International Journal of Latest Engineering Research and Applications (IJLERA) ISSN: 2455-7137

Volume – 02, Issue – 02, February – 2017, PP – 49-53

Effect of Initial Chirp on Gaussian Pulse in an Optical Fiber

Ali S. Ghammeid[1],Abdosllam M. Abobaker[1], P. Ramesh Babu[2] and K. Senthilnathan[2]

Department of Communications Engineering,College of Electronic Technology, BaniWalid, Libya
Photonics Division, School of Advanced Sciences, VIT University, Vellore, Tamilnadu, India, 632 014

Abstract: In this paper, we intend to study the effect of initial frequency chirp on Gaussian pulse in anoptical fiber at 1550 nm wavelength. Over a certain propagation distance, the Gaussian pulse evolves into a soliton pulse when the chirp induced by self-phase modulation (SPM) gets exactly balanced by the chirp produced by group velocity dispersion (GVD). Further, the introduction of appropriate chirp into the appropriate dispersion regime leads to the generation of ultrashort pulses which signifies the compression process.

Keywords: Frequency chirp, Gaussian optical pulse, group velocity dispersion, self-phase modulation.

1. Introduction

The search for a new communication technology has always been the quest of human society for the betterment of our living conditions. The communication technology is always at the forefront of all other sciences and technologies. Ever since the invention of telephone at the end of 19^{th} century, the dissemination of information has become faster and the volume of information being transferred has grown exponentially.Nowadays, in addition to the telephone, people use the internet in their everyday activities such as e-shopping, e-business transaction, playing games and downloading (music and scientific articles) and they also communicate by e-mail and voice chatting with other people anywhere on the globe. These services ultimately demand high bandwidth information transmission networks. Undoubtedly, optical fiber communication (OFC) system is the only answer to cope with such a phenomenal growth in the bandwidth requirement [1].

Fiber optic technology has advanced to the stage where it has become one of the most attractive solutions for reliable high speed and high capacity communication. The ease at which we quickly browse the internet and the clarity in voice communication between the regions on the globe have all been possible mainly because of optical fiber communications technology [1].

As we virtually live in the information era, the amount of data produced keeps on increasing every day. This ultimately demands more and more information to be handled by the existing communication links. It is necessary at this stage to raise the following question: “What is the requirement of a modern telecommunication system”? Undoubtedly, the answer to the above question is simply the information carrying capacity i.e., “Bandwidth”. As an OFC system operates with light frequency (of the order of 1000 THz), the bandwidth of OFC system can theoretically be as large as 50 THz. Obviously, such a large bandwidth cannot be achieved with copper or coaxial or satellite communication system. Further, note that the aggregate bit rate of commercial fiber systems is now available around a data transfer capability of 400 Gb/s on a single fiber. Experiments have been demonstrated in laboratories where the aggregate bit rate was 1.6 Tb/s over a few hundred kilometers. Based on the above-mentioned facts, recently, there is an increased interest towards optical fiber communication system.

Though there are several above said advantages in OFC, in the case of long distance communication, the information carrying capacity is quite severely affected due to attenuation, dispersion, nonlinearity and amplifier induced noise. The attenuation, nowadays, is being taken care by optical amplifiers.Pulse width gets increased due to dispersion and hence it is highly difficult to distinguish between pulses. This eventually leads to bit error rate (BER). So, the dispersion is considered to be the most threatening aspect of OFC system. In order to fight out the problem of dispersion, in recent years, there have been many dramatic improvements with regard to the design of fiber such as dispersion shifted fiber, dispersion compensating fiber, etc.

To cope with the problem of linear dispersion effect, fortunately there is a nonlinear, counter-effect which shortens the width of the pulse. This effect is called self-phase modulation (SPM). This nonlinearity comes into play when high intensity light pulses propagate through fiber. SPM leads to frequency chirping, ultimately expanding the pulse in frequency domain.In a fiber, a clever configuration of both linear (dispersion) and the nonlinear (SPM) effect does end up with the generation of a pulse that can keep its shape over a long propagation distance, withstanding minor perturbations. These steady pulses are called optical fiber solitons.

Due to their short pulse duration and high stability, solitons could form the backbone of high-speed communications of tomorrow's information super-highway.

Having realized the importance of soliton in communication system, in this paper, we investigate the generation of a soliton pulse through chirped Gaussian pulse at 1550 nm wavelength in a standard telecommunication optical fiber. The paper is arranged as follows. In section 2, we discuss the theoretical model for describing nonlinear pulse propagation in an optical fiber. In section 3, we discuss the pulse broadening factor of a Gaussian pulse for various values of the input chirp. Then, the chirped pulse evolves into a soliton pulse when the chirping effects are counter balanced. We describe the soliton formation in terms of 2D and 3D plots in section 4. Finally, we summarize the results in section5.

2. Theoretical Model

The nonlinear pulse propagation in a standard optical fiber is governed by the well-known nonlinear Schrödinger (NLS) equation and the same is given by [1-3],

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

Here, the physical parameters$U$, z, T, β and γ represent the amplitude, propagation distance, time, anomalous GVD and SPM, respectively.

3. Pulse Broadening Ratio

In this section, we discuss the influence of initial chirp over the Gaussian pulse during the course of propagation in a standard telecommunication optical fiber at 1550 nm wavelength. We start the discussion with the chirped Gaussian pulse and the same is given by,

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

where Cis a chirp parameter. We note that this instantaneous frequency increases linearly from the leading to the trailing edge when C> 0 and is referred to as up-chirp/positive chirp. On the other hand, the frequency decreases linearly from the leading to the trailing edge C< 0 and the same is termed as down-chirp/negative chirp. Thus, it is common to refer to the chirp as either a positive or negative depending on whether C is positive or negative.

Now, we consider the above chirped Gaussian pulse as an input and solve the NLS equation numerically by adopting the split-step Fourier method for initially analyzing the pulse broadening ratio. This we do it by using the pulse broadening ratio of the evolved pulses. Pulse broadening ratio is calculated by using the full width at half maximum (FWHM). That is, pulse broadening ratio = FWHM of final pulse / FWHM of input pulse. The pulse broadening ratio signifies the change in pulse width of the propagating pulse when compared to the pulse width of the input pulse. It is established that the pulse broadening ratio depends on the values of GVD, SPM, chirp parameter C, and the distance of propagation. We use the following parameters of standard telecommunication fiber, $\beta_2 = -20\, ps^2/km, \gamma \cong 2\, W^{-1}Km^{-1}$,$T_0 = 140\, ps$ and the input power $P_0 = 2mW$ for studying the pulse broadening ratio. We carry out the pulse broadening ratio for various values of the chirp, C=-2,-1, -0.5, 0, 0.5, 1 and 2 and the same is shown in Fig.(1). From Fig. (1), it is very clear that both GVD and SPM act simultaneously on the Gaussian pulse. For initial negative chirp, the evolution pattern shows that pulse broadens at first for a relatively smaller distance of propagation length. However, it seems that the pulse broadening ratio seems to reach a constant value after the certain propagation distance. This means that the pulse moves at a slightly larger but constant width as it propagates along the length of the fiber. Although the width of the pulse seems to be a constant, GVD and SPM effects cancel each other out when the GVD induced negative chirp equals the SPM induced positive chirp.

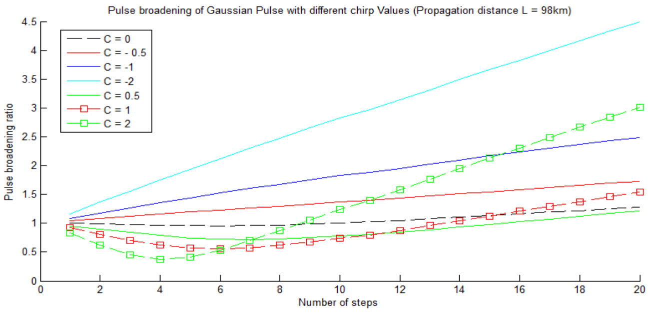
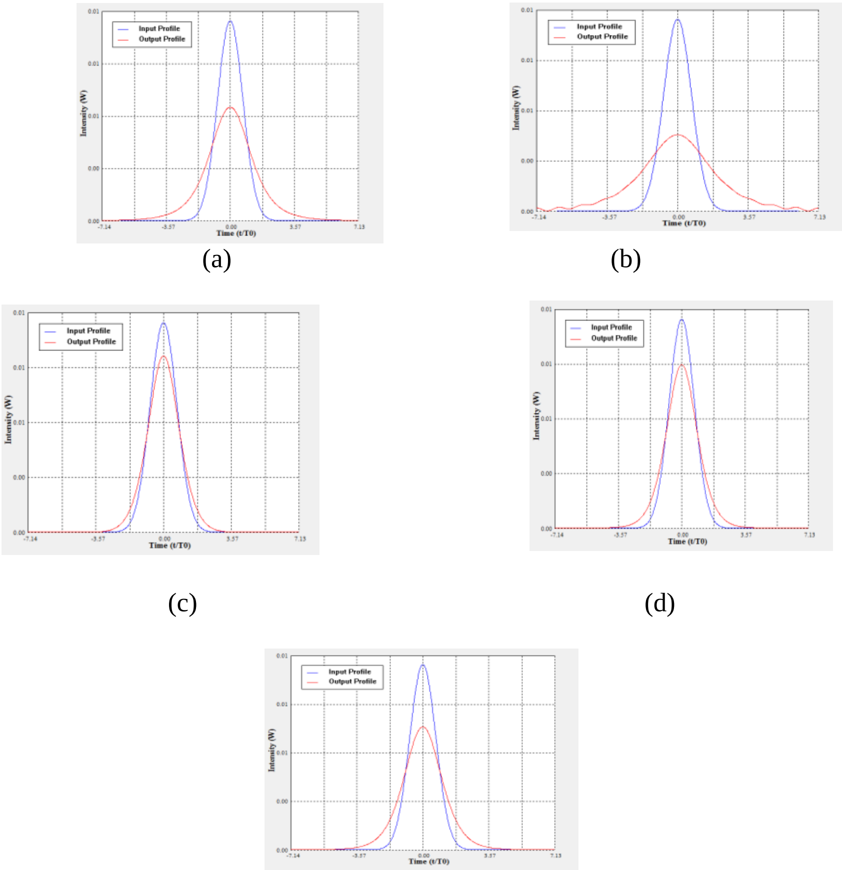


Fig.1:The pulse broadening ratio of Gaussian pulse for various values of chirp

We find that in this case the initial chirp affects in the same way as that of GVD and SPM. The chirp parameter of value -1 adds to the negative chirp of the GVD and deducts from the positive chirp of SPM causing the net value of chirp to be negative. This means that GVD is dominant during the early stages of propagation causing broadening of the pulse. However,in the case of positive chirp, both GVD and SPM act simultaneously but the positive chirp and SPM will cancel the GVD or decrease its amount. But as the propagation distance increases, the effect of the initial chirp decreases as shown in Fig.(1).

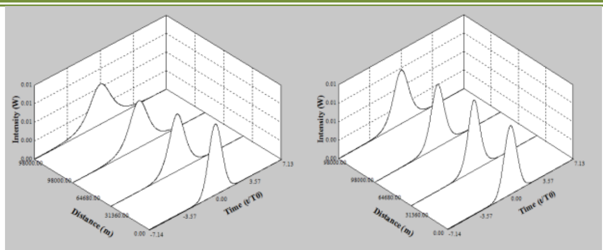
4. Evolution of Chirped Gaussian Pulse into Soliton Pulse

In this section, we delineate the evolution of chirped Gaussian pulse into a soliton pulse by solving the NLS equation numerically using split-step Fourier method. In Fig.(2), we plot the intensity of the input and output Gaussian pulses against the normalized time(t/T_0) for various values of the chirp parameter. Here, we note that the pulse undergoes maximum broadening only when c = -0.1 and the pulse undergoes minimum broadening for c = 1. In Fig.(3), weplot the 3-dimensional chirped Gaussian pulse in terms of its intensity, normalized time (t/T_0) and distance (z) for various values of the chirp parameter C. When the pulse is initially chirped and the condition $\beta_2 C < 0$ is satisfied, it is known that the chirp indeuced by the dispersionis in opposite direction to that of the initial chirp. Consequently, the net chirp is reduced and itleads to pulse narrowing as depicted in Fig.(4).In Fig. (4), the minimum pulse width occurs at a point where the two chirps cancel each other. This is the point where the chirped Gaussian pulse evolves into a soliton pulse where the chirp produced by the GVD gets balanced by SPM. With a further increase in the propagation distance, the chirp produced by dispersion starts to dominate over the initial chirp. Hence, the pulse begins to broaden.

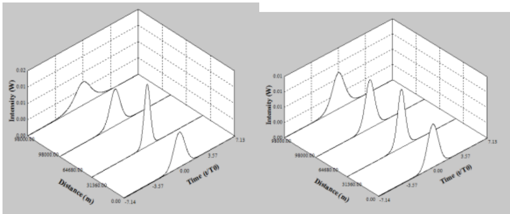


(a) (b) (c) (d) (e)

Fig.2:The input and output pulse of Gaussian optical pulses for different values of chirp parameter a) c=0 , b) c=-0.1 , c) c=0.5 , d) c= 1, e) c=2 .



(a) (b)



(c) (d)

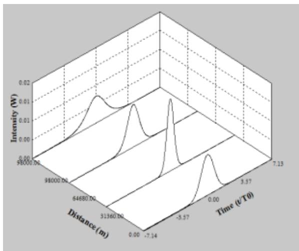
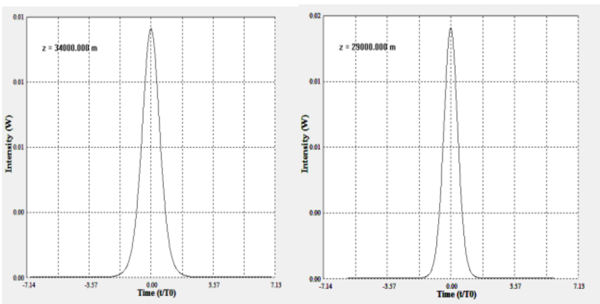
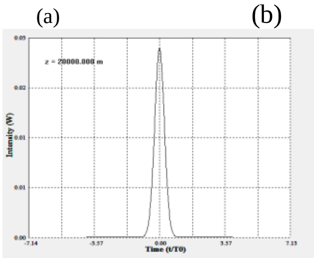


Fig.3:The 3-dimensional Gaussian optical pulse for different values of chirp parameter a) c=0 , b) c=-0.5 , c) c=0.5 , d) c= 1, e) c=2 .



(a) (b)



(c)

Fig (4):The intensity of minimum pulse widthfor different chirp parameter a) c= 0.5 , b) c= 1 , d) c=2.

5. Conclusion

We have investigated the influence of initial chirp on Gaussian pulse in a standard telecommunication optical fiber wherein the pulse propagation is modeled by the NLS equation. By numerically solving the NLS equation, we have studied the pulse broadening ratio for various values of the chirp parameter. Besides these investigations, we have also carried out the numerical simulation for plotting 2-d and 3-d chirped Gaussian pulses. From the detailed investigation, we have found that the chirped Gaussian pulse evolves into a soliton pulse at 1550 nm wavelength.

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