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Diminishing Dispersive And Nonlinear Effects Of Optical Soliton Using Group Velocity Dispersion

Anumeet Kaur
Research Schloar, Electronics and Communication Engineering Department,
A.S.E.T., Amity University, Noida, U.P., India

Himanshu Chaurasiya
Assistant Professor, Electronics and Communication Engineering Department
A.S.E.T., Amity University, Noida, U.P., India

Abstract

The main objective of our work is to investigate the ultra-short optical soliton pulses dynamics in amplifying optical fibers with smooth and strong group velocity dispersion. It is well known that the self-frequency shift effect shifts the spectrum of a soliton pulse from under the gain line profile and is one of the main factors that limits the maximum energy and minimum duration of the output pulses. We analyse the possibility of using soliton to weaken undesirable effect for variable nonlinearity and group velocity dispersion. As follow from our simulations it is possible to capture the ultra-short optical soliton by a dispersion formed in an amplifying optical fiber. This process makes it possible to accumulate an additional energy in the soliton dispersion and reduce significantly the soliton pulse duration. In analysis and study 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 and Super-Gaussian pulses.

KEYWORDS: *Soliton, Nonlinear Schrödinger Equation (NLSE), Group velocity dispersion (GVD), Gaussian pulses, Super-Gaussian pulses.*

1. 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.

2. 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):

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

(1)

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

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

(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. Soliton Self-Frequency Shift

When propagating in an optical fiber, soliton pulses are subject not only to the Kerr nonlinearity, but also to stimulated Raman scattering. For very short solitons (with durations of e.g. <100 f_s), the optical spectrum becomes so broad that the longer-wavelength tail can experience Raman amplification at the expense of power in the shorter-wavelength tail. This causes an overall spectral shift of the soliton towards longer wavelengths, i.e., a soliton self-frequency shift [5, 6, 12, 16, 17]. The strength of this effect depends strongly on the pulse duration, since shorter solitons exhibit a higher peak power and a broader optical spectrum. The latter is important because the Raman gain is weak for small frequency offsets. During propagation, the rate of the frequency shift often slows down because the pulse energy is reduced and the pulse duration increased [17].The soliton self-frequency shift can be exploited for reaching spectral regions which are otherwise difficult to access. By adjusting the pulse energy in the fiber, it is possible to tune the output wavelength in a large range [10, 11, 13–15].

2.3. Dissipative Solitons

The solitons as discussed above arise in a situation where the pulse does not exchange energy with the fiber. These (ordinary) solitons are therefore called conservative solitons. A much wider range of phenomena is possible when dissipative effects also come into play. For example, so-called dissipative solitons may arise even for normal chromatic dispersion in combination with a positive nonlinear index, if there is in addition a spectral band pass filtering effect and also optical gain (amplification) to compensate for the energy losses in the filter. Another possible dissipative effect is related to saturable absorption.

Although it is hardly conceivable to have an optical fiber in which all these effects take place in order to form a dissipative soliton, one may a similar phenomenon in the resonator of a passively mode-locked laser, containing not only a fiber, but also other optical components such as a spectral band pass filter and a saturable absorber. If each of the relevant effects is sufficiently weak within one resonator round trip, the resulting dynamics are similar as if all the effects would be occurred in a distributed fashion within the fiber. In that sense, one may describe the circulating pulse in certain mode-locked fiber lasers as dissipative solitons.

Note that strictly speaking we can never have a conservative soliton in a passively mode-locked laser, because we always have some saturable absorption and laser gain. A consequence of that is that the pulse energy and pulse duration in the steady state are fixed, whereas solitons in a fiber could have a wide range of energies and durations, where only their product is fixed. These fixed parameters are actually characteristic for dispersive solitons. However, as the dominant pulse shaping effects are often the conservative ones (namely dispersion and nonlinearity), one nevertheless doesn't call these pulses dissipative solitons.

2.4. Spatial Solitons

Apart from the temporal solitons as discussed above, there are also spatial solitons. In that case, a non-linearity of the medium (possibly of photorefractive type) cancels the diffraction, so that a beam with constant beam radius can be formed even in a medium which would be homogeneous without the influence of the light beam. The fact that soliton wave packets do not spread imposes unusual constraints on the wave motion. Pulses (wave-packets) in nature have a natural tendency to broaden during propagation in a dispersive linear medium. This feature is observed in many different systems in which waves propagate, such as density waves in fluids, charge waves in condensed matter, and electromagnetic waves in media with small absorption. In optics, a localized pulse in space or in time can either broaden in its temporal shape, its spatial extent, or both. For temporal pulses this broadening (temporal lengthening) is due to chromatic dispersion: the various frequency components that constitute the temporal pulse possess different velocities (due to the presence of some, usually distant, resonance). The narrowest pulse forms when the relative phase among all components is zero. However, as the pulse starts to propagate, the frequency components travel at different phase velocities. Hence their relative phase is no longer zero and the pulse broadens. For `pulses' in space (so-called `beams'), the broadening is caused by diffraction. Consider a quasi-monochromatic light beam propagating within a medium of refractive index n in some (arbitrary) general direction that is called the `optical axis', for example along z. The beam can be represented as a linear superposition of plane-waves (sometimes called `spatial frequencies'), all having the same wave vector (k= nx/c, i.e. the ratio between the frequency and the speed of light c/n), with each wave propagating at a slightly different angle with respect to the optical axis. Since each plane-wave component is characterized by a different projection of its wave vector on the optical axis, each component propagates at a different phase velocity with respect to that axis. In this way, the component that propagates `on' the optical axis propagates faster than a component that propagates at some angle a, whose propagation constant is proportional to cos(α). Just as for temporal pulses, the narrowest width of the spatial beam is obtained at a particular plane in space at which all components are in-phase. However, as the beam propagates a distance z away from that plane, each plane-wave component `i' acquires a different phase. This causes the spatial frequency components to differ in phase and the beam broadens (diffracts). In general, the narrower the initial beam, the broader is its plane-wave spectrum (spatial spectrum) and the faster it diverges (diffracts) with propagation along the z-axis. A commonly used method to eliminate spatial spreading (diffraction) is to use wave guiding. In a waveguide, the propagation behaviour of the beam in a high index medium is modified by the total internal reflection from boundaries with media of lower refractive index, and under conditions of constructive interference between the reflections the beam becomes trapped between these boundaries and thus forms a `guided mode'. A planar dielectric waveguide is an example of such a wave guiding system, typically called (1+1) D (or 1D), because propagation occurs along one coordinate (say, z) and guidance along a single `transverse' coordinate y. The guided optical beam is here assumed to be uniform in the other transverse direction x. This is equivalent to Russell's spatial solitary wave case which is also (1+1) D with the water displacement occurring along one spatial coordinate (`height'). An optical fibre is an example of a (2+1) D wave guiding system, in which spatial guidance occurs in both transverse dimensions.

In principle, one can also use an optical nonlinearity to confine a spatial pulse (a narrow optical beam) without using an external wave guiding system. Intuitively, this can occur when the optical beam modifies the refractive index in such a way that it generates an elective positive lens, i.e. the refractive index in the centre of the beam becomes larger than that at the beam's margins. The medium now resembles a graded-index waveguide in the vicinity of the optical beam. When the optical beam that has induced the waveguide is also a guided mode of the waveguide that it induces, the beam's propagation becomes stationary, that is, the entire beam propagates as a whole with a single propagation constant. All the plane-wave components that constitute the beam propagate at the same velocity. As a result, the beam becomes `self-trapped' and its divergence is eliminated altogether, keeping the beam at a very narrow diameter which can be as small as 10 vacuum wavelengths.

2.5. 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 $v = 3.0\times 10^8$ 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.

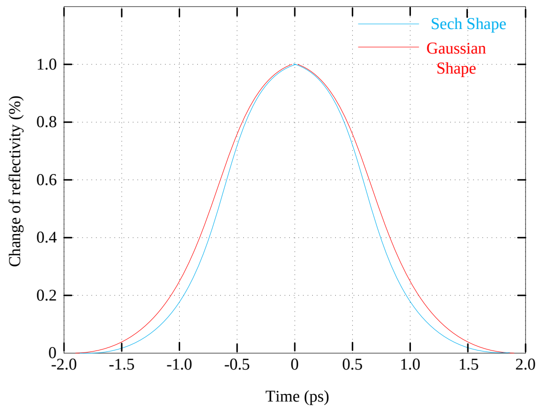

Fig.1 A Gaussian Pulse

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.

2.6. 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.

2.7. 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.

2.8. Self-phase Modulation in Semiconductors via Carrier Density Changes

The term self-phase modulation is occasionally used outside the context of the Kerr effect, when other effects cause intensity-dependent phase changes. In particular, this is the case in semiconductor lasers and semiconductor optical amplifiers, where a high signal intensity can reduce the carrier densities, which in turn lead to a modification of the refractive index and thus the phase change per unit length during propagation. Comparing this effect with SPM via the Kerr effect, there is an important difference: such carrier-related phase changes do not simply follow the temporal intensity profile, because the carrier densities do not instantly adjust to modified intensities. This effect is pronounced for pulse durations below the relaxation time of the carriers, which is typically in the range of picoseconds to a few nanoseconds.

2.9. Self-phase Modulation in Mode-locked Lasers

Self-phase modulation has important effects in mode-locked femtosecond lasers. It results mainly from the Kerr nonlinearity of the gain medium, although for very long laser resonators even the Kerr nonlinearity of air can be relevant [5]. Without dispersion, the nonlinear phase shifts can be so strong that stable operation is no longer possible. In that case, soliton mode locking [4] is a good solution, where a balance of self-phase modulation and dispersion is utilized, similar to the situation of solitons in fibers.

2.10. Self-phase Modulation via Cascaded Nonlinearities

Strong self-phase modulation can also arise from cascaded nonlinearities. Basically this means that a not phase-matched nonlinear interaction leads to frequency doubling, but with subsequent back conversion. In effect, there is little power conversion to other wavelengths, but the phase changes on the original wave can be substantial. The result is that the refractive index of a material increases with the increasing light intensity. Phenomenological consequences of this intensity dependence of refractive index in fiber optic are known as fiber nonlinearities.

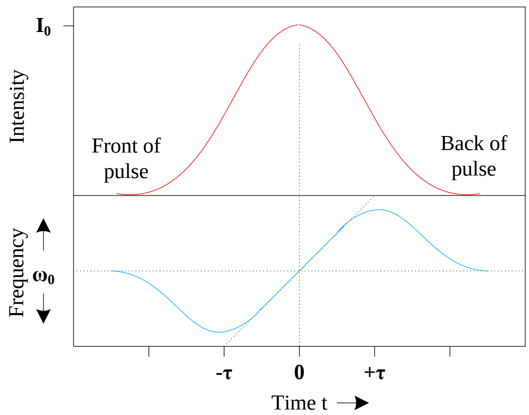

Figure 2. Self-Phase Modulation

In figure 2, a pulse (top curve) propagating through a nonlinear medium undergoes a self-frequency shift (bottom curve) due to self-phase modulation. The front of the pulse is shifted to lower frequencies, the back to higher frequencies. In the centre of the pulse the frequency shift is approximately linear. For an ultra-short pulse with a Gaussian shape and constant phase, the intensity at time t is given by I(t) :

$$I(t)=I_o \exp\left(-\frac{t^2}{\tau^2}\right)$$
(4)

Where I_o the peak intensity and τ is is half the pulse duration.

If the pulse is travelling in a medium, the optical Kerr effect produces a refractive index change with intensity:

$$n(I)=n_o + n_2.I$$
(5)

Where n_0 is the linear refractive index and n_2 is the second-order nonlinear refractive index of the medium.

As the pulse propagates, the intensity at any one point in the medium rises and then falls as the pulse goes past. This will produce a time-varying refractive index:

$$\frac{dn(I)}{dt} = \frac{dI}{dt} = n_2.I_o.-\frac{2t}{\tau^2}.\exp\left(-\frac{t^2}{\tau^2}\right)$$
(6)

This variation in refractive index produces a shift in the instantaneous phase of the pulse.

$$\emptyset(t) = \omega_o t - \frac{2\pi}{\lambda_o}.n(I)\ L$$
(7)

Where ω_0 and λ_0 are the carrier frequency and (vacuum) wavelength of the pulse, and L is the distance the pulse has propagated. The phase shift results in a frequency shift of the pulse. The instantaneous frequency ω (t) is given by

$$\omega(t) = \frac{d\Phi(t)}{dt} = \omega_o - \frac{2\pi l}{\lambda 0}\frac{dn(I)}{dt}$$
(8)

And from the equation for dn/dt above, this is:

$$\omega(t) = \omega_o + \frac{4\pi L n_2.I_o}{\lambda 0\ \tau^2}.t.exp\left(-\frac{t^2}{\tau^2}\right)$$
(9)

Plotting ω (t) shows the frequency shift of each part of the pulse. The leading edge shifts to lower frequencies ("redder" wavelengths), trailing edge to higher frequencies ("bluer") and the very peak of the pulse is not shifted. For the centre portion of the pulse (between t = ±τ/2), there is an approximately linear frequency shift (chirp) given by:

$$\omega(t) = \omega_o + \alpha.t$$
(10)

Where α is:

$$\alpha = \frac{d\omega}{dt}\Big|_0 = \frac{4\pi L n_2 I_o}{\lambda 0\ \tau^2}$$
(11)

2.11. 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) [18]

$$\frac{\partial A}{\partial z}+\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}=i\gamma|A^2|A - \frac{\alpha}{2}A$$
(12)

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 [19].

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.

2.12. 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):

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

(13)

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:

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

(14)

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.

3. 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 [11].

The value of h is chosen for $\emptyset_{max}=\gamma|A|^2h$, 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.

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

(15)

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

Linear part

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

(16)

Nonlinear part

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

(17)

4. Analysis of Different Pulses

A Pulse is a rapid change in some characteristic of a signal. The characteristic can be phase or frequency from a baseline value to a higher or lower value, followed by a rapid return to the baseline value. Here we have analysed three types of pulses which are Gaussian Pulse and Super - Gaussian Pulse.

4.1. Gaussian Pulse

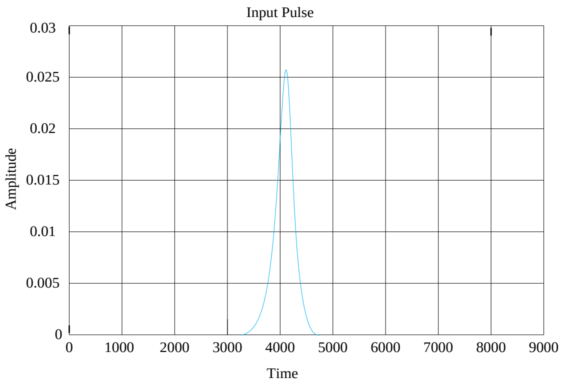

Figure 3. Gaussian Pulse

In Gaussian pulses while propagating they maintain their fundamental shape as shown in figure 3, however their amplitude width and phase varies over given distance. Many quantitative equations can be followed to study the properties of Gaussian pulses as it propagates over a distance of z.
The incident field for Gaussian pulses can be written as

$$U(0, \tau) = A_0 * exp\left(-\frac{\tau^2}{2T^2}\right) \quad (18)$$

T is the initial pulse width of the pulse.

Under the effect of dispersion this equation shows how the Gaussian pulse width broadens over z.

4.2. Super-Gaussian Pulse
The input field for such pulse is described by

$$U(0, \tau) = A_0 * exp\left(-\frac{(1+iC)\tau^{2m}}{2T0^2}\right) \quad (19)$$

Here m is the order of the super-Gaussian pulse and determines the sharpness of the edges of the input. The higher the value of m steeper is the leading and trailing edges of the pulse shown in figure 4.

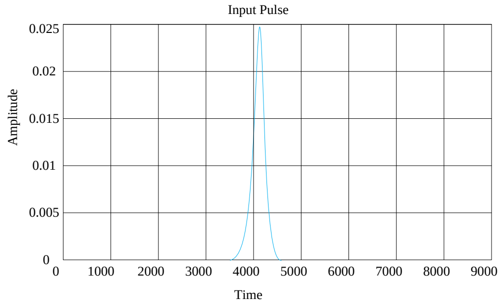

Figure 4. Super-Gaussian pulse

As we continue increasing m, we eventually get a rectangular pulse shape which evidently has very sharp edges. In case of m=1 we get the Gaussian chirped pulse. The sharpness of the edges plays an important part in the broadening ratio because broadening caused by dispersion is sensitive to such a quality.

4.3. Conditions for soliton
The conditions for soliton are:
1) The dispersion region must be anomalous. That is $\beta_2<0$.
2) The input pulse must be an un-chirped hyperbolic secant pulse. In our simulation we used the following pulse-

$$U(0, \tau) = sech^2\left(\frac{\tau}{To}\right) \quad (20)$$

3) The dispersion length must be approximately the same as the nonlinear length.
4) The GVD induced chirp should exactly cancel the SPM induced chirp.

5. Result and Analysis
In this paper we have used Gaussian pulse and Super-Gaussian pulse 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 6 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.

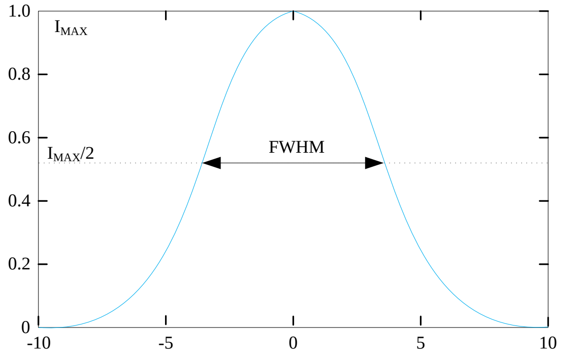

Fig 6. Full Widths at Half Maximum

5.1. 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.

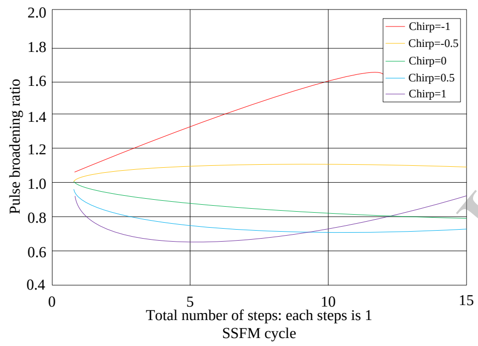

Figure 7: Pulse Broadening Ratio of Gaussian Pulse with different chirp

Here, both GVD and SPM act simultaneously on the Gaussian pulse with initial negative chirp. The evolution pattern shown in figure 7 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:

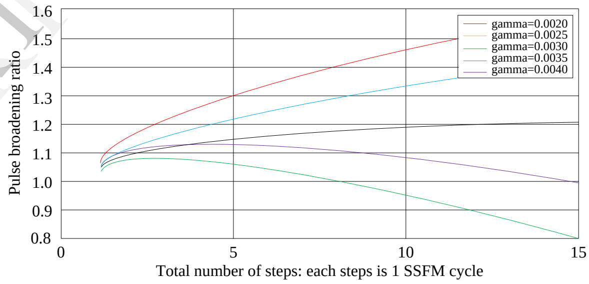

Figure 8: Pulse Broadening Ratio for different values of Nonlinearity

In Figure 8, 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

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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.

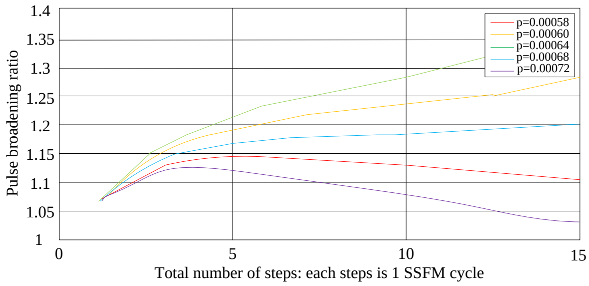

Figure 9. Pulse Broadening Ratio for different values of Power

In Figure 9, 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

$$L_N = \frac{1}{\gamma P_o}$$

(21)

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.

5.2. Super-Gaussian Pulse

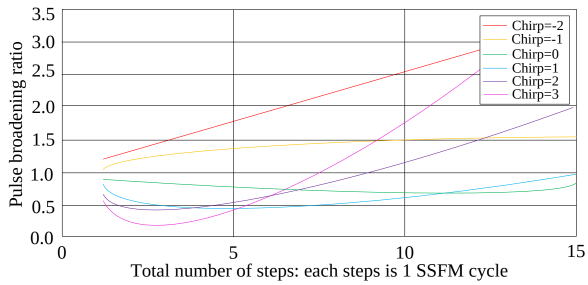

Figure 11: Pulse Broadening Ratio for different values of chirp

In this case, chirp =0, 1, 2, 3, -1, -2 are studied. The pulse broadening ratio curves reveal that as the magnitude of pulse broadening ratio is close to 1 where chirp is from 0 to 1, the effect of dispersion seems to increase as shown in figure 11. But as chirp is increased from 1 to 2 and then 2 to 3, dispersion effects increases largely.

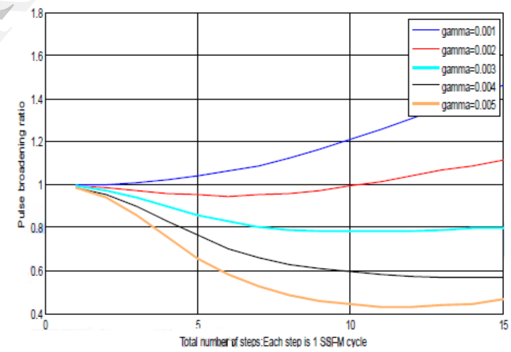

Figure 12: Pulse Broadening Ratio for different values of gamma

In this case, gamma =0.001, 0.002, 0.003, 0.004, 0.005 are studied. The pulse broadening ratio curves reveal that as the magnitude of pulse broadening ratio is close to 1 where gamma is from 0.002 to 0.003, the effect of dispersion seems to increase as shown in figure 12.

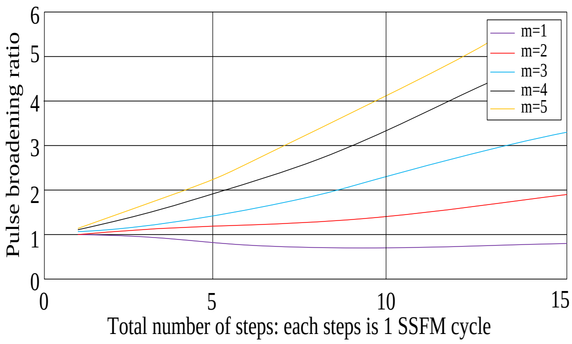

Figure 13: Pulse Broadening Ratio for different values of m

Super-Gaussian pulse broadening ratios for various powers of Super-Gaussian pulses are studied. In figure 13 here we obtain pulse broadening ratio curves for m = 1, 2, 3, 4 and 5. The behaviour of the pulses is easily viewed. As we continue increasing the power *m* of the Super-Gaussian, the slopes of the straight lines of each of the curves increase elsewhere.

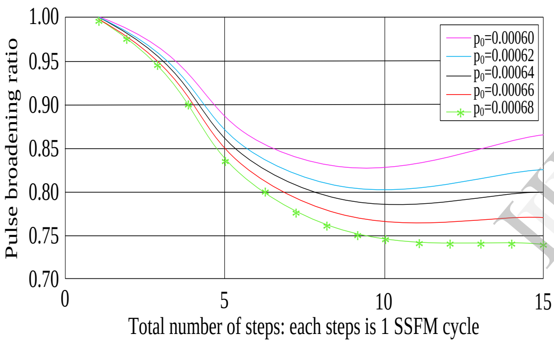

Figure 14: Pulse Broadening Ratio for different values of power

Super-Gaussian pulse broadening ratios for various input powers of Super-Gaussian pulses are studied. In figure 14 here we obtain pulse broadening ratio curves for P_o = 0.00060, 0.00062, 0.00064, 0.00066 and 0.00068. The behaviour of the pulses is easily viewed. As we continue increasing the power P_o of the Super-Gaussian, it goes far away from the value pulse broadening ratio 1.

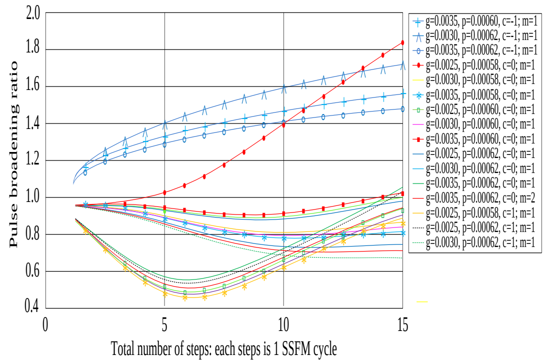

Figure 15: Pulse Broadening Ratio for different parameters

Previously we plotted the graph by varying one parameter and kept constant other two parameters. In this figure 15 here we varied all three parameters and found the optimum values for pulse broadening ratio close to one which are g=0.0025, p=0.00058, c=0, m=1.

6. Conclusion

In this paper we explored the combined effects of various types of pulses including Gaussian pulses and Super-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. For the Super-Gaussian pulse propagation we first considered an un-chirped input with zero nonlinearity parameter to understand the effects of the power of the Super-Gaussian pulse m on the pulse width and found that pulse broadening ratio curve becomes steeper for higher powered Super-Gaussians. We then applied initial chirp on the Super-Gaussian pulses and found that for values of chirp 2 and -2 or higher, the high power Super-Gaussian pulse broadening steadies signifying a decrease in dispersive effects. We also generated pulse broadening ratio curves and evolution patterns for higher order solitons. Here, we demonstrated that as we increase the soliton order, for N=2 the pulse width periodically varies and regains the original pulse after soliton period z_o. However, increasing the soliton order further results in initial periodic behaviour of pulse width before settling at a much lower value indicating that pulse splitting has occurred.

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