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Study of femtosecond soliton dynamics in photonic crystal fiber using the moment method

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ABSTRACT

We investigate the dynamics of femtosecond solitons in photonic crystal fibers (PCFs) by including high-order dispersion terms until to sixth-order in the generalized nonlinear Schrödinger equation, in addition to the nonlinear effects of the self phase modulation, self steepening and Raman scattering. We calculate theoretically the pulse parameters using the moment method. In the case of the fundamental soliton, our computed equations are coupled and difficult to solve analytically. However, we use the finite difference method to calculate numerically pulse parameters using an initially hyperbolic secant pulse at 1550-nm with different peak powers along 10m-PCF. Our numerical results show that the nonlinear regimes allow obtaining pulse compressions and initial pulse amplitudes. Furthermore, we remark a pulse broadening, and weak shifts of the peak power positions and frequencies in the critical and dispersive regimes. The use of an initial chirp provides a better pulse compressions and especially for low input powers. Also, the initial positive chirp reduces the optimal compression position lengths, while the negative one increases them. Therefore, we conclude that our theoretical calculations and numerical simulation results show that the moment method associated with the finite differences method is effective for the study of femtosecond pulse dynamics in PCFs.

1. Introduction

The photonic crystal fibers (PCFs) are actually used in a great number of application areas like telecommunication, biology and sensors. The PCFs allow the control of dispersion and nonlinear effects during the engineering and a fabrication process. Several designs for the nearly zero ultra-flattened chromatic dispersion photonic crystal fiber have been proposed [1–5], and some highly nonlinear glasses such as chalcogenide have been introduced in the realization of PCF in order to obtain large nonlinearities and excellent transmission at the infrared wavelengths [6–8]. The chalcogenide nonlinear Kerr effect can be as much as $\sim 900\times$ that in silica [9,10].

The propagation of femtosecond pulses in PCFs is described by the generalized nonlinear Schrödinger equation (GNLSE), where linear and nonlinear effects including the high order dispersions (HOD), self phase modulation (SPM), self steepening and Raman scattering are considered [11]. The intrapulse Raman scattering induces a frequency downshift in a soliton subpicosecond regime. This effect is known as soliton self frequency shift (SSFS). Golovchenko et al. [12] have first discovered in 1985 the red shift of an ultrashort optical pulse spectrum in the anomalous regime. In 1986, the effect of the SSFS was first observed experimentally by Mitschke and Mollenauer for pulses shorter than 1 ps [13], and Gordon used a perturbation theory of solitons to demonstrate theoretically that the rate of the SSFS is approximately proportional to τ^{-4}, where τ is the pulse temporal width [14,15]. Santhanam and Agrawal [16] have used the moment method to show that such a spectral shift occurs both in the normal and anomalous dispersion regimes, depends on the initial width and chirp associated with an optical pulse. The problem of the dynamics of solitons near the zero-dispersion wavelength (ZDW) has been well studied taking into account the higher orders of linear and nonlinear effects. The studies were restricted mainly to the action of the third-order dispersion (TOD) [17–19]. Tsoy and de Sterke [15] analyzed the effect of the quadratic dispersion (QD) for optical fibers containing a double ZDW where dispersion can have two regions of anomalous GVD separated by a region of normal one. Fedotov et al. [20] have demonstrated a spectral compression based on SSFS using a highly nonlinear PCF with ZDW at 750 nm, where a spectral-compression factor of 6.5 has been obtained for 50-fs, 1270-nm solitons red-shifted to a center wavelength of 1580 nm [21]. The impact of PCF

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positive TOD and initial pulse chirp on spectral-compression performance has been numerically investigated for 50-fs, 1550-nm pulses propagating in anomalously dispersive PCFs [21,22].

The aim of this work is to include the HOD effects terms until to sixth-order in the GNLSE equation, in addition to the nonlinear effects of the SPM, self steepening and Raman scattering, to calculate theoretically pulse parameters using the moment method. We do not consider the weak interaction between a soliton and radiated waves. Therefore, we neglect the energy losses in PCFs. Considering the fundamental soliton, our computed equations are coupled and difficult to solve analytically. So, we use the finite difference method to determine numerically pulse parameters. We present there numerical evolution in terms of the PCF length z, using the measured linear and nonlinear characteristics of a PCF found in the references [4–7]. We first consider the propagation of an initially unchirped 100 fs hyperbolic secant pulse at 1550-nm with different peak powers P_0 = 0.4, 0.56, 0.7 and 1 kW along 10m-PCF. Our numerical results show that the nonlinear regime P_0 = 0.7 kW and 1 kW allows obtaining pulse compressions to 67.3 fs and 39.3 fs and peak powers of 1.02 kW and 2.54 kW for respectively 3 m and 1.9 m of the PCF length. As we can see some lengths of PCF where pulse amplitude takes its original form, although these solitons are chirped and shifted in time and frequency. Furthermore, we remark a pulse broadening, and a weak shifts of the peak power position T and frequency Ù in the critical P_0 = 0.56 kW (the soliton number is equal to 1) and dispersive P_0 = 0.4 kW regimes. However, the use of an initial chirp provides a better pulse compressions and especially for low input powers. Also, the initial positive chirp reduces optimal compression position lengths z_c, while the negative one increases them. Therefore, we conclude that our theoretical calculations and numerical simulation results show that the moment method associated with the finite differences method is effective for the study of femtosecond pulse dynamics in PCFs.

We present in Section 2, the GNLSE model that describes the propagation of ultrashort pulses equation, using dispersion terms until to sixth-order, SPM, self steepening and Raman effects. The soliton parameters calculation by the moment method is described in Section 3, analysis and application to the fundamental soliton are given in Section 4. Then, we present our numerical simulation results in Section 5 and finally we give our conclusions for this work.

2. GNLSE model

The equation that describes the propagation of the ultrashort pulses in PCFs, including dispersion until to sixth-order, SPM, self steepening and Raman effects is the generalized nonlinear Schrödinger equation (GNLSE) given by

$$\frac{\partial B}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 B}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 B}{\partial t^3}+\frac{i\beta_4}{24}\frac{\partial^4 B}{\partial t^4}-\frac{\beta_5}{120}\frac{\partial^5 B}{\partial t^5}+\frac{i\beta_6}{720}\frac{\partial^6 B}{\partial t^6} = i\gamma\left(|B|^2B+\frac{i}{\omega_0}\frac{\partial}{\partial t}(|B|^2B)-T_R B\frac{\partial|B|^2}{\partial t}\right) \quad (1)$$

where $B(z,t)$ is the envelope of the slowly varying pulse, β_j (j = 1,. . .,6) is the jth-order dispersion coefficient at the pump frequency ω_0, and γ is the nonlinear coefficient of the SPM due to optical Kerr effect. T_R is the Raman time constant estimated from the slope of the Raman gain spectrum (stimulated Raman scattering (SRS)). The quantity $t = t' - z/v_g$ is the retarded time where z is the position along the fiber, t' is the physical time and v_g is the group velocity at the center wavelength λ_0.

3. Pulse parameters computation using the moment method

The basic idea of the moment method is to treat the optical pulse as a particle [16] whose energy E, position T frequency Ω variance σ^2, and chirp $\tilde{C}$ are defined by

$$E=\int_{-\infty}^{+\infty}|B|^2dt \quad (2)$$

$$T=\frac{1}{E}\int_{-\infty}^{+\infty}t|B|^2dt \quad (3)$$

$$\Omega=\frac{i}{2E}\int_{-\infty}^{+\infty}\left(B^*\frac{\partial B}{\partial t}-B\frac{\partial B^*}{\partial t}\right)dt \quad (4)$$

$$\sigma^2=\frac{1}{E}\int_{-\infty}^{+\infty}(t-T)^2|B|^2dt \quad (5)$$

$$\tilde{C}=\frac{i}{2E}\int_{-\infty}^{+\infty}(t-T)\left(B^*\frac{\partial B}{\partial t}-B\frac{\partial B^*}{\partial t}\right)dt \quad (6)$$

Obviously, the evolution of these parameters depends on that of the pulse itself in the fiber which is governed by the GNLSE. Using Eqs. (1)–(6), we obtain the evolution of pulse parameters with respect to z. For this, we first differentiated the Eqs. (2)–(6) with respect to z. Then, the term $\frac{\partial B}{\partial z}$ appeared in the second member of each equation, we have substituted that of the Eq. (1). Thus, we integrate by parts the new equations taking into account that the field must vanish at infinity. So $B(z,t)$, $\frac{\partial^n B}{\partial t^n}$ and $\frac{\partial^n B^*}{\partial t^n}$ converge exponentially to zero at $t\to\pm\infty$. Finally, we obtain the following equations:

$$\frac{dE}{dz}=0, \quad (7)$$

$$\begin{aligned}\frac{dT}{dz} &= \beta_2\Omega+\frac{\beta_3}{2E}\int_{-\infty}^{+\infty}\left|\frac{\partial B}{\partial t}\right|^2dt+\frac{i\beta_4}{12E}\int_{-\infty}^{+\infty}\left(\frac{\partial B}{\partial t}\frac{\partial^2 B^*}{\partial t^2}-\frac{\partial B^*}{\partial t}\frac{\partial^2 B}{\partial t^2}\right)dt\\ &-\frac{\beta_5}{24E}\int_{-\infty}^{+\infty}\left|\frac{\partial^2 B}{\partial t^2}\right|^2dt-\frac{i\beta_6}{240E}\int_{-\infty}^{+\infty}\left(\frac{\partial^2 B}{\partial t^2}\frac{\partial^3 B^*}{\partial t^3}-\frac{\partial^2 B^*}{\partial t^2}\frac{\partial^3 B}{\partial t^3}\right)dt\\ &+\frac{3\gamma}{2\omega_0 E}\int_{-\infty}^{+\infty}|B|^4dt\end{aligned} \quad (8)$$

$$\begin{aligned}\frac{d\Omega}{dz} &= -\frac{i\gamma}{\omega_0 E}\int_{-\infty}^{+\infty}\frac{\partial|B|^2}{\partial t}\left(B^*\frac{\partial B}{\partial t}-B\frac{\partial B^*}{\partial t}\right)dt\\ &-\frac{\gamma}{E}T_R\int_{-\infty}^{+\infty}\left(\frac{\partial|B|^2}{\partial t}\right)^2dt,\end{aligned} \quad (9)$$

$$\begin{aligned}&\left|\frac{\partial^2 B}{\partial t^2}\right|^2dt+\frac{i\beta_5}{48E}\int_{-\infty}^{+\infty}\left(\frac{\partial^2 B}{\partial t^2}\frac{\partial^3 B^*}{\partial t^3}-\frac{\partial^2 B^*}{\partial t^2}\frac{\partial^3 B}{\partial t^3}\right)dt\\ &+\frac{\beta_6}{120E}\int_{-\infty}^{+\infty}\left|\frac{\partial^3 B}{\partial t^3}\right|^2dt+\frac{i\gamma}{\omega_0 E}\int_{-\infty}^{+\infty}(t-T)\frac{\partial|B|^2}{\partial t}\left(B\frac{\partial B^*}{\partial t}-B^*\frac{\partial B}{\partial t}\right)dt\\ &-\frac{i\gamma}{2\omega_0 E}\int_{-\infty}^{+\infty}|B|^2\left(B\frac{\partial B^*}{\partial t}-B^*\frac{\partial B}{\partial t}\right)dt\\ &-\frac{\gamma}{E}T_R\int_{-\infty}^{+\infty}(t-T)\left(\frac{\partial\left|B\right|^2}{\partial t}\right)^2dt+\frac{\gamma}{2E}\int_{-\infty}^{+\infty}|B|^4dt\end{aligned} \quad (10)$$