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Theme

Impact of dispersive and nonlinear effects on pulse propagation in single-mode optical fibers

In front of the jury composed of :

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I dedicate this work to:

Whoever strives for my success and strives for my comfort, is the key to my patience and the secret of my happiness, my dear father “Ali”

To whom is thinner than the breeze and sweeter than perfume To my support in the days and nights, my dear “mother “God save them for me

To the source of my pride and support in life "My Brothers"

To the sweetheart of my heart and the companion of my life "sister"

To the one who supervised its achievement, Our supervisor Mr. "Medjouri AbdelKader"

To share this work with my colleagues "Issam", " Dhahir El-Din "

Sara

Contents

Liste des abréviations

- **CVD………………. chemical vapor deposition**
- **PCF ……………………. photonic crystal fiber**
- **SSFM………………. split-step Fourier method**
- **FFT……………………. fast Fourier transform**
- **SRS……….……. stimulated Raman scattering**
- **SBS……………. stimulated Brillouin scattering**
- **NLS ………….………. nonlinear Schrödinger**
- **SPM…………..………. self-phase modulation**
- **GVD…………………. group-velocity dispersion**
- **FTTH…………………. …… Fiber to the Home**

General Introduction

General Introduction

Fiber optic

Optical fibers are flexible transparent fibers made of pure glass (silica) or plastic, with a diameter slightly thicker than the diameter of a human hair, and used in optical communications, due to their ability to transmit farther distances and at higher longitudinal waves data transmission) than traditional wire cables

Fiber optics is the technology used to transmit information as pulses of light through strands of fiber made of glass or plastic over long distances.

Optical fibers are about the diameter of a strand of human hair and when bundled into a fiber-optic cable, they're capable of transmitting more data over longer distances and faster than other mediums. It is this technology that provides homes and businesses with fiber-optic internet, phone and TV services.

A fiber-optic cable contains anywhere from a few to hundreds of optical fibers within a plastic casing. Also known as optic cables or optical fiber cables, they transfer data signals in the form of light and travel hundreds of miles significantly faster than those used in traditional electrical cables. And because fiber-optic cables are non-metallic, they are not affected by electromagnetic interference (i.e. weather) that can reduce speed of transmission. Fiber cables are also safer as they do not carry a current and therefore cannot generate a spark.

What is a fiber-optic network ?

There are several different types of fiber-optic networks but they all begin with optic cables running from the network hub to the curb near your home or straight to your home to provide a fiber-optic internet connection. The fastest type of fiber network is called Fiber to the Home (FTTH) or Fiber to the Premises (FTTP) because it's a 100% fiber-optic connection with optical fiber cables installed to terminals directly connected to houses, apartment buildings and businesses.

On the other hand, Fiber to the Curb (FTTC) is a partial fiber connection because the optical cables run to the curb near homes and businesses and copper cables carry the signals from the curb the rest of the way. Similarly, Fiber to the Building (FTTB) is when fiber cable goes to a point on a shared property and the other cabling provides the connection to offices or other spaces.

Fiber-optic internet

Fios -- the most awarded network for internet service satisfaction over the past 10 years.

Now that you know how fiber optics work, let’s talk about the many benefits of fiber-optic speed.

When you’re on a FTTH network, you’ll experience significantly faster upload and download speeds, more bandwidth for multiple devices at home and a reliable connection. And that’s exactly what you’ll get with Verizon Fios, the 100% fiber-optic network.

With Fios Gigabit Connection speeds up to a blistering 940/880 Mbps Speeds up to 940 Mbps download and 880 Mbps upload available in select areas., you’ll enjoy HD streaming, gaming, video conferencing and so much more on up 100 devices at a time –virtually lag-free. No wonder Fios has been rated #1 by industry leaders time and again. Shop for Verizon Fios and see if fiber internet is available in your area.

Search plane

So on this search We will discuss a group of fiber generalities its basic components (The core-Cladding - Buffer cladding - Buffer cladding) and the function of each one of them and how the final form of fiber is formed and what it is made of (silicon dioxide (SiO_2)) and what are its most important uses(Defense/Government -Telecommunications – Networking..)

AND as second chapter will discuss Optical Fiber Effects

The chromatic dispersion is considered an influential factor in the transmission of the signal through optical fibers, which is divided into two types: the single signal and the multiple signal. The multi-signal differs from the single signal by the number of transmitted color spectra, which causes the difference in the transmission distances between each of them. As we know, optical effects are divided into two types: linear and non-linear, which result in several types of different effects and special cases, including Kerr effect, Raman scattering and Brillwin scattering. the phiscal process can be represented by the Schrödinger equation particulary the The nonlinear Schrödinger equation in fiber optics or the Split-step Fourier method

AND as Final chapter will discuss Simulation Results for the Most important Optical Fiber Effects

Like Group-velocity dispersion and Chirped Gaussian pulses & Self-phase modulation & Optical solitons

Chapter I

Optical fiber Generals

Introduction

In this chapter we will Explanation of a group of phenomena and the basics of the optic system   Optical fiber components Types of optical fibers Microstructur   Applications of Optical Fiber And more …..

I.1 Optical fiber components

If you look at any fiber optic, you will find it consists of:

I.1.1 The core

It is the thin cylindrical part made of glass and made of silica grafted with germanium, which is the center of light transmission.

It is the smallest and most important part of the optical fiber. The core of the optical fiber is usually made of glass although some are of plastic. Used in the core, is a highly pure silicon dioxide (Si02), a very clear material. Refractive index is raised under controlled conditions through dopants such as Germania, phosphorous pentoxide, or alumina during manufacturing.

There are no specific diameters for optical fiber cores as different sizes depend on the application The range of usual glass cores is from as small as 3.7um up to 200um. For telecommunication, core sizes usually used is 9um, 50um and 62.5um.

I.1.2 Cladding

It is that cylinder that surrounds the nucleus and is made of glass, where the refractive index is different from the refractive index in the nucleus, which works to preserve the light that passes through the heart and thus save the signals from changing covers the core. Its refractive index is lower to ensure the optical fiber works. The cladding and the core are manufactured together from the same silicon dioxide-based material in a permanently fused state whenever the glass cladding is used. A difference in refractive indexes of about 1% is maintained due to different amounts of dopants being added to the core and the cladding during the manufacturing process. Although the numbers are dependent upon the wavelength, the usual core is likely to have a refractive index of 1,49 at 1300nm while that of the cladding is 1.47.

The cladding is manufactured, using standard diameters. Two mostly used diameters are 125um and 140um. Core sizes such as 9um, 50um, and 62.5um, are typically supported by the 125um cladding while 140um cladding has 100um

I.1.3 Buffer cladding

It is a plastic wrap that surrounds the inner shell and the core together and protects them from the factors of nature and from breakage.

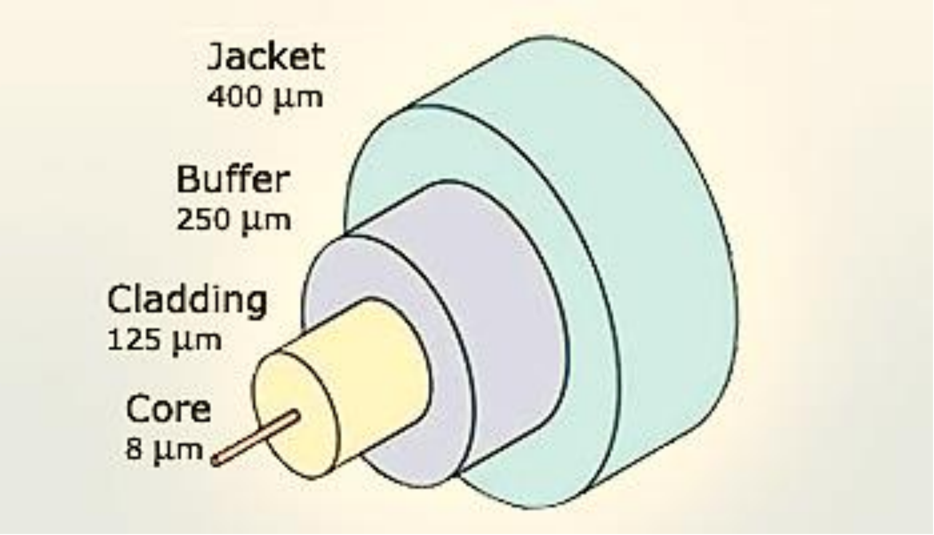

Fig 1-1: Internal Reflection in Optical Fibers {1}

I.1.4Outer jacke

The jacket is the plastic covering that protects the optical fibers that are arranged inside it in the form of bundles. We find that hundreds and perhaps thousands of these optical fibers are lined up together in one bundle in order to form t

I.2 Types of optical fibers

I.2.1 Single-mode fiber

This type is used in the transmission of data for telephone networks or cable television, as it depends on transmitting only one mode in any optical fiber from the existing packet. This type is characterized by the fact that its core radius is very small, about 8.3 microns to 9 microns, and is used to transmit data over very long distances.

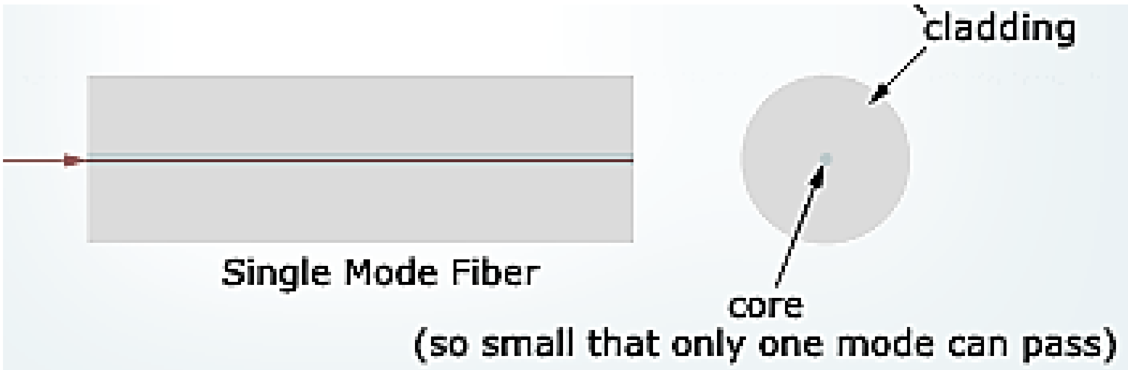

Fig 1-2: Single-mode fiber section {2}

I.2.2 Multi-mode fibers

This type of fiber cable allows the passage of many different types of fibers at one time and at the same time, the radius of it inside the core is about 50 to 62.5 microns, which allows infrared rays to penetrate through it more quickly, so this type may be good for networks The internet is used to transmit data over short distances.

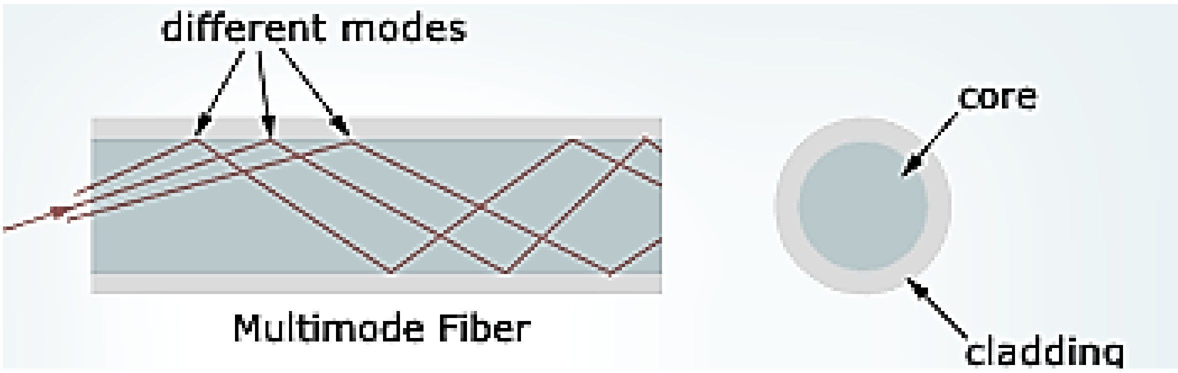

Fig 1-3: Multi-mode fiber section {3}

I.3 Optical fiber Microstructured

A common technique for fabricating microstructured fibers consists of first making a preform by stackingmultiple capillary tubes of pure silica (diameter about 1 mm) in a hexagonal pattern around a solid silica rod. The preform is then drawn into a fiber form using a standard fiber-drawing apparatus, shown schematically in. A polymer coating is added on the outside to

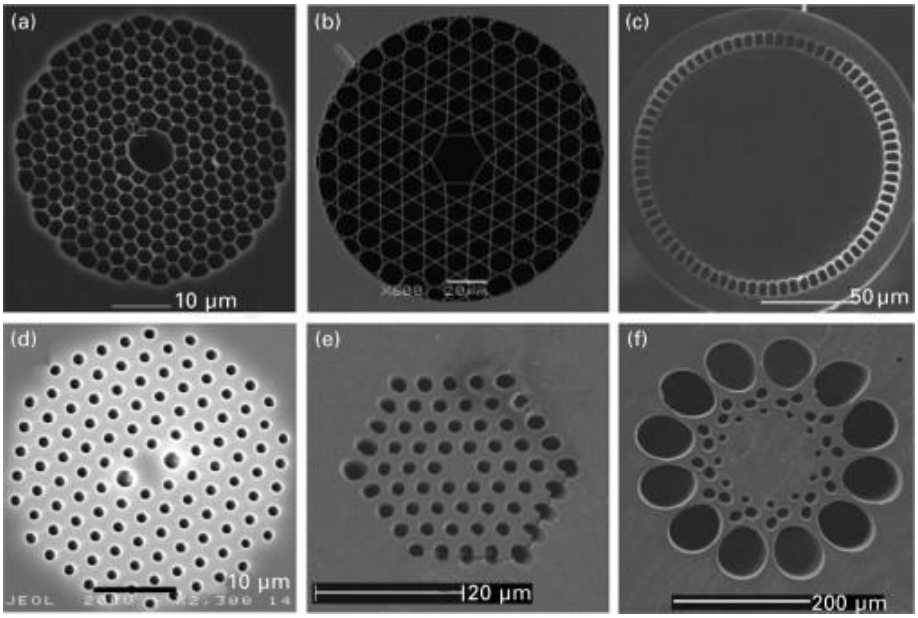

Fig1-4:microstructured fibers{4}

protect the resulting fiber. When viewed under a scanning electron microscope (SEM), such a fiber shows a two-dimensional pattern of air holes around the central region acting as a core. shows the SEM images of several PCFs together with a few optical near-field images. A hollow core fiber can be made with the same technique by removing the central silica rod at the preform stage . In contrast with the tapered fibers of Section, the length of a microstructured fiber can be quite long (it can exceed 1 km) while maintaining uniform properties all across it. Such fibers are as easy to handle as conventional fibers because of a polymer coating added on top of the cladding. They can also be spliced to other kinds of fibers, although splice losses typically exceed 1 dB unless special precautions are taken. Another technique used for fabricating microstructured fibers is known as the extrusion technique. In this approach, the preform is produced by extruding material selectively from a solid glass rod of 1 to 2 cm diameter. More specifically, the molten glass rod is forced through a die containing the required pattern of holes. This technique allows one to draw fibers directly from any bulk material, whether crystalline or amorphous, and it is often used in practice with polymers or compound glasses. The structured preform with the desired pattern of holes is reduced in scale using a fiber-drawing tower in two steps. First, the outside diameter is reduced by a factor of 10 or so. The resulting "cane" is inserted into a glass tube whose size is then further reduced by a factor of more than 100. A shortcoming of all microstructured fibers is that they exhibit much higher losses compared with those of conventional fibers. Typically, losses exceed 1000 dB/km when the core diameter is reduced to enhance the nonlinear parameter γ. The origin of such losses is related to the nature of mode confinement in such fibers. More specifically, both the core and the cladding are made of silica, and the mode confinement to the

I.4 Raw Materials

Optical fibers are composed primarily of silicon dioxide (SiO_2), though minute amounts of other chemicals are often added. Highly purified silica powder was used in the now-outmoded crucible manufacturing method, while liquid silicon tetrachloride ($SiCl_4$) in a gaseous stream of pure oxygen (02) is the principal source of silicon for the vapor deposition method currently in widespread use. Other chemical compounds such as germanium tetrachloride ($GeCl_4$) and phosphorus oxychloride ($POC1_3$) can be used to produce core fibers and outer shells, or *claddings,* with function-specific optical properties.

Because the purity and chemical composition of the glass used in optical fibers determine the most important characteristic of a fiber—degree of attenuation—research now focuses on developing glasses with the highest possible purity. Glasses with a high fluoride content hold the most promise for improving optical fiber performance because they are transparent to almost the entire range of visible light frequencies. This makes them especially valuable for multimode optical fibers, which can transmit hundreds of discrete light wave signals concurrently.

I.5 Design fiber

In a fiber optic cable, many individual optical fibers are bound together around a central steel cable or high-strength plastic carrier for support. This core is then covered with protective layers of materials such as aluminum, Kevlar, and polyethylene (the cladding). Because the core and the cladding are constructed of slightly differing materials, light

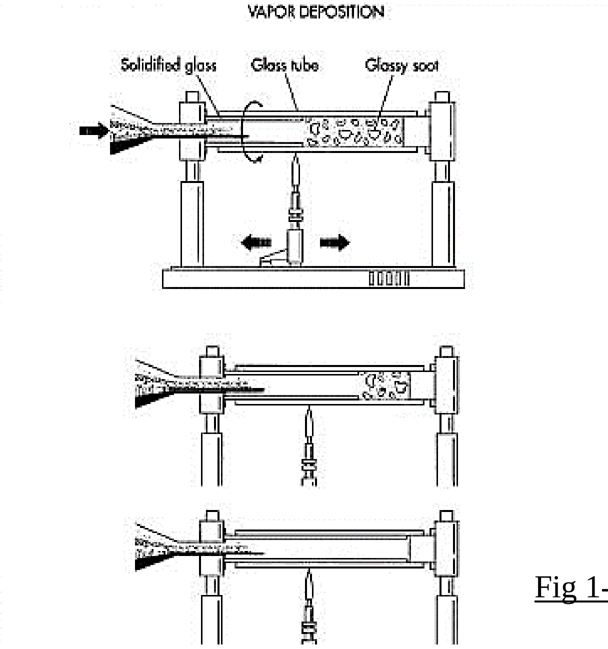

Fig 1-5:vapor deposit {5}

Travels through them at different speeds. As a light wave traveling in the fiber core reaches the boundary between the core and cladding, these compositional differences between the two cause the light wave to bend back into the core. Thus, as a pulse of light travels through an optical fiber, it is constantly bouncing away from the cladding. A pulse moves through the optical fiber at the speed of light—186,290 miles per second (299,340 kilometers per second) in a vacuum, somewhat slower in practice—losing energy only because of impurities in the glass and because of energy absorption by irregularities in the glass structure.

Energy losses (attenuation) in an optical fiber are measured in terms of loss (in decibels, a unit of energy) per distance of fiber. Typically, an optical fiber has losses as low as 0.2 decibels per kilometer, meaning that after a certain distance the signal becomes weak and must be strengthened, or *repeated.* With current datalink technology, laser signal repeaters are necessary about every 30 kilometers (18.5 miles) in a long-distance cable. However, on-going research in optical material purity is aimed at extending the distance between repeaters of an optical fiber up to 100 kilometers (62 miles).

There are two types of optical fibers. In a single-mode fiber, the core is smaller, typically 10 micrometers (a micrometer is one-millionth of a meter) in diameter, and the cladding is 100 micrometers in diameter. A single-mode fiber is used to carry just one light wave over very long distances. Bundles of single-mode optical fibers are used in long-distance telephone lines and undersea cables. Multimode optical fibers, which have a core diameter of 50 micrometers and a cladding diameter of 125 micrometers, can carry hundreds of separate light wave signals over shorter distances. This type of fiber is used in urban systems where many signals must be carried to central switching stations for distribution

I.6 The Manufacturing Process

Both the core and the cladding of an optical fiber are made of highly purified silica glass. An optical fiber is manufactured from silicon dioxide by either of two methods. The first, the crucible method, in which powdered silica is melted, produces fatter, multimode fibers suitable for short-distance transmission of many light wave signals. The second, the vapor deposition process, creates a solid cylinder of core and cladding material that is then heated and drawn into a thinner, single-mode fiber for long-distance communication.

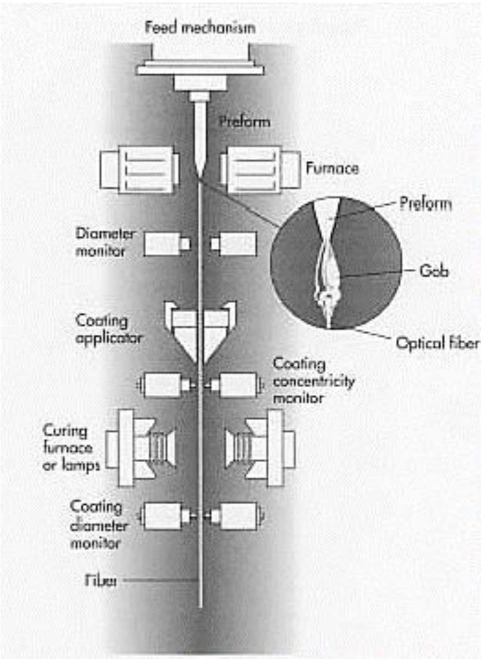

Fig 1-6: feed mechanism{6}

There are three types of vapor deposition techniques : Outer Vapor Phase Deposition, Vapor Phase Axial Deposition, and Modified Chemical Vapor Deposition (MCVD). This section will focus on the MCVD process, the most common manufacturing technique now in use. MCVD yields a low-loss fiber well-suited for long-distance cables.

I.7 Applications of Optical Fiber

Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:

Medical: Used as light guides, imaging tools and also as lasers for surgeries

Defense/Government: Used as hydrophones for seismic waves and SONAR, as wiring in aircraft, submarines and other vehicles and also for field networking

Data Storage: Used for data transmission

Telecommunications: Fiber is laid and used for transmitting and receiving purposes

Networking: Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission

Industrial/Commercial: Used for imaging in hard-to-reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings

Broadcast/CATV: Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications

Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables. Fiber optic cables are also used in research and development and testing across all the above-mentioned industries.

Conclusion

Optical fiber is components of 4 different materials call the core Cladding Cladding Outer Jacket Each one has specific thickness and job. It determines the type Optical fiber (Single-mode fiber. Multi-mode fibers) and the fabrication of fiber optic is sensitive a process needs a specific material to be processed shaped more accurate as possible because the fiber-optic is the backbone of communication in the world and Broadcasting

Chapter II

Optical Fiber Effects

Introduction

In this chapter, we will study the most important effects and mathematical equations that help optical fibers work efficiently Like (Chromatic Dispersion & Birefringence & Confinement Loss & Kerr Effect & Raman scattering & Brillouin scattering & Schrödinger equation & SPFM

II.1Chromatic dispersion and losses of microstructure optical fibers

II.1.1 Chromatic Dispersion

Chromatic dispersion is a phenomenon that is an important factor in optical fiber communications. It is the result of the different colors, or wavelengths, in a light beam arriving at their destination at slightly different times. In multimode optic fiber links, we have a similar problem. Different wavelengths of light propagate at different speeds. This material dispersion causes the light to break up and the carrier signal is lost due to this disruption. This is why multimode optical fiber links cannot travel as far as single mode fiber links. Single mode uses a single wavelength and not the full visible spectrum to transmit a signal to they do not suffer from

the chromatic dispersion problem.

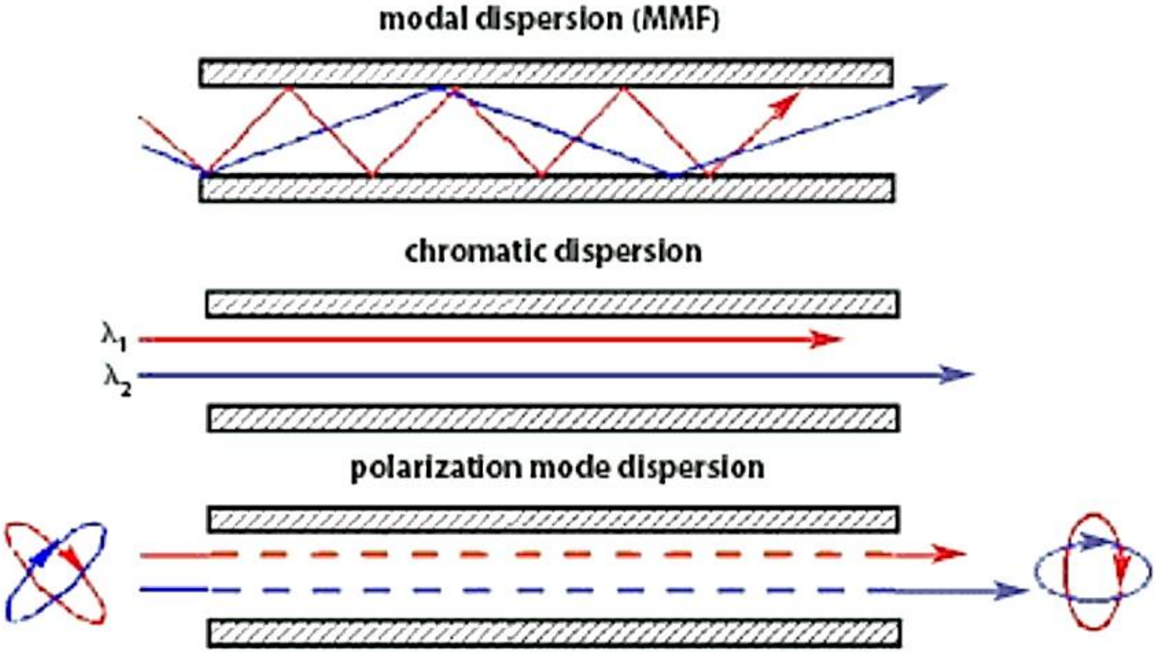

Fig 2-1: Modal dispersion & Chromatic dispersion & polarization Mode{7}

Chromatic dispersion is the term given to the phenomenon by which different spectral components of a pulse travel at different velocities. To understand the effect of chromatic dispersion, we must understand the significance of the propagation constant β. We will restrict our discussion to single mode fiber since in the case of multimode fiber, the effects of intermodal dispersion usually overshadow those of chromatic dispersion. So the propagation constant β in our discussions will be that associated with the fundamental mode of the fiber. Chromatic dispersion arises for two reasons.

1./ The first reason is that the refractive index of silica, the material used to make optical fiber, is frequency dependent. Thus different frequency components travel at different speeds in silica. This component of chromatic dispersion is called material dispersion

2./ Although material dispersion is the principle component of chromatic dispersion for most fibers, there is a second component, called waveguide dispersion.

II.1.2 Birefringence

The birefringence of a Photonique Crystal fibre is determined by the difference between the real part of the effective indices Re(n_{eff}^{x}) and Re(n_{eff}^{x}),

Which corresponds to the two fundamental core eigenmodes LP_{01}^{x} and LP_{01}^{y} mainly polarized along the x- and y-axes, respectively

$$B = | \; Re\left(n_{eff}^{x}\right) - Re\left(n_{eff}^{x}\right) \; | \qquad \text{Eq: 2.1}$$

II.1.3 Confinement Loss

When the optical mode is propagating in the core region, due to a finite number of layers of air holes, the mode leakage from the core region into the outer air hole region is unavoidable, and then, the confinement loss due to the extent of the cladding is occurring. The confinement loss of the fundamental mode is calculated from the imaginary part of the complex effective index neff, using

$$\text{Conf. loss} = \frac{40\pi}{ln(10)\lambda} \; Im\left(n_{eff}\right) \; [\text{dB/m}] \qquad \text{Eq: 2.2}$$

where Im is the imaginary part of then_{eff}.

II.2 Kerr Effect

the Kerr effect is a nonlinear optical effect which can occur when light propagates in crystals and glasses, but also in other media such as gases. It can be described as a change in refractive index caused by electric fields, and being proportional to the square of the electric field strength. It comes in two different forms, which are explained in the following sections.

II.2 1 Kerr Electro-optic Effect (DC Kerr Effect)

Another variant of the Kerr effect occurs without an externally applied electric field, based on the electric field of a light wave only. The Kerr effect is the effect of an instantaneously occurring nonlinear response, which can be described as modifying the refractive index. In particular, the refractive index for the high intensity light beam itself is modified according to

$$\Delta n = n_2 I \qquad \text{Eq: 2.3}$$

with the optical intensity I proportional to the modulus squared of the electric field strength and the nonlinear index n2. The third-order susceptibility of a medium is related to its n2 value, which may be tested using the z-scan technique, for example. It's worth noting that, in addition to the Kerr effect (a purely electronic nonlinearity), electrostriction can have a considerable impact on the nonlinear index's value. The photo elastic effect influences the refractive index by causing density changes (acoustic waves) caused by the electric field of light. However, because that process operates on a considerably longer time scale, it is only significant for somewhat sluggish power modulations, not ultrashort pulses.

The nonlinear index of fused silica, as utilized in silica fibers, is 3 1016 cm2/W. It can be substantially greater for soft glasses and, in particular, semiconductors, because the band gap energy is so important. For photon energies exceedingly around 70% of the bandgap energy, nonlinearity is frequently negative (self-defocusing nonlinearity).

Self-phase modulation and Kerr lensing result from time and frequency-dependent refractive index changes, as well as cross-phase modulation for various overlapping light beams. Note that, assuming both beams are in the same polarization state, the effective refractive index rise generated by one powerful beam for other beams is twice as great as that predicted by the equation indicated above.

II.3 Raman scattering

The first nonlinear phenomenon described exploiting the enhancement given by a carbon dauphine liquid-filled hollow core fiber was stimulated Raman scattering (Ippen 1970), an idea that has resurfaced with the advent of air core photonic band gap fiber. The first observation of self-phase modulation in an optical fiber was also made using a similar experimental setup. All of the major nonlinear effects that had previously been found in bulk materials were quickly defined and published, although at considerably lower power levels, thanks to the availability of typical low loss fibers. Stimulated Raman scattering, stimulated Brillouin scattering, the optical Kerr effect, four-wave mixing, and self-phase modulation are all examples of techniques that may be used to generate supercontinuum. in fibers

II.3.1 Basic Raman scattering

In any molecular medium, spontaneous Raman scattering may transmit a tiny proportion of power (usually 106 watts) from one optical field to another, whose frequency is downshifted by a factor dictated by the medium's vibrational modes. This

The Raman effect is a phenomenon that was discovered by Raman in 1928. It's possible.A molecule converts a photon of energy h p into a quantum mechanically characterized photon of energy h p.

As the molecule transitions to a higher-frequency photon with energy has, it changes to a lower-frequency photon with energy has.

condition of vibratory excitement Incident light has a practical purpose.

as a pump and produces frequency-shifted radiation, often known as the Stokes wave

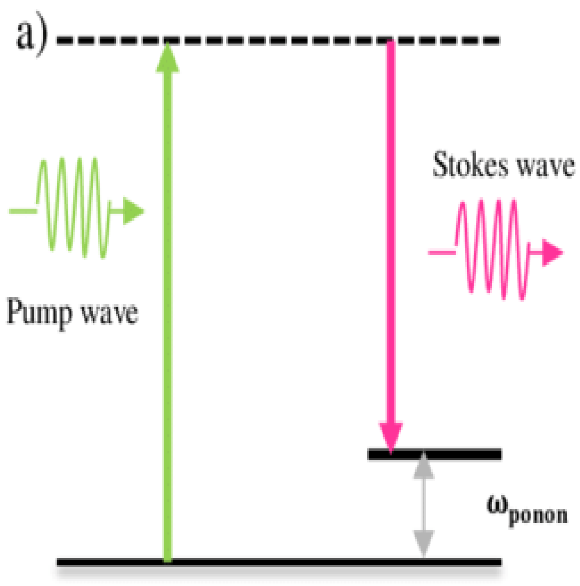

Fig1-2:Raman scattering {8}

It can be used as a spectroscopic tool. In 1962, it was discovered that for powerful pump fields,

SRS can cause a nonlinear phenomenon in which the Stokes wave increases fast.

inside the medium, such that it receives the majority of the pump's energy Since then, a lot has happened.

II.4 Brillouin scattering

SBS (stimulated Brillouin scattering) is a nonlinear phenomenon that may happen in optical fibers at significantly lower input power levels than stimulated Raman scattering (SRS). Once the Brillouin threshold is achieved, it reveals itself by the formation of a backward-propagating Stokes wave that carries the majority of the input power. As a result, in optical communication systems, SBS restricts channel power. At the same time, fiber-based Brillouin lasers and amplifiers may be possible.

II.4.1 Brillouin scattering Basic

SBS, a nonlinear phenomenon initially identified in 1964, has been widely explored.

SBS is similar to SRS in that it is manifested by the formation of a Stokes wave, whose frequency is downshifted by an amount determined by the nonlinear medium from that of the incoming light. However, there are some significant distinctions between the two.

When SBS happens in a single-mode optical fiber, for example, the Stokes wave propagates backward, but SRS can occur in both directions. When compared to SRS, SBS has a three-order-of-magnitude smaller Stokes shift (10 GHz).

The spectral width linked with the pump wave determines the SBS threshold pump power. For a small device, a surge of pumping For a CW pump or when the pumping is in the form of rather large pulses (width >1 s), it can be as low as 2 mW. SBS is also almost non-existent for short pump pulses (width 1 ns). All of these distinctions originate from a single basic difference: in SBS, acoustic phonons are engaged, whereas in SRS, optical phonons are involved.

II.4.2 Physical process

The process of SBS can be described classically as a nonlinear interaction among the pump and Stokes fields and an acoustic wave (initially generated thermally) through the process of electrostriction. The acoustic wave produces density modulations that in turn modulate the refractive index of the medium. This pump-induced index grating scatters the pump light through Bragg diffraction. Scattered light is downshifted in frequency because of the Doppler shift associated with a grating moving at the acoustic velocity vA. The same scattering process can be viewed quantum mechanically as if annihilation of a pump photon creates a Stokes photon and an acoustic phonon simultaneously. As both the energy and the momentum must be conserved during each scattering event, the frequencies and the wave vectors of the three waves are related by

$$\omega B=\omega p-\omega s. \qquad Ka=kp-ks. \qquad \text{Eq: 2.4}$$

where ωp and ωs are the frequencies, and kp and ks are the wave vectors, of the pump and Stokes waves, respectively. The frequency B and the wave vector kA of the acoustic wave satisfy the standard dispersion relation

$$\omega B = vA|\mathbf{k}A| \approx 2vA|\mathbf{k}p|\sin(\theta/2), \qquad \text{Eq: 2.5}$$

where θ is the angle between the pump and Stokes fields, and we used |kp|≈|ks|. that the frequency shift of the Stokes wave depends on the scattering angle. In particular, ωB is maximum in the backward direction (θ = π) and vanishes in the forward direction (θ = 0). In a single-mode optical fiber, only relevant directions are the forward and backward directions. For this reason, SBS occurs only in the backward direction with the Brillouin shift given by

$$\nu B = \Omega B/2\pi = 2npvA/\lambda p, \qquad \text{Eq: 2.6}$$

where was used with |kp| = 2πnp/λp and np is the effective mode index at the pump wavelength λp. If we use vA = 5.96 km/s and np = 1.45, the values appropriate for silica fibers, νB ≈ 11.1 GHz at λp = 1.55 μm. predicts correctly that SBS should occur only in the backward direction in single-mode fibers, spontaneous Brillouin scattering can occur in the forward direction. This happens because the guided nature of acoustic waves leads to a relaxation of the wave-vector selection rule. As a result, a small amount of Stokes light is generated in the forward direction. This phenomenon is referred to as guided-acousticwave Brillouin scattering. In practice, the Stokes spectrum shows multiple lines with frequency shifts ranging from 10 to 1000 MHz. Because of its extremely weak character,

II.5 Schrödinger equation

The (one-dimensional) nonlinear Schrödinger equation (NLSE) is a nonlinear variant of the Schrödinger equation in theoretical physics. It is a classical field equation with applications in the mean-field regime to light propagation in nonlinear optical fibers and planar waveguides, as well as Bose–Einstein condensates confined to highly anisotropic cigar-shaped traps. The equation is also used in investigations of small-amplitude gravity waves on the surface of deep inviscid fluids (zero-viscosity)

II.5. 1 The nonlinear Schrödinger equation in fiber optics

n optics, the nonlinear Schrödinger equation occurs in the Manakov system, a model of wave propagation in fiber optics. The function ψ represents a wave and the nonlinear Schrödinger equation describes the propagation of the wave through a nonlinear medium. The second-order derivative represents the dispersion, while the κ term represents the nonlinearity. The equation models many nonlinearity effects in a fiber, including but not limited to self-phase modulation, four-wave mixing, second-harmonic generation, stimulated Raman scattering, optical solitons, ultrashort pulses, etc.

The critical nonlinear Schrödinger equation (NLS)

$$i\psi t + \Delta\psi + |\psi| 2 (1) \psi = 0, \psi(0, x, y) = \psi 0(x, y)$$ Eq: 2.7

is the model equation for the propagation of an intense laser beam through a medium with Kerr nonlinearity. In this model ψ (t, x, y) is electric field amplitude, t is distance in the direction of propagation, x and y are the transverse spatial coordinates, and $\Delta = \partial xx + \partial yy$ is the two-dimensional Laplacian. It is well known that if the initial beam power $\|\psi 0\|2\ 2$ is above a threshold value Nc, solutions of can self-focus and become singular in a finite time. Since physical quantities do not become infinite, this implies that the validity of breaks down near the singularity and that additional physical mechanisms, which are initially small, become important there and prevent the singularity formation. In this study we analyze the effect of small damping on NLS self-focusing and singularity formation. In physical self-focusing, an electromagnetic wave is absorbed by the medium through which it propagates, an effect which is neglected in which models propagation under "ideal transparency." When damping (absorption) is included, the model equation becomes

$$i\psi t + \Delta\psi + |\psi| 2 (2) \psi + i\delta\psi = 0 , \psi(0, x, y) = \psi 0(x, y)$$ Eq: 2.8

In the nonlinear optics context, the nondimensional expression for δ is (see Appendix A)

$$\delta \;=\; r_0^2 k_0^2 \,\frac{Im(n2\ 0)}{\mathrm{Re}(n2\ 0)} \;=\; \mathrm{L_{DF}}\ \mathrm{k_0}\ \frac{\mathrm{Im}(n2\ 0)}{\mathrm{Re}(n2\ 0)}\ , \qquad \text{Eq: 2.9}$$

where r0 is the transverse width of the input beam, k0 is the (real part of the) wavenumber, $\mathrm{L_{DF}} = r_0^2 k_0^2$ is the diffraction length, and n0 is the linear index of refraction of the media. By definition, transparency means that damping is small. For example, for water in the visible regime

$$\frac{\mathrm{Im}(n2\ 0)}{\mathrm{Re}(n2\ 0)} \;\sim\; 10 - 7\,. \qquad \text{Eq: 2.10}$$

Since physical damping is always positive, δ > 0. Equation with δ positive also arises in the study of the collapse of Langmuir waves with collisional damping. Our analysis, however, applies also to negative values of δ, which is of interest in the context of the complex Ginzburg–Landau equation where δ plays the role of the “instability parameter”

II.6 Split-step Fourier method

To understand the philosophy behind the split-step Fourier method (SSFM),

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A \qquad \text{Eq: 2.11}$$

$\hat{D}$ is a differential operator that accounts for dispersion and losses within a linear medium, while $\hat{N}$ is a nonlinear operator that determines the influence of fiber nonlinearities on transmission.

$$\hat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2}\ A \qquad \text{Eq: 2.12}$$

$$\hat{N} = i\gamma\left(|A|^2 + \frac{i}{\omega_0}\frac{1}{A}\frac{\partial}{\partial T}(|A|^2 A) - T_R\frac{\partial |A|^2}{\partial T}\right). \qquad \text{Eq: 2.13}$$

Dispersion and nonlinearity work together over the length of a fiber in general. By assuming that the dispersive and nonlinear effects work separately for propagating the optical field across a limited distance h, the SSFM provides an approximate solution. In more detail, propagation from z to $z + h$ is accomplished in two phases. The nonlinearity acts alone in the first step,

$$A(z+h,T) \approx \exp(h\widehat{D})\exp(h\widehat{N})A(z,T)\ A$$ Eq: 2.14

The exponential operator exp(hDˆ) can be evaluated in the Fourier domain using the prescription

$$\exp(h\widehat{D})A(z,T) = F_T^{-1}\exp[hD(\omega)]F_T A(z,T)\ A$$ Eq: 2.15

where F_T denotes the Fourier-transform operation, $D(\omega)$ is obtained from Eq. (2.4.2) by replacing the operator $\partial/\partial T$ by $-i\omega$ and ω is the frequency in the Fourier domains. As D(ω) is just a complex number in the frequency domain, the use of the FFT algorithm makes numerical evaluation

To estimate the accuracy of the SSFM, we note that a formally exact solution given by

$$A(z+h,T) = \exp[h(\widehat{D}+\widehat{N})]A(z,T)\ A$$ Eq: 2.16

if $\hat{N}$ is assumed to be z independent. At this point, it is useful to recall the Baker-Hausdorff formula [51] for two noncommitting operators $\hat{a}$ and $\hat{b}$,

$$\exp(\hat{a})\exp(\hat{b}) = \exp\left(\hat{a}+\hat{b}+\frac{1}{2}[\hat{a},\hat{b}]+\frac{1}{12}[\hat{a}-\hat{b},[\hat{a},\hat{b}]]+\cdots\right)A$$ Eq: 2.17

The SSFM overlooks the non-commuting character of the operators D and N, as shown by Eq 2.14 and 2.16. The dominating error term is discovered to originate from the commutator 1 2 h2[D,N] when Eq. 2.17 is used with a = hD and b = hN. As a result, at the step size h, the SSFM is accurate to second order. By using a new approach to propagate the optical pulse through one segment from z to z + h, the SSFM's accuracy may be increased. Eq. 2.14 is substituted by Eq. 2.14 in this technique.

$$A(z+h,T) \approx \exp\left(\frac{h}{2}\widehat{D}\right)\exp\left(\int_z^{z+h}\widehat{N}(z')dz'\right)\exp\left(\frac{h}{2}\widehat{D}\right)A(z,T)\ A$$ Eq: 2.18

The main difference is that the effect of nonlinearity is included in the middle of the segment rather than at the segment boundary. Because of the symmetric form of the exponential operators in Eq. 2.18. this scheme is known as the symmetrized SSFM method. The integral in the middle exponential is useful to include the z de-pendence of the nonlinear operator Nˆ . If the step size h is small enough, it can be approximated by exp(hNˆ), similar to Eq. 2.14. The most important advantage of using the symmetrized form in Eq. 2.18 is that the leading error term results from the double commutator in Eq. 2.17 and is of third order in the step size h. This can be verified by applying Eq. 2.1.7 twice in Eq. 2.1.8. The accuracy of the SSFM can be further improved by evaluating the integral in Eq. 2.1.8 more accurately than approximating it by hNˆ (z). A simple approach is to employ the trapezoidal rule and approximate

$$\int_{z}^{z+h} \hat{N}(z')dz' \approx \frac{h}{2}[\hat{N}(z) + \hat{N}(z+h)]\, A \qquad \text{Eq: 2.19}$$

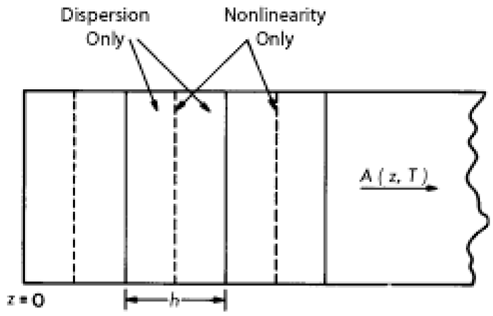

Fig 1-3: SSFM{9}

However, the implementation of Eq. 2.19 is not simple because Nˆ (z+h) is unknown at the mid-segment located at z + h/2. It is necessary to follow an iterative procedure that is initiated by replacing Nˆ (z + h) by Nˆ (z). Eq. 2.18 is then used to estimate A(z + h,T) which in turn is used to calculate the new value of Nˆ (z + h). Although the iteration procedure is time-consuming, it can still reduce the overall computing time if the step size h can be increased because of the improved accuracy of the numerical algorithm. Two iterations are generally enough in practice.

The implementation of the SSFM is relatively straightforward. As shown in Fig. 2.3, the fiber length is divided into a large number of segments that need not be spaced equally. The optical pulse is propagated from segment to segment using the prescription of Eq. 2.18. More specifically, the optical field A(z,T) is first propagated for a distance h/2 with dispersion only using the FFT algorithm and Eq. 2.15 . At the midplane z + h/2, the field is multiplied by a nonlinear term that represents the effect of nonlinearity over the whole segment length h.

Finally, the field is propagated for the remaining distance h/2 with dispersion only to obtain A(z + h,T). In effect, the nonlinearity is assumed to be lumped at the midplane of each segment (dashed lines in Fig. 2.3). In practice, the SSFM can be made faster by noting that the application of Eq. 2.18 over M successive steps results in the following expression

$$\mathrm{A(L,T)} \;\approx\; \mathrm{e}^{-1/2\,\mathrm{hD}}\,(\prod_{m=1}^{M} e^{hD}e^{hN})e^{1/2hD}A(0,T)$$

where L = Mh is the total fiber length and the integral in Eq. 2.19 was approximated with hNˆ . Thus, except for the first and last dispersive steps, all intermediate steps can be carried over the whole segment length h. This feature reduces the required number of FFTs roughly by a factor of 2 and speeds up the numerical code by the same factor. Pulse propagation in fibers 49 Note also that a different algorithm is obtained if we use Eq. 2.17 with aˆ = hNˆ and ˆ b = hDˆ . In that case, Eq. 2.10 is replaced with

$$\mathrm{A(L,T)} \;\approx\; \mathrm{e}^{-1/2\,\mathrm{hD}}\,(\prod\nolimits_{m=1}^{M} e^{hD}e^{hN})e^{1/2hD}A(0,T)\,) \qquad \text{Eq: 2.21}$$

Both of these algorithms provide the same accuracy and are easy to implement in practice (see Appendix D). One must pay attention to several issues before writing a SSFM code. The FFT algorithm replaces the Fourier integral

$$\tilde{A}(\omega) = \int_{-\infty}^{\infty} A(t)e^{i\omega t}dt \approx \delta t \sum_{n=0}^{N-1} A(t_n)e^{i\omega t_n}) \qquad \text{Eq: 2.22}$$

with a finite Fourier series with N terms by assuming that A(t) is a periodic function over the range −Tm ≤ t ≤ Tm, where the boundaries ±Tm must be chosen suitably. Clearly, the temporal window used for simulations must be much wider than the pulse width. The temporal resolution δt = 2Tm/N is set by the number of FFT points. It is important to realize that the FFT algorithm sets the frequency grid automatically once Tm and N are specified. More specifically, the frequency range in hertz is just the inverse of δt, or the frequency resolution is

$$\delta\omega = \frac{2\pi}{\delta t}\frac{1}{N} = \frac{\pi}{T_m}) \qquad \text{Eq: 2.23}$$

where we used the relation 2Tm = Nδt. Thus, the angular frequency ω lies in the range −(π/δt) ≤ ω ≤ (π/δt). For an accurate calculation, N and Tm must be large enough, or δt and δω must be small enough, that both A(t) and A˜ (ω) are sampled properly over their entire ranges. Typically, Tm is chosen to be 20 to 25 times the width of input pulses with N = 210 (because FFT runs faster when N is a power of 2). However, the window size also depends on the length of the fiber over which simulations are carried out. If a pulse breaks up into several parts propagating at different speeds, its energy may spread so rapidly that it may hit the window boundary before a simulation is complete. This can lead to numerical instabilities because energy reaching one edge of the window automatically re-enters at the other edge (in view of the periodic nature of the function A). An "absorbing window" is sometimes deployed so that the radiation reaching window edges is artificially absorbed, even though such an implementation does not preserve pulse energy. Some problems, such as supercontinuum generation require much larger values of Tm (> 100 times pulse width) and N (> 216) before one obtains accurate results

Two more points are noteworthy. First, most FFT algorithms require just the array A(tn) as the input and return its Fourier transform in the same array, ignoring the multiplication by δt in Eq. 2.12. The inverse FFT algorithm also ignores multiplication by δω but divides the result by N to ensure that A(tn) is recovered. The division by N can be understood from Eq. 2.13 by noting that δt(δω/2π) = 1/N. However, one must remember that the Fourier transform of A(t) calculated through FFT does not have correct units and is related to it as A˜ (ω) = (δt)FFT(A). This is important to know if one wants to match the numerical values to an analytical formula for a known function A(t). Second, any FFT algorithm must make a choice of sign for the exponential term in Eq. 2.12. Most of them assume a negative sign and thus do not calculate the sum as indicated in Eq. 2.12. This problem can be solved by using the inverse FFT algorithm first and then using FFT to take the inverse Fourier transform. With these clarifications, the reader should be able to follow the SSFM code provided in Appendix D and to use it effectively to solve the problems discussed in later chapters. Another practical issue is related to the step size h in the z direction. The SSFM code provided in Appendix D assumes a constant h over the entire fiber length. This works reasonably well in practice but becomes time-consuming in the case of long fibers with multiple segments in which pulses do not evolve in a uniform fashion. The use of an adaptive step size along z can help in reducing the computational time in such problems. Several generalizations of the SSFM method have been developed that retain the basic idea behind the SSFM but employ an expansion other than the Fourier series; examples include splines and wavelets

Conclusion

Fiber optic is one of the most important technologies in the word so it must be very detailed so fiber is using Chromatic dispersion (Chromatic dispersion is a phenomenon that is an important factor in optical fiber communications. It is the result of the different colors, or wavelengths, in a light beam arriving at their destination at slightly different times.) Birefringence (The occurrence of linear birefringence is inevitable when dealing with fiber optics. Intrinsic birefringence can be minimized, but deploying the fiber on an experiment will introduce stress birefringence due to bending and pressure.) Kerr Effect(the Kerr effect is a nonlinear optical effect which can occur when light propagates in crystals and glasses) Raman scattering(The first nonlinear phenomenon described exploiting the enhancement given by a carbon desulphated liquid-filled hollow core fiber was stimulated Raman scattering (Ippen 1970)) Brillouin scattering (SBS (stimulated Brillouin scattering) is a nonlinear phenomenon that may happen in optical fibers at significantly lower input power levels than stimulated Raman scattering (SRS)) Schrödinger equation (The (one-dimensional) nonlinear Schrödinger equation (NLSE) is a nonlinear variant of the Schrödinger equation in theoretical physics)

Chapter III

Simulation & Results

Introduction

In this chapter we will present some simulate results about pulses probated will in nonlinear and dispersity filer core using MATLAB and some software Libraries Like: gaussian _ sechpulse_ solitonpulse_ stokes _ wspace

The effect we will simulate and results is:

Group-velocity dispersion (Gaussian pulses &Chirped Gaussian pulses & Super-Gaussian pulses) & Third-order dispersion (Chirped Gaussian pulses & Broadening factor & Self-phase modulation & Effect of pulse shape and initial chirp) & Optical solitons (Second and higher-order solitons) &Effect of group-velocity dispersion & Pulse evolution

III.1 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):

III.1.1 Gaussian pulses

As a simple example, consider the case of a Gaussian pulse for which the incident field

$$U(0.\omega) = exp\left(\frac{T^2}{2T_0^2}\right) \qquad \text{Eq: 3.1}$$

where T0 is the half-width (at 1/e-intensity point) introduced it is customary to use the full width at half maximum (FWHM) of |U| 2 in place of T0. For a Gaussian pulse, the two are related as

$$T_{FWHM} = 2(ln2)^{\frac{1}{2}}\, T_0 \approx 1.665\, T_0 \qquad \text{Eq: 3.2}$$

Mathlab simulation results:

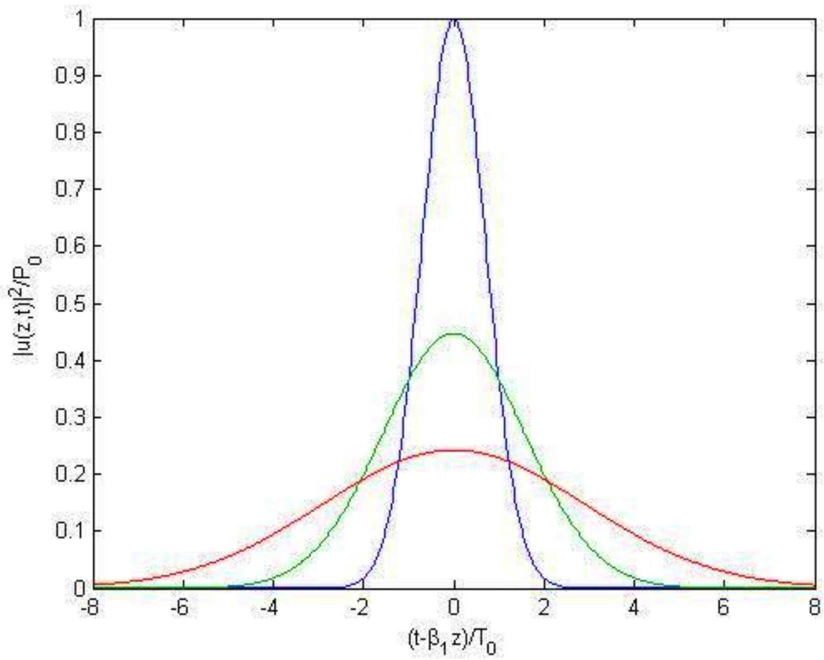

Fig 3-1 : Normalized intensity |*U*|2 Gaussian

III.1.2 Chirped Gaussian pulses

Since |U (z, T) |2 remains a Gaussian function, we conclude that a chirped pulse maintains

$$U(z, T) = \frac{T_0}{\left[T_0^2 - i\beta_2\, z(1+iC)\right]^{1/2}} \exp\left(-\frac{(1+iC)T^2}{2\left[T_0^2 - i\beta_2\, z(1+iC)\right]}\right) \qquad \text{Eq: 3.3}$$

its initial Gaussian shape on propagation even though its width changes. The width T1 after propagating a distance z is related to the initial width T0

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{C\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2 z}{T_0^2}\right)\right]^{1/2} \qquad \text{Eq: 3.4}$$

The chirp parameter of the pulse also changes from C to C1 such that

$$C1(z) = C + (1 + C^2)(\beta_2 z / T_0^2). \qquad \text{Eq: 3.5}$$

It is useful to define a normalized distance ξ as ξ = z/LD, where LD ≡ T20 /|β2| is the dispersion length introduced earlier. Fig. 3.1.2 shows (A) the broadening factor T1/T0 and (B) the chirp parameter C1 as a function of ξ in the case of anomalous GVD (β2 < 0). An unchirped pulse

(C = 0) broadens monotonically by a factor of (1 + ξ 2)1/2 and develops a negative chirp such that C1 = −ξ (the dotted curves). Chirped pulses, on the other hand, may broaden or compress depending on whether β2 and C have the same or opposite signs. When β2C > 0, a chirped Gaussian pulse broadens monotonically at

III.1.3 Super-Gaussian pulses

So far, we have considered pulse shapes with relatively smooth leading and trailing edges. As one may expect, dispersion-induced broadening is sensitive to the steepness of pulse edges. In general, a pulse with steeper leading and trailing edges broadens more rapidly with propagation simply because such a pulse has a wider spectrum to start with. A super-Gaussian shape can be used to model the effects of steep leading and trailing edges on GVD-induced pulse broadening. For a super-Gaussian pulse,

$$U(0,T) = \exp\left[-\frac{1+iC}{2}\left(\frac{T}{T_0}\right)^{2m}\right] \qquad \text{Eq: 3.6}$$

Mathlab simulation results:

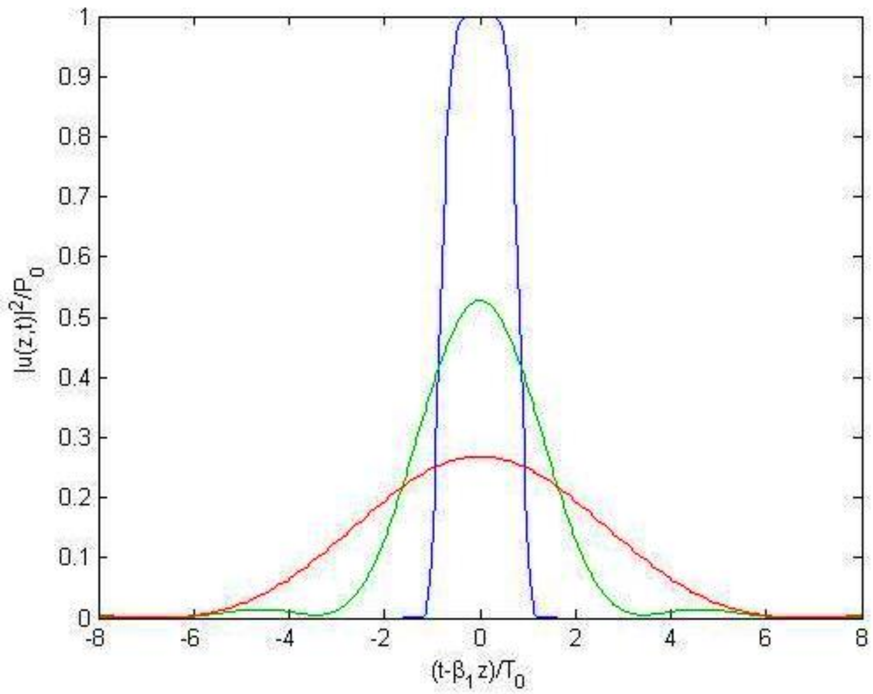

Fig 3-1 : Normalized intensity $|U|2$ Super-Gaussian

III.2 Third-order dispersion

Dynamics of platicons caused by the third-order dispersion is studied. It is shown that under the influence of the third-order dispersion platicons obtain angular velocity depending both on dispersion and on detuning value. A method of tuning of platicon associated optical frequency comb repetition rate is proposed.

III.2.1 Chirped Gaussian pulses

In the case of a chirped Gaussian pulse Have the following expression:

$$U(z,T) = \frac{A_0}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp\left(-x^2 + \frac{ib}{3}x^3 - \frac{iT}{p}x\right) dx \qquad \text{Eq: 3.7}$$

where b = β3z/(2p3). The x2 term can be eliminated with the transformation x =b−1/3u − i/b. The result can be written in terms of the Airy function Ai(x) as

$$U(z,T) = \frac{2A_0\sqrt{\pi}}{|b|^{\frac{1}{3}}} \exp\left(\frac{2p - 3bT}{3pb^2}\right) \mathrm{Ai}\left(\frac{p - bT}{p|b|^{\frac{4}{3}}}\right), \qquad \text{Eq: 3.8}$$

s one may expect, pulse evolution along the fiber depends on the relative magnitudes of β2 and β3. To compare the relative importance of the β2 and β3

$$L'_D = \frac{T_0^3}{|\beta_3|} \qquad \text{Eq: 3.9}$$

Mathlab simulation results:

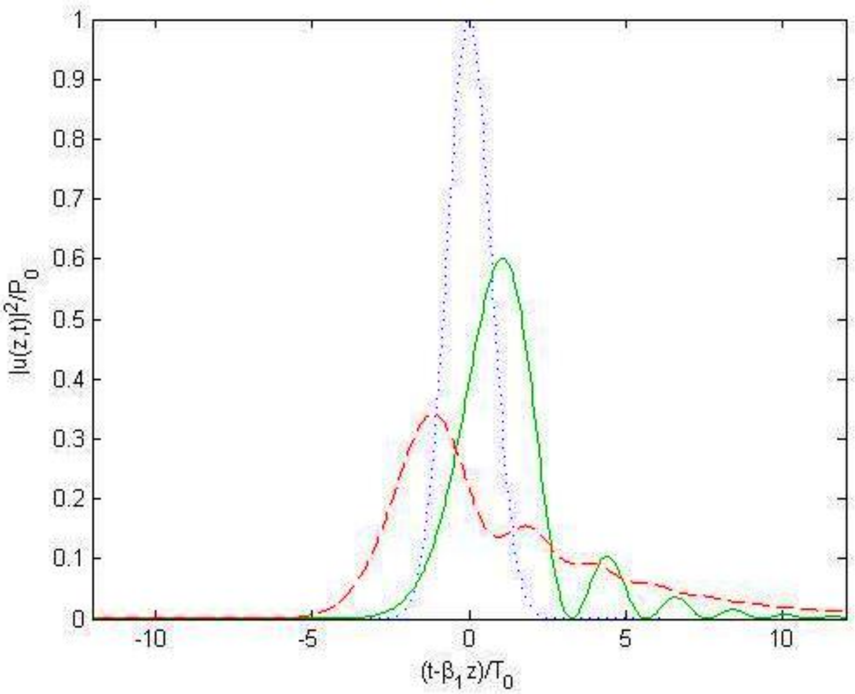

Fig 3.3 Normalized intensity |*U*|2 Chirped Gaussian pulses

III.2.2- Broadening factor

In semiconductor lasers, current injection not only provides the optical gain, but also induces variation of the refractive index, as governed by the Kramers-Krönig relation. The linear coupling between the changes of the effective refractive index and the modal gain is described by the linewidth broadening factor

Evolution of a super-Gaussian pulse with m = 3 along the fiber length for the case of $\beta 2 = 0$ and $\beta 3 > 0$. Third-order dispersion is responsible for the oscillatory structure near the trailing edge of the pulse

Mathlab simulation results:

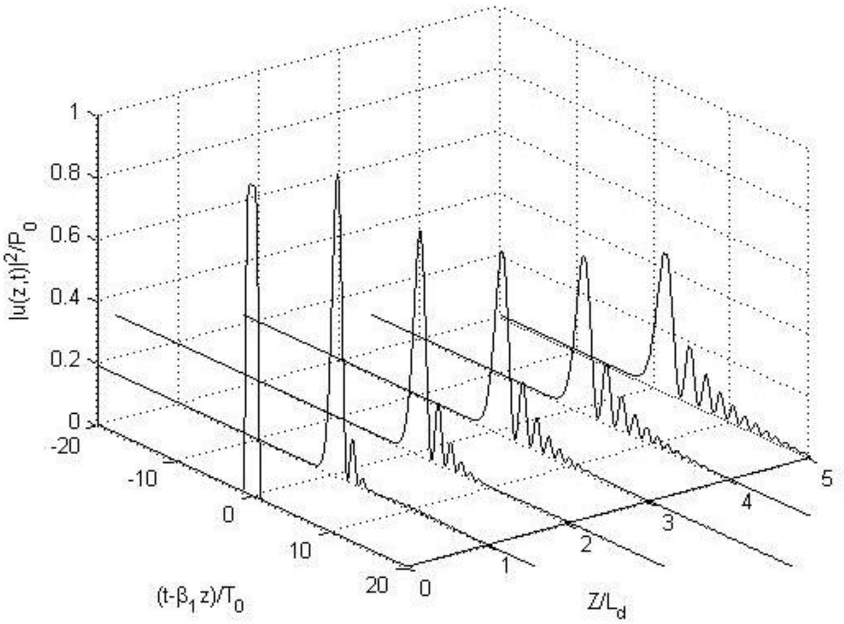

Fig 3.4 Normalized intensity |*U*|2 Broadening

III.3- Self-phase modulation

The first nonlinear effect that we focus on is the self-phase modulation (SPM), a phenomenon that leads to spectral broadening of optical pulses. SPM is the temporal analog of self-focusing of CW beams occurring inside any nonlinear medium with n2 > 0. It was first observed in 1967 in the context of transient self-focusing of optical pulses propagating through a CS2-filled cell. By 1970, SPM had been observed in solids and glasses by using picosecond pulses. The earliest observation of SPM in optical fibers was made with a fiber whose core was filled with CS2 liquid. This work led by 1978 to a systematic study of SPM in a silica-core fiber. This chapter considers SPM as a simple example of the nonlinear effects that can occur inside optical fibers. Devoted to the case of pure SPM as it neglects the GVD effects and focuses on spectral changes induced by SPM. The combined effects of GVD and SPM with emphasis on the SPM-induced frequency chirp. Section 4.3 presents two analytic techniques and uses them to solve the NLS equation approximately. Extends the analysis to include the higher-order nonlinear effects such as self-steepening.

III.3.1 Effect of pulse shape and initial chirp

As mentioned earlier, the shape of the SPM-broadened spectrum depends on the pulse shape, and on the initial chirp if input pulse is chirped

evolution of pulse spectra for Gaussian (m = 1) and super-Gaussian (m = 2) pulses over 50LNL using

$$U(0,T) = \exp\left[-\frac{1+iC}{2}\left(\frac{T}{T_0}\right)^{2m}\right] \qquad \text{Eq: 3.10}$$

$$\text{In } S(\omega) = \left|\int_{-\infty}^{\infty} U(0,T)\exp\left[i\phi_{\mathrm{NL}}(L,T) + i(\omega-\omega_0)T\right]dT\right|^2 \qquad \text{Eq: 3.11}$$

and performing the integration numerically. In both cases, input pulses are assumed to be unchirped (C = 0) and fiber losses are ignored (α = 0). The qualitative differences between the two spectra can be understood by referring

Mathlab simulation results:

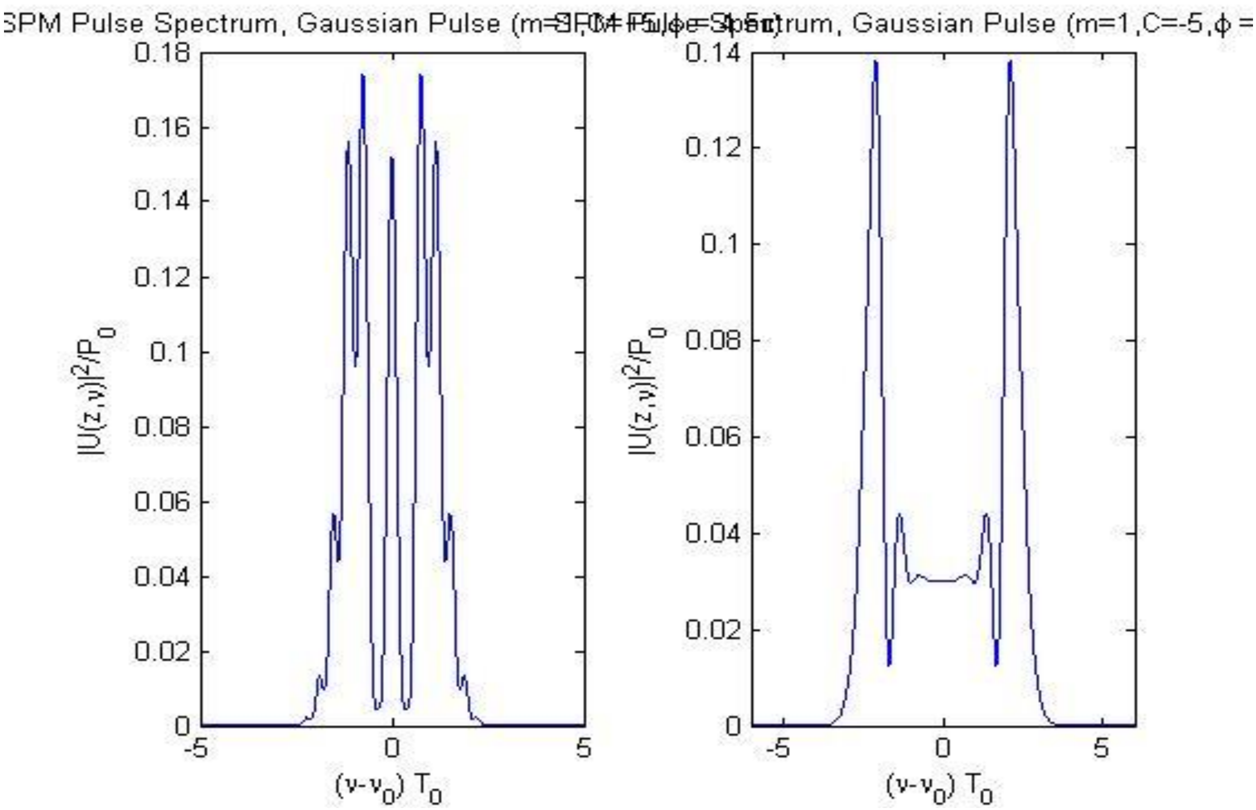

Figure 3.5 Normalized intensity |*U*|2 Chirped Gaussian pulses

III.3.2 Pulse evolution

The starting point is the NLS equation can be written in a normalized form as

$$i\frac{\partial U}{\partial \xi} = \text{sgn}\ (\beta_2)\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2 e^{-\alpha z} \mid U \mid^2 U \qquad \text{Eq: 3.11}$$

where the normalized variables ξ and τ are defined as

$$\xi = z/L_D, \tau = T/T_0, \qquad \text{Eq: 3.12}$$

and the parameter N is introduced by using

$$N^2 = \frac{L_D}{L_{\text{NL}}} \equiv \frac{\gamma P_0 T_0^2}{|\beta_2|}. \qquad \text{Eq: 3.13}$$

The physical significance of N will become clear. The practical significance of this dimensionless parameter is that solutions of Eq. (3.11) obtained for a specific N value are applicable to multiple practical situations through the scaling relation in Eq. (3.13). For example, if N = 1 for T0 = 1 ps and

P0 = 1 W, the calculated results apply equally well for T0 = 10 PS and P0 = 10 mW, or for T0 = 0.1 ps and P0 = 100 W. As evident from Eq. (3.11), N governs the relative importance of the SPM and GVD effects on pulse evolution along the fiber. Dispersion dominates for N 1, while SPM dominates for N 1. For values of N ∼ 1, both SPM and GVD play an equally important role during pulse evolution. sgn(β2) = −1 in the case of anomalous GVD (β2 < 0) and 1 otherwise. The split-step Fourier can be used to solve Eq. (3.11) numerically. Fig. 3.x shows (A) temporal and (B) spectral evolutions of an initially unchirped Gaussian pulse in the normal-GVD region of a fiber using N = 1 and α = 0. The qualitative behavior is quite different from that expected when either GVD or SPM dominates. In particular, the pulse broadens much more rapidly compared with the N = 0 case (no SPM). This can be understood by noting that SPM generates new frequency components that are red-shifted near the leading edge and blue-shifted near the trailing edge of the pulse. As the red components travel faster than the blue components

Mathlab simulation results:

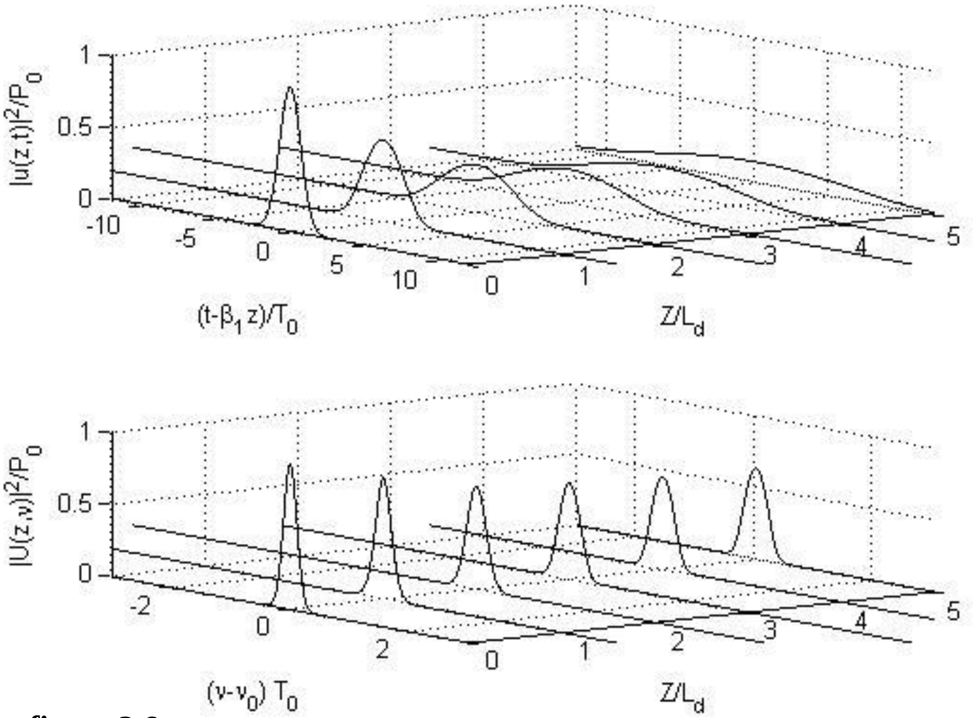

figure 3.6: Evolution of (A) pulse shapes and (B) optical spectra over a distance of 5LD for an initially unchirped Gaussian pulse propagating in the normal-GVD

in the normal-GVD region, SPM enhances rate of pulse broadening compared with that expected from GVD alone. This in turn affects spectral broadening as the SPM induced phase shift φNL becomes less than that occurring if the pulse shape were to remain unchanged. Indeed, φmax = 5 at z = 5LD, and a two-peak spectrum is expected in the absence of GVD. The single-peak spectrum at z/LD = 5 in Fig. 3.x-1 implies that the effective φmax is below π because of pulse broadening. The situation is different for pulses experiencing anomalous GVD inside the fiber. Fig. 3.x shows the pulse shapes and spectra under conditions identical to those of Fig. 3.x-1 except that the sign of the GVD parameter has been reversed (β2 < 0). The pulse broadens initially but much less than that expected in the absence of SPM, and its broadening ceases to occur after 2LD or so. Moreover, the pulse shape appears to stop changing its shape for z > 4LD. At the same time, the spectrum narrows rather than exhibiting broadening expected by SPM in the absence of GVD and its shape also stops changing for z > 4LD. This behavior can be understood by noting that the SPM-induced chirp) is positive, while the dispersion-induced chirp

Eq: 3.14

$$\delta\omega(T) = -\frac{\partial\phi}{\partial T} = \frac{\mathrm{sgn}\ (\beta_2)(z/L_D)}{1+(z/L_D)^2}\frac{T}{T_0^2}$$

in $\delta\omega(T)$ is negative for β2 < 0. The two chirp contributions nearly cancel each other along the center portion of the Gaussian pulse when LD = LNL (N = 1). The pulse adjusts itself during propagation to make such cancellation as complete as possible, i.e., GVD and SPM cooperate to maintain a chirp-free pulse. The preceding scenario corresponds to the formation of an optical soliton. Initial broadening of a

Gaussian pulse occurs because the Gaussian profile is not the character-

Mathlab simulation results:

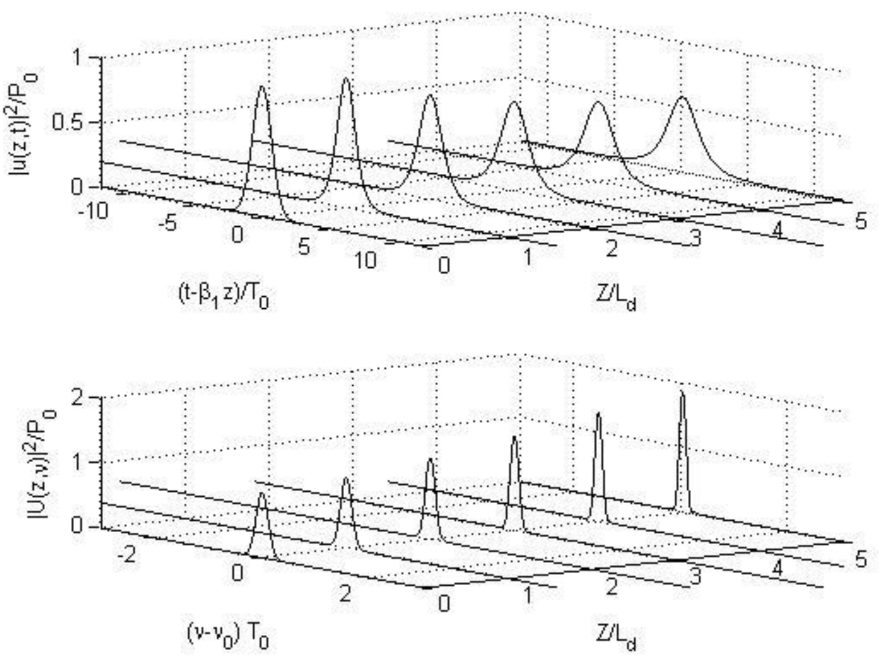

figure 3.7: Evolution of (A) pulse shapes and (B) optical spectra under conditions identical to those

III.4 Optical solitons

A fascinating manifestation of the fiber nonlinearity occurs through optical solitons, formed as a result of the interplay between the dispersive and nonlinear effects. The word soliton refers to special kinds of wave packets that can propagate undistorted over long distances. Solitons have been discovered in many branches of physics. This chapter focuses on pulse propagation inside optical fibers in the regime in which both the group velocity dispersion (GVD) and self-phase modulation (SPM) are equally important and must be considered simultaneously.

III.4.1 Second and higher-order solitons

Higher-order solitons are also described by the general solution. Various combinations of the eigenvalues ηj and the residues cj generally lead to an infinite variety of soliton forms. If the soliton is assumed to be symmetric about τ = 0, the residues are related to the eigenvalues

$$c_j = \frac{\prod_{k=1}^{N} (\eta_j + \eta_k)}{\prod_{k \neq j}^{N} |\eta_j - \eta_k|} \qquad \text{Eq: 3.15}$$

This condition selects a subset of all possible solitons. Among this subset, a special role is played by solitons whose initial shape at ξ = 0 is given by

$$\mu(0, \tau) = N\ sesh(\tau) \qquad \text{Eq: 3.16}$$

Mathlab simulation results:

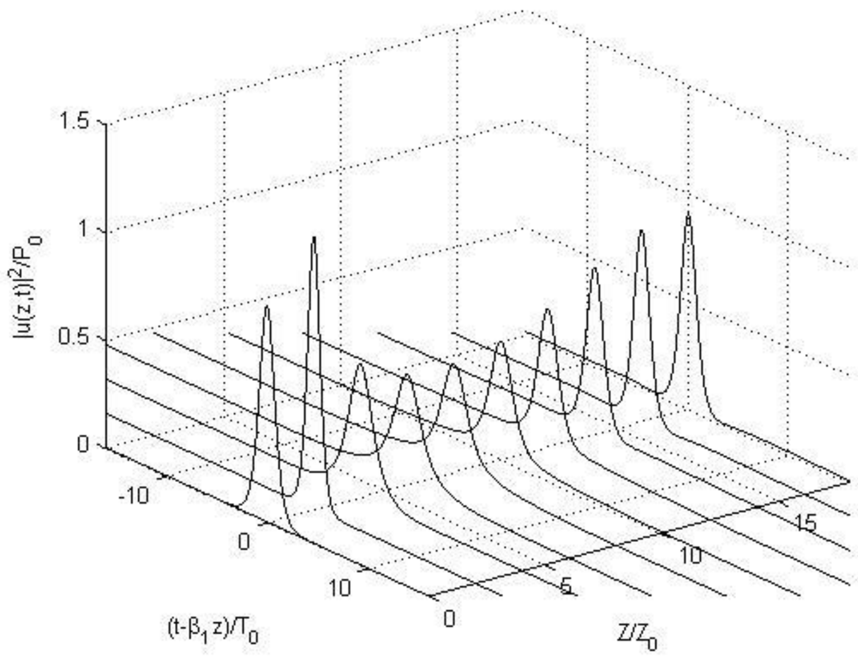

figure 3.7: spectral evolution of the third-order soliton over one soliton period.

6 Conclusion

The third chapter was a presentation of the simulation results for Group-velocity dispersion, where we provide a study about the Gaussian pulses and their variant cases and then simulate them, then we have simulated Third-order dispersion where we're able to simulate both Chirped Gaussian pulses and the Broadening factor, the next simulation was Effect of pulse shape and initial chirp, in the fourth title we saw the Second and higher-order solitons as Optical solitons. at last, we have seen the Effect of group-velocity dispersion such as Effect of group-velocity dispersion, represents the effective refractive index, attenuation, and chromatic dispersion as a function of wavelength

General conclusion

As we learned before Optical Fiber make up 4 components The core. Cladding. Buffer cladding. Jacket And each one Have specific function that Determine the type Of the Fiber Itself between Two Types. Single-mode fiber that can Only transmit One Single at the Time and Multi-mode fibers That Can transmit Loot Single at the Time. And for the fiber to do that sensitive Job Need to Be study So carefully to make sure It Will Do his job perfectly. this is the most important effects

Chromatic Dispersion. (Chromatic dispersion is a phenomenon that is an important factor in optical fiber)

Birefringence (The birefringence of a Photonic Crystal fiber is determined by the difference between the real part of the effective indices)

Confinement Loss. (When the optical mode is propagating in the core region, due to a finite number of layers of air holes, the mode leakage from the core region into the outer air hole region is unavoidable, and then)

Kerr Effect. (The Kerr effect is a nonlinear optical effect which can occur when light propagates in crystals and glasses)

Raman scattering. (The first nonlinear phenomenon described exploiting the enhancement given by a carbon dauphine liquid-filled hollow core fiber was stimulated Raman scattering)

Brillouin scattering (SBS (stimulated Brillouin scattering) is a nonlinear phenomenon that may happen in optical fibers at significantly lower input power levels than stimulated Raman scattering (SRS).)

Schrödinger equation. (The (one-dimensional) nonlinear Schrödinger equation (NLSE) is a nonlinear variant of the Schrödinger equation in theoretical physics. It is a classical field equation with applications in the mean-field regime to light propagation in nonlinear optical fibers and planar waveguides,)

SSFM (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.)

Références

1. Yeh, Chai. *Handbook of Fiber Optics.* Academic Press, 1990. {2} {3}
2. J.C. Knight, T.A. Birks, P.St.J. Russell, D.M. Atkin, Opt. Lett. 21 (1996) 1547.
3. P.S.J. Russell, J. Lightwave Technol. 24 (2006) 4729.
4. T.P. White, R.C. McPhedran, C.M. de Sterke, L.C. Botten, M.J. Steel, Opt. Lett. 26 (2001) 1660.
5. B. Kibler, P.-A. Lacourt, F. Courvoisier, J.M. Dudley, Electron. Lett. 43 (2007) 967.
6. Q. Li, K. Nakkeeran, P.K.A. Wai, J. Opt. Soc. Am. B 31 (2014) 1886
7. {1} - web : www.timbercon.com/resources/glossary/cladding
8. {4} -web : home.iitj.ac.in/~k.r.hiremath/research/mr/mr.html
9. {5} – web : www.madehow.com/Volume-1/Optical-Fiber.html
10. {6} - web : www.madehow.com/Volume-1/Optical-Fiber.html
11. {7} - webwww.photonics.com/Articles/PolarizationModeDispersionConceptsand
12. {8} - web : www.researchgate.net/figure/a-Schematic-of-Spontaneous-Raman-scattering-phenomenon-b-Stimulated-Raman-scattering_fig1_343962720
13. {9} - web : www.simphotek.net/bckg/bckg.split-step.html