The Pulse Evolution Picture In The Presence Of Interference

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Abstract **– In this paper the determination results of the interference influence on a soliton evolution in optical fiber are shown. Both the interference and the signal are Gaussian pulses but at the different frequencies. Computations were conducted by solving the system of Nonlinear Differential Schrödingers Equations. The influence of different fiber parameters on the level of interference and its implication on basic signal are also discussed. It is evident that the parameter *N* is with a dominant influence. If one is increasing it, the propagation characteristics are getting worse.**

Keywords **– Optical fiber, optical pulse, parameter *N*.**

I. Introduction

In nowdays telecommunication systems, using the optical fibers as a good transmission medium is a reasonable need. However, optical fibers have very significant dispersion and nonlinearity that can be decreased with the appropriate pulse shape, namely soliton [1]. The optical system consists of a transmitter, transmission medium and a receiver. Due to imperfection of the transmitter and a system of mirrors which are reflecting the beam into the optical fiber, there is a possibility of interference appearance as an unwonted pulse at the different frequency that interact with the useful signal.

In this paper the case with two optical pulses which are propagating together into the single-mode fiber is considered. Generally, two optical fields can differ not only in its wavelenghts but also in their polarization states. Furthermore, polarization of each field can be changed during the propagation as a result of optically induced nonlinear birefringence. Here, the case in which the two optical fields at the different wavelenghts are linearly polarized along one of the axes of polarization-preserving fiber so that they maintain their polarization during propagation is given.

The Cross-Phase Modulation (XPM) is always followed by the Self-Phase Modulation (SPM) and it is present because the effective refraction coefficient depends not only from intensity of that propagating wave but also from intensities of all other copropagating waves [2]. This paper considers the case where both the nonlinearity and dispersion occurs in the fiber and the influence of these two effects on the signal when one of them is dominant in the presence of the interference.

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Different values of the fiber parameters, namely, dispersive or nonlinear lenght imply a different influence on the pulse propagation, it's shape and intensity, which then again influence on the probability error. This study results involve only the evolution pictures of a propagating pulse along the fiber. Fiber losses along the fiber are neglected with the assumption that they are very small.

It is well known that the pulse propagation in an nonlinear dispersive medium, as the optical fiber is, can be described with the Schrödingers Partial Differential Equation. A solution of the system of Schrödingers equations gives the influence of interference on the useful signal as a result. System is normalized with the adequate normalization factors. This paper considers the pulse evolution picture along the optical fiber in case when the basic signal is at the frequency f_1 and the interference is at the frequency f_2. Solving of the system of the Schrödingers equations is conducted by using the well-known split-step Fourier method that finds the extensive usage in solving the problems with pulse propagation in nonlinear dispersive medium [3]. In a lot of studies it showed satisfactory accuracy. Although in general the dispersion and nonlinearity act together along the fiber, the split-step Fourier method gives an approximate solution by assuming that in propagating the optical field over a small distance h one can pretend that dispersive and nonlinear effects act independently. Hence, propagation from z to $z+h$ is carried out in two steps that are: in the first step, nonlinearity acts alone and in the second step dispersion acts alone. That is why it is named a “split-step” method. Although the method is relatively straightforward to implement, it should be noted that it requires that the step size h along z and time discretization are selected carefully to maintain the required accuracy.

II. Determination of the Pulse Evolution Picture

Propagation of two pulses at different frequencies is considered. One pulse represents the useful signal and the other one is interference. The determination begins with the common system of nonlinear Schrödinger equations defined like [3]

$$\begin{aligned}\frac{\partial A_1}{\partial z}+\frac{1}{v_{g1}}\frac{\partial A_1}{\partial t}+\frac{i}{2}\beta_{21}\frac{\partial^2 A_1}{\partial t^2}+\frac{\alpha_1}{2}A_1=i\gamma_1\left(\left|A_1\right|^2+2\left|A_2\right|^2\right)A_1\\ \frac{\partial A_2}{\partial z}+\frac{1}{v_{g2}}\frac{\partial A_2}{\partial t}+\frac{i}{2}\beta_{22}\frac{\partial^2 A_2}{\partial t^2}+\frac{\alpha_2}{2}A_2=i\gamma_2\left(\left|A_2\right|^2+2\left|A_1\right|^2\right)A_2\end{aligned}\qquad(1)$$

where γ_j is nonlinearity coefficient defined as

$$\gamma_j=\frac{n_2\omega_j}{cA_{\text{eff}}}\ \text{ i } j=1,2\qquad(2)$$

and A_{eff} represents the effective core area (typically 10-20 μm^2 in visible region), c is speed of light, ω_1 and ω_2 are the pulses central frequencies and n_2=3,2×10^{-16}cm^2/W for silica fiber. Corresponding values for γ_1 and γ_2 are in 20-30 1/kmW range depending on ω_1 and ω_2. Both the useful signal and the interference are assumed to be a Gaussian pulses at the different frequencies. Both pulses have the same width and there is no initial time delay between them. Useful signal is described as

$$A_1(0,T)=\sqrt{P_1}\,e^{-T^2/2T_0^2} \tag{3}$$

Normalization factors are introduced as

$$\begin{aligned}\xi &= \frac{z}{L_D}\\ \tau &= \frac{t-z/v_{g1}}{T_0}=\frac{T}{T_0}\\ U_j &= \frac{A_j}{\sqrt{P_1}}\end{aligned} \tag{4}$$

where T_0 represents the pulse width. System (1) govern the evolution of pulses along the fiber by including nonlinear and dispersion effects, and if the fiber loss is neglected for simplicity, these equations become

$$\begin{aligned}&\frac{\partial U_1}{\partial \xi}+\frac{i}{2}\frac{\partial^2 U_1}{\partial \tau^2}=iN^2(|U_1|^2+2|U_2|^2)U_1\\ &\frac{\partial U_2}{\partial \xi}\pm\frac{L_D}{L_W}\frac{\partial U_2}{\partial \tau}+\frac{i}{2}\frac{\beta_{22}}{\beta_{21}}\frac{\partial^2 U_2}{\partial \tau^2}=iN^2\frac{\omega_2}{\omega_1}(|U_2|^2+2|U_1|^2)U_2\end{aligned} \tag{5}$$

and dispersive lenght L_{D}, walk-off lenght L_{W}, nonlinear lenght L_{NL} and parameter N are defined as follows

$$\begin{aligned}L_{\text{D}} &= \frac{T_0^2}{|\beta_2|}\\ L_{\text{W}} &= \frac{T_0}{|d|}\\ N^2 &= \frac{L_{\text{D}}}{L_{\text{NL}}}=\frac{\gamma_1 P_1 T_0^2}{|\beta_2|}\end{aligned} \tag{6}$$

In the second equation of system (5) ratio $L_{\text{D}}/L_{\text{W}}$ can take positive or negative values that depends from the fact which pulse is faster which refers to the sign of coefficient d known as a walk-off parameter. One of the most important features of chromatic dispersion is that the pulses at different wavelenghts are propagating at different speeds inside the fiber due to mismatch of group velocities, which leads to walk-off effect that plays an important role in the description of the nonlinear phenomena involving two or more overlapping optical pulses [3,4]. As a matter of fact, the nonlinear interaction between two optical pulses stops when the faster moving pulse has completely walked through the slower moving pulse. The separation between these two pulses is governed by the walk-off parameter d defined by

$$d=\frac{v_{g1}-v_{g2}}{v_{g1}v_{g2}} \tag{7}$$

where v_{g1} and v_{g2} represents the group velocities of the first and the second pulse, respectively. Losses in the optical fiber are neglected by the assumption that $\alpha_j L$<<1 for j=1,2 where L represents the fiber lenght.

When the fiber lenght L is such that L<<L_{NL} and L<<L_{D}, neither dispersive nor nonlinear effects play a significant role during pulse propagation. In that case both nonlinear and dispersive terms can be neglected (it is assumed that the pulse has a smooth temporal profile so that $\partial^2 U/\partial\tau^2$~1). As a result, $U(z,\tau)=U(0,\tau)$ so the pulse maintains its shape during propagation. The optical fiber plays a passive role in this regime and acts as mere transporter of optical pulses (with the exception of reducing the pulse energy because of fiber losses). This regime is useful for optical communication systems (Fig. 1). Parameters L_{D} and L_{NL} should be about 10 times greater then L for distortion-free transmission [3].

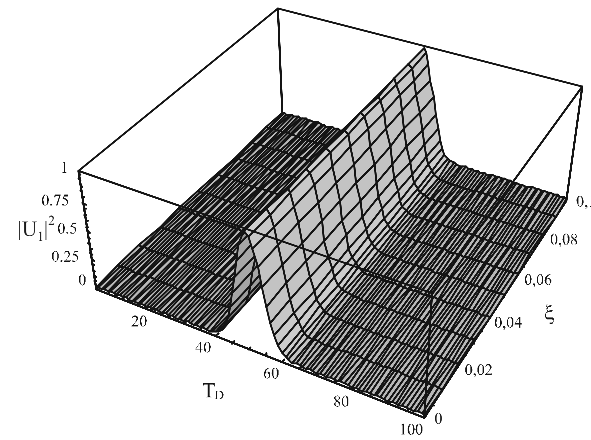

Fig 1. Pulse evolution picture for L<<L_{NL} and L<<L_{D}

In the case of L<<L_{NL} but $L \geq L_{\text{D}}$, nonlinearity is negligible compared to dispersion effect. The pulse propagation is governed by Group Velocity Dispersion (GVD) effect (dispersion is dominant) and nonlinear effect plays relatively negligible role. This is applicable whenever N^2<<1.

When the fiber lenght L is such that L<<L_{D} but $L \geq L_{\text{NL}}$, the dispersion term becomes negligible comparing to a nonlinearity term (as long as the pulse has the smooth temporal profile). In that case pulse evolution in the optical fiber is governed by SPM that leads to spectral broadening of the pulse. This regime where nonlinearity dominates is applicable whenever N^2>>1. This condition is mostly satisfied for relatively wide pulses (T_0>100ps) with the peak power $P_0 \geq$1W.

When the optical fiber lenght L is longer or comparable to both L_{D} and L_{NL}, dispersion and nonlinearity acts together as the pulse propagates along the fiber. This mutual activity of SPM and GVD effects may lead to a qualitatively different behavior compared with the expected from GVD or SPM alone. In anomalous-dispersion regime ($\beta_2<0$), the fiber can support solitons, but in normal-dispersion regime ($\beta_2>0$), the GVD and SPM effects can be used for pulse compression. In the case of anomalous-dispersive regime in optical fiber ($\beta_2<0$), SPM-induced chirp is positive while the dispersion-induced chirp is negative. The two chirp contributions nearly cancel each other along the center portion of the Gaussian pulse when $L_D=L_{NL}$ (N=1). Pulse shape adjusts itself during propagation to make such cancellation as complete as possible. Thus, GVD i SPM cooperate with each other to maintain the chirp-free pulse. This scenario corresponds to soliton evolution. It should be noted that Gaussian profile is not the fundamental soliton. Indeed, if the pulse shape is chosen to be hyperbolic secant, both pulse shape and pulse spectrum remain unchanged during propagation [5].

Figs. 2-6 show the pulse evolution pictures ($|U_1|^2$) when the basic signal is interfered by the same shape pulse at the different frequency so the frequency ratio is ω_1/ω_2=1,2, and for different ratios for dispersive and nonlinear fiber lenghts (N) and dispersive fiber lenght and walk-off lenght (L_D/L_W) (T_D represents the discrete time and ξ normalized distance). Dispersion parameters are taken as $\beta_{21}\approx\beta_{22}>0$.

In the case when N=1 and dispersive lenght is much shorter than walk-off lenght nonlinear effect is dominant and the pulse shape and intensity are significantly changing after $z=5L_D$ (Fig. 2). The pulse is noticeably distorted and the influence of walk-off parameter can be neglected comparing to nonlinear effect. Let us consider now the case when $L_D=L_W$ where it is noticeable that the pulse is additionally distorted because now walk-off effect has a grater influence on the pulse propagation (Fig. 3). It should be noted that the additional distortion appeared on one side of the pulse when the ratio L_D/L_W takes positive value, but if ratio L_D/L_W was taken with the negative sign distortion would appear on the other side of the pulse considering the direction of pulse propagation. In the case when the dispersive lenght is equal to the nonlinear lenght (N=1) and much grater than walk-off lenght, it is noticeable that the pulse intensity is collapsing slower than in case when the walk-off parameter is negligible (Fig. 4).

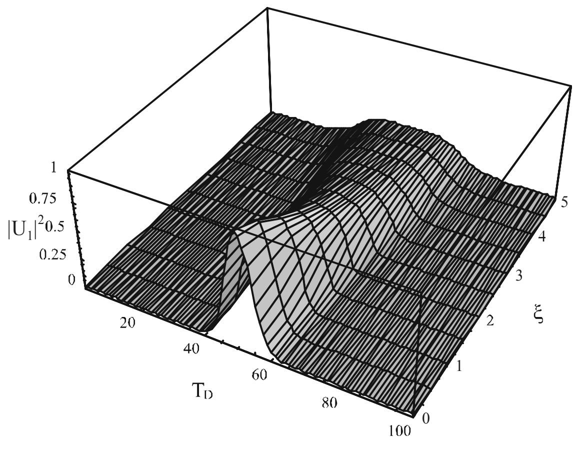

Fig. 2. Pulse evolution picture for ω_1/ω_2=1,2, N=1 and $L_D<<L_W$

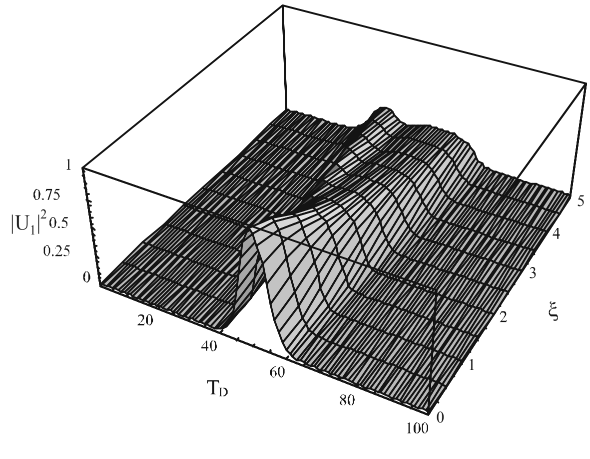

Fig. 3. Pulse evolution picture for ω_1/ω_2=1,2, N=1 and $L_D=L_W$

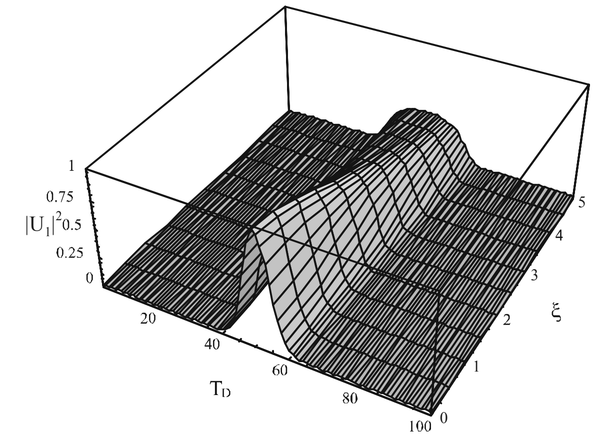

Fig 4. Pulse evolution picture for ω_1/ω_2=1,2, N=1 and $L_D>>L_W$

It would be interesting now to take into the consideration the case when $N^2<<1$ or when parameter N takes very small value (N=0,1). In this case pulse propagation is governed by the GVD effect and nonlinearity can be neglected. It is evident that in this case dispersion effect is dominant during the pulse propagation becouse for the different dispersion lenght L_D and walk-off lenght L_W ratios the pulse evolution picture is not changing significantly. Encountering the fact that in this case dispersive lenght L_D is comparable to the fiber lenght L but much smaller than nonlinear lenght L_{NL} which has the greatest contribution to the pulse distortion and decreasing, it is noticeable that the pulse intensity significantly drops after $z=15L_D$ and for $z=30L_D$ drops to a 23,2% of its initial value and it is wider about 4,5 times (Fig. 5).

When the dispersive lenght is much longer than nonlinear lenght ($N^2>>1$) that nonlinear effect is dominant in the fiber and the puls is rapidly losing it's propagation characteristics and already at $z=0,1L_D$ it is distorted that much that it can be detected only as a noise. Fig. 6 shows the case when N=10 and $L_D<<L_W$. Different dispersive lenght and walk-off lenght ratios show no meaningful influence on the pulse evolution picture so those pulse evolution pictures are not shown.

In all those examples it is assumed that the fiber losses are negligible which simplifies the obtaining of the pulse evolution pictures. Dispersion is taken into account and it is present because of the wave propagation velocity dependence on the wavelenght. Dispersion is limiting the transmission speed in optical telecommunication systems and can be expressed in picoseconds of pulse broadening per fiber kilometer and nanometer of optical source spectral width (ps/nm km). It should be noted that the nonlinear effects are present because of the small fiber cross-section that causes the sufficiently intense signals to produce a nonlinear interactions that are propagating due to a small fiber losses along the very long fibers.

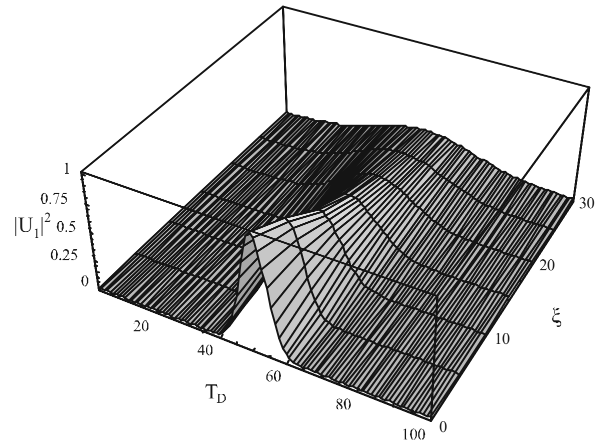

Fig. 5. Pulse evolution picture for ω_1/ω_2=1,2 and N=0,1

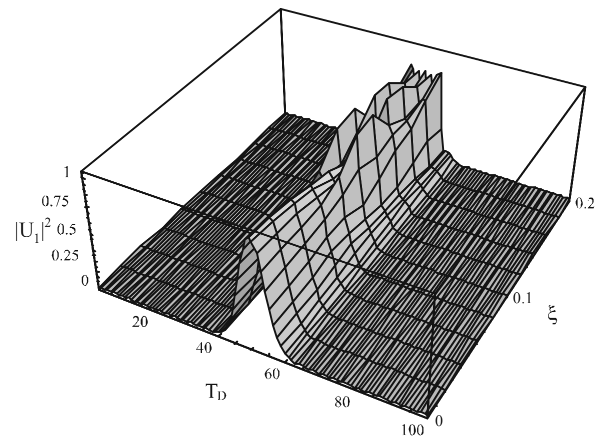

Fig. 6. Pulse evolution for ω_1/ω_2=1,2, N=10 and $L_D \ll L_W$.

III. Conclusion

This paper takes into the consideration the influence of fiber parameters on the pulse propagation in a nonlinear and dispersive fiber. It is shown that the dominant parameter in pulse propagation is parameter N. Its influence is the greatest when L_D dominates comparing to L_{NL}. The bigger the parameter N is, the fiber propagation characteristics are diminishing. The pulse maintains its shape along the fiber due to a cancellation of the positive and negative chirp produced by the mutual activities of the GVD and SPM effects.

The physical significance of N is clearer in [3] where integer values of N are found to be related to the soliton order. The practical significance of parameter N is that the solutions of Schrödinger Nonlinear Equation obtained for a specific N value are applicable to many practical situations by using the scaling of equation. For example, if N=1 and T_0=1ps and P_0=1W, the calculated results apply equally well for T_0=10ps and P_0=10mW or T_0=0,1ps and P_0=100W [3]. As it is obvious from the Eq. (5), N governs relative importance of SPM and GVD effects on pulse propagation along the fiber. Dispersion dominates for $N \ll 1$ while SPM dominates for $N \gg 1$. For values N~1, both SPM and GVD plays equally important role during the pulse propagation.

References

[1] W. Xue, G. Zhou, Z. Li, and S. Guo, “Stable Propagation of Solitons in Strongly Dispersion-Managed Unequal-Lenght Optical Fiber Link with Loss,” *Journal of Lightwave Technology*, vol. 18, pp. 926-932, No. 7, July 2000.

[2] A. R. Chraplyvy, “Limitations of lightwave communications imposed by optical fiber nonlinearities,” *Journal of Lightwave Technol.,* vol. 8, pp. 1548–1557, 1990.

[3] Govind P. Agrawal, *Nonlinear Fiber Optics*, The Instityt of Optics, University of Rochester, Rochester, New York.

[4] L. Bergman, J. Morookian, and C. Yeh, “An All-Optical Long-Distance Multi-Gbytes/s Bit-Parallel WDM Single-Fiber Link,” *Journal of Lightwave Technology*, vol. 16, pp. 1577-1582, September 1998.

[5] G. L. Lamb, Jr., *Elements of Soliton Theory*, New York, Wiley, 1980.