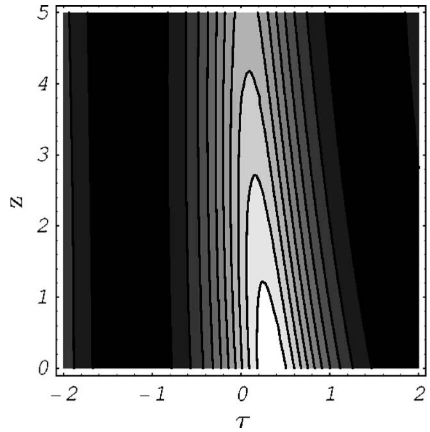

FIG. 2. Contour plot depicting the nonlinear compression of the trigonometric solution (in arbitrary units).

comparison with Refs. [23,24], we assume that the GVD and the nonlinearity are distributed according to the relations

$$\beta(z) = \beta_0 \exp(-\sigma z), \quad \gamma(z) = \gamma_0 \exp(\alpha z), \tag{30}$$

where $\beta_0 \leqslant 0$, $\gamma_0 \geqslant 0$, and $\sigma \neq 0$. Then from Eq. (13) the expression for gain can be calculated as

$$g(z) = -\alpha + \nu\sigma \frac{e^{-\sigma z}}{1-\nu(1-e^{-\sigma z})} - \frac{\mu\lambda m_0 \beta_0 e^{-\sigma z}}{[1-\nu(1-e^{-\sigma z})]^2}, \tag{31}$$

where $\nu = \sigma/2c_0\beta_0$.

Let us consider the most typical physical situation when the loss in an optical fiber is constant—i.e., when $\gamma(z)$ is constant. According to Eq. (31), this occurs when $\nu=1$ and $\alpha>0$: $g(z)=-\alpha$; hence the gain is negative. It is remarkable that the width of the solutions presented here tend to zero when $z \to \infty$.

We apply the above insights to nonlinear compression of the solitary wave solutions given by Eqs. (21) and (24):

$$P(z,\tau) = U(z) \frac{\cos^2[T/W(z)]}{1-(2/3)\cos^2[T/W(z)]},$$

$$P(z,\tau) = V(z) \frac{A + B\,\mathrm{sech}^2[T/W(z)]}{1 + D\,\mathrm{sech}^2[T/W(z)]}, \tag{32}$$

where

$$U(z) = (\varepsilon/2) \frac{\sqrt{(m_0^2 - 2)\dfrac{\beta_0}{\gamma_0} e^{-(\alpha+\sigma)z}}}{\sqrt{2}[1-\nu(1-e^{-\sigma z})]},$$

and similarly $V(z)$. And $W(z) = \tau_0/\nu[\nu - 1 + \exp(-\sigma z)]$. Figures 2 and 3 show that for the constant loss these pulses can be compressed to any required degree as $z \to \infty$, while maintaining their respective original shapes.

The analytical findings of the present model suggest potential applications especially in areas such as optical fiber compressors involving asymmetric cores, optical fiber amplifiers, nonlinear optical switches, and optical communications. For example, the case $\sigma>0$, $\alpha=0$, and $\nu>1$ implying that the gain

$$g(z) = \nu\sigma \frac{e^{-\sigma z}}{1-\nu(1-e^{-\sigma z})} - \frac{\mu\lambda m_0 \beta_0 e^{-\sigma z}}{[1-\nu(1-e^{-\sigma z})]^2}$$

has application to long-haul chirped soliton links where fiber losses are compensated periodically by an amplification system. This long-haul link is based on a distributed dispersion-loss-managed chirped soliton propagation regime and serves as an alternative to loss-managed soliton systems [37]. The main advantage of such systems is the absence of soliton radiation as the solitary waves propagating in this regime are an exact solution of Eq. (1) and hence generate no radiative noise.

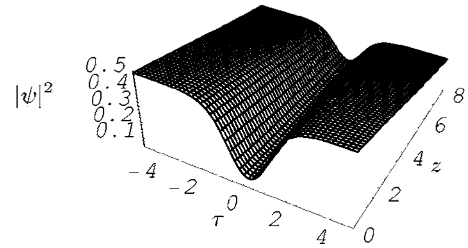

FIG. 3. The nonlinear compression of the dark soliton solution (nonsingular) for $\varepsilon=0.6$, $\lambda=-3$, and $\kappa=1.5$.

VI. CONCLUSION

In conclusion, we would like to point out that the present work is a natural but significant generalization of Ref. [25] by considering the nonlinear gain term. We have studied ultrashort pulse propagation in asymmetric twin-core fiber amplifiers with the aid of a self-similarity analysis of the Schrödinger-type equation interacting with a source, variable dispersion, variable Kerr nonlinearity, variable gain or loss, and nonlinear gain. Exact chirped pulses that can propagate self-similarly subject to simple scaling rules of this model have been found. The fact that the pulse position of these chirped pulses can be precisely piloted by appropriately tailoring the dispersion profile is profitably exploited to achieve optimal pulse compression of these chirped self-similar solutions. Realizing all-optical switching processing in the present model will be of a great interest. We hope that these solitary-wave solutions can be launched in long-haul telecommunication networks for achieving pulse compression. We should also like to point out that, in the presence of appropriate nonlinearity, our results may find application in twin-core photonic crystal fibers [38].

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