NUMERICAL SIMULATION OF DEGRADATION EFFECTS IN OPTICAL FIBERS

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1. Introduction

The nonlinear Schrödinger equation (NLSE) is a nonlinear partial differential equation that does not generally offer analytic solutions except for some specific cases in which the inverse scattering method can be employed. The solution of NLSE is often necessary for an understanding of the nonlinear effects in optical fibers [1]. A large number of numerical methods can be used to solve partial differential equations. These can be classified into two categories known as finite-difference method (FDM) and the pseudo-spectral methods. One method of the pseudospectral category used extensively to solve the pulse-propagation problem in nonlinear dispersive media is the split-step Fourier method (SSFM). Generally speaking, pseudo-spectral methods are faster by up to one order of magnitude to achieve the same accuracy.

The finite-difference method solves the NLS equation explicitly in the time-domain under the assumption of the paraxial approximation [2]. We apply this method to the solving NLSE and simulate the propagation of the chirped Gaussian pulse in the nonlinear optical fiber. As the increasing the number of high-speed links, there occurs also a demand for increasing the data transfers rate and the bandwidth of recently communication systems. These systems are divided into different wavelength patterns CWDM and DWDM.

2. Theoretical overview

The GVD (Group velocity dispersion) broadens optical pulses during their propagation inside an optical fiber. These pulses can be initially chirped or chirp can be generated inside the pulse during propagation. More specifically, a chirped pulse can be compressed during the early stage of propagation depending on the sings of chirp parameter C and the the GVD parameter β_2. Since $\beta_2 < 0$ in the 1.55 μm wavelength region of silica fibers, the condition $\beta_2 C < 0$ is satisfied. SPM- induced chirp is power dependent so we can imagine that under certain condition the SPM- induced chirp can cancel the GVD- induced broadening of the pulse.

The optical pulse would then propagate undistorted in the form of a soliton [3]. The study of most nonlinear effects in optical fibers involves the use of short pulses with widths ranging from ~ 10 ns to 10 fs. When such optical pulses propagate inside a fiber, both dispersive and nonlinear effects influence their shape and spectrum. For pulses of width $T_0 >$ 5 ps the contribution of the third-order dispersion term is also small (as the carrier wavelength is not too close to the zero dispersion wavelength) we can use NLS equation in the form

$$i\frac{\partial A}{\partial z}+i\frac{\alpha}{2}A-\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}+\gamma|A|^2 A=0 \qquad (1)$$

The pulse amplitude $|A|^2$ is assumed to be normalized such that represents the optical power. The quantity $\gamma|A|^2$ is then measured in units of m^{-1} if n_2 is expressed in units of m^2/W. Equation (1) includes the effects of fiber losses through α, of chromatic dispersion through β_2, and of fiber nonlinearity through γ [4]. Briefly, the pulse envelope moves at the group velocity $v_g=1/\beta_1$ while the effects of group-velocity dispersion (GVD) are generated by β_2. The GVD parameter β_2 can be positive or negative depending on whether the wavelength λ is bellow or above the zero-dispersion wavelength λ_D of the fiber. In the anomalous dispersion regime ($\lambda > \lambda_D$), β_2 is negative, and the fiber can support optical solitons. In standard silica fibers, β_2 ~ 50ps$_2$/km in the visible region but becomes close to -20ps^2/km near wavelengths ~1.5µm the change in sing occurring in the vicinity of 1.3 µm. Let us now consider the input Gaussian pulse that has been initially chirped. In the case of linearly chirped Gaussian pulses, the incident field can be written as

$$A(0,T)=\exp\left(-\frac{(1+iC)}{2}\left(\frac{T}{T_0}\right)^{2m}\right), \qquad (2)$$

where C is the chirp parameter. When $\beta_2 C>0$, a chirped Gaussian pulse broadens monotonically at a rate faster than that of unchirped pulse. The reason is related to the fact that the dispersion-induced chirp adds to the input chirp because the two contributions have the same sign. The situation change for $\beta_2 C<0$. In this case, the contribution of the dispersion-induced chirp is of kind opposite to that of the input chirp [5].

3. Numerical results

Most of used laser pulses can be approximated by the Gaussian distribution. Equation (1) describes the amplitude envelope of this kind of pulses. The chirp parameter C describes the frequency change inside the pulse envelope. By increasing value of the parameter m to infinity, we can achieve rectangular shape of input signal as Fig. 1 shows. Here we can observe the shape of the input pulse depending on the m parameter. The case m > 1 corresponds to super-Gaussian pulses.

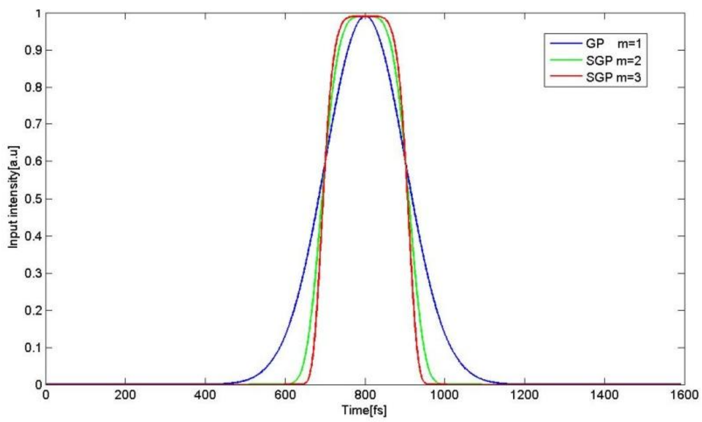

Fig.1: *Various shapes of input signal depending on m parameter for Gaussian pulse and super-Gaussian pulse.*

The second step of our investigation includes the space-time step and this problem was solved by using the time vector moving in space direction. Distance was calculated as a ratio of distance z and the calculated dispersion length L_D. Inside of a cycle of program the z was calculated distance using the equation (1). As result of this program were the space-time movement of Gaussian and super-Gaussian pulses. From Fig. 2 we can observe at the left side the shape of input pulse and on the right side the 3-D model of Gaussian pulse after propagated distance including the dispersion and nonlinear effects.

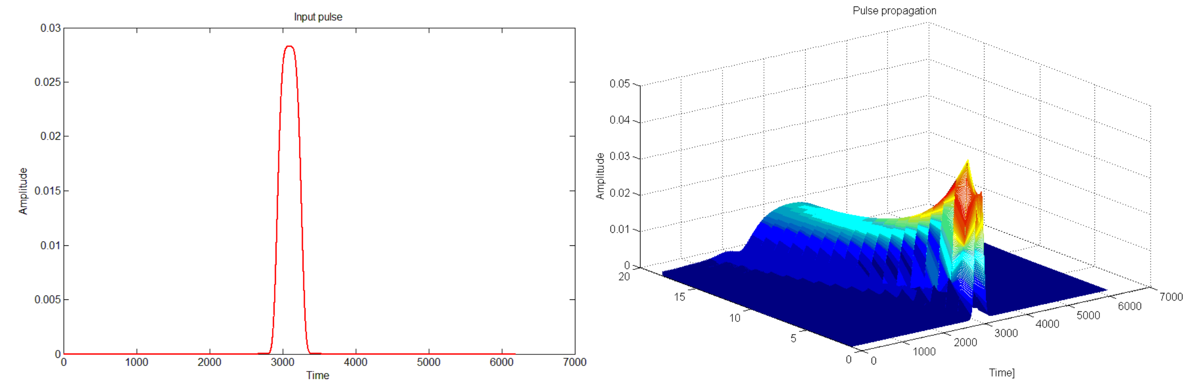

Fig.2: *propagation of super-Gaussian pulse with considering dispersion and nonlinear effects*

The pulse shape change can be described as a back-reflection of input signal. After some commutating cycles, the broadening an also the low amplitude can be observed. If we continue in the simulation we must consider the effect of self-phase modulation that can generate a positive signal chirp.

Due to this chirp the shape of the propagated pulse can by repaired. The main problem in this case is to define the direct impact of self-phase modulation and to predict the exact distance for self-phase induced chirp domination. We can also observe the pulse phase changes as an impact of these chirp changes. When the dispersion is dominating through the positive chirp the phase goes to higher values and on the other side for pulse chirp generated by self-phase modulation leads to lower values. The Figure 3 right shows the amplitude spectrum of propagated super-Gaussian pulse. Most of the frequency components are situated on low or height frequencies and the middle part of frequency range is empty. This effect is caused by the nature of super-Gaussian leading and trailing edge.

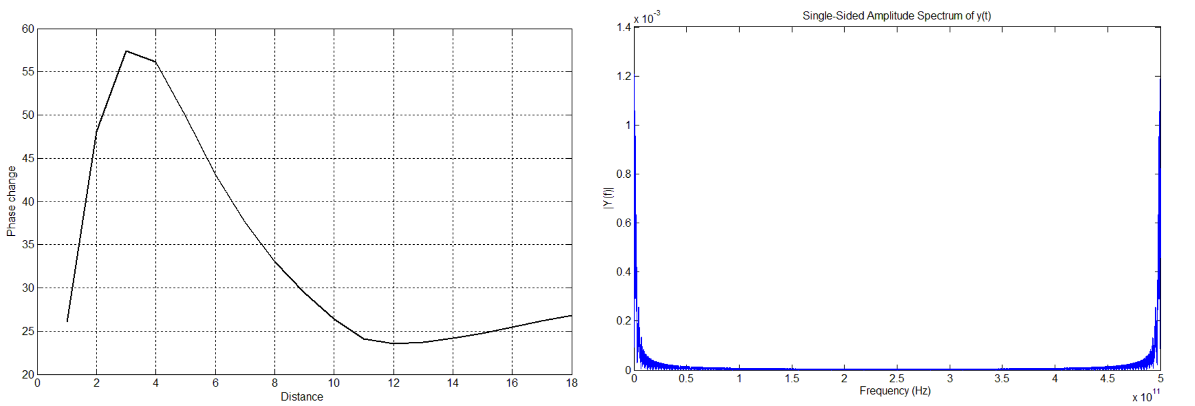

Fig.3: left: *phase change due to dispersion effects* right: *amplitude spectrum of Gaussian pulse after some distance travelled*

4. Conclusion

In this paper we have demonstrated not frequently used numerical simulations of the super-Gaussian pulses propagation in the optical fibers. The first part of this paper presents the theoretical fundamentals of the nonlinearities formulation and signal degradation effects that must be considered in high-speed communication systems. The main goal of this paper was to create the starting point for future numerical research with new generation networks using the phase sensitive detectors or in case of coherent systems and detectors.

Acknowledgement

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