International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.7, pp : 686-690 1 July 2013

Subjugating Dispersive and Nonlinear Effects of Optical Soliton using Group Velocity Dispersion

Anumeet Kaur
Research Scholar, A.S.E.T.,Amity University, Noida, U.P. India
anumeetkr20@gmail.com

Abstract— Main objective of our work is to analyse the possibility of using soliton to weaken undesirable effect for variable nonlinearity and group velocity dispersion. In analysis of the pulse propagation in optical fiber of a new nonlinear effect, solitons pass through localized fibers and the effect of non-linearity and dispersion of the pulse propagation causes temporal spreading of pulse and it can be compensated by non- linear effect using different types of pulse including Gaussian pulses
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Keywords—Soliton, Nonlinear Schrödinger Equation (NLSE), Group velocity dispersion (GVD), Gaussian pulses, Super-Gaussian pulses.

I. Introduction

With the advance of the information technology and the explosive growth of the graphics around the world, the demand for high bit rate communication systems has been raising exponentially. In recent time, the intense desire to exchange the information technology has refuelled extensive research efforts worldwide to develop and improve all optical fiber based transmission systems.

Optical solitons are pulse of light which are considered the natural mode of an optical fiber. Solitons are able to propagate for long distance in optical fiber, because it can maintain its shapes when propagating through fibers. We are just at the beginning of what will likely be known as the photonics. One of the keys of success is ensuring photonics revolution and use the optical solitons in fiber optic communications system. Solitons are a special type of optical pulses that can propagate through an optical fiber undistorted for tens of thousands of km. the key of solitons formation is the careful balance of the opposing forces of dispersion and self-phase modulation.

In this paper, we will discuss the origin of optical solitons starting with the basic concepts of optical pulse propagation. In this paper, we will discuss about theory of soliton, pulse dispersion, self-phase modulation and nonlinear Schrödinger equation (NLSE) for pulse propagation through optical fiber. We study different pulses and implement them using NLSE. In the last, we will show our research result regarding different pulses to generate soliton.

II. Theory

2.1. Soliton

In mathematics and physics a soliton is a self-reinforcing solitary wave. It is also a wave packet or pulse that maintains its shape while it travels at constant speed. Solitons are caused by a cancellation of nonlinear and dispersive effect in the medium. Dispersive effects mean a certain systems where the speed of the waves varies according to frequency. Solitons arise as the solutions of a widespread class of weakly nonlinear dispersive partial differential equation describing physical systems. Soliton is an isolated particle like wave that is a solution of certain equation for propagating, acquiring when two solitary waves do not change their form after collision and subsequently travel for considerable distance. Moreover, soliton is a quantum of energy or quasi particle that can be propagated as a travelling wave in non-linear system and cannot be followed other disturbance. This process does not obey the superposition principal and does not dissipate. Soliton wave can travel long distance with little loss of energy or structure.

In general, the temporal and spectral shape of a short optical pulse changes during propagation in a transparent medium due to the Kerr effect and chromatic dispersion. Under certain circumstances, however, the effects of Kerr nonlinearity and dispersion can exactly cancel each other, apart from a constant phase delay per unit propagation distance, so that the temporal and spectral shape of the pulses is preserved even over long propagation distances [1, 3]. This phenomenon was first observed in the context of water waves [1], but later also in optical fibers [4]. The conditions for (fundamental) soliton pulse propagation in a lossless medium are:

For a positive value of the nonlinear coefficient n_2 (as occur for most media), the chromatic dispersion needs to be anomalous. The temporal shape of the pulse has to be that of an un-chirped $sech^2$ pulse (assuming that the group delay dispersion is constant, i.e. there is no higher-order dispersion):

$$P(t) = P_p sech^2(t/\tau) = \frac{P_p}{cosh^2(t/\tau)} \qquad (1)$$

The pulse energy E_p and soliton pulse duration τ have to meet the following condition:

$$E_p = \frac{2|\beta_2|}{|\gamma|\tau} \qquad (2)$$

Here, the full-width at half-maximum (FWHM) pulse duration is $\approx 1.7627 \times \tau$, γ is the SPM coefficient in rad / (W m), and β_2 is the group velocity dispersion defined as a derivative with respect to angular frequency, i.e. the group delay dispersion per unit length (in s^2/m).

2.2. Pulse Dispersion

In digital communication systems, information is encoded in the form of pulses and then these light pulses are transmitted from the transmitter to the receiver. The larger the number of pulses that can be sent per unit time and still be resolvable at the receiver end, the larger is the capacity of the system. However, when the light pulses travel down the fiber, the pulses spread out, and this phenomenon is called Pulse Dispersion.

Pulse dispersion is one of the two most important factors that limit a fiber's capacity (the other is fiber's losses). Pulse dispersion happens because of four main reasons:

i. Intermodal Dispersion
ii. Material Dispersion
iii. Waveguide Dispersion
iv. Polarization Mode Dispersion (PMD)

An electromagnetic wave, such as the light sent through an optical fiber is actually a combination of electric and magnetic fields oscillating perpendicular to each other. When an electromagnetic wave propagates through free space, it travels at the constant speed of 3.0×10^8 meters.

However, when light propagates through a material rather than through free space, the electric and magnetic fields of the light induce a polarization in the electron clouds of the material. This polarization makes it more difficult for the light to travel through the material, so the light must slow down to a speed less than its original 3.0×10^8 meters per second. The degree to which the light is slowed down is given by the materials refractive index n. The speed of light within material is then v = 3.0×10^8 meters per second/n.

This shows that a high refractive index means a slow light propagation speed. Higher refractive indices generally occur in materials with higher densities, since a high density implies a high concentration of electron clouds to slow the light.

Since the interaction of the light with the material depends on the frequency of the propagating light, the refractive index is also dependent on the light frequency. This, in turn, dictates that the speed of light in the material depends on the light's frequency, a phenomenon known as chromatic dispersion.

Optical pulses are often characterized by their shape. We consider a typical pulse shape named Gaussian, shown in Figure 1. In a Gaussian pulse, the constituent photons are concentrated toward the centre of the pulse, making it more intense than the outer tails.

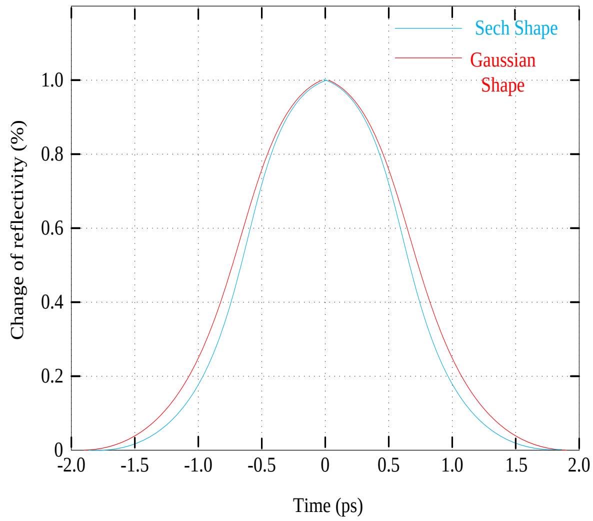

Fig.1 A Gaussian Pulse

Optical pulses are generated by a near-monochromatic light source such as a laser or an LED. If the light source were completely monochromatic, then it would generate photons at a single frequency only, and all of the photons would travel through the fiber at the same speed. In reality, small thermal fluctuations and quantum uncertainties prevent any light source from being truly monochromatic. This means that the photons in an optical pulse actually include a range of different frequencies. Since the speed of a photon in an optical fiber depends on its frequency, the photons within a pulse will travel at slightly different speeds from each other.

Chromatic dispersion may be classified into two different regimes: normal and anomalous. With normal dispersion, the lower frequency components of an optical pulse travel faster than the higher frequency components. The opposite is true with anomalous dispersion. The type of dispersion a pulse experiences depends on its wavelength; a typical fiber optic communication system uses a pulse wavelength of 1.55 µm, which falls within the anomalous dispersion regime of most optical fiber.

Pulse broadening, and hence chromatic dispersion, can be a major problem in fiber optic communication systems for obvious reasons. A broadened pulse has much lower peak intensity than the initial pulse launched into the fiber, making it more difficult to detect. Worse yet, the broadening of two neighbouring pulses may cause them to overlap, leading to errors at the receiving end of the system.

However, chromatic dispersion is not always a harmful occurrence. As we shall soon see, when combined with self-phase modulation, chromatic dispersion in the anomalous regime may lead to the formation of optical solitons.

2.3. Self-Phase Modulation

Self-phase modulation (SPM) is a nonlinear effect of light-matter interaction. With self-phase modulation, the optical pulse exhibits a phase shift induced by the intensity-dependent refractive index. An ultra-short pulse light, when travelling in a medium, will induce a varying refractive index in the medium due to the optical Kerr effect. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum. The refractive index is also dependent on the intensity of the light. This is due to the fact that the induced electron cloud polarization in a material is not actually a linear function of the light intensity. The degree of polarization increases nonlinearly with light intensity, so the material exerts greater slowing forces on more intense light.

Due to the Kerr effect, high optical intensity in a medium (e.g. an optical fiber) causes a nonlinear phase delay which has the same temporal shape as the optical intensity. This can be described as a nonlinear change in the refractive index: $\Delta n = n_2 / n_1$ with the nonlinear index n_2 and the optical intensity I. In the context of self-phase modulation, the emphasis is on the temporal dependence of the phase shift, whereas the transverse dependence for some beam profile leads to the phenomenon of self-focusing.

2.4. Effects on Optical Pulses

If an optical pulse is transmitted through a medium, the Kerr effect causes a time-dependent phase shift according to the time-dependent pulse intensity. In this way, an initial un-chirped optical pulse acquires a so-called chirp, i.e., a temporally varying instantaneous frequency.

For a Gaussian beam with beam radius w in a medium with length L, the phase change per unit optical power is described by the proportionality constant

$$\gamma_{SPM} = \frac{2\pi}{\lambda} n_2 L \left(\frac{\pi}{2} w^2\right)^{-1} = \frac{4 n_2 L}{\lambda w^2} \quad (3)$$

(In some cases, it may be more convenient to omit the factor L, obtaining the phase change per unit optical power and unit length.) Note that two times smaller coefficients sometimes occur in the literature, if an incorrect equation for the peak intensity of a Gaussian beam is used.

The time-dependent phase change caused by SPM is associated with a modification of the optical spectrum. If the pulse is initially un-chirped or up-chirped, SPM leads to spectral broadening (an increase in optical bandwidth), whereas spectral compression can result if the initial pulse is down chirped (always assuming a positive nonlinear index). For strong SPM, the optical spectrum can exhibit strong oscillations. The reason for the oscillatory character is essentially that the instantaneous frequency undergoes strong excursions, so that in general there are contributions from two different times to the Fourier integral for a given frequency component. Depending on the exact frequency, these contributions may constructively add up or cancel each.

In optical fibers with anomalous chromatic dispersion, the chirp from self-phase modulation may be compensated by dispersion; this can lead to the formation of solitons. In the case of fundamental solitons in a lossless fiber, the spectral width of the pulses stays constant during propagation, despite the SPM effect.

2.5. Nonlinear Schrödinger Equation (NLSE)

Most nonlinear effects in optical fibers are observed by using short optical pulses because the dispersive effects are enhanced for such pulses. Propagation of optical pulses through fibers can be studied by solving Maxwell's equations. In the slowly varying envelope approximation, these equations lead to the following nonlinear Schrodinger equation (NSE) [10]

$$\frac{\partial A}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} = i\gamma |A^2| A - \frac{\alpha}{2} A \quad (4)$$

where A(z,t) is the slowly varying envelope associated with the optical pulse, α accounts for fiber losses, β_2 governs the GVD effects, and γ is the nonlinear parameter. For an accurate description of shorter pulses, several higher-order dispersive and nonlinear terms must be added to the NSE [9].

The generalized NLSE can be described as a complete form of nonlinear Schrodinger equation in optical fiber because it contains all relevant parameters for solving pulse propagation in nonlinear media.

2.6. Group velocity dispersion

Group velocity dispersion is the phenomenon that the group velocity of light in a transparent medium depends on the optical frequency or wavelength. The term can also be used as a precisely defined quantity, namely the derivative of the inverse group velocity with respect to the angular frequency (or sometimes the wavelength):

$$\text{GVD} = \frac{\partial}{\partial \omega}\frac{1}{\vartheta_g} = \frac{\partial}{\partial \omega}\left(\frac{\partial k}{\partial \omega}\right) = \frac{\partial^2 k}{\partial \omega^2} \quad (5)$$

The group velocity dispersion is the group delay dispersion per unit length. The basic units are s^2/m. For example, the group velocity dispersion of silica is +35 fs^2/mm at 800 nm and −26 fs^2/mm at 1500 nm. Somewhere between these wavelengths (at about 1.3 μm), there is the zero-dispersion wavelength.

For optical fibers (e.g. in the context of optical fiber communications), the group velocity dispersion is usually defined as a derivative with respect to wavelength (rather than angular frequency). This can be calculated from the above-mentioned GVD parameter:

$$D_\lambda = -\frac{2\pi c}{\lambda^2}.GVD = -\frac{2\pi c}{\lambda^2}.\frac{\partial^2 k}{\partial \omega^2} \quad (6)$$

This quantity is usually specified with units of ps/(nm km) (picoseconds per nanometre wavelength change and kilometre propagation distance). For example, 20 ps/(nm km) at 1550 nm (a typical value for telecom fibers) corresponds to −25509 fs^2/m.

III. Analysing Method

There are many methods to solve NLSE equation. In this paper, we have used split step Fourier method to solve nonlinear Schrödinger equation. It is applied because of greater computation speed and increased accuracy compared to other numerical techniques.

3.1. Split Step Fourier Method

In numerical analysis, the split-step (Fourier) method is a pseudo-spectral numerical method used to solve nonlinear partial differential equations like the nonlinear Schrödinger equation. The name arises for two reasons. First, the method relies on computing the solution in small steps, and treating the linear and the nonlinear steps separately. Second, it is necessary to Fourier transform back and forth because the linear step is made in the frequency domain while the nonlinear step is made in the time domain.

Dispersion and nonlinear effects act simultaneously on propagating pulses during nonlinear pulse propagation in optical fibers. However, analytic solution cannot be employed to solve the NLSE with both dispersive and nonlinear terms present. Hence the numerical split step Fourier method is utilized, which breaks the entire length of the fiber into small step sizes of length h and then solves the nonlinear Schrödinger equation by splitting it into two halves.

Each part is solved individually and then combined together afterwards to obtain the aggregate output of the traversed pulse. It solves the linear dispersive part first, in the Fourier domain using the fast Fourier transforms and then inverse Fourier transforms to the time domain where it solves the equation for the nonlinear term before combining them. The process is repeated over the entire span of the fiber to approximate nonlinear pulse propagation. The equations describing them are offered below [10]. The value of h is chosen for $\emptyset_{max} = \gamma |A|^2 h$, where $\emptyset_{max} = 0.07$;

A_p = peak power of A (z, t) and $\emptyset_{max}$ =maximum phase shift.

In the following part the solution of the generalized Schrödinger equation is described using this method.

$$\frac{\partial A}{\partial z}=\left(-\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3}-\frac{\alpha}{2}A\right)+\left(i\gamma|A|^2A-\frac{\gamma}{\omega_o}\frac{1}{A}\frac{\partial}{\partial t}(|A|^2A-i\gamma T_r\frac{\partial|A|^2}{\partial T})\right) \quad (7)$$

The linear part (dispersive part) and the nonlinear part are separated.

Linear part

$$\hat{L}=\left(-\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3}-\frac{\alpha}{2}A\right) \quad (8)$$

Nonlinear part

$$\hat{N}=\left(i\gamma|A|^2A-\frac{\gamma}{\omega_o}\frac{1}{A}\frac{\partial}{\partial t}(|A|^2A-i\gamma T_r\frac{\partial|A|^2}{\partial T})\right) \quad (9)$$

IV. Result and Analysis

In this paper we have used Gaussian pulse and varying chirp, gamma, input power, soliton order in Matlab simulation to analysis pulse broadening ratio. Pulse broadening ratio should be one throughout all steps of pulse propagation in order to generate soliton. In this thesis, analysis is done by using the pulse broadening ratio of the evolved pulses. Pulse broadening ratio is calculated by using the Full Width at Half Maximum (FWHM).

Pulse broadening ratio = FWHM of propagating pulse / FWHM of First pulse.

Pulse broadening ratio in figure 2 signifies the change of the propagating pulse width compared to the pulse width at the very beginning of the pulse propagation. At the half or middle of the pulse amplitude, the power of the pulse reaches maximum. The width of the pulse at that point is called full width half maximum.

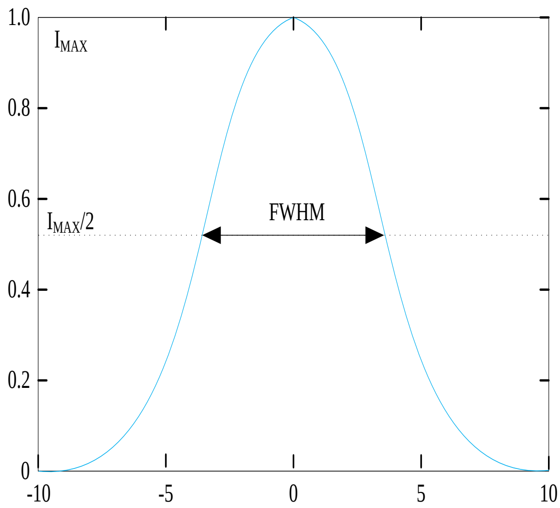

Fig 2. Full Widths at Half Maximum

4.1. Gaussian Pulse

We will vary different nonlinear and dispersive parameters to find pulse broadening ratio through optical fiber. Pulse broadening ratio of Gaussian pulse with chirp, C= -1, -0.5, 0, 0.5, 1.

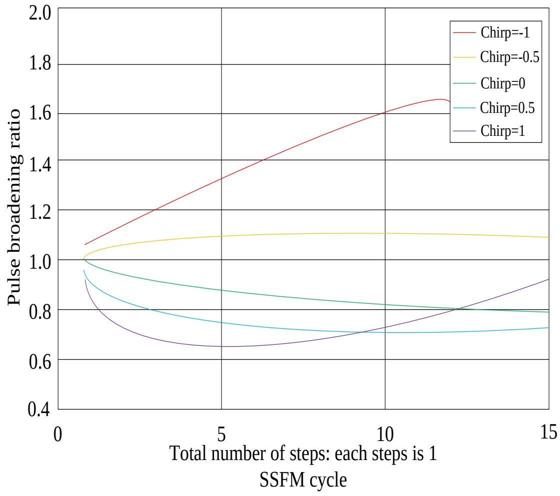

Figure 3: Pulse Broadening Ratio of Gaussian Pulse with different chirp

Here, both GVD and SPM act simultaneously on the Gaussian pulse with initial negative chirp. The evolution pattern shown in figure 3 is that pulse broadens at first for a small period of length. But gradually the rate at which it broadens slowly declines and the pulse broadening ratio seems to reach a constant value. 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 constant, it does not completely resemble a hyperbolic secant pulse evolution. We compare the pulse evolution of the Gaussian pulse with no initial chirp and the negative chirped Gaussian pulse evolution to see the difference in shape and width of each of these evolutions. As we previously established GVD and SPM effects cancel each other out when the GVD induced negative chirp equals the SPM induced positive chirp. But in this case the initial chirp affects the way both GVD and SPM behave. 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. But as the propagation distance increases the effect of the initial chirp decreases while the induced chirp effect of both GVD and SPM regains control. The difference between positive and negative induced is lessened and just like in the case of Gaussian pulse propagation without initial chirp the GVD and SPM effects eventually cancels out each other to propagate at constant width. If both GVD and SPM act simultaneously on the propagating Gaussian pulse with no initial chirp then the pulse shrinks initially for a very small period of propagating length. After that the broadening ratio reaches a constant value and a stable pulse is seemed to propagate. GVD acting individually results in the pulse to spread gradually before it loses shape. SPM acting individually results in the narrowing of pulses and losing its intended shape. Pulse broadening ratio for various nonlinear parameter γ is given below:

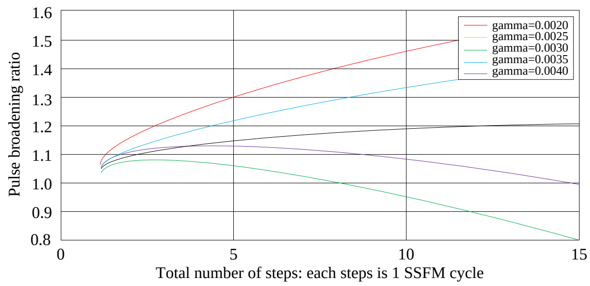

Figure 4: Pulse Broadening Ratio for different values of Nonlinearity

In Figure 4, we study the importance of magnitude of nonlinear parameter γ on nonlinear optical fiber. By keeping the input power and the GVD parameter constant, we generate curves for various values of γ. The ideal value of the nonlinear parameter is one, where GVD effect cancels out SPM effect to obtain constant pulse width. Values chosen for this study are γ = 0.002, 0.0025, 0.003, 0.0035 and 0.004 /W/m.

The purpose is to observe the effect of increasing and decreasing nonlinear parameter on pulse broadening ratio. For γ=0.003, the SPM induced positive chirp and GVD induced negative chirp gradually cancels out.

This results in the pulse propagating at a constant width throughout a given length of fiber. For γ =0.0035, the pulse appears initially more narrow than the previous case. This is because of increasing nonlinearity which results in increased SPM effect. For γ =0.004, the pulse broadening ratio initially decreases to a minimum value. For γ =0.002, it is obvious that the SPM effect is not large enough to counter the larger GVD effect. For this reason pulse broadens. Figure of pulse broadening ratio for Gaussian pulse with input power =0.00056W, 0.0006W, 0.00064W, 0.00068W and 0.00072W.

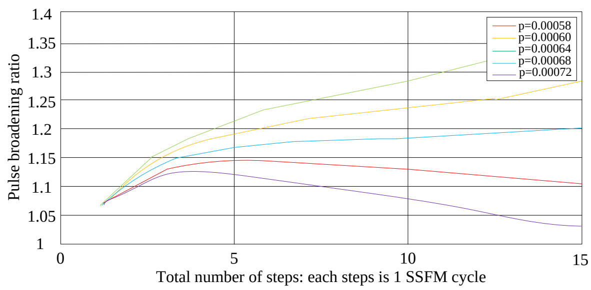

Figure 5. Pulse Broadening Ratio for different values of Power

In Figure 5 we study the importance of magnitude of power on nonlinear optical fiber. By keeping the nonlinear parameter and the GVD parameter constant, we generate curves for various values of input power. It is observed from this plot that, the pulse broadening ratio is more for curves with smaller input power than for those with larger input power.

This property can be explained by the following equation

$$L_N = \frac{1}{\gamma P_o} \quad (10)$$

Where, γP_o is the input power and L_N is the nonlinear length.

This equation shows that the nonlinear length is inversely proportional to the input power. As a result L_N decreases for higher values of P_o. For P_o=0.00072W it is observed that the pulse broadening ratio decreases, meaning narrowing of pulses. Here, the nonlinear parameter γ is also constant so, narrowing of pulses continues to occur. The reason is that the same amount of nonlinear effect occurs, but it manifests itself over L_N . Reducing P_o has the opposite effect. Here, γ stays constant but L_N is larger. So the same SPM effect occurs but over a greater nonlinear length. This means that GVD effect occurs at faster rate when dispersion length is comparatively smaller than the nonlinear length. As a result, GVD effect become more dominant for lower input powers, it results in spreading of pulses.

V. Conclusion

In this paper we explored the effects Gaussian pulses. At first, a Gaussian pulse is launched into the optical fiber and we observed the results for variable nonlinearity, variable group velocity dispersion and variable input power in three separate studies. We find that for low nonlinear parameter values the pulse regains initial shape for a given input power.

The perfect disharmonious interaction of the GVD and SPM induced chirps result in diminishing of both dispersive and nonlinear narrowing effects and hence soliton is obtained. Gaussian pulses are also propagated with or without pre-induced (initial) chirp to study the pattern of propagation. It is found that in the case of chirp 0 and chirp -1, the Gaussian pulse acquires a hyperbolic secant pulse shape and travels as a pseudo-soliton. However, higher values of initial chirp leads to indefinite dispersion and pulse shape is not retained; a fact that can be attributed to the critical chirp, a chirp value beyond which no constant width pulse propagation is possible.

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