

THE NONLINEAR DYNAMICS OF COSH-SUPER GAUSSIAN PULSE IN CUBIC QUINTIC NONLINEAR MEDIUM

A thesis submitted in partial fulfillment of the requirements for the award of
degree of

**Master of Science
In
Physics**

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I affectionately dedicate this thesis at the Lotus feet of Bhagwan 'Sri Sathya Sai Baba' and to my Family, who have been guiding and supporting me throughout my work.

Certificate

I hereby certify that the work which has been presented in this thesis entitled, "**The Nonlinear Dynamics of Cosh-Super Gaussian Pulse in Cubic Quintic Nonlinear Medium**", submitted in partial fulfillment of the requirements for the award of degree of **Master of Science in Physics at Thapar University**, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Soumendu Jana, Assistant Professor, SPMS** and refers other researcher's work which are duly listed in reference section.

The matter embodied in this thesis has not been submitted for the award of any other degree of this or any other university.

Date: 10-7-2013

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Date: 10-7-2013

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CHAPTER 1

1.1 Introduction

Modern age is the age of information technology. From the break of dawn to the late night we come across many devices and applications those depends on huge amount of data communication. Day-by-day the demand for ultra high speed data transfer is increasing with incredible speed. Thus data communication systems have been evolved very fast from the old age copper cable to modern optical fiber based optical communication system [1-3]. The present technology enables optical fiber to carry multimedia data at an unbelievable bit rate (\sim tera bit/s and even peta bit/s in some special case). When light propagates through a fiber, which is a dispersive medium, it experiences broadening. Many techniques have been adopted to minimize such dispersion induced broadening, e.g., dispersion management. However, use of optical nonlinearity to counter balance the broadening has been proved to be most effective. Although, now-a-days common optical fiber based communication systems operate on linear zone, some amount of nonlinear effect will be there due to use of laser and presence of doping. Thus, nonlinearity should be included in the investigation of the fiber optic communication. More importantly, the nonlinearity induced self phase modulation (SPM). This SPM causes contraction of the light pulse, which can nullify the dispersion-induced broadening. And the light pulse will propagate as self trapped structure. This type of light pulse, which is referred as ‘temporal soliton’, as they are confined in time domain, is our present topic of investigation.

Therefore, our investigation is very much within the area of nonlinear optics. Nonlinear optics can be defined as the study of phenomena that occurs as a result of the modification of the optical properties of a material system by the presence of a highly intense light, i.e., Laser light [1-9]. Nonlinear optical phenomena are ‘nonlinear’ in the sense that they occur when the response of a material system to an applied optical field depends in a nonlinear manner on the strength of the optical field. Research on nonlinear optics was initiated almost instantly after the invention of laser in 1960. The first reported nonlinear optical phenomena is second harmonic generation (SHG) in 1961 by P.A.Franken et.al. Back to back several discoveries gave pace to the research in this area. For example, N.Bolemborgen and his coworkers did the theoretical work on optical wave mixing in 1962, THG etc. Since, then the development in this field has

been observed at tremendous rate. Soliton has an old history, however, in non optical case. Long back in 1844 shallow water wave soliton was accidentally observed and further investigated by John Scott Russel, a Scottish naval engineer [10]. Zakharov and Sabat first solved the governing equation of the propagating solitonic waves [11]. Significant theoretical was observed during this period. However, the possibility of optical soliton through optical fiber was predicted by Hasegawa et. al. in 1973 [12]. This theoretical prediction was experimentally verified by Mollenauer et. al [13-15] and a new era has been started which is evolving with an unbelievable rate.

Although known earlier, the first experimental demonstration of spatial optical solitons came from Ashkin and Bjorkholm in 1974 [16]. However, spatial soliton attracted proper attention only after the work of Barthelemy et.al. [17].

The basics of soliton formation follow a balance between dispersion and nonlinear effect. SPM is the temporal analog of self-focusing (narrowing of the spot size) and contracts the pulse. It is well known that dispersion, both normal and anomalous, alone leads to the pulse broadening that would limit transmission capacity through optical fiber [18]. Soliton based communication systems are free from that error, thus important.

Temporal solitons formation has been studied in media with wide variety of nonlinearity such as Kerr [11], cubic-quintic [19], power law [20, 21], saturating [22], quadratically nonlinear [23], and in photorefractive nonlinear crystals [24].

Optical sources those are used for fiber optic communication has temporal profile is very close to Gaussian. Compression of chirped Gaussian pulses has been investigated thoroughly [25]. Other pulse shapes, such as sech hyperbolic (which is also the ideal solution of the corresponding soliton propagation equation), hyperbolic cosine, super Gaussian have been also considered [3]. However, the propagation of cosh-super Gaussian pulses has not received much consideration. Such pulses can be useful in optical communication systems. We thus explore the possibility of temporal soliton formation in cubic-quintic with cosh-super Gaussian pulses. Before going to details of the main investigation model and results it is worthy to discuss about the basics of nonlinear optics.

1.2 Origin of Optical Nonlinearity

The main cause behind the generation of nonlinear optical phenomena is light-matter interaction. Depending on the nature of material and coherence property of light this nonlinear light matter interactions may be of four types:

- Nonresonant interaction with incoherent light.
- Nonresonant interaction with coherent light.
- Resonant interaction with incoherent light.
- Resonant interaction with coherent light.

Under the interaction of an applied optical electric field, the atoms or molecules of the medium may respond in two ways: (i) a real transition of a certain amount of atoms or molecules from one quantum eigen state to another, and (ii) the perturbation of normal distribution or motion of internal electric charges within an atoms or molecules. The first is predominant for **resonant** interactions and the second is predominant for **non or near resonant** interactions. A simple way to describe the interaction effect is through the change in electric polarization.

1.3 Nonlinear Electric Polarization Approach

In this approach nonlinear changes in the medium leads to the modification of electric polarization of the dielectric medium due to intense light. Particularly for nonresonant interactions, i.e., where the matter does not absorb the incident radiation this approach is appropriate. Maxwell's equations in association with nonlinear polarization are used to describe this kind of interaction. A large number of nonlinear optical phenomena can be theoretically explained through this approach.

1.3.1 Various Mechanisms Causing Nonlinear Polarization in a Medium

Depending on the applied field frequency and the phase of the medium one or more of the mechanisms discuss below become the major contributor to the nonlinear behavior of the medium.

- **Distortion Of Electronic Cloud Model**

The collection of charged particles can be considered as an optical material, i.e., negatively charged electrons (that form electron cloud) and positively charged cores. In the absence of electromagnetic radiation the center of mass of negative electron cloud coincides with that of positive core and counter-balance each other therefore, the atoms of the dielectric optical medium show no net dipole moment. But on applying optical field, the negatively charged electron cloud moves in one direction, whilst the positive core tends to move along the direction of the field. As a result, the center of the atom's negative charge does not coincide with the positive cores. Thus, molecules of the dielectric are distorted. This mechanism has very fast response time and approximately less than $(10^{-16} - 10^{-15})$ seconds.

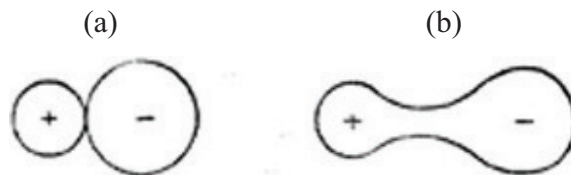


Fig.1.1 Schematic of the distortion of electronic cloud model

(a) The atom in the absence of Electric field E, (b) the elongated atom in the influence of E

- **Intramolecular Motion**

It denotes the polarization contribution from an optical field induced relative motion (vibration, rotation, etc.) between the nuclei (or ions) within a molecule. The response time of this mechanism is around 10^{-12} second, e.g. some Raman resonance-enhanced four-wave-mixing effects and Raman enhanced refractive index change.

- **Molecular Reorientation**

It denotes the additional electric polarization contribution from an optical field induced reorientation of anisotropic molecules in a liquid. The response time of this process is dependent on the rotational viscosity of molecules in the liquid and is approximately $(10^{-12} - 10^{-13})$ second, e.g. stimulated Kerr scattering and Kerr-effect related refractive index change.

- **Induced Acoustic Motion**

It is the polarization contribution from an optical induced macroscopic acoustic motion related to the so called electrostriction interaction. The response time of this mechanism is ($10^{-9} - 10^{-10}$) second depending on the phase state of the medium, e.g. Brillouin scattering, self focusing and optical breakdown damage.

- **Induced Population Change**

The distribution of molecules in their different eigen states may be changed owing to one-photon or two-photon absorption or Raman transition for resonant interaction. The response time of this additional polarization of the medium is strongly dependent on the dynamic properties of molecular transition and relaxation of the medium and in general slower than that of first three mechanisms.

1.4 Density Matrix Formalism

This a quantum mechanical approach. It is especially applicable for resonant interactions (i.e., matter will absorb light) of coherent light with matter [2, 26]. In this the introduction of the density matrix the quantum mechanical description of a single particle of the optical material is extended for averaging over the ensemble, the elements of which represents the population of the different states of the matter including the transition states.

1.5 Self-Focusing

When an intense beam of light passes through a nonlinear optical medium it creates a refractive index profile similar to the intensity profile of the beam. For example a Gaussian beam whose maximum intensity at central region virtually induces a waveguide consisting of maximum refractive index at the axis and decreasing value at off axis region. Now due to its own intensity induced refractive index profile the beam converges during propagating This phenomenon of focusing of a beam by virtue of self-induced lens is referred to as self-focusing.

1.6 Dispersion

The components of a pulse will have different velocities through a medium. That leads to broadening or squeezing of the pulse. This is dispersion. This occurs due to different group velocity thus called group velocity dispersion (GVD).

1.7 Self Phase Modulation (SPM)

Pulse means time varying intensity. An intense pulse then induces time varying nonlinear refractive index. This time varying refractive index again changes the phase of the pulse itself. Due to phase change instantaneous frequency will change. This redistribution of instantaneous frequency is chirping. And the phenomena of modulation in phase of a pulse due to its own intensity are referred as self-phase modulation (SPM).

1.8 Soliton Formation

The idea of soliton has become one of the most promising way in the current communication revolution. This phenomenon was first noticed by the Scottish engineer John Scott Russell in water waves of union canal, in 1834. It took more than a century to get the momentum in research on this special localized waves. Korteweg-de Vries (1895) [27] and Boissinesq (1872) [28] have widely studied shallow water waves to prove the existence of solitary waves theoretically. In 1965 Martin Kruskal and Norman Zabusky [29] coined the name “soliton”. The localized states of waves, which are capable of traveling with a self-similar shape and behave like a particle during interaction, are called soliton. In other words, if a wave propagates keeping its shape and width unaltered even after collision with another similar wave, it will be considered as soliton. Solitons can be found in water waves, plasma, and light waves and in many other media even in bio-mass (bio-soliton) [1-9, 30-40]. But our concern is only with optical solitons, which are localized pulses or beams.

Optical solitons are classified into two broad categories, namely temporal soliton and spatial soliton, depending on their confinement in time or space domain. **Temporal** solitons are pulses that remain confined in time domain, whereas, the **Spatial** solitons are confined in a

direction transverse to the direction of propagation. A combination of them, that is localization in both time and space domain leads to **spatiotemporal** solitons.

There are many sub groups of solitons, e.g., photorefractive soliton, quadratic soliton, vortex soliton, bright soliton, dark soliton, propeller soliton, vector solitons, gap-solitons, zig-zag solitons, snake-solitons etc.

1.8.1 Spatial Soliton

Simply to say, optical spatial solitons are optical beams that remain self-trapped by due to the balance between diffraction and nonlinearity induced self-lensing or self-focusing effects, as shown schematically in Fig.1.2

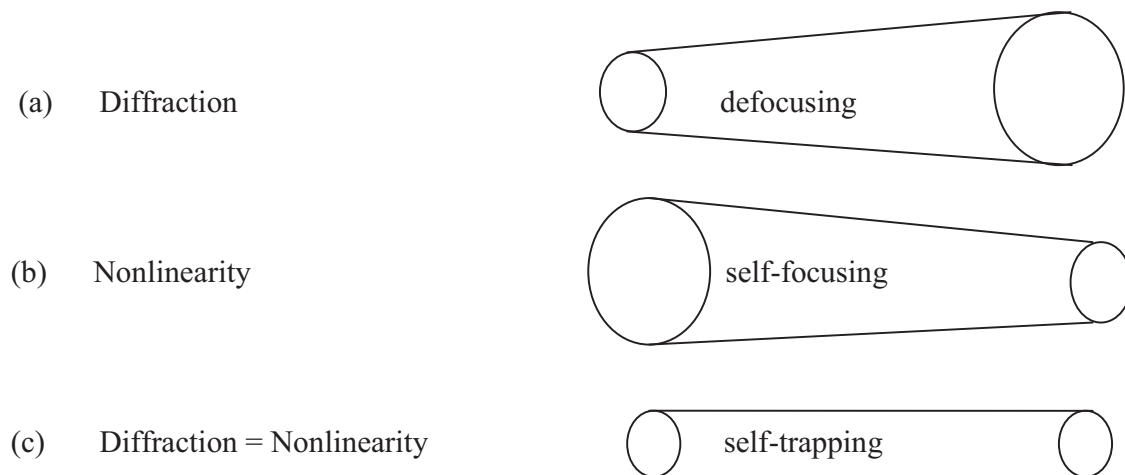


Fig.1.2 Schematic showing the spatial beam profiles (a) normal beam diffraction, (b) beam self-focusing, and (c) soliton propagation.

All solitons require that a strong nonlinear interaction takes place between themselves and the material in which they propagate. Any laser beam gets diffracted due to its small aperture. This is self diffraction. Now, some materials possess considerable optical nonlinearities, that is, their properties (refractive index or absorption) are modified by the presence of intense light. This intensity dependent refractive index profile may self-focus the beam. Thus these two

counteracting phenomena can lead to self-trapped beam propagation. This is spatial soliton. The beam width either will be constant or oscillate periodically.

1.8.2 Temporal Soliton

The existence of temporal solitons [3-5, 9, 41-45] in optical fibers and their use for optical communications were suggested in 1973 [12]. In 1980 such solitons had been observed experimentally [13]. Temporal solitons form inside optical fibers because of a balance between the group-velocity dispersion (GVD) and self-phase modulation (SPM) induced by the Kerr nonlinearity. At this point it is worthy to mention that cubic/Kerr nonlinearity is the most important nonlinearity in optical fiber. However, introduction of quintic nonlinearity modifies the propagation properties significantly.

However, the GVD broadens optical pulses during their propagation inside an optical fiber, shown in Fig. 1.3 (a & b) Now, a chirped pulse can be compressed during the early stage of propagation because of the nonlinearity induced SPM as seen in Fig1.3 (c & d). Under certain conditions SPM and GVD may cooperate in such a way that SPM-induced contraction will cancel the GVD-induced broadening of the pulse. The optical pulse then propagates in the form of a soliton shown in Fig. (e).

Due to GVD in anomalous dispersive medium, the leading edge gets blue shifted and trailing edge gets red shifted. This causes a temporal spreading of the pulse. Whereas, when nonlinearity is dominant in the medium, SPM will occur which has opposite sense of chirping with respect to that of GVD. Thus, combine effect of both dispersion and self focusing leads to the formation of a temporal soliton.

Hence, temporal solitons are light pulses that neither broaden nor squeeze in both temporal and spectral domain. After counterbalancing the effects of SPM and GVD the pulse propagates with constant temporal as well as spectral width. These localized pulses are sometimes also called as longitudinal soliton. Since, it is a waveguide whose longitudinal dimension rather than transverse dimension is significant for light propagation.

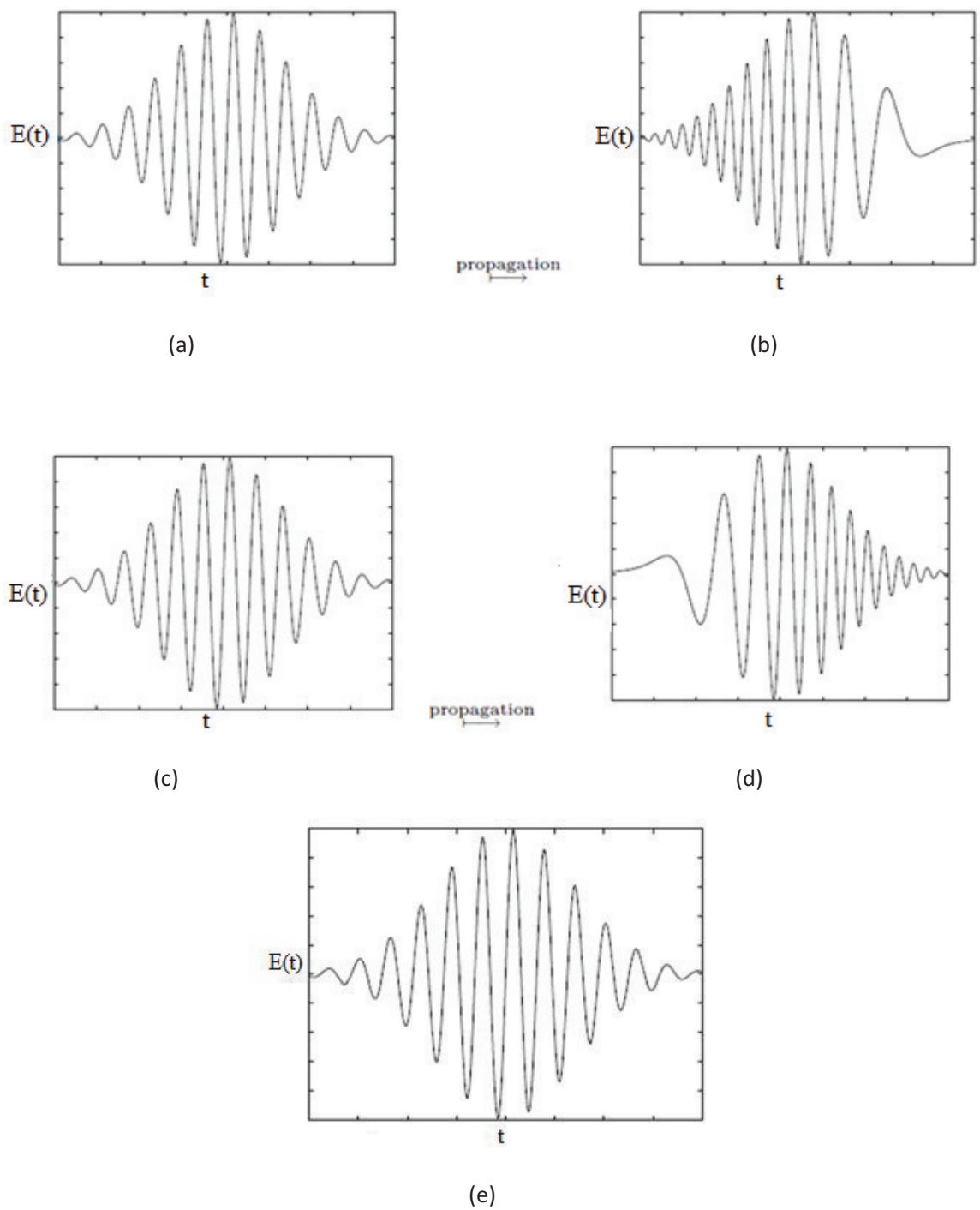


Fig.1.3 (a) Initial pulse, (b) GVD induced Blue shift and red shift at leading and trailing edge respectively, (c) Initial pulse, (d) SPM induced red shift and Blue shift at leading and trailing edge respectively, (e) Temporal Soliton, result of dispersion and self-focusing

1.8.3 Spatiotemporal Soliton

Spatiotemporal optical solitons are the most significant as far as application is concerned [46, 47]. Spatiotemporal solitons are self-trapped in both the temporal and spatial domain. Thus generation of spatiotemporal solitons are always challenging as this multidimensional balance cannot be achieved easily. However, in this case of soliton self-trapping is obtained through simultaneous balance between diffraction, group velocity dispersion and nonlinearity. Three dimensional (3D) spatiotemporal solitons that are self-localized in two transverse dimensions and one longitudinal dimension were predicted by Silberberg in 1990. This was termed as ‘light bullets’ due to its confinement in all direction [48]. For higher dimension the pulsed beam experiences a fluctuation in intensity, beam size and temporal pulse width that gives rise to spatiotemporal collapse whereas, stability analysis shows that shape-preserving solutions are stable in 1D. There is critical pulse energy in self-focusing Kerr nonlinear media above which a pulse condenses to zero in both spatial and temporal domain.

Both quadratic as well as Kerr nonlinear medium (however, with some modification) may host STS. They are theoretically unstable in third order optical media [49, 50] but stable in saturating nonlinearity [51]. Recently, existences of stable and quasistable STS have been predicted in cubic quintic nonlinear medium.

1.9 Motivation

Temporal soliton have been studied in different nonlinear media such as Kerr, cubic quintic, power law, saturating, quadratically nonlinear, and in photorefractive nonlinear crystals. To the best of our knowledge the cosh-Super Gaussian pulse propagation in cubic-quintic nonlinear media has yet to be explored. Therefore, I propose to investigate the nonlinear dynamics of cosh-Super Gaussian pulse in cubic-quintic nonlinear media.

1.10 Objectives

- To study the dispersion induced broadening characteristics of cosh-Super Gaussian pulses in linear dispersive media.
- To investigate the nonlinear propagation of cosh-Super Gaussian pulse in cubic-quintic nonlinear media.

- To explore the possibility of soliton formation with cosh-Super Gaussian pulse in cubic-quintic nonlinear media.

CHAPTER 2

2.1 Mathematical Formulation

We investigate cosh-super Gaussian pulse propagation and soliton formation through cubic quintic nonlinearity. The propagation of the pulse can be given by the following normalized nonlinear Schrödinger equation (NLSE):

$$i \frac{\partial Q}{\partial \xi} + \frac{1}{2} \frac{\partial^2 Q}{\partial \tau^2} + |Q|^2 Q + s|Q|^4 Q = 0 \quad (1)$$

where, $Q(\xi, \tau)$ is the slowly varying pulse envelope.

We also consider the cosh-super Gaussian pulse form:

$$Q(\xi, \tau) = \frac{A}{2} \sqrt{P} . e^{i\phi} \left[e^{-\left(\frac{P^2 - iC}{2}\right) \left(\frac{t}{T_0} - \Omega_0\right)^{2m}} + e^{-\left(\frac{P^2 - iC}{2}\right) \left(\frac{t}{T_0} + \Omega_0\right)^{2m}} \right] \quad (2)$$

Where A , $p(\xi)$, $C(\xi)$ and $\phi(\xi)$ are amplitude, inverse of the pulse width, chirp and longitudinal phase, Ω_0 is cosh-gaussian parameter, T_0 is the pulse width, τ is time, ξ is propagation distance, s is the relative strength of quintic nonlinearity and m is super Gaussian parameter respectively.

The NLSE (given by eq. (1)) possess of infinite number of conserved quantities. These conserved quantities are actually integral of motion. Two most important conserved quantities are energy P or wave power,

$$P = \int_{-\infty}^{\infty} |Q|^2 d\tau \quad (3)$$

And, linear momentum,
$$M = \frac{i}{2} \int_{-\infty}^{\infty} \left(Q \frac{\partial Q^*}{\partial \tau} - Q^* \frac{\partial Q}{\partial \tau} \right) d\tau \quad (4)$$

The above mentioned NLSE is integrable. However, since our aim is to investigate the propagation dynamics of cosh-super Gaussian pulse, we tried variational method. This is an approximate analytical method based on variation of the Lagrangian of the system.

The main advantage of this method is its simplicity and capacity to provide clear qualitative and quantitative result. This has motivated the use of this method in present investigation.

The field Lagrangian density L for our NLSE, Eq. (1) may be written as:

$$L = \frac{i}{2} \left(Q \frac{\partial Q^*}{\partial \xi} - Q^* \frac{\partial Q}{\partial \xi} \right) + \frac{1}{2} \left| \frac{\partial Q}{\partial \tau} \right|^2 - \frac{1}{2} |Q|^4 - \frac{s}{3} |Q|^6 \quad (5)$$

Eq. 5 can be used to get the evolution equation of the pulse parameters by the vanishing of the Lagrangian variation:

$$\delta \int_0^\xi \langle L \rangle d\xi = 0 \quad (6)$$

Where,

$$\langle L \rangle = \int_{-\infty}^{\infty} L d\tau \quad (7)$$

As stated earlier, the NLS Eq. (1) is integrable resulting in one soliton, two soliton and N-soliton solutions. We can get an idea about the initial pulse shape, amplitude and width of the pulse which is propagating through the nonlinear media with the solution of one soliton which is hyperbolic secant shaped pulse. However, since Eq. (1) is nonlinear, it may also allow propagating optical pulses that are not hyperbolic secant shaped and that are not obtainable by direct integration. Practically speaking, what happens to the pulse that is not ideal soliton propagates through nonlinear medium.

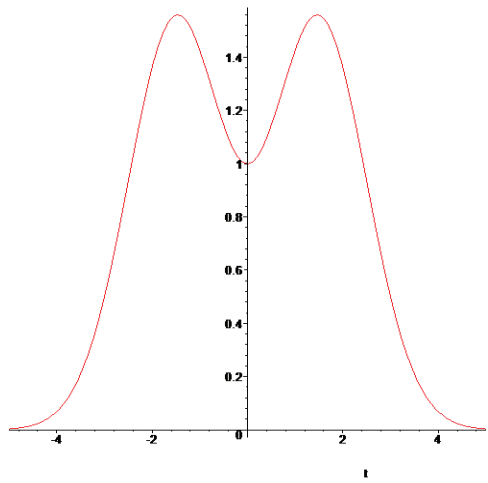
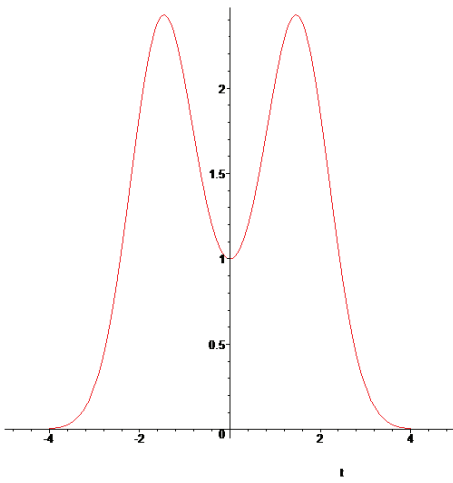
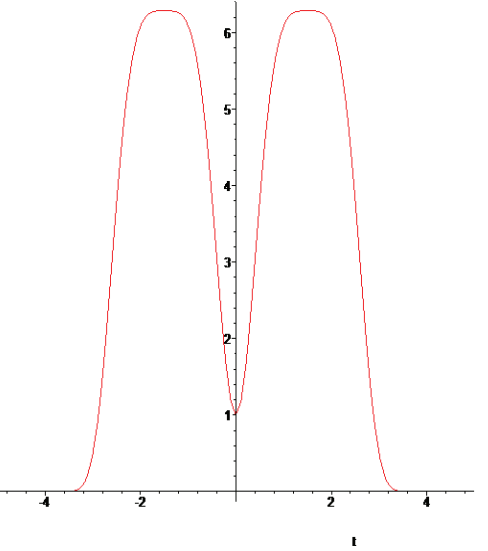
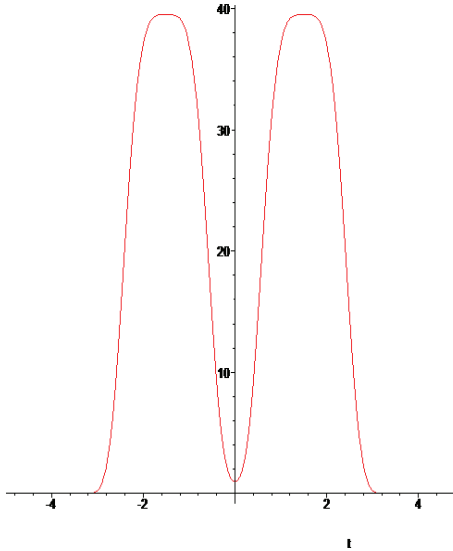
Our investigation shows a very complicated and lengthy Lagrangian. Thus further variation of such Lagrangian is too robust to handle. Particularly, the presence of the super Gaussian parameter m made it almost impossible for analytical treatment. So this way becomes an open challenge. Rather a numerical method would suggest the propagation dynamics more easily. Therefore, we solve the NLSE with the above mentioned cosh-super Gaussian pulse using split-step Fourier Method (SSFM). In general, dispersion and nonlinearity act together along the length of the fiber. But in this method, the dispersion and nonlinearity act independently. Then on combining both the effects of dispersion and nonlinearity we get the solution of the problem numerically.

The results of the intensive study are described in the following chapter.

CHAPTER 3

3.1 Results And Discussion

The cosh-super Gaussian pulse we considered for our investigation has the following amplitude and intensity profile:

Super Gaussian parameter	Amplitude profile of the pulse	Intensity profile of the pulse
m=1		
m=2		

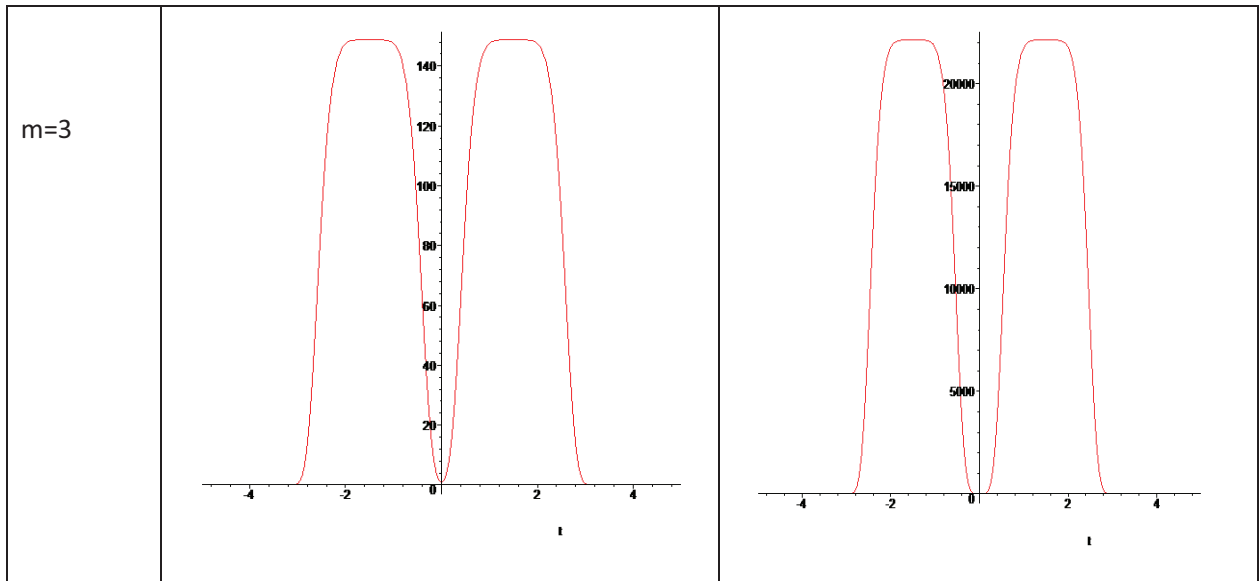
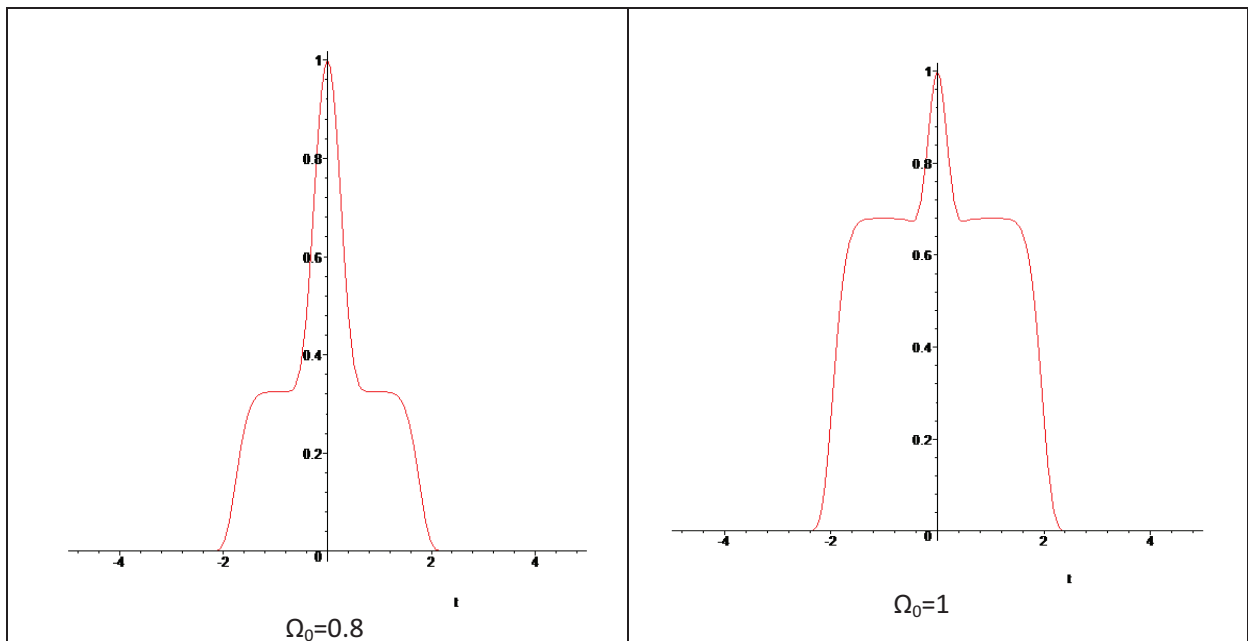


Fig.3.1 Amplitude and Intensity profile of the cosh-super Gaussian pulse for different super Gaussian parameter: $A_0 = 1, T_0 = 1, C = 0, \Omega_0 = 1.5$;

From the profile it is clear that the super Gaussian parameter controls the flatness of the pulse. This pulse can be formed by two de-centered super Gaussian pulses.



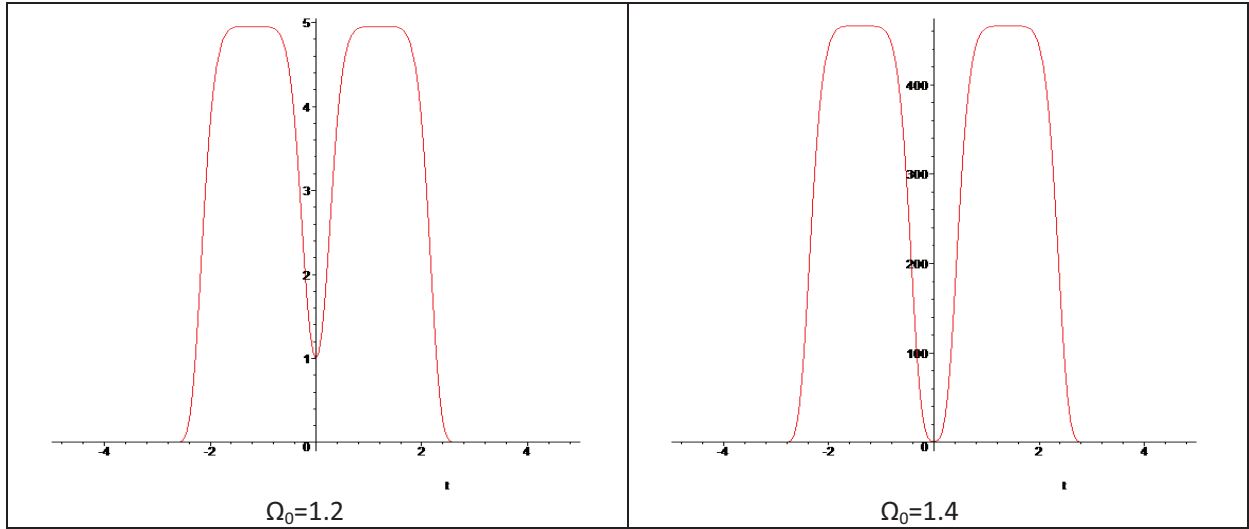


Fig.3.2 Intensity profile of the cosh-super Gaussian pulse for different cos-hyperbolic parameter Ω_0 and $A_0 = 1, T_0 = 1, C = 0, m = 3.0$;

The figures show that at higher value of the cos-hyperbolic parameter a central deep appears which increase with further increase of the parameter.

We use SSFM for the search of stable soliton. Fig. 3.3 (a), (b) and (c) depict the stable first order soliton for $m=1, 2$ and 3 . The cos-hyperbolic Super Gaussian pulse transforms into Super Gaussian form with propagation. This is to achieve the stability. The solitonic pulse intensity periodically changes with propagation, thus can be considered as temporal soliton.

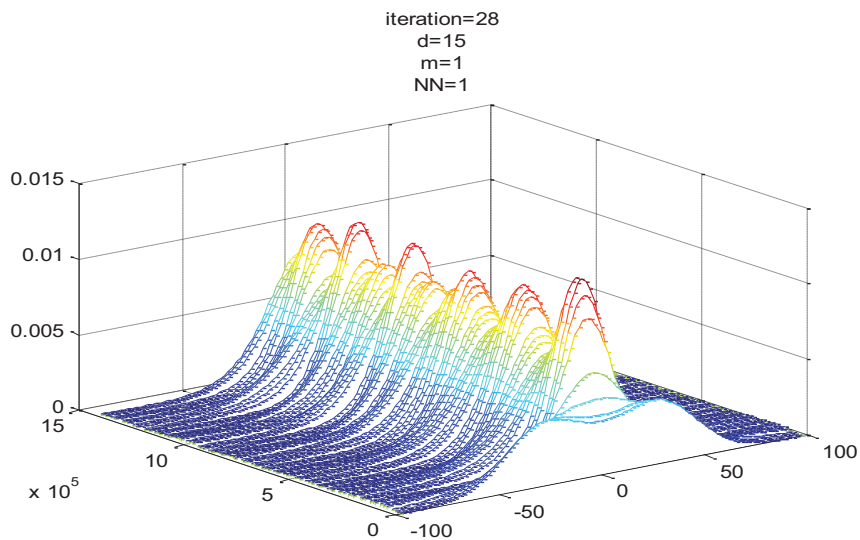


Fig.3.3 (a) First order soliton formation with cosh-super gaussian pulse for $m=1$

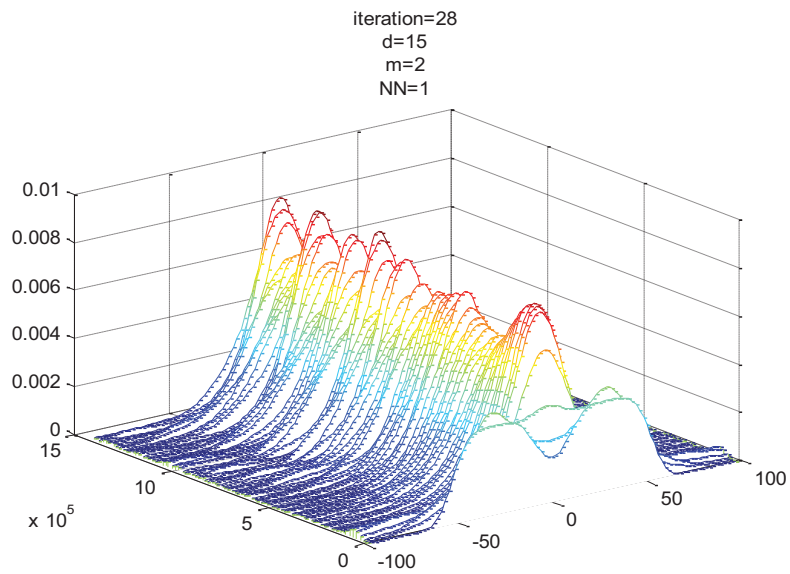


Fig.3.3 (b) First order soliton formation with cosh-super gaussian pulse for $m=2$

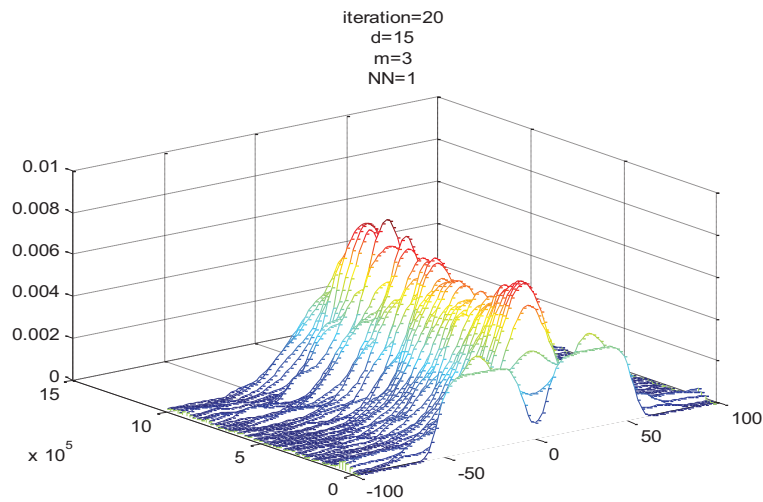


Fig.3.3 (c) First order soliton formation with cosh-super gaussian pulse for $m=3$

Fig. 3.4 (a), (b) and (c) portray the second order soliton formation and propagation for $m=1, 2$ and 3 . Here the cos-hyperbolic Super Gaussian pulse separates into two Super Gaussian like branch and again reunite. This repeats throughout the propagation. Thus very interesting soliton forms, which are stable has been achieved in second order.

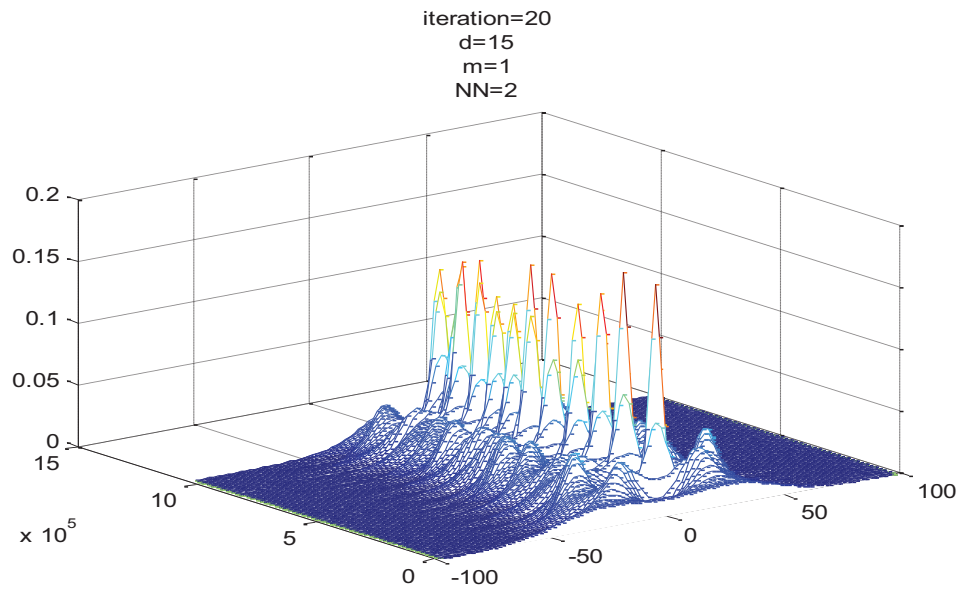


Fig.3.4 (a) Second order soliton formation with cosh-super gaussian pulse for $m=1$

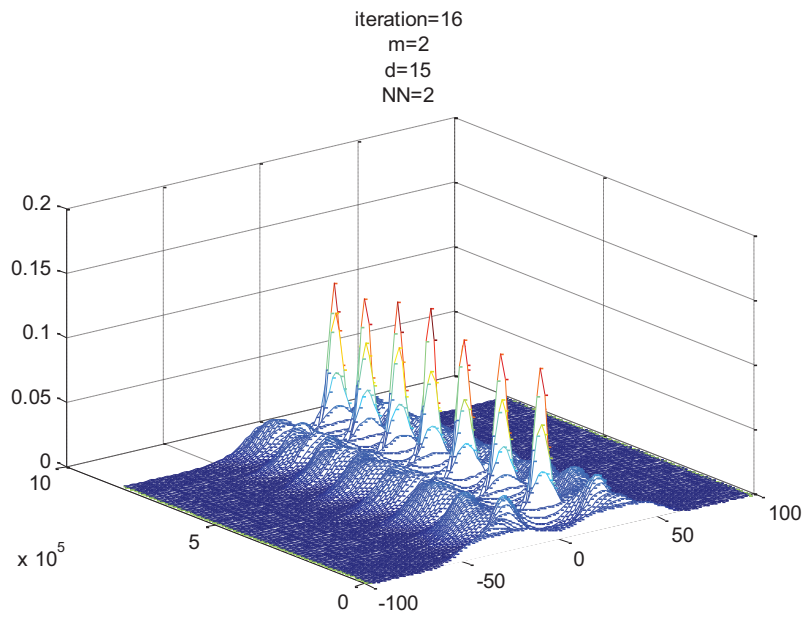


Fig.3.4 (b) Second order soliton formation with cosh-super Gaussian pulse for $m=2$

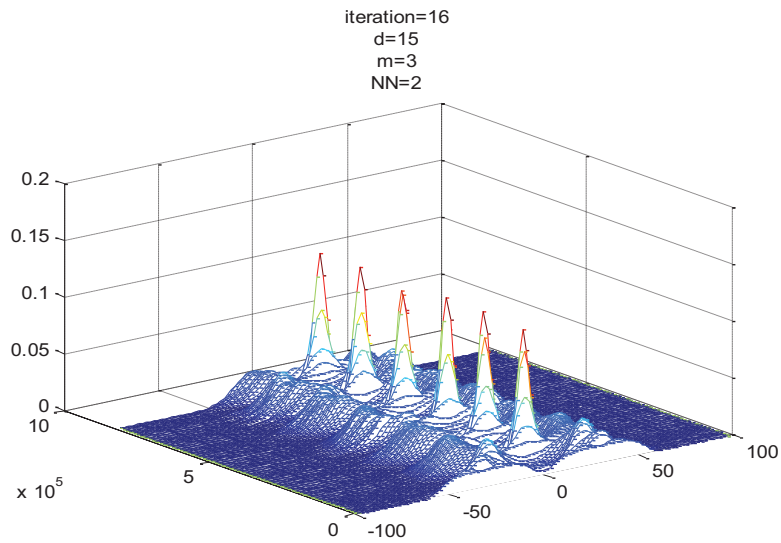


Fig.3.4 (c) Second order soliton formation with cosh-super gaussian pulse for $m=3$

Third order soliton formation and propagation for $m=1, 2$ and 3 has been depicted by Fig. 3.5 (a), (b) and (c). Here complicated and somewhat undesired form of soliton is observed. The cos-hyperbolic Super Gaussian pulse experiences a complicated branching at the beginning. Then three branches emerge along propagation direction. The two side branches will be lost due to the absorption by the fiber walls. However, the middle branch survives and propagates as soliton. One more important observation is that, for first and third order soliton the side branches are less intense, while for second order the central soliton branch is too feeble to be used as soliton.

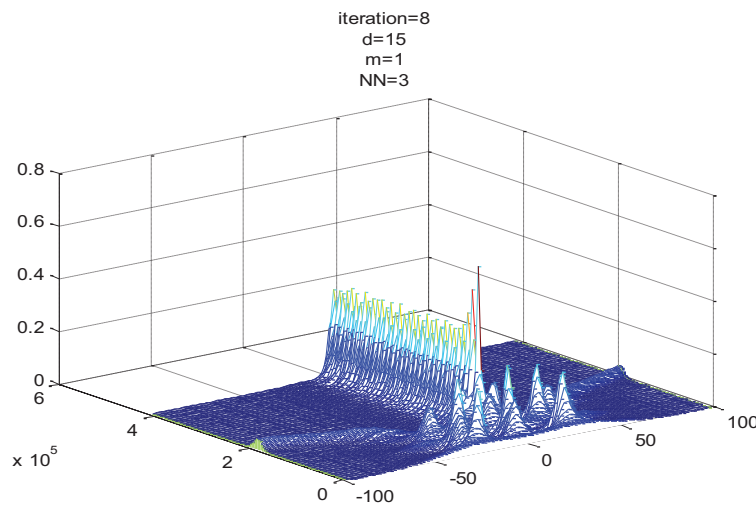


Fig.3.5 (a) Third order soliton formation with cosh-super Gaussian pulse for $m=1$

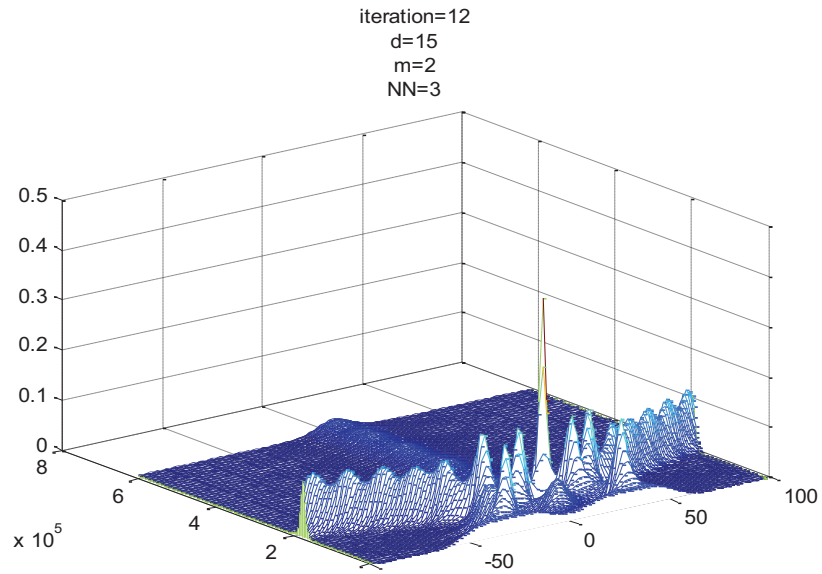


Fig.3.5 (b) Third order soliton formation with cosh-super Gaussian pulse for $m=2$

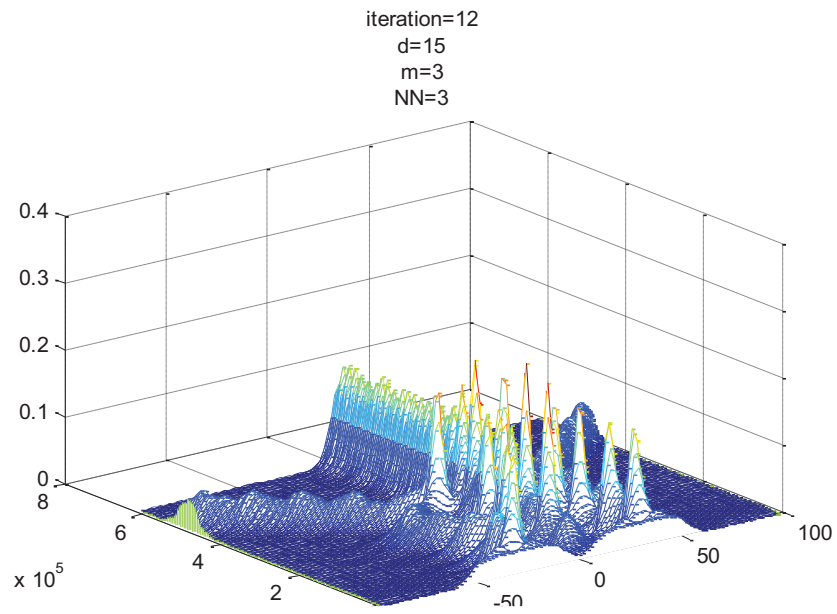


Fig.3.5 (c) Third Order soliton formation with cosh-super gaussian pulse for $m=3$

3.2 Conclusion

We investigate cosh-super Gaussian pulse propagation and soliton formation through cubic quintic nonlinearity. The effect of cosh and super-Gaussian parameters on the pulse profile has been shown. By controlling these two parameters a desired pulse shape can be generated. We further found solitons of first, second and third order. Very interesting soliton formation has been observed in third order. The theoretical results can be used for experimental demonstration of the soliton with cosh-super Gaussian pulse. Although the system loss has not been considered, our result provides a seed value for numerical simulation and guide experiments. As a future work the interaction between such pulses can be investigated.

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