Simulation of Effects of Group Velocity Dispersion on Gaussian Pulse Propagation through Optical Fiber

Petar Spalević[1], Branimir Jakšić[1], Aleksandar Marković[2], Zoran Todorović[1] and Vladislav Simić[3]

Abstract – **In this paper, using a software package OptiSystem is designed system with optical fiber in a linear regime. Analyzed the Gaussian pulse propagation through the fiber under the influence of group velocity dispersion and chirp. Shows the Gaussian pulse shapes in characteristic sections under the influence of group velocity dispersion with and without initial chirp. Shows the compensation group velocity dispersion and dispersion induced chirp.**

Keywords – **Gaussian pulse, Group velocity dispersion (GVD), Chirp, Pulse width, Peak power.**

I. Introduction

An optical signal will be degraded by attenuation and dispersion as it propagates through the fiber optics. Dispersion can sometime be compensated or eliminated through an excellent design, but attenuation simply leads to a loss of signal [1]. Many optical fiber properties increase signal loss and reduce system bandwidth. Eventually the energy in the signal becomes weaker and weaker so that it cannot be distinguished with sufficient reliability from the noise that always present in the system, then an error may occur. Attenuation therefore determines the maximum distance that optical links can be operated without amplification. There are several component options available in fiber optic technologies that lead to particular system configurations. For longer distance optical amplifiers are needed. In general, when a system has a very wide-bandwidth used over a long distance, a single-mode fiber is used [2-4].

There are two different types of dispersion in optical fibers. The first type is intermodal, or modal, dispersion occurs only in multimode fibers. The second type is intramodal, or chromatic, dispersion occurs in all types of fibers. Each type of dispersion mechanism leads to pulse spreading. As a pulse spreads, energy is overlapped [5].

There are two types of intramodal dispersion. The first type is material dispersion. The second type is waveguide dispersion. Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds. Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times [3], [4], [6].

Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths. Waveguide dispersion occurs because the mode propagation constant is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding [7].

The main advantage of single-mode fibers is that intermodal dispersion is absent simply because the energy of the injected pulse is transported by a single mode. However, pulse broadening does not disappear altogether. The group velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. As a result, different spectral components of the pulse travel at slightly different group velocities, a phenomenon referred to as group velocity dispersion (GVD), intramodal dispersion, or simply fiber dispersion. Intramodal dispersion has two contributions, material dispersion and waveguide dispersion. We consider both of them and discuss how GVD limits the performance of lightwave systems employing single-mode fibers [8-11].

II. Effect of Group Velocity Dispersion

The equation, which describes the effect of group velocity dispersion (GVD) on optical pulse propagation neglecting the losses and nonlinearities, is [4]:

$$i\frac{\partial E}{\partial z}=\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} \tag{1}$$

where z is the propagation direction, t is the time, E is the electric field envelope, and $\beta_2=\frac{\partial^2\beta}{\partial\omega^2}$ is the GVD parameter, defined as the second derivative of the fiber mode propagation constant with respect to frequency.

For an input pulse with a Gaussian shape

$$E(z=0,t)=\sqrt{P_0}\exp\left(-\frac{t^2}{2T_0^2}\right) \tag{2}$$

the pulse width T_0, related to the pulse full width at half maximum by

[1]Petar Spalević, Branimir Jakšić and Zoran Todorović are with the Faculty of Technical Sciences at University of Pristina, Kneza Miloša 7, Kosovska Mitrovica 38200, Serbia, E-mail: petarspalevic@yahoo.com.

[2]Aleksandar Marković is with the Faculty of Electronic at University of Niš, A. Medvedeva 14, Niš 18000, Serbia.

[3]Vladislav Simić is with the Telekom Srbija, Takovska 2, Beograd 11100, Serbia.

$$T_{FWHM} \approx 1.665 T_0 \tag{3}$$

increases with z (the pulse broadens) according to [4]:

$$T(z) = \left[1 + \left(\frac{z}{L_D}\right)^2\right]^{1/2} T_0 \tag{4}$$

and, consequently, the peak power changes, due to GVD, are given by:

$$P(z) = \frac{P_0}{\left[1 + \left(\frac{z}{L_D}\right)^2\right]^{1/2}} \tag{5}$$

In Eqs. (4) and (5):

$$L_D = \frac{T_0^2}{|\beta_2|} \tag{6}$$

is the dispersion length. Its meaning is quite straightforward: after propagating a distance equal to L_D, the pulse broadens by a factor of $\sqrt{2}$.

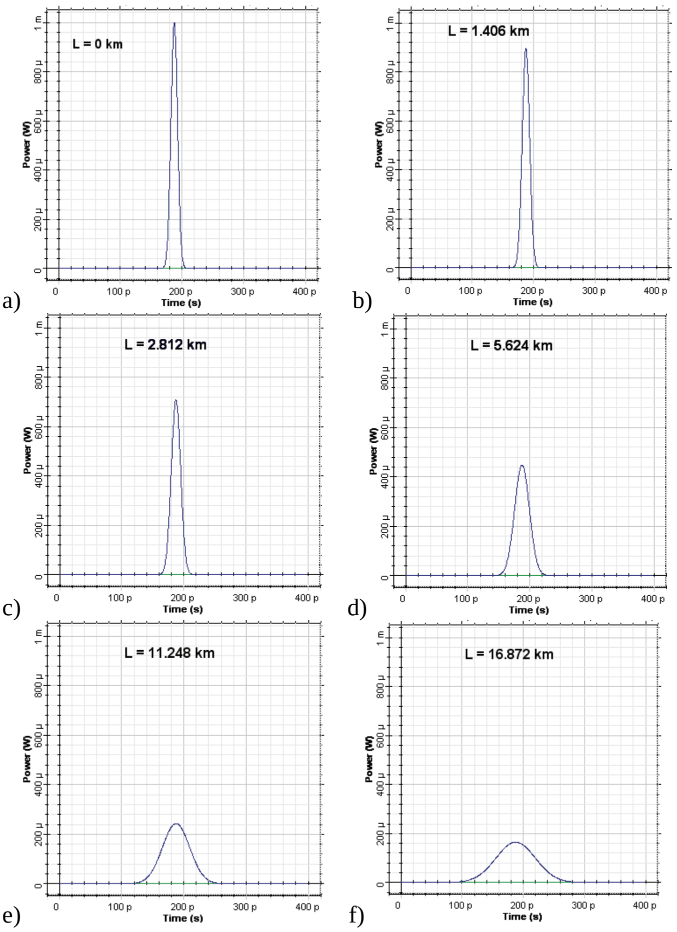

Fig. 1. Gaussian pulse on optical fiber length of: a) L=0, b) L=0.5L_D, c) L=L_D, d) L=2L_D, e) L=4L_D, f) L=6L_D

Effect of GVD on the Gaussian pulse is analyzed in the software OptiSystem [12]. Characteristics of the system include: bit rate signal is 40 Gb/s, bit duration 25 ps, the width of the Gaussian pulse is 0.5, and the power of 0 dBm (1 mW). The system is observed at wavelengths 1.55 µm. Value of GVD parameter is $\beta_2 \approx -20(ps)^2/km$ on 1.55 µm for single-mode fiber.

Based on Eqs (3) and (6) and the values of the parameters observable system we obtain values T_0 = *7.5* ps and L_D = *2.812* km.

Fig. 1 shows the Gaussian pulse at the output of the transmitter (*L=0*) and after transmission through an optical fiber length $L=nL_D$, n=0.5, 1, 2, 4, 6.

From Fig. 1 we can see that with the increase of the length of the distance is to spread the impulse and to reduce its power. The peak power decreases in accordance with Eq. (5). The origin of pulse broadening can be understood be looking at the instant frequency of the pulse, namely the chirp.

Whereas the input pulse is chirpless, the instantaneous frequency of the output pulse decreases from the leading to the trailing edge of the pulse. The reason for this is GVD. In the case of anomalous GVD ($\beta_2<0$), the higher frequency components of the pulse travel faster than the lower frequency.

III. Effect of Initial Chirp with Group Velocity Dispersion

If the input pulse is frequency modulated (i.e. chirped), Eq. (2) is replaced by:

$$E(z=0,t) = \sqrt{P_0}\exp\left(-\frac{1+iC}{2}\frac{t^2}{T_0^2}\right) \tag{7}$$

and the expression for the dependence of the pulse width on z is:

$$T(z) = T_0\left[\left(1 + \frac{C\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2 z}{T_0^2}\right)^2\right]^{1/2} \tag{8}$$

The pulse broadens monotonically with z if $\beta_2 C>0$, however, it goes through initial narrowing when $\beta_2 C<0$. In the latter case, the pulse width becomes minimum at distance [4]:

$$z_{\min} = \frac{|C|}{1+C^2} L_D \tag{9}$$

and is given by:

$$T(z_{\min}) = \frac{T_0}{\left(1+C^2\right)^{1/2}} \tag{10}$$

where C is chirp parameter.

The peak power of the pulse in this case is:

$$P(z_{\min}) = P_0\left(1+C^2\right)^{1/2} \tag{11}$$

Table 1 provides the values of the length of the optical fiber in which the minimum pulse width and peak power at that point for different values of the chirp parameter.

TABLE I
VALUES OF Z_{MIN} AND P (Z_{MIN}) FOR DIFFERENT CHIRP PARAMETER

C	z_{min} [km]	P (z_{min}) [mW]
1	1.406	1.414
2	1.125	2.236
3	0.844	3.162
4	0.662	4.123
5	0.541	5.099
6	0.456	6.083
7	0.394	7.071
8	0.346	8.062
9	0.309	9.055
10	0.278	10.05

Figs. 2 and 3 shows the Gaussian pulse in the characteristic points for chirp parameter *C=1* and *C=5*, respectively.

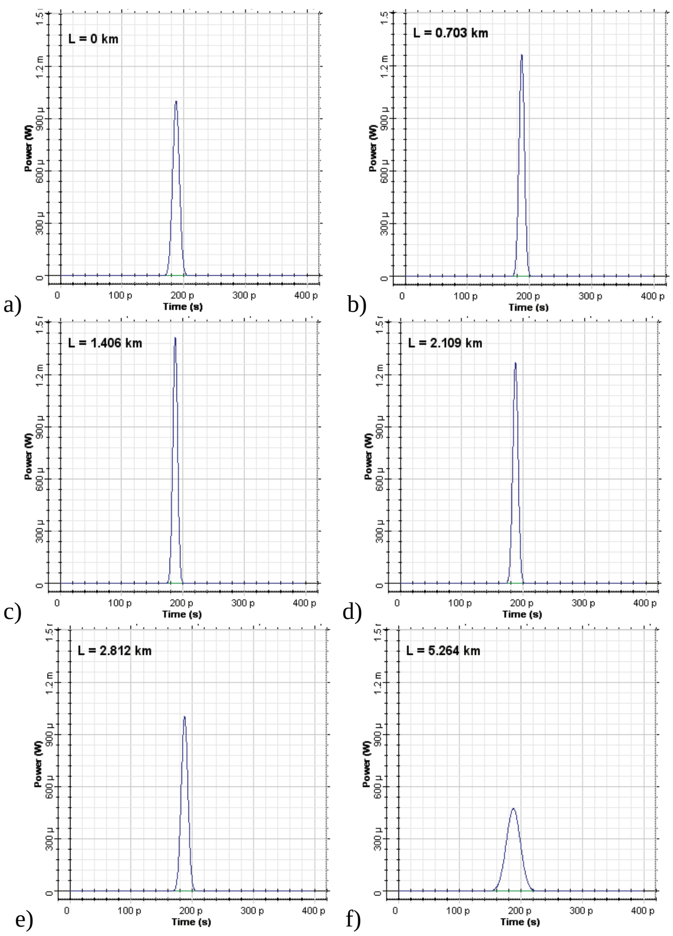

Fig. 2. Gaussian pulse for C=1 at distance: a) L=0, b) L=0.5z_{min}, c) L=z_{min}, d) L=2z_{min}, e) L=L_D, f) L=2L_D

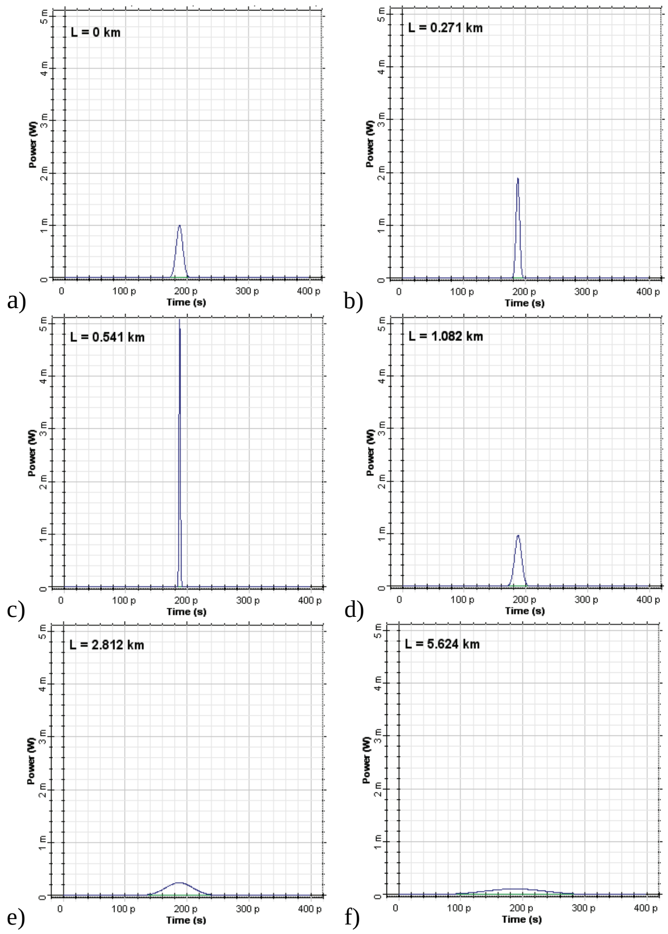

Fig. 3. Gaussian pulse for C=5 at distance: a) L=0, b) L=0.5z_{min}, c) L=z_{min}, d) L=2z_{min}, e) L=L_D, f) L=2L_D

With the given figure can be seen under the influence of chirp leads to increase peak power and reduce the pulse width to the point $L=z_{min}$, where it reaches its maximum power and a minimun width. After a distance zmin comes to a sharp decline of peak power and a significant expansion of impulse. These effects are much more expressed for higher values of chirp parameter *C*.

IV. CONCLUSION

Initial narrowing of the pulse for the case $\beta_2 C<0$ can be explained by noticing that in this case the frequency modulation (or "chirp") is such that the faster frequency components are in the trailing edge, and the slower in the leading edge of the pulse. As the pulse propagates, the faster components will overtake the slower ones, leading to pulse narrowing. At the same time, the dispersion induced chirp will compensate for the initial one. At $L=z_{min}$, full compensation between both will occur. With further propagation, the fast and the slow frequency components will tend to separate in time from each other and, consequently, pulse broadening will be observed.

ACKNOWLEDGEMENT

This work was done within the research project TR32023 and TR35026 of the Ministry of Science and Technological Development of Republic Serbia.

REFERENCES

[1] S. Nilsson-Gistoik, *Optical Fiber Theory for Communication Networks*, Ericsson, Sweden, 1994.
[2] L. Harte, D. Eckard, *Fiber Optic Basics, Technology, Systems and Installation*, Athos Publishing, USA, 2006.
[3] E. G. Sauter, *Nonlinear Optics*, New York, Wiley, 1996.
[4] G. P. Agrawal, *Nonlinear Fiber Optics*, Academic Press, 2nd Ed., 2001.
[5] F. Yaman, Q. Lin, S. Radic, G. P. Agrawal, "Impact of Dispersion Fluctuations on Dual-Pump Fiber-Optic Parametric Amplifiers", Photonics Technology Letters, IEEE vol. 16, no. 5, pp. 1292 – 1294, May 2004.
[6] M. Stefanovic, D. Draca, P. Spalevic, A. Panajotovic: “The influence of crosstalk signal interference to signal propagation along nonlinear and dispersive fiber”, Journal of Optical Communications, vol. 26, no. 1, pp. 9-12, 2005.
[7] V. B. Katok, M. Kotenko, O. Kotenko, "Features of Calculation of Wideband Dispersion Compensator for Fiber-Optic Transmission System", 3rd International Workshop on Laser and Fiber-Optical Networks Modeling, Proceedings of LFNM 2001, pp. 88 – 91, 2001.
[8] G. P. Agrawal, *Fiber-Optic Comunication Systems*, New York, Wiley, 3nd Ed., 2002.
[9] P. Lekić, B. Jakšić, P. Spalević, S. Milosavljević, “Analysis of the Interaction of two Solitons and Violation of Their Linear Superposition in the Transmission Path”, UNITECH conference, vol. 1, pp. 307–311, Gabrovo, Bulgaria, 2010.
[10] M. Stefanović, P. Spalevic, D. Martinovic, M. Petrovic, "Comparison of Chirped Interference Influence on Propagation Gaussian and Super Gaussian Pulse along the Optical Fiber", Journal of Optical Communications vol. 28, no. 1, 2007.
[11] M. Stefanovic, D. Draca, P. Spalevic, A. Panajotovic, “Performance of IM-DD Optical System in the Presence of Interference at Input of the Fiber”, Nonlinear Phenomena in Complex System, vol. 6, no. 4, pp. 870-878, 2003.
[12] www.optiwave.com.