Probing Higher-Order Nonlinearities with Ultrashort Solitons

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Abstract: We analyze the impact of higher-order nonlinearity on ultrashort solitons by means of a photon-conserving propagation equation, and propose an original and direct method for its estimation.

1. Summary

The propagation of pulses in waveguides is usually modeled by the generalized nonlinear Schrödinger equation (GNLSE) [1]. However, this equation is only valid for a particular type of nonlinear profiles. To make this point clear, let us expand the nonlinear coefficient $\gamma(\Omega) = \gamma_0\,(1 + s_1(\Omega/\omega_0))$, where ω_0 is the pulse central frequency and $\Omega = \omega - \omega_0$ is the frequency detuning from ω_0, and s_1 is the self-steepening (SS) parameter. Let us recall that if $s_1 \neq 1$ the GNLSE fails to preserve the photon number even in lossless media [2]. Furthermore, the GNLSE only predicts physically sound results when positive zeroth-order nonlinear coefficients (γ_0) are taken into account. For negative coefficients, however, the GNLSE predicts an unphysical blueshift of short pulses [3], a problem worsened when the SS parameter departs from the photon-conserving condition $s_1 = 1$. In view of these limitations, the GNLSE is not suitable to study the complex interplay between the Raman frequency shift and SS in ultrashort pulses, where the influence of the SS parameter is of the utmost relevance. To tackle this issue, we have derived a modified GNLSE, the photon-conserving generalized nonlinear Schrödinger equation (pcGNLSE) [3], an equation that ensures strict conservation of the photon number for any arbitrary waveguide nonlinear profile.

Raman scattering is responsible for the soliton self-frequency shift (SSFS), and both the SSFS and self-steepening lead to a time delay of the soliton [1,4]. To point out the correlation between these two effects and the photon-number evolution, we study the dependence of the SSFS and the photon number vs. the self-steepening parameter, both using the GNLSE and the pcGNLSE. Results for a 25-fs, 2-kW soliton at 1550 nm, and at propagated distance of $15L_D$, where L_D is the characteristic dispersion length, are shown in Fig. 1. Fiber parameters are $\beta_2 = -20$ ps^2/km, $\gamma_0 = 1$ W^{-1}km^{-1}, and Raman parameters are those of silica [1] A direct correlation between an increase in photon number and a larger frequency shift is readily observed. Note that, as expected, when $s_1 = 1$ the GNLSE conserves the photon number. However, for a larger SS parameter the GNLSE predicts a slight

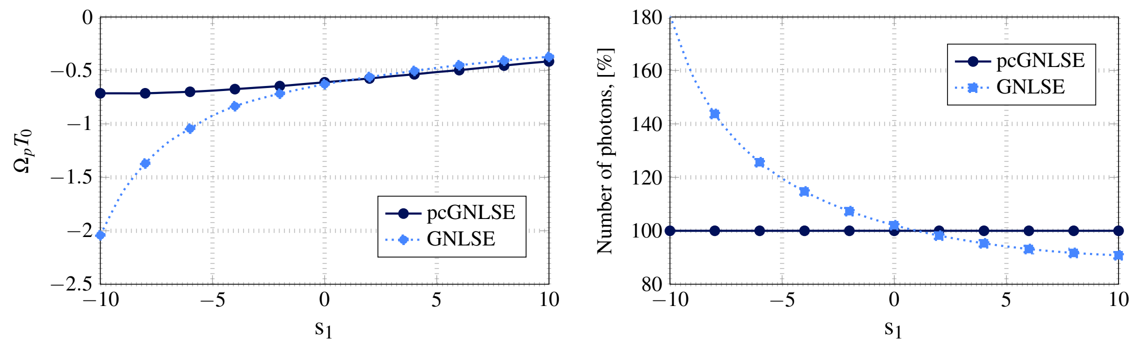

Fig. 1. (left) Frequency shifts experienced by 25-fs solitons, at a distance of $15L_D$, as predicted by the pcGNLSE (circles) and GNLSE (squares), and for different SS parameters. (Right) Normalized photon-number evolution.

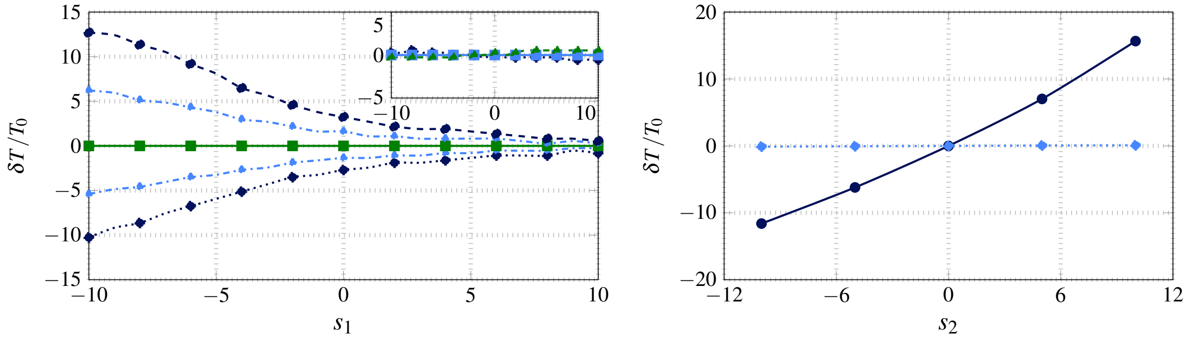

Fig. 2. (left) Normalized relative time delay experienced by 10-fs solitons propagated $45L_D$, and for different SS parameters and $s_2 = 0 \pm 5 \pm 10$. Time delays are relative to $s_2 = 0$. (Inset) Neglecting Raman scattering. (Right) Influence of s_2 in the time delay experienced by ultrashort (circles) and short (squares) pulses. $s_1 = -1.5$. Fiber parameters are the same as in Fig. 1

loss of photons. Since the difference is considerable smaller as compared to cases with $s_1 < 1$, the predicted frequency and time delays approach those obtained with the pcGNLSE. In physical terms, this asymmetric behavior of the GNLSE around $s_1 = 1$ can be explained by the presence of a zero-nonlinearity wavelength (ZNW) in the low-frequency side of the spectrum for $s_1 > 0$ that limits the SSFS [5].

It is important to emphasize that usually in the literature only linear $\gamma(\Omega)$ profiles are assumed for propagation-modeling purposes. Some waveguides, however, exhibit a more complex frequency-dependence of the nonlinearity [6]. This fact motivates the question of whether the effect of such profiles can be properly addressed with the pcGNLSE and how it can be estimated.

Let us introduce a second order parameter s_2 by letting $\gamma(\Omega) = \gamma_0\,(1 + s_1(\Omega/\omega_0) + s_2(\Omega/\omega_0)^2)$. Figure 2 (left) shows that the effect of s_2 can be revealed by measurable variations in the time delay experienced by a 10-fs soliton. For the sake of clearness, Fig. 2 (left) shows a relative time delay δT, i.e., the deviation with respect to the delay for $s_2 = 0$. It is worthwhile pointing out that Raman scattering acts as an enabler of the higher-order nonlinearity. Indeed, when switching off the Raman contribution, the delay no longer depends on s_2, as shown in the inset of Fig. 2 (left).

The dependence of the time delay with the higher-order nonlinear coefficient s_2 depicted in Fig. 2 (left) suggests a way to estimate it. By extensive numerical simulations, we verified that the delay is largely unaffected by the higher-order nonlinearity when considering 100-fs pulses. Thus, by propagating a pulse with $T_0 \geq 100$ fs, s_1 can be obtained from measurements of the observed time delay (see Ref. [4]). Then, propagation of an ultrashort pulse, $T_0 \ll 100$ fs, s_2 can be estimated from a numerical fit performed with the pcGNLSE. This method is presented in Fig. 2 (right), where the relative time delay is shown for $s_1 = -1.5$.

In conclusion, we have revisited the complex interplay between the SSFS and SS in ultra-short solitons in the framework of a photon-conserving equation, the pcGNLSE. For sub-100-fs solitons, the GNLSE fails to preserve the photon number, leading to a large overestimation of both the SSFS and the time delay. We analyzed the impact of the high-order nonlinear term s_2 on ultrashort soliton propagation and proposed an original and direct method for its estimation.

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