All Optical Switching in Non Linear Medium

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

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CERTIFICATE

I hereby declare that the report entitled "All optical switching in a nonlinear medium" is an authentic record of my own work carried out for the partial fulfillment of the requirement for the award of the degree of M.Sc. (Masters of Science) at Thapar University, Patiala (Punjab), under the guidance of **Dr. Soumendu Jana** (School of Physics and Materials Science).The matter presented in this dissertation has not been submitted in part or full for the award of any other degree.

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It is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.

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I affectionately dedicate this thesis to the most adorable person of my life "Dear Chachu and loving Papa".

CONTENTS

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ABSTRACT

We studied spectral switching in nonlinear media. A soliton pulse is incident on the aperture after travelling through a nonlinear media. The diffraction through the aperture leads to spectral anomalies and eventually switching at zero intensity points (which are also phase singular points) in the diffraction pattern. It is shown that for a change in the nonlinear medium there is also change in width of the soliton pulse before it incident on aperture, hence spectral switching changes. The role of positive and negative group velocity dispersion is found to have significant consequences in spectral switching. The role of loss on spectral switching is investigated to realize the case for a practical dissipative system. Using super-Gaussian pulse, the effect of pulse shape on spectral switching is demonstrated. We have shown that spectral switching can also be controlled by relative phase between two interacting soliton pulses.

CHAPTER 1

1.1 INTRODUCTION

In present days information technology and management is playing governing role. The huge demand of data per capita is increasing day by day. To match with this significant advancement in data processing and transmission is become essential. Besides being more powerful the system needs to be more compact. All-optical devices are a potential solution for such crisis and no surprise that there is a huge demand of them as of now. However, the present demand of data transfer and processing is rising each day with tremendous rate. The conventional optoelectronic devices are not adequate to cope up with the current requirement. All-optical devices have been emerged as the best solution of this problem. During the last few decades optical fiber based optical transmission lines have almost replaced the old coaxial cable based system. As of today the transmission rate and capacity is more or less up to the demand. But still those optical transmission lines use many optoelectronic devices, which are comparatively slower than all-optical devices. Therefore, there is a huge requirement of all-optical devices to avoid bottle-neck effect in the communication links, data processing and management. In this context all-optical switching devices are at the core of interest. Though this advancement lead to an advancement in the technology but these optical transmission lines still use the opto-electronic devices leading to the drawbacks in the processing, management as well as transmission. Currently we are using electronic devices to perform calculations with Boolean algebra. For future data networks it is more wise decision to use optical data instead of electronics. Optical switches and optical gates are important such devices which are used for optical communication. For better understanding, we need to know the physics behind the optical switch, as far we found there is a correlation between spectral switch. So, all optical switching devices can help to overcome such situation. Spectral switching or coherency of two laser beams, these two methods can work out well in enhancement of optical logic gates for the optical switching devices. For better understanding, we need to know the physics behind the optical switch, as far we found there is a correlation between spectral switch. Spectral switching was highlighted from the fact that the light gets diffracted at the ends of the obstacle. The points of zero intensity attracted lots of attention. So in order to study spectral switching, we must observe the diffraction patterns and its various cases. In the present thesis we are going to make discussions on how various factors affect spectral switching. In other words, how it is depending on group velocity dispersion with various losses and so on.

In a monochromatic wave field, we find many points of zero intensity, which are of great interest for us. At these zero intensity points, we can interpret many results like phase is indeterminate .These zero intensity points are known as singular points or phase singularity [1, 2]. The wave amplitude is also determined to be zero at these points. Spectral switching occurs at these zero intensity points which are also known as phase singular points. Also wave front dislocation, optical vortices, occurs at these points. These points are of several interests for us. Here are two major spectra i.e. on axis and off axis.

Before going further we need to know about power spectrum. These are the points of several interests for us as per our concern using different apertures and deferent beams; we can interpret so many results from it. It has a huge application in material science, astronomical science, data analysis in condensed matter physics and many more. We are here with a new view i.e. its being longer to use electronic devices and now a days idea came out of mind to switch in the optics and now we get an idea of optical switching in nonlinear domain. When a high intense laser is passed through aperture and there we study the how spectral switching is occurring in nonlinear medium, the modifier is induced in the system.

The twenty first century has advanced the communication systems to a greater extent in order to provide a new platform for a wider dissemination of information from one point to another. In other words, information technology is defined as a term for transfer of information via computers and electronic media. Co-axial cables were firstly used to transmit data, and then electronic systems were highlighted for the same. And now, optoelectronics has revolutionized the communication links. With the advancement of technology, there is an avalanche of demands related to data transfer techniques and processing. The present need cannot be exactly fulfilled with the help of the conventional opto -electronic devices. The use of optical logic gates based optical devices ruled out the use of other conventional methods for data transmission. Though this advancement lead to an advancement in the technology but these optical transmission lines still use the opto-electronic devices leading to the drawbacks in the processing, management as well as transmission. So, all optical switching devices can help to overcome such situation.

Spectral switching has been studied theoretically and experimentally for different optical systems in different ways [1, 2, 3]. Spectral switching has come into picture when a polychromatic light is diffracted. When light passes through an aperture in a nonlinear media, zero intensity points are visualized on diffraction pattern.

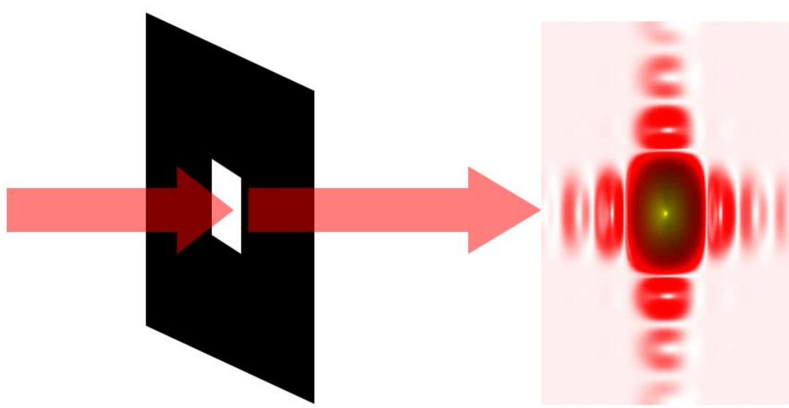


Fig 1.1 Intensity pattern when light diffracts through rectangular aperture

These points are of our interest because we observe an anomalous behavior where phase is not found. So far certain applications of spectral switching are used in information exchange in free space and are based on optical communication [3, 4, 5].

1.2. LITERATURE REVIEW

Singular optics has proved out to be an interesting field and it is emerging as a new field in optics. And more interestingly evolved a new branch physical optics. In monochromatic field, at these singular points phase cannot be determined. These points are also known as phase singular points or phase singularity. The phase amplitude is zero at these points [1, 2]. Such spectral behavior is basically induced by the phenomenon of diffraction. Nye and berry and Wright, via their experiments found different behaviors of optical singularities. Spectral anomalies and spectral switching, wave front dislocation etc. are some of the interesting optical phenomena observed due to phase singularities [3]. These phenomena arise due to singular optics, so they are the key points in exploring the field of singular optics. Gbur, Visser and Wolf showed that when a fully coherent and partially coherent light propagates through a given space, it will undergo drastic change at phase singularities i.e. they showed spectral shifting and hence spectral switching [4, 5]. Monochromatic light was perfectly chosen to observe above behaviors but later with further advancement in researches, polychromatic light came into picture undergoing the above phenomena. Diffraction and coherence are the reasons behind the fully coherent as well as partially coherent wave fields respectively. At the vicinity of singular points, interesting and remarkable spectral changes take place [6, 7, 8]. These changes prove out to be a major aspect in the further study about the characteristics of polychromatic field near phase singularities. In 2002, Gbur et.al explained the concept theoretically that phase singularity points, when light diffracts and these points show spectral anomalies [6].

The amplitude and the phase is dependent on propagation media. In case, incident pulse is disturbed through the free space ,propagation of pulse is disturbed hence amplitude.. Hence the problem has been solved by considering a perfectly conducting sphere; which is known as Mie scattering and detailed [9].Research in the area of optics mainly showed that when a fully coherent or partially coherent light propagates through a given space and it undergoes drastic change at phase singularity i.e. where concept of spectral switching as well as spectral shift arises. Spectral switching is also investigated for fully and partial coherent beams of light. We have observed spectral shifts by taking different pulses like (Gaussian, super Gaussian) and with different apertures (circular, rectangular

Spatial coherence properties of the source was studied extensively both experimentally and theoretically with different apertures [10-24].However the cases of limiting apertures or from which we get limiting spectrum are also studied [25-29]. Here limiting spectrum or the limiting aperture means where after passing through a source in far zone. A spectra is observed which shifts towards the lower and higher frequency. These lower and higher frequency are also termed as red shift and blue shift.

The spectral shift is defined as the difference between the frequency at which the spectrum is maximum and that of the spectrum at original value. When a partially coherent light is incident on a circular aperture at a fix distance from the source with a constant radius, it is shown that as spectral shift aperture parameter changes (z/z0) then there is a gradual change in the spectral shift i.e. as the position of spectral switch or aperture parameter (z/z0) decreases then there is a gradual change in spectral shift [30].The spectral switching takes place very quickly at a critical value of *(z/z0)*.

In future, spectral switching has many applications like spectrum selection and optical interconnects etc [31].

In an extensive experimental[32-37] and theoretical[38-43] study ,it is found that either the coherent source or the spatial coherent field produced by the source leads to the change in spectral shift of light .During the propagation of radiation the changes that are produced in spectra belong to those systems or category of sources which do not follow the so –called scaling law for the degree of spatial coherence[51].It has also been shown that when the light incident on an aperture it also shows spectral changes if the produced field obey scaling law[51].Intensity distribution is investigated at far field region.[44-45].It has many applications and important findings in determining the angular radii of stars and separation angle in double stars[46,47]. While obeying the scaling law when a partial coherent light incident on a circular aperture[50] then for a critical value of axial coordinate shows phenomenon of spectral switching at an on axis spectrum in the near field. Spectral switching is tuned by varying size of circular aperture and coherence degree.Also spectral shifts is controlled by these parameters. Later, by the number of theoretical studies, we found the number of applications which is based on phenomenon of spectral shifting i.e. optical-signal processing, astronomy and cryptography [48, 49].

1.3. MOTIVATION

Diffraction induced spectral anomaly is such an optical phenomena, which is simple in nature but has significant technological applications. This is phenomena occurs due to singularity in optical field. In any optical pattern the zero intensity points show phase singularity.

Till date all the investigation is done in linear optical domain as aperture diffraction in air is considered. Once non linearity is introduced in such a system, many interesting behavior may surface. The primary target of this investigation is to introduce nonlinearity in the system and to get benefit of it.

Till now linear medium has been used in order to observe spectral switching. But if the nonlinear medium is placed between the source and the aperture, due to variations in the intensity dependent refractive index of medium, there will be a change in the spectral switching. Since, spectral switching can create several switching points, using nonlinearity induced soliton it can

be used in parallel data processing. Due to several switching points, using different order of solitons as per our requirement can be used in coding and decoding.
Currently we are using electronic devices to perform calculations with Boolean algebra. Optical switches and optical gates are important such devices which are used for optical communication. Using optical logic gates we can increase the efficiency and accuracy.

1.4. OBJECTIVE

Basically, till date spectral switching was investigated for the cases where both sides of the aperture are having air, which have negligible nonlinearity. Here, instead we insert a nonlinear medium in the side of the aperture along which laser light falls on it. The other side of the aperture is air as usual. The nonlinearity and other properties (e.g., loss) of the media in the side of incidence has significant role in controlling spectral switching. Thus the main objective of the current investigation is:
To demonstrate all-optical spectral switching in nonlinear domain.

CHAPTER 2

BASICS OF SPECTRAL SWITCHING & METHODOLOGY

INTRODUCTION:

In this chapter, we will discuss how spectral switching takes place in nonlinear medium. We will derive the basic equation of diffraction induced far field intensity pattern that will be used for investigation spectral anomalies and hence spectral switching. Further, we will discuss how the pulse propagation can be investigated by using split step Fourier transformation method (SSFM) in nonlinear medium. The output of the SSFM is considered as the incident pulse, which will now diffract through the aperture. The far field spectral switching is obtained by another numerical routine.

2.1. SINGULAR OPTICS

In the last few decades, structure, zero intensity points and neighborhood of these points grab a huge attention. Like at these amplitudes amplitude has zero value, hence many applications arise, for e.g. in structure of wave fields. In a circular diffraction pattern, each ring is separated by zero intensity points. At these zero intensity points, phase is indeterminate. Also wave amplitude is zero for all the phases. Thus these points are called phase singular points. And at these points several interesting phenomena occurs. Physical optics is a wide field and so many different phenomena may occur .

Singular optics gave origin to various spectral anomalies and several area of interest in optics [1-10] i.e. wave front dislocation [5, 6, 8], optical vortices [6] and spectral switching may occur. In optics, a singular point is a point where the curve has "nasty "behavior. At zero intensity the phase is indeterminate and the wave amplitude is zero for all phase. These points are called phase singularity points [3, 5, 8]. Collectively the study of this phenomenon with phase singularity is known as singular optics.

2.2. POWER SPECTRUM

When a pulse is travelling with a constant frequency or in restricted frequency region. Then power spectrum is generated for the signal pulse which depicts about the power of signal or energy per unit time. Discrete Fourier method is widely used for plotting a power spectrum. Maximum entropy methods or other techniques can also be used for generating power spectrum. During last decade singular optics has been approached higher and drawn much attention [4].

2.3. SPECTRAL SWITCHING

The phenomena of spectral switching occur at singular point. When a light pulse is passed through an aperture diffraction comes into picture. As the light wave signal or pulse get diffracted, at that instant automatically power spectrum shifts. This shift takes place at some critical value. At some critical angle and also along propagation line spectral switching occurs. Initially spectrum in equally distributed and has equal height. For an on-axis case, far field power spectrum splits into two parts of equal heights at a critical value. This critical value is known as critical position or angle of spectral switching. Polychromatic light is studied in two major parts for betterment of research in phase singularity points. The two main categories are fully coherent light and partially coherent light. It is depicted that spectral switching takes place in neighborhood of singular points. Spectral switching is also remarkably depicted for different types of pulse beams like Gaussian, super-Gaussian etc. One can study this phenomenon of spectral switching by different methods, pulses, aperture and different systems

When a partially or fully coherent light is incident on a circular aperture. We found an important spectral behavior. In far zone, the on axis spectra is different from the spectrum of light at aperture. With some numerical analysis and calculations it is shown that spectral shift is tuned by varying parameters. Some parameters, such as the half-width at half-maximum of the source spectrum / Gamma/ and the ratio of the central obstruction of the source which affect the spectral switch positions and the spectral switch performance. The generation of multi-spectral lines in the far zone from a single spectral line is also known.

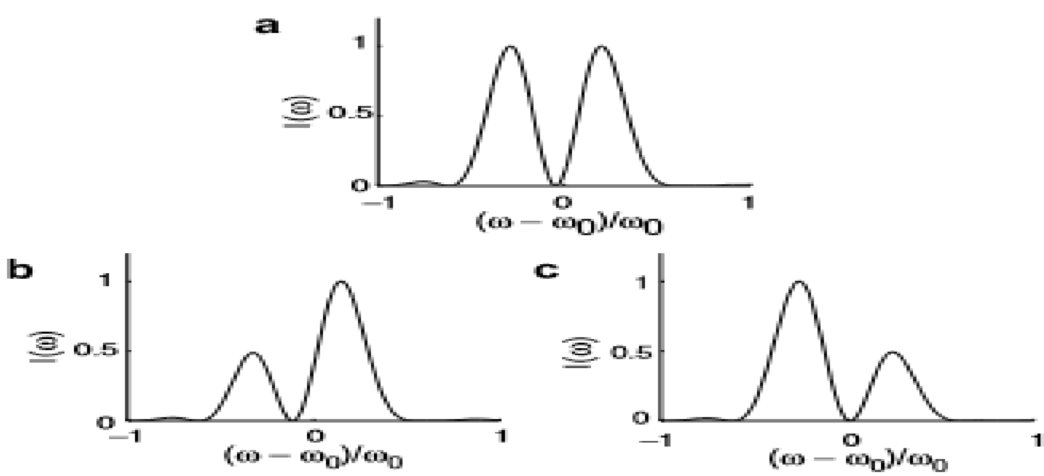


Fig 2.2 Spectral switching [8]

At critical angle, initial pulse is divided into two pulses of equal height as shown in fig 2.2(a).With slight increase or decrease in critical angle it shifts towards the region of higher frequency i.e. blue region and hence known as blue shift. Also with slight decrease in critical angle it approaches to the region of lower frequency i.e. Red colour ,also known as red shift. This phenomenon is known as spectral switching [8].

2.4 ON-AXIS Spectral Switching

Earlier we have seen a significant and remarkable behavior of super–Gaussian pulse. We investigated that by incrementing the value of super-Gaussian parameter, there is increase in on axis diffracted power spectrum. This is also known as blue shift. Hence for an on axis there is always a blue shift. The shift is observed when the diffraction angle is greater than critical angle.

Assume the radius of a circular aperture is *R* and also S and P are the two points which lie on the normal as well through Centre [9].

Z1 and Z2 are the two assumptions which can be made in solving Kirchhoff integral. If radius of circular aperture is small then by making use of above assumptions obliquity factor comes out to be 1.

The irradiance at P point fluctuates as we increase the radius of aperture [10, 52].

Irradiance is found to be different for even and odd Fresnel zones. It is found to be zero on the on-axis.

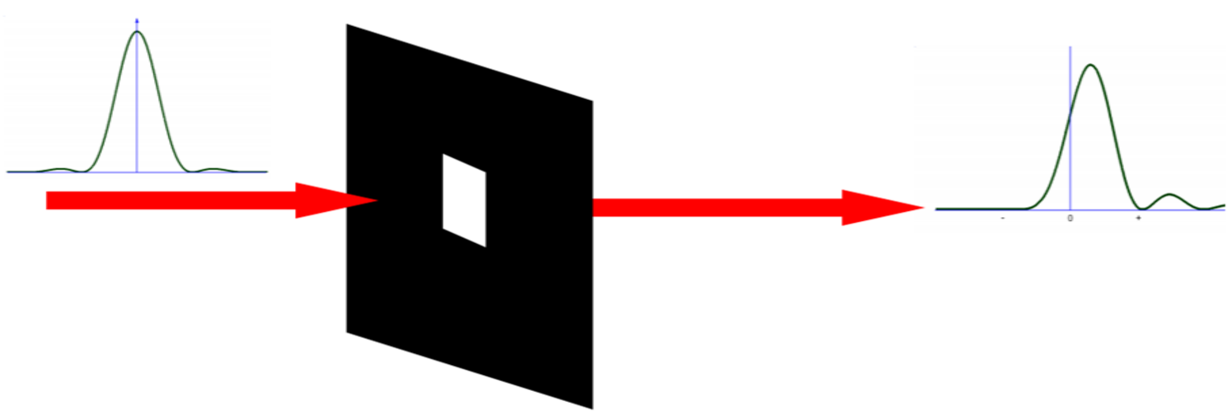


Fig 2.3 On axis spectrum showing blue shift

Initially, far field power spectrum is symmetrically distributed and has equal height around the central frequency. While at higher frequencies far field power spectrum is modified and shifts towards the frequency of blue light. This is known as Blue shift[9].

2.5 OFF-AXIS Spectral Switching

We now switch to the off-axis case. Spectral switching is demonstrated in off-axis. In this phenomena far field power spectrum breaks up into two lines of equal height. With a slight change in value of critical angle power spectrum shifts. This shift is towards the higher frequency and lower frequency. The value at which this shift occurs is called as critical value.

When the far field power spectrum has higher frequency than it is called as blue shift. This blue shift is observed when the diffraction angle is greater than the critical angle. When the diffraction angle is less than the critical angle, frequency gets lowered and we get a red shift. The spectral switching is controlled by super-Gaussian parameter.

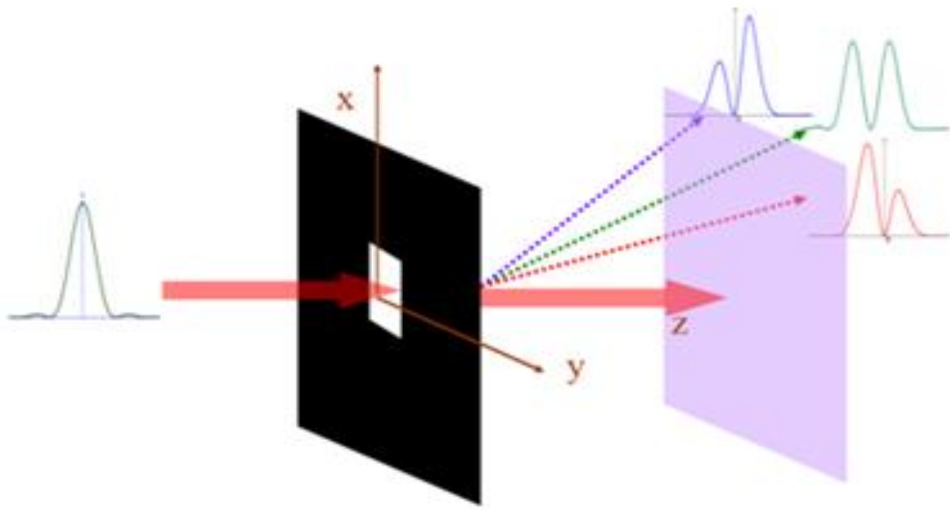


Fig 2.4 Off-axis spectrum demonstrating spectral switching

2.6 METHODOLOGY

Wolf showed in their experiments that when a fully coherent or partially coherent light light propagates through a given space, it will undergo drastic change at phase singularities i.e. the showed spectral shifting as well spectral switching. Monochromatic light was basically considered to be perfectly used for observing such behaviors but later with further studies, use of polychromatic light came into picture.

For better understanding following mathematical approach is followed using the equations and Fourier transform how we observe the spectral switching in nonlinear domain.

We consider a laser pulse (Gaussian, Super Gaussian, Ultra short pulses etc.) incident on a rectangular aperture at $z=0$ plane. The widths of the aperture along x and y directions are 2a and 2b respectively. The initial field of the incident field is given by [54, 55]

$$E(x_{o,}y_o, z, t) = \exp\left(-\ \frac{x_o^2+y_o^2}{w_o^2}\right) A(t) \qquad (2.1)$$

Where w_o is the beam waist, $A(t)$ is the temporal profile of the pulse which has the form

$$A(t) = \exp\left(-\frac{(1+iC)t^2}{2T^2}\right) \exp(-i\omega_o t), \qquad (2.2)$$

Where T is the pulse duration, C is the chirp parameter and ω_o is the central frequency of the pulse.

The filed given by the above equation (2.1) can be described in the space frequency domain by Fourier Transformations as:

$$E\left(x_{o,}y_o, 0, t\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E\left(x_{o,}y_o, 0, t\right) \exp(i\omega t)\, dt \qquad (2.3)$$

$$E\left(x_{o,}y_o, 0, t\right) \qquad = \exp\left(-\ \frac{x_o^2+y_o^2}{w_o^2}\right) F(\omega) \qquad (2.4)$$

Where F $(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(t) \exp(i\omega t)\, dt,$

Represents the Fourier Spectrum of the pulse at the incident plane and ω is the frequency.The initial power spectrum at the incident plane z=0 cane be obtained as

$$I_0(\omega) = |F(\omega)|^2 \qquad (2.5)$$

The field described by equation (2.4) satisfies Huygens-Fresnel integration during its propagation and can be expressed as [15]:

$$E\left(x_, y, z, \omega\right) = \frac{i}{\lambda z} \exp(-ikz) \iint_{-a-b}^{a\ b} E\left(x_{o,}y_o, 0, \omega\right) \times \exp\left[-\frac{ik}{2z}\{(x-x_0)^2 + (y-y_0)^2\}\right] dx_{o,}dy_o \qquad (2.6)$$

Where k is the wave number related to the wavelength through $k = 2\pi/\lambda$.

Thus we can derive an analytical expression for far field power spectrum of a pulse using Fourier Transformations and far field approximations in order to observe spectral switching [56].

Spectral switching can be studied using various phenomenon. We can use different apertures of varying size and shapes. Also the change in the shape of the aperture can affect the spectral switching. Various experiments have been performed using different beams as explained above.

Maxwell's equations are used to study the propagation of optical fields in fibers as well as in bulk materials, likely in electromagnetic and electrodynamics it is used. These equations are of great use to obtain the wave equation, which best describes the propagation of light we used in optical fibers or in bulk material. Maxwell's equations are:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla . D = \rho_f$$

$$\nabla . B = 0$$

(2.7)

Here, E and H are electric and magnetic field vectors, also D and B are corresponding electric and magnetic flux densities. Source for the electromagnetic field is given by J which represents current density as well as ρ represents charge density. In an optical fiber if there are no free charge carrier in the medium than in such a case both current density and charge density is zero. When an optical fiber propagate in a medium of electrical and magnetic field, than in such case flux density arise in form of D and B, and the relation is given by:

$$D = \varepsilon_0 E + P \qquad (2.8)$$

$$B = \mu_0 H + M \qquad (2.9)$$

Where ε_0 is vacuum permittivity and μ_0 is vacuum permeability

P and M are induced electric and magnetic polarizations. For optical fiber in case of nonmagnetic medium, M=0. To get the electric field and magnetic polarization, we can eliminate magnetic flux densities and magnetic field and we get an another equation:

$$\nabla \times \nabla \times E = -\frac{1}{C^2}\frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2} \qquad (2.10)$$

In contrast to quantum mechanical approach, a complete description of above equation is required.SO, a relation between the electric field E and induced polarization P is needed which also evaluates P.A relation between P and E has its own significance far from the medium resonance i.e. this approach is necessary when the optical frequency is near a medium resonance. In nonlinear medium wavelength ranges from 0.25 to 2µm is of great interest in case of optical fibers. There is rise of linear and nonlinear part both in the term of induced polarization, if we include the third order nonlinear effects in susceptibility term given by χ.

$$P(r,t) = P_L(r,t) + P_{NL}(r,t) \qquad (2.11)$$

The linear part and the nonlinear part related to electric field is followed by this relation:

$$P_L(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} \chi^{(1)}(t - t').E(r,t')dt' \qquad (2.12)$$

$$P_{NL}(r,t) = \varepsilon_0 \iiint_{-\infty}^{\infty} \chi^{(3)}(t-t_1, t-t_2, t-t_3) \vdots$$
$$\times E(r,t_1)E(r,t_2)E(r,t_3)dt_1dt_2dt_3 \qquad (2.13)$$

In an electric – dipole approximations above relations are valid and assumed that in such case medium response is local. All the above three relations gives a general formula to study optical fiber when third order nonlinearity is induced. The nonlinear polarization $\boldsymbol{P_{NL}}$is contained as a small perturbed term to the induced polarization. And above statement is justified because in silica fibers the nonlinear effects are comparatively weak. Hence it is a wise decision to write frequency domain term only in linear medium (i.e. $P_{NL} = 0$)

$$\nabla \times \nabla \times \tilde{E}(r,\omega) - \varepsilon(\omega)\frac{\omega^2}{c^2}\tilde{E}(r,\omega) = 0 \qquad (2.14)$$

Fourier transform of E(r, t) is given by $\tilde{E}(r,\omega)$ and it is defined as:

$$\tilde{E}(r,\omega) = \int_{-\infty}^{\infty} E(r,t)exp(\iota\omega t)dt \qquad (2.15)$$

Dielectric constant term appearing in frequency dependent term is given by:

$$\varepsilon(\omega) = 1 + \tilde{\chi}^{(1)}(\omega)$$

In general $\tilde{\chi}^{(1)}(\omega)$ is complex and is Fourier transform of$\chi^{(1)}(t)$, also it can be related to the term refractive index which is given by $n(\omega)$ and absorption coefficient by $\alpha(\omega)$. Hence refractive index is followed by equation below:

$$\varepsilon = (n + i\alpha c/2\omega)^2$$

α and n are related to χ^1 by the relation:

$$n(\omega) = 1 + \frac{1}{2}Re[\tilde{\chi}^{(1)}(\omega)] \qquad (2.16)$$

$$\alpha(\omega) = \frac{\omega}{nc}Im[\tilde{\chi}^{(1)}(\omega)] \qquad (2.17)$$

In the wavelength region of our interest, there is very low and minimum optical loss in fiber. Henceforth, imaginary part is small as compared to real part of $\varepsilon(\omega)$.Thus in case of fiber modes, which also include fiber losses $\varepsilon(\omega)$ is replaced by $n^2(\omega)$.It is noticed that for both core and cladding of step index fiber , $n(\omega)$ is often independent of the spatial coordinates.

$$\nabla \times \nabla \times E \equiv \nabla(\nabla.E) - \nabla^2 E$$

Above equation is simplified by using the relation $\nabla . D = \varepsilon \nabla . E = 0$ and formulates to

$$\nabla^2 \tilde{E} + n^2(\omega) \frac{\omega^2}{c^2} \tilde{E} = 0 \quad (2.18)$$

In case of holding the symmetry, fiber constitutes of cylindrical symmetry and the wave equation in terms of cylindrical coordinate's ρ, φ and z is given by:

$$\frac{\partial^2 \tilde{E}}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial \tilde{E}}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 \tilde{E}}{\partial \varphi^2} + \frac{\partial^2 \tilde{E}}{\partial z^2} + n^2 k_0^2 \tilde{E} = 0 \quad (2.19)$$

Here $k_0 = \frac{\omega}{c} = 2\pi/\lambda$ and Fourier transform of electric field is given by $\widetilde{E}$.

$$E(r,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}(r,\omega) \exp(-i\omega t)\, d\omega \quad (2.20)$$

Maxwell's equations satisfy electric field and magnetic field equations only for two independent components rather there are six independent components. It is necessary to choose $\tilde{E}_Z$ and $\widetilde{H_Z}$ as independent components .By using the variable separation method one can easily solve the wave equation and resulting in generalized form as

$$\tilde{E}_z(r,\omega) = A(\omega)F(\rho) \exp(\pm im\phi) \exp(i\beta z) \quad (2.21)$$

Where, A= normalization constant, β is propagation constant, m is an integer and solution is given by F(ρ)

$$\frac{d^2F}{d\rho^2} + \frac{1}{\rho}\frac{dF}{d\rho} + \left(n^2 k_0^2 - \beta^2 - \frac{m^2}{\rho^2}\right) F = 0 \quad (2.22)$$

For radius of fiber core a, ρ ≤a if the refractive index is n = n1, but it takes the value of refractive index which is outside the core i.e. n2. Equation of fiber core is in the form of Bessel function and hence its general solution is given by:

$$F(\rho) = C_1 J_m(\kappa\rho) + C_2 N_m(\kappa\rho) \quad (2.23)$$

Where J_m and N_m are Bessel function and Neumann function and also

$$\kappa = (n_1^2 k_0^2 - \beta^2)^{1/2} \quad (2.24)$$

Boundary conditions are used for further solving and calculating the value of constants C1 and C2.As Neumann function has a singularity at ρ=0 .

$$F(\rho) = J_m(\kappa\rho), \quad \rho \le a \quad (2.25)$$

Further solution is given by modified Bessel function and it is represented by:

$$F(\rho) = K_m(\gamma\rho) \qquad \rho \ge a \quad (2.26)$$

$$\gamma = (\beta^2 - n_2^2\kappa_0^2)^{1/2}$$

$$\kappa^2 + \gamma^2 = (n_1^2 - n_2^2)k_0^2 \qquad (2.27)$$

Under ideal condition, single mode fiber are said to be degenerate if their two polarization modes are perpendicular to each other .In other words it is said that if two modes of same fiber are orthogonal to each other, than they have same propagation constant. There are several factors which break the degeneracy of fiber as in if there is random variation in the core shape and size then it weakens the fiber length and propagation of fiber is lowered.

It is assumed that incident light is polarized on principle axis, and then electric field is given by:

$$\tilde{E}(r,\omega) = \hat{x}\{A(\omega)F(x,y)\exp[i\beta(\omega)z]\} \qquad (2.28)$$

The perpendicular (transverse) component of incident polarized inside the core is given by

$$F(x,y) = J_0(\kappa\rho) \qquad \rho \le a \qquad (2.29)$$

While the field decays exponentially outside the core as

$$F(x,y) = (\frac{a}{\rho})^{\frac{1}{2}} J_0(\kappa a)\exp[-\gamma(\rho - a)] \qquad \rho \ge a \qquad (2.30)$$

The fundamental equation in a fiber mode is best defined by Gaussian distribution form as

$$F(x,y) \approx \exp\left[-\frac{x^2+y^2}{w^2}\right] \qquad (2.31)$$

A small perturbation term in linearity give rise to nonlinearityP_{NL}.Rapidly changing component in electric field is solved by adopting slowly varying envelope approximation

$$E(r,t) = \frac{1}{2}\hat{x}[E(r,t)exp(-i\omega_0 t) + c.c] \qquad (2.32)$$

$E(r,t)$ is a function of time which is varying slowly and it is related to the optical period. Polarization component in linear and nonlinear medium is also expressed in this way:

$$P_L(r,t) = \frac{1}{2}\hat{x}[P_L(r,t)\exp(-i\omega_0 t) + c.c] \qquad (2.33)$$

$$P_{NL}(r,t) = \frac{1}{2}\hat{x}[P_{NL}(r,t)\exp(-i\omega_0 t) + c.c] \qquad (2.34)$$

The linear polarization component is again simplified with the help of above equations

$$P_L(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} \chi_{xx}^1(t-t')E(r,t')\exp[i\omega_0\,(t-t')]d\tau'$$

$$P_L(r,t) = \frac{\varepsilon_0}{2\pi}\int_{-\infty}^{\infty} \tilde{\chi}_{xx}^{(1)}(\omega)\tilde{E}(r,\omega-\omega_0)\exp[-i(\omega-\omega_0)t]\,d\omega \qquad (2.35)$$

Above used symbols have their usual meanings

Nonlinear polarization term is obtained by making the certain assumptions such that if nonlinear term is instantaneous then time dependence is given by delta terms.

$$P_{NL}(r,t) = \varepsilon_0\chi^{(3)} \vdots E(r,t)E(r,t)E(r,t) \qquad (2.36)$$

In nonlinear medium, electrons and nuclei both are stimulus towards the optical field.in comparison to nuclei electronic response is relevantly slower.

In general phase matching is neglected in optical fibers. And hence nonlinear polarization term is given by

$$P_{NL}(r,t) \approx \varepsilon_0\varepsilon_{NL}E(r,t) \qquad (2.37)$$

In contrast to nonlinearity, dielectric constant is given by

$$\varepsilon_{NL} = \frac{3}{4}\chi_{xxxx}^{(3)}|E(r,t)|^2 \qquad (2.38)$$

It is easy to work by taking Fourier method, whenever we wish to have the wave equation in slowly varying amplitude. From above equation dielectric constant is dependent on intensity, therefore in general it does not hold good for nonlinear medium. Hence the Fourier transform is given by

$$\tilde{E}(r,\omega-\omega_0) = \int_{-\infty}^{\infty} E(r,t)\exp[i(\omega-\omega_0)t]\,dt \qquad (2.39)$$

2.7 Split Step Fourier Method

Irrespective of split step Fourier method, psuedospectral methods are relatively faster. In nonlinear medium it’s split step Fourier method which is widely used for solving pulse propagating equations.

The normal form to understand split step Fourier method is

$$\frac{\partial A}{\partial z} = (\hat{D}+\hat{N})A \qquad (2.40)$$

$\hat{D}$ and $\hat{N}$ are the operators which are used to study the fiber losses and dispersion losses in linear and nonlinear medium.

$$\hat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2} \qquad (2.41)$$

$$\hat{N} = i\gamma\left(|A|^2 + \frac{i}{\omega_0}\frac{1}{A}\frac{\partial}{\partial T}(|A|^2A) - T_R\frac{\partial|A|^2}{\partial T}\right) \qquad (2.42)$$

In the split step Fourier method it is assumed that over a small distance say h dispersive and nonlinear effects act independently in optical field.it is carried out in two steps.in first step linear effects are not taken into consideration, only nonlinear effects came into picture and vice versa.

Hence in first step $\hat{D}$ = 0 and in second step $\hat{N}$ = 0.

$$A(z+h,T) \approx \exp\left(h\hat{D}\right)\exp\left(h\hat{N}\right)A(z,T) \qquad (2.43)$$

In Fourier domain exponential factor is evaluated by following operation:

$$\exp\left(h\hat{D}\right)B(z,T) = F_T^{-1}\exp[h\hat{D}(-i\omega)]F_T B(z,T) \qquad (2.44)$$

ω is the frequency in the Fourier domain, Fourier transformation operator is given by F_T,replacing $\frac{\partial}{\partial T}$ by –iω gives rise to a new operator $\hat{D}(-i\omega)$.It is just a number in fourier space and its evaluation is very easy as well as straight forward.

In comparison to finite differences methods, spit step Fourier method is relatively faster by two orders of magnitude. Also the use of fast Fourier transforms ease the numerical evaluation processes and makes it faster.

Exact solution in split step Fourier method is given by:

$$A(z+h,T) = \exp\left[h\left(\hat{D}+\hat{N}\right)\right]A(z,T)$$

The two upcoming operators $\hat{a}$ and $\hat{b}$ is given by Baker-Hausdorff formula and $\hat{N}$ is assumed to be z independent.

$$\exp(\hat{a})\exp\left(\hat{b}\right) = \exp(\hat{a} + \hat{b} + \tfrac{1}{2}\left[\hat{a},\hat{b}\right] + \tfrac{1}{12}[\hat{a}-\hat{b},\left[\hat{a},\hat{b}\right]] + \ldots\ldots) \qquad (2.45)$$

$$\left[\hat{a},\hat{b}\right] = \hat{a}\hat{b} - \hat{b}\hat{a} \qquad (2.46)$$

$\hat{D}$ And $\hat{N}$ are two noncommutating operator in split step Fourier method, in above equation $\hat{a}$ and $\hat{b}$ is given by $\hat{a} = h\hat{D}$ and $\hat{b} = h\hat{N}$.

$\frac{1}{2}h^2\left[\hat{D},\hat{N}\right]$ Is found to be dominant error term result from the commutator. This is accurate to second order step size h. An optical pulse is propagated over one segment from z to z+h so that accuracy can be improved in split step Fourier method.

$$A(z+h,T) \approx \exp\left(\frac{h}{2}\hat{D}\right)\exp(\int_z^{z+h}\hat{N}(z')dz')\exp(\frac{h}{2}\hat{D})A(z,T) \qquad (2.47)$$

The effect of nonlinearity is induced in the middle of fiber segment instead of boundary because of symmetric nature of exponential operator .Hence this method is also known as symmetric split step Fourier method [59].

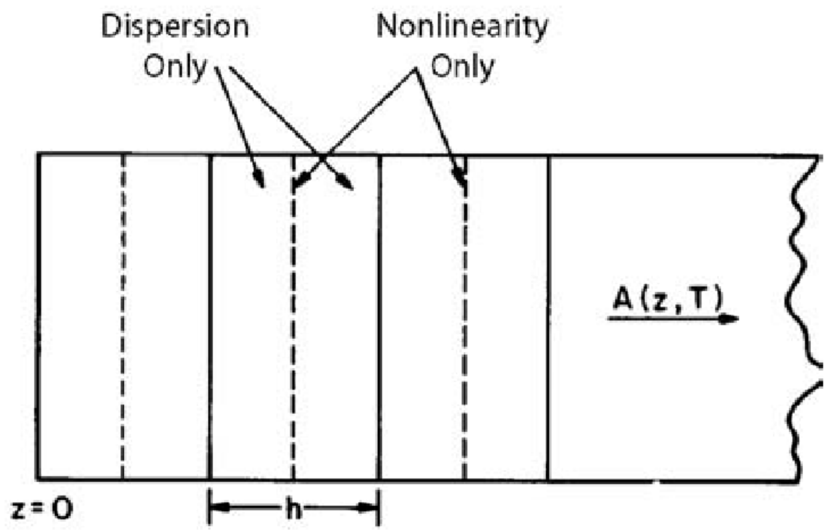
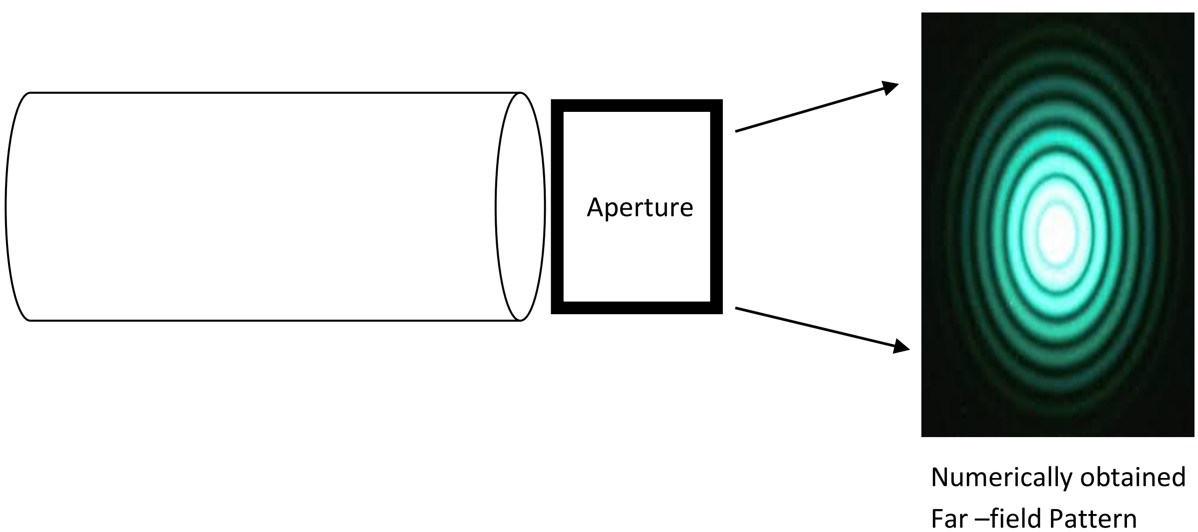


Fig 2.1 split step Fourier method used for numerical method [58]

The combined method is demonstrated pictorially as follows:



CHAPTER 3

RESULTS AND DISCUSSION

Here we describe the results of our investigation of spectral switching in nonlinear domain. Due to group velocity dispersion (GVD) the pulse broadens. Nonlinearity induced self-phase modulation (SPM) can compress the pulse. A perfect counterbalance between the GVD and nonlinearity induced SPM can generate a soliton-pulse. We create such soliton-pulse in the nonlinear media. This soliton now incidents on the aperture. We present the results obtained in different conditions viz. anomalous and normal GVD; with and without loss. A change in the medium usually results in variation in GVD. The variation in GVD will disturb the solitonic shape of the pulse (as nonlinearity is fixed) and hence will change the pulse width which in turn will change the truncation parameter. If truncation parameter gets changed the critical angle of switching also gets modified. Primarily we study variation of the truncation parameter with the critical angle of switching to look for where spectral switching actually occurs. Further variation of the truncation parameter with GVD is obtained. Combining these two one can get the variation of spectral switching by GVD. Similarly, variation of truncation parameter with the order of soliton is observed. Finally, we considered interaction of two solitons in nonlinear media. Since the solitons are slightly separated they unite before entering the aperture. Depending on their relative phase (phase difference) the width of the incident soliton (on aperture) varies. Thus variation in relative phase results in variation in truncation parameter and hence spectral switching. The detailed results are follows.

3.1 Variation of critical angle of switching (alpha_c) with truncation parameter (delta)

Fig 3.1 shows the variation of critical angle of switching (alpha_c) with truncation parameter (delta). It is clear that at lower values of delta spectral switching takes place at higher critical angle. With the increase in delta the critical angle lowers and spectral switching occurs very fast with small deviation.

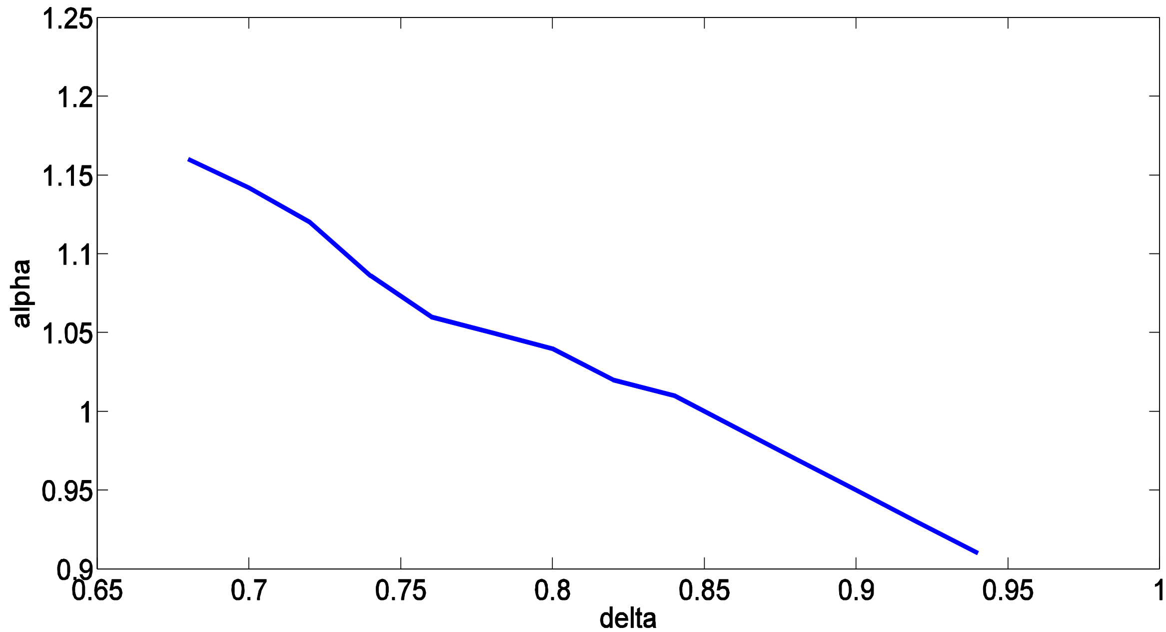


Fig 3.1 Variation of critical angle of switching α_c with truncation parameter δ for first order (N=1)

3.2 Effect of positive GVD on Spectral Switching

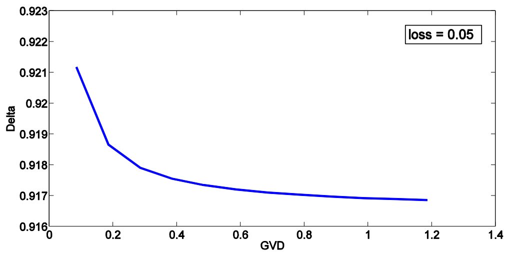
The variation of spectral switching is studied by at different GVD taking loss as parameter. In this stage we take positive GVD. Variation in the GVD varies full width half maxima (FWHM) and hence truncation parameter of the pulse. Following table describes such variation at a loss of 0.05.

Table 3.1 variation of FWHM and delta with positive group velocity dispersion parameter for loss = 0.5 and aperture width =27.

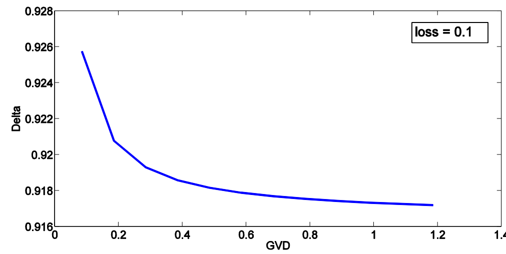
GVD	FWHM	Delta
0.085	79.2468	0.92117
0.185	79.4628	0.91866
0.285	79.5278	0.91791
0.385	79.5591	0.917556
0.485	79.5775	0.917344
0.585	79.5896	0.9172052
0.685	79.5982	0.9171061
0.785	79.6046	0.917032
0.885	79.6096	0.916974
0.985	79.6135	0.91692
1.085	79.6168	0.916891
1.185	79.6195	0.91686

Fig.3.2 (a) depicts the variation of truncation parameter with GVD for a loss of 0.05. Similar variations for different losses are depicted in fig. 3.2 (b) to 3.2(n).

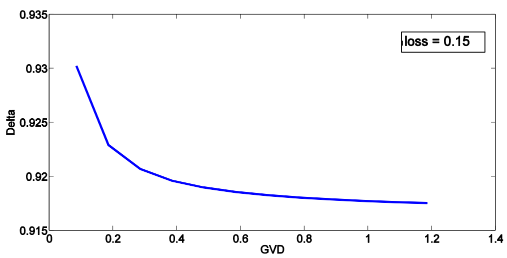
(a)



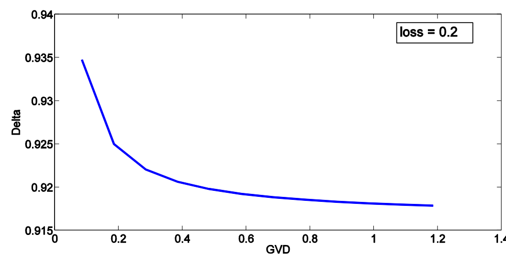
(b)



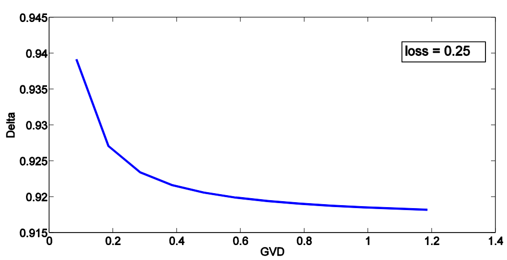
(c)



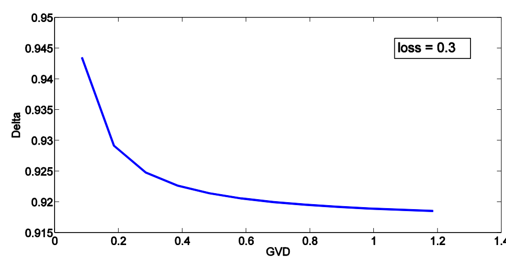
(d)



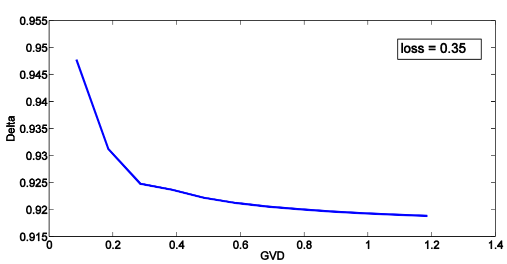
(e)



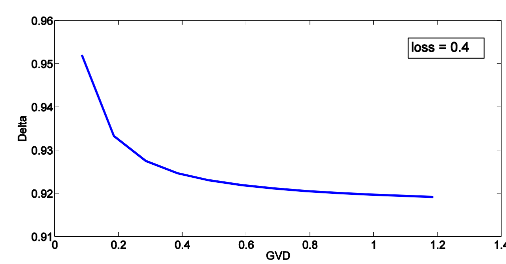
(f)



(g)



(h)



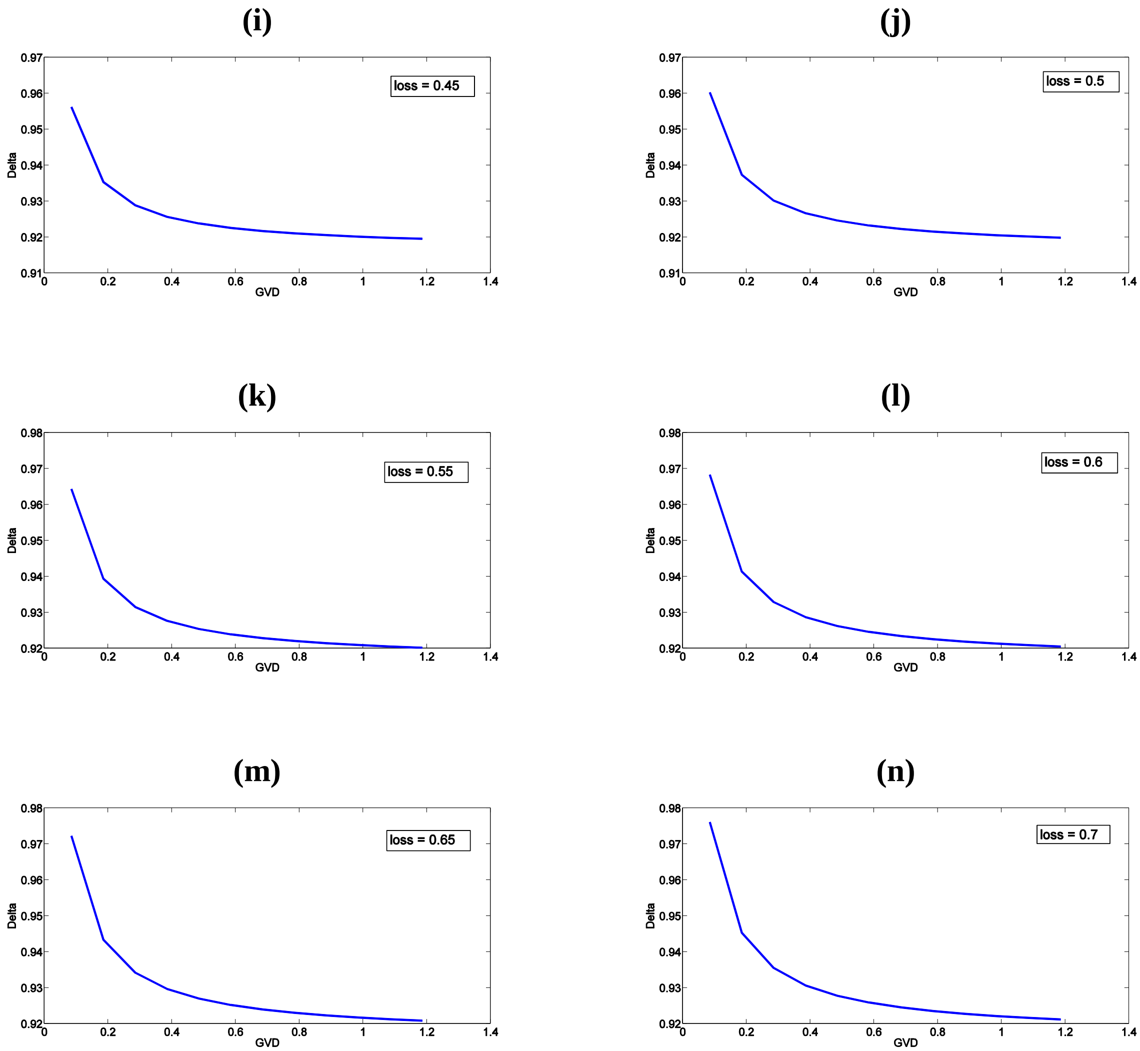


Fig. 3.2 Variation of delta with GVD for different losses.

A combined figure of the above is plotted below:

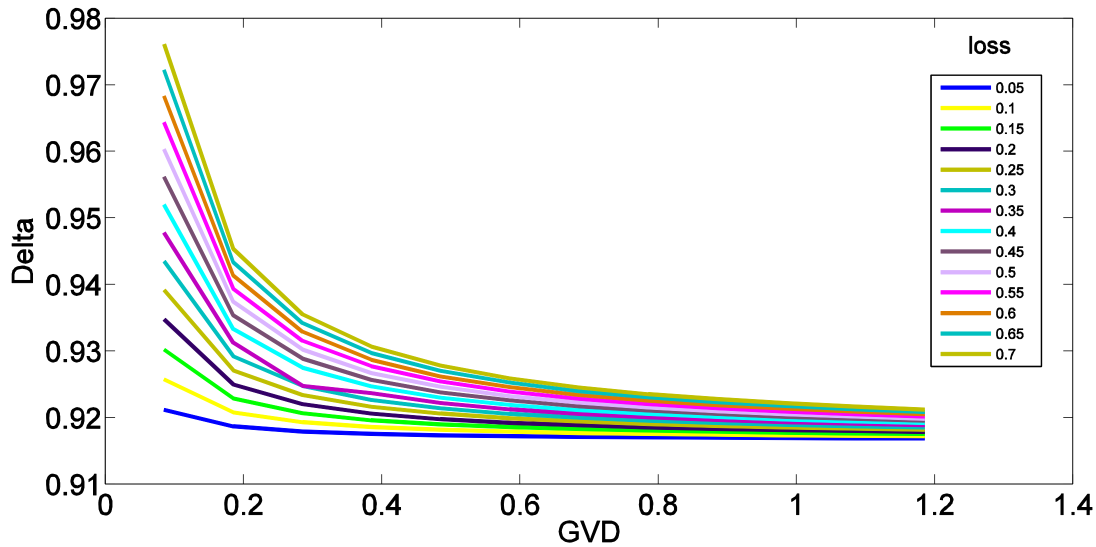


Fig 3.3 Variation of delta with GVD for different loss

Fig 3.3 depicts an important conclusion according to which as loss in the system increases FWHM gradually decreases and truncation parameter increases. Data given in the table show how loss controls FWHM, which in turn varies delta (at a particular GVD). Once delta is obtained the corresponding critical angle of spectral switching can be found from the master plot, i.e., Fig.3.1

Table 3.2 variation of delta with loss for gvd = 0.085 and aperture width = 73

LOSS	FULL W	DELTA
0.0	79.6486	0.91652
0.05	79.2468	0.92117
0.1	78.8542	0.92575
0.15	78.4706	0.93022
0.2	78.0957	0.93475
0.25	77.7293	0.93915
0.3	77.3713	0.94350
0.35	77.0216	0.94778
0.4	76.6798	0.95201
0.45	76.3458	0.95617
0.5	76.0194	0.96028
0.55	75.7006	0.96432
0.6	75.3890	0.96831
0.65	75.0845	0.97223
0.7	74.7871	0.97610

3.3 Effect of negative GVD on Spectral Switching

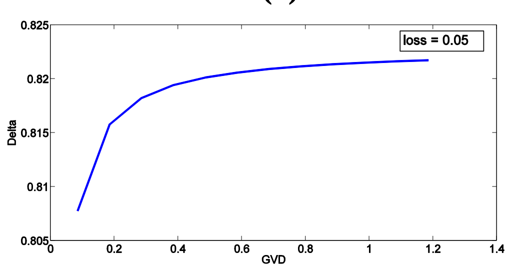
We now investigate spectral switching under the influence of negative GVD parameter with different losses. Following table shows the corresponding data of variation of FWHM and hence delta with negative group velocity dispersion parameter for loss = 0.5.

Table 3.3 variation of FWHM and delta with negative group velocity dispersion parameter for loss = 0.5 and aperture width =29.

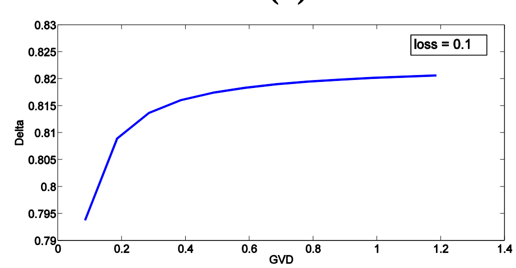
-gvd	Full w	Delta
0.085	35.9016	0.807763
0.185	35.5492	0.8157708
0.285	35.4426	0.81822439
0.385	35.3911	0.81941505
0.485	35.3608	0.82011719
0.585	35.3408	0.82058131
0.685	35.3266	0.82091115
0.785	35.3160	0.82115754
0.885	35.3078	0.82134825
0.985	35.3013	0.8214994
1.085	35.2960	0.82162284
1.185	35.2916	0.8217252

The variation of delta with negative GVD is depicted in fig. 3.4 (a) to (l) for different losses. The variation is inverse in nature in comparison to the positive GVD parameter. Once delta is obtained the corresponding critical angle of spectral switching can be found from the master plot, i.e., Fig.3.1

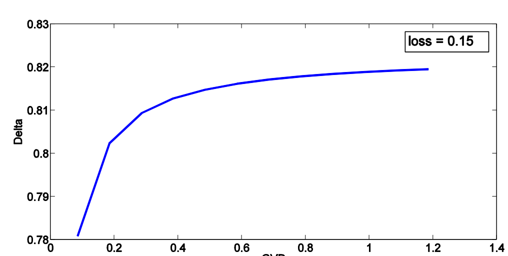
(a)



(b)



(c)



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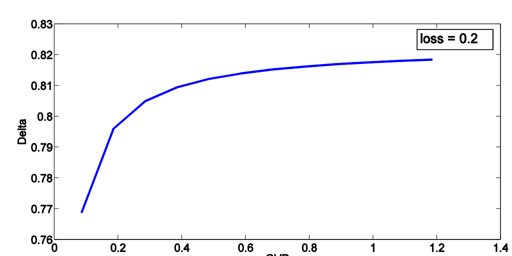
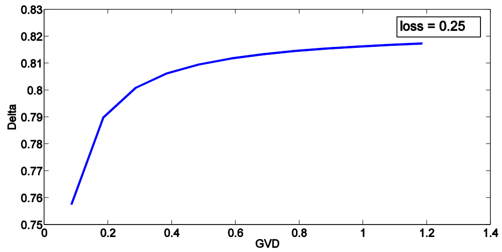
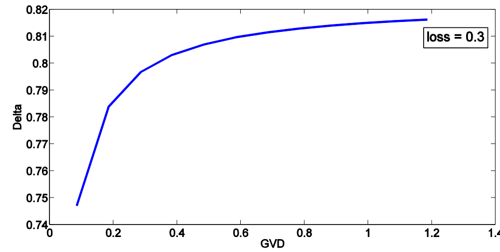


(e)



(f)



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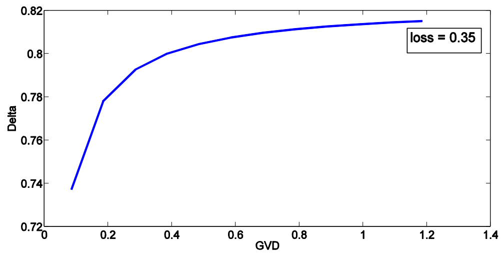

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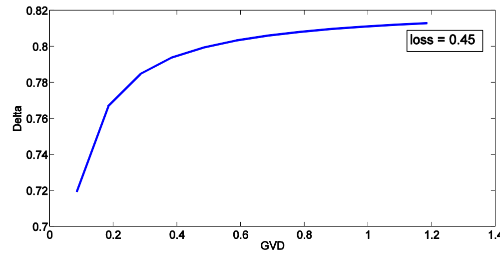
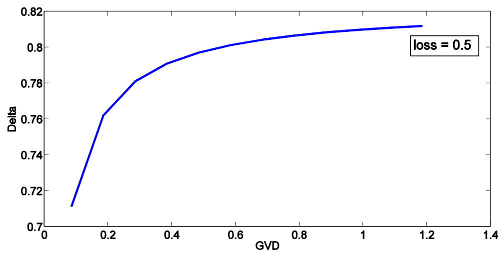
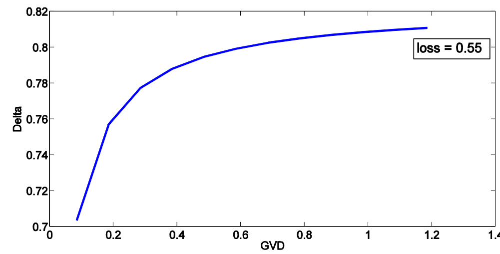


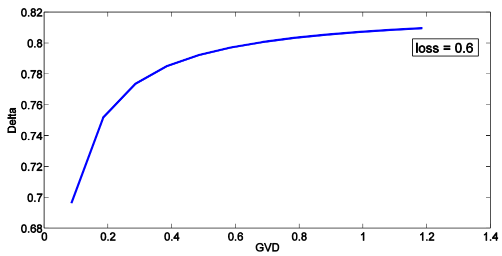
(i)



(j)



(k)



(l)

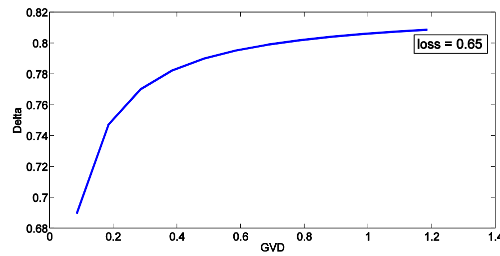
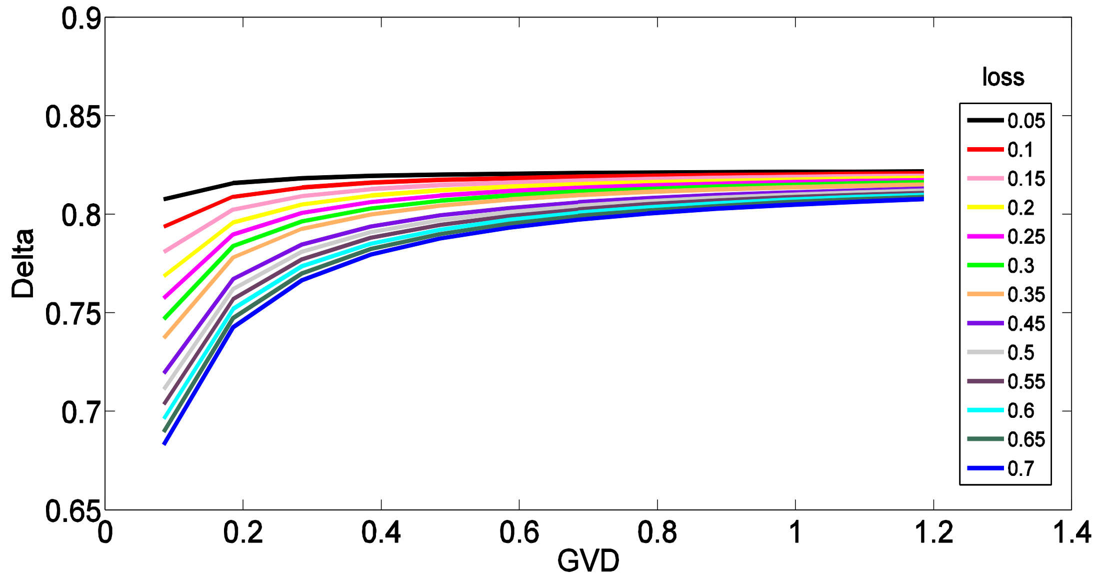


Fig 3.4 Variation of delta with negative gvd for different losses

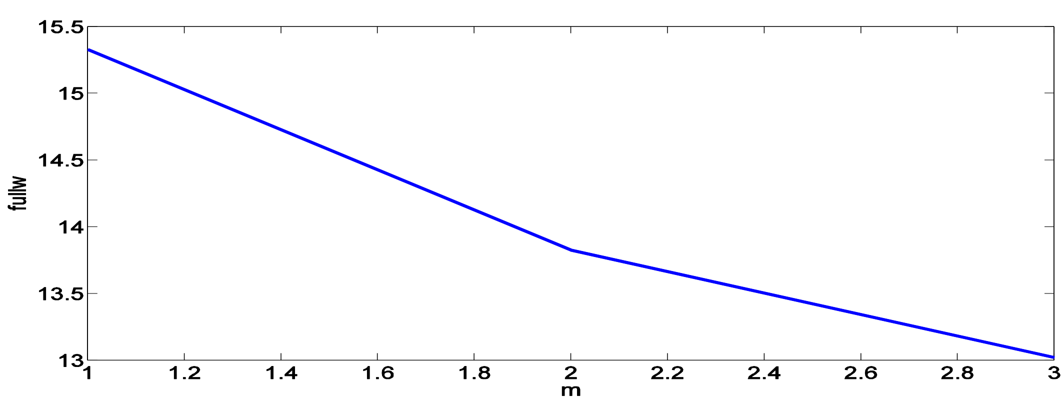


<u>Fig 3.5 Variation of delta with negative group velocity dispersion parameter for different losses</u>

Comparative study analysis (fig. 3.5) gives useful information regarding how loss factor effects the switching.as shown in fig 3.4(a)-(l). The effect of loss is prominent in low GVD region.

3.4 Spectral Switching with Super Gaussian pulse.

We now investigate the effect of pulse profile on spectral switching. To do that we consider a super-Gaussian pulse. Super Gaussian parameter controls the FWHM of the pulse and hence the delta parameter and ultimately the spectral switching. Here we study the spectral switching with super-Gaussian pulse in nonlinear domain. Here m is the super Gaussian parameter. We send super-Gaussian pulse in the nonlinear media, find its FWHM at aperture, which is depicted in fig. 3.6. As usual the change in FWHM will change critical angle of switching via delta (not shown explicitly).



<u>Fig 3.6 Variation of full width with super Gaussian parameter.</u>

3.5 Spectral switching with higher order soliton pulse.

By now it is clear that any change in the FWHM will change the truncation parameter. If the truncation parameter changes critical angle of spectral switching will also change. In this line we investigate the effect of higher order soliton on spectral switching as the shapes of different order soliton pulse is significantly different. Table 3.3 depicts how order of soliton affects the switching in nonlinear domain. N is order of soliton and so correspondingly using MATLAB full width is determined and hence the corresponding delta is obtained where spectral switching takes place. It is far easy to get the switching at lower order of soliton as the shifting is clearly visualize while at higher order soliton there are so many complications. After the N =6, there is huge turbulence and frequent fragmentation takes place and the switching is very complicated.

Table 3.3 Variation of FWHM and delta with order of soliton

N	FULL W	DELTA
1	35.2434	0.76610
2	34.5349	0.78181
3	35.1680	0.767743
4	34.8929	0.77379
5	23.9437	1.12764
6	45.7220	0.590525

Fig. 3.7 portrays the variation of delta with the order of the soliton pulse. The drastic reduction in the higher order is prominent.

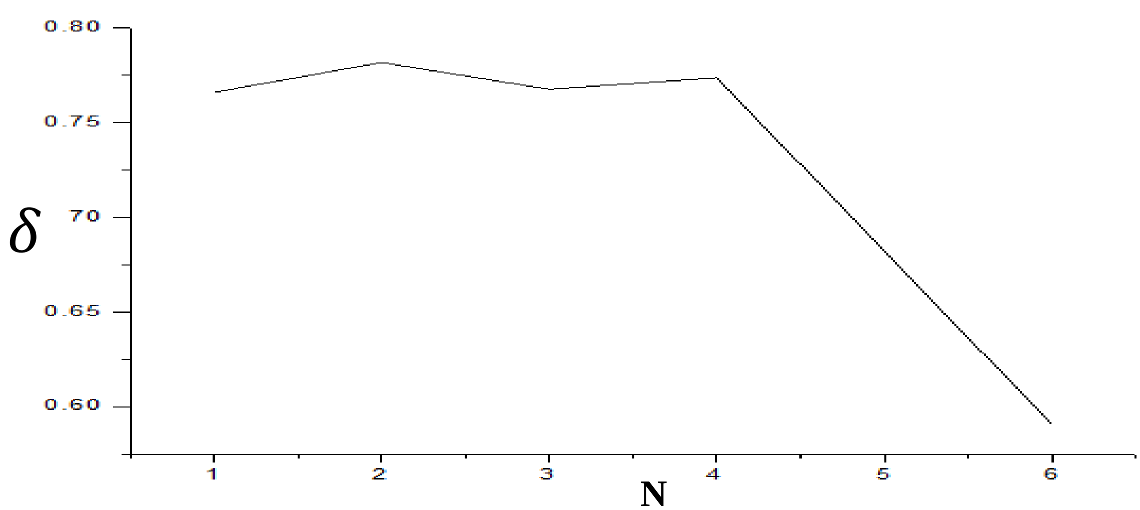


Fig 3.7 Variation of delta with the order of soliton

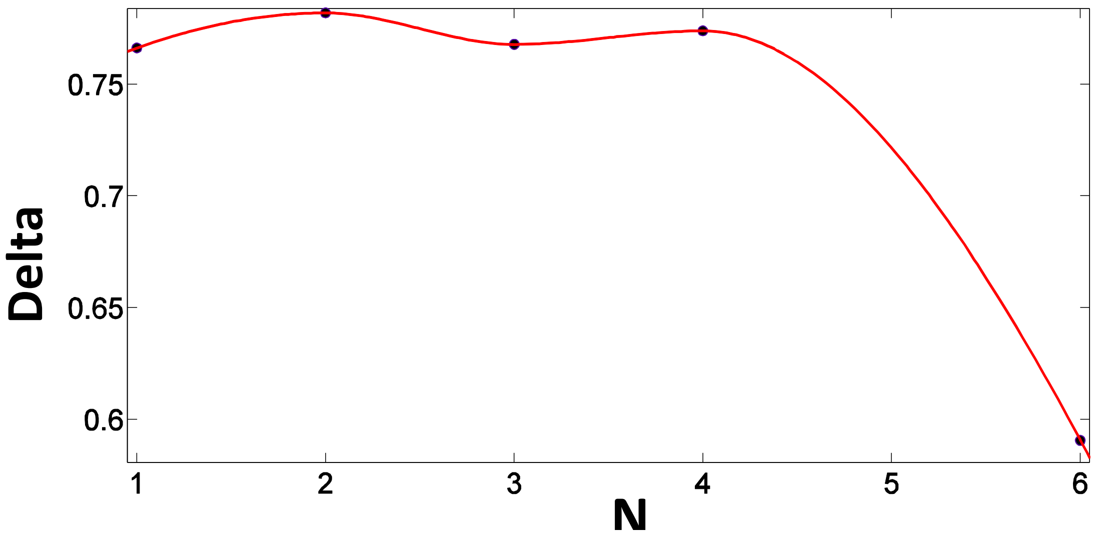


Fig 3.8 delta versus order of soliton (curve fitting graph)

3.6 Phase controlled Spectral switching

In this section we have studied the interaction of two soliton pulses of different phases. The initial separation of those pulses is small and they unite after short distance. The interesting point is that the relative phase of the pulses controls the FWHM and hence delta. Thus spectral switching can be controlled by relative phase of the pulses. Shift in the incident pulse with respect to the modified pulse. With a fixed aperture we found different truncation parameter for different relative phases. Here, we got delta (δ_f)using the following formula

$$\delta_f = \delta_i - \delta_2 - shift$$

Where,

δ_i	Delta of incident pulse 1
δ_2	Delta of incident pulse 2
Shift	Amount of shift from incident pulse to modified pulse
δ_f	δ_i - δ_2 – shift

Table 3.4 Set of parameters

Here we have taken the case of rectangular apertur.e Fig. 3.9 shows the interaction of pulses. Even at the starting point two pulses are not distinctly seen and appears as flat top as the initial separation is small (15 units only). However with propagation it modifies.

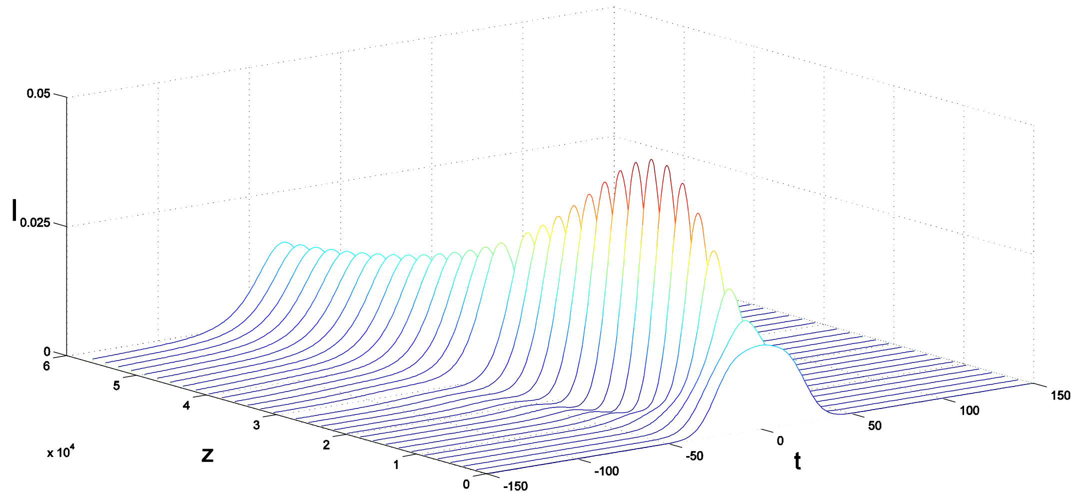


Fig 3.9 3D plot of pulse evolution during propagation.

Corresponding contour plot is shown in fig. 3.10. This shows that pulse not only changes its width but also shifts. The delta will be changed accordingly.

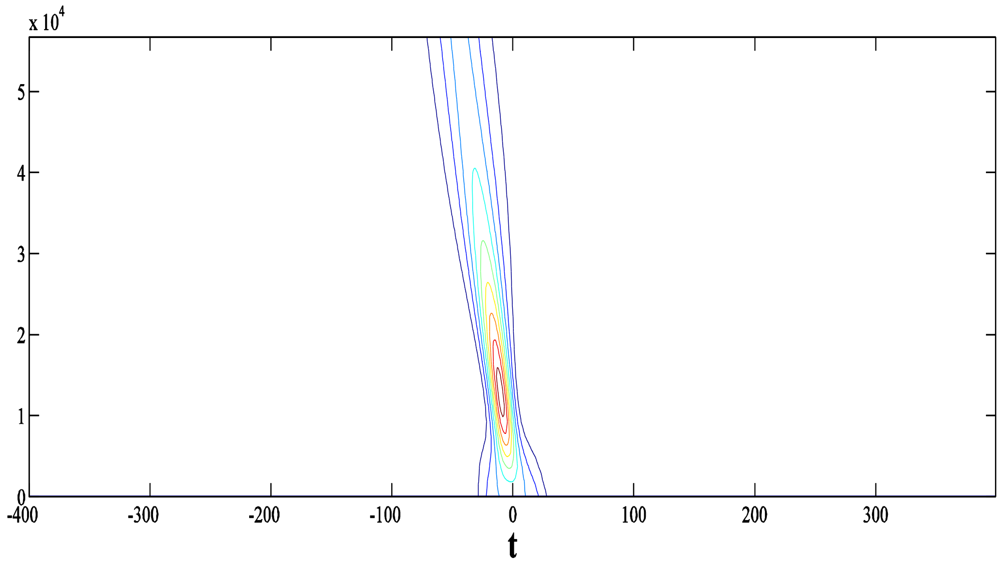


Fig 3.10 contour plot of pulse propagation

The initial and final pulse (that incidents on aperture) profiles are given in the upper panel of the fig. 3.11. Solid blue line shows incident pulse and dotted green line the final pulse.The lower pannel depicts the change in FWHM with propagation distance Z.

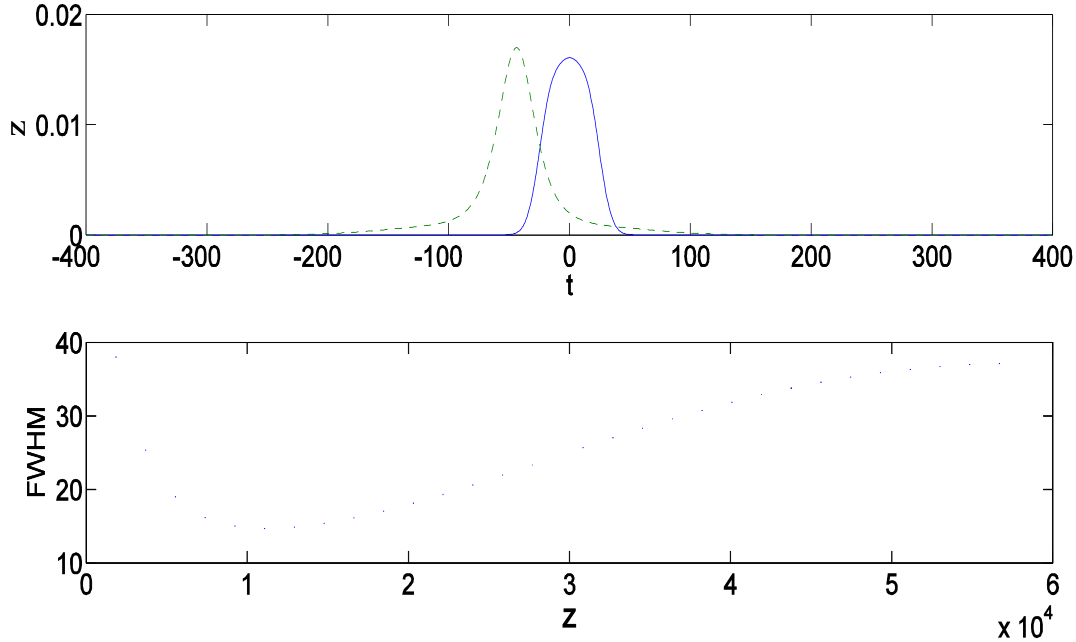


Fig 3.11 Initial and final pulse when phi =pi/44 and t0 = 15.

Calculated full width of incident pulse is 47.809 and full width for modified pulse is 29.426.and shift in incident pulse is 32.676. Hence using the e data in table 3.5 fig 3.12 is plotted.fig 3.13 is curve fitting data drawn using the MATLAB curve fitting tools.

We now investigate how spectral switching at different relative phases. With the change in relative phase there is a change in the final pulse. Also the truncation parameter changes. Following table shows the variation.

Table 3.5

w1	w2	Aw	del1	del2	Shift	Delfinal	Phi
41.034	29.426	35	0.8529	1.189	30.986	31.3221	pi/30
48.52	32.003	35	0.721	1.093	33.261	33.633	pi/31
47.989	32.327	35	0.7293	1.082	29.735	30.0877	pi/33
48.8	32.067	35	0.7172	1.091	32.023	32.397	pi/34
46.444	32.511	35	0.753	1.076	31.35	31.673	pi/35
48.659	32.456	35	0.7192	1.0783	32.129	32.4883	pi/37
46.043	33.482	35	0.7601	1.0453	31.08	31.365	pi/38
48.484	32.314	35	0.721	1.0831	32.021	32.3831	pi/39
47.325	32.352	35	0.739	1.0818	31.387	31.7298	pi/40
47.384	32.361	35	0.738	1.0815	33.275	33.6185	pi/42
47.809	32.676	35	0.732	1.0711	31.711	32.0501	pi/44
48.66	34.47	35	0.719	1.0153	31.836	32.1323	pi/46
46.42	31.333	35	0.753	1.117	31.542	31.906	pi/48

44.843	32.748	35	0.7805	1.0687	30.114	30.4022	pi/50
48.422	33.429	35	0.7228	1.0469	32.367	32.6911	pi/52
49.295	32.774	35	0.71	1.067	32.623	32.98	pi/54
47.993	33.92	35	0.7292	1.031	30.384	30.6858	pi/58

Table 3.6 Set of parameters

Parameter	Meaning
W1	Full width of incident pulse
W2	Full width of modified pulse
Aw	Aperture width
Phi	Phase

The variation of truncation parameter with relative phase phi is depicted in the following two figures. It is evident that delta switches sharply with variation of phi. Which is an interesting outcome of this phase controlled spectral switching.

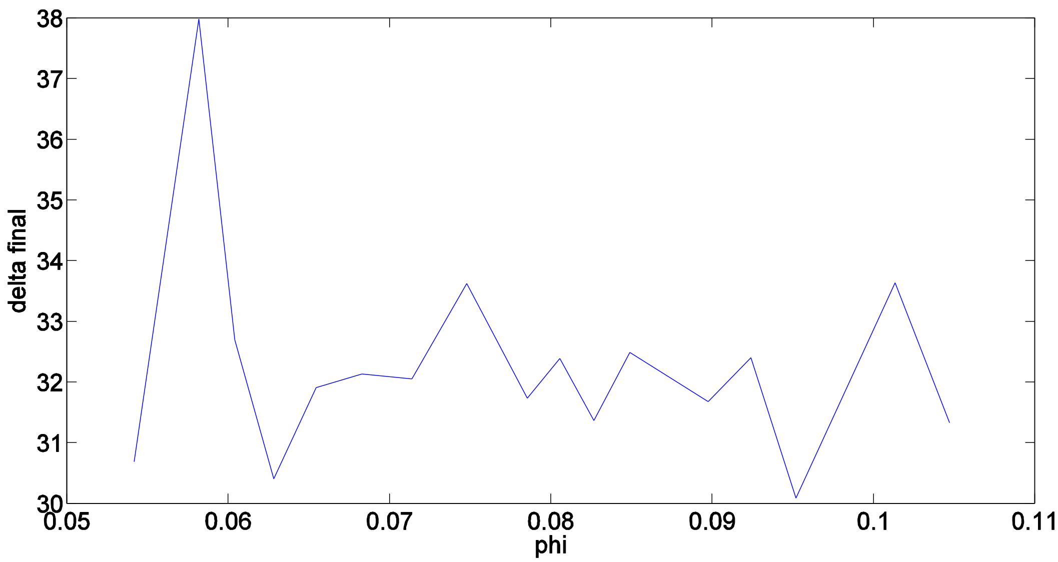


Fig 3.12 Variation of truncation parameter (delfinal) with relative phase (phi)

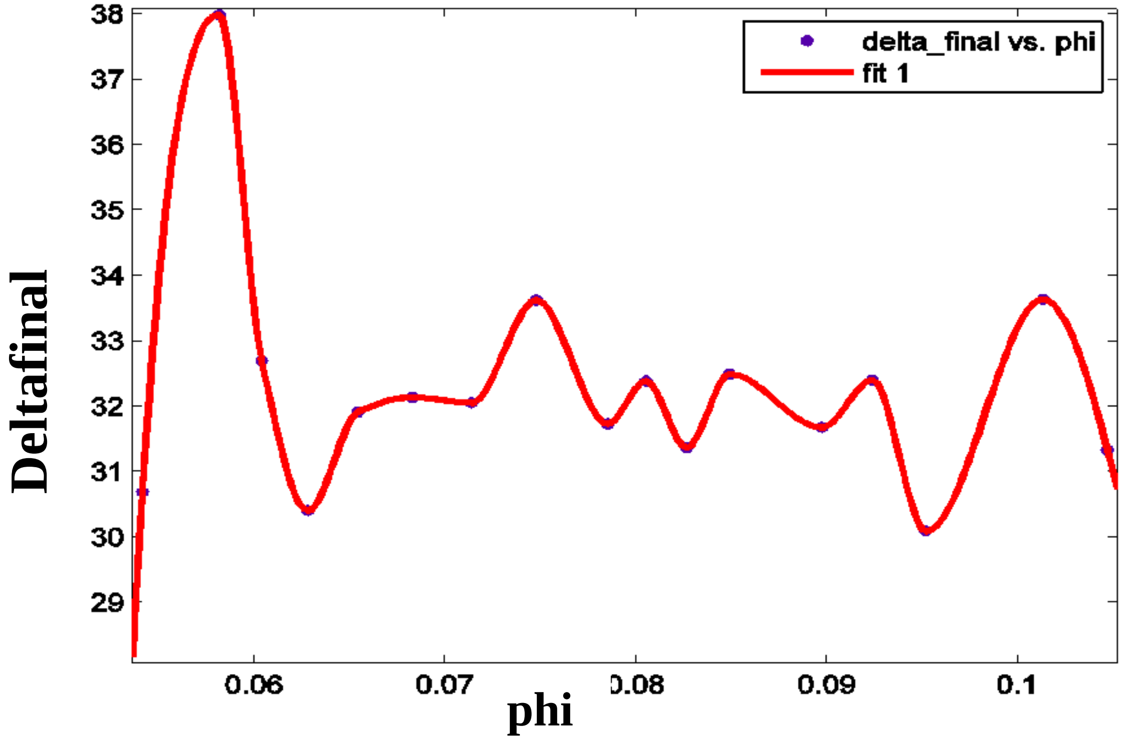


Fig 3.13(Interpolant, shape fitting curve from MATLAB)

3.7. Conclusion

We studied spectral switching in nonlinear media. Initially a soliton pulse is formed in the nonlinear media and then it is made to incident on the aperture. The diffraction of the aperture induces the spectral switching. Now a change in the medium through which the pulse propagates before incidence in the aperture will cause the change in width (and hence full width half maxima) of the soliton pulse. This in turn changes the spectral switching. We studied the effect of positive and negative group velocity dispersion on the spectral switching. The effect of loss is also studied. The effect of pulse shape on spectral switching is investigated using a super-Gaussian pulse. The order of the soliton pulse is found to have significant role in spectral switching. Phase controlled Spectral switching has been demonstrated in nonlinear media. The results have potential application in data processing, synchronized switching. Also one can fabricate different sensors out of these results.

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