Elements of Optical Solitons: An Overview

V C Kuriakose and K Porsezian

Existence of solitons in nonlinear optical fibres was first predicted by Hasegawa and Tappert in 1973 and its experimental verification came in 1980. Ever since, both experimental and theoretical physicists have shown keen interest in this topic due to its versatile applications. Optical solitons are formed due to the balance between the group velocity dispersion and the self phase modulation in the anomalous dispersion regime, and the governing wave equation is the Nonlinear Schrödinger (NLS) equation. Optical solitons can exist in various systems like photonic crystal fibres, bulk materials like photorefractive materials, photopolymers, etc. What follows is an introduction to optical soiltons and their applications.


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1. Introduction

The word soliton was born in science vocabulary in 1964 mainly through the work of M Kruskal and N Zabusky and it refers to highly stable localized solutions of certain nonlinear partial differential equations describing physical phenomena. The soliton concept has deeply penetrated into almost all branches of science wherever scientific phenomena are described by nonlinear partial differential equations. This concept was first discovered in hydrodynamics in the 19th century and entered into other branches in physics. Scottish Naval Architect John Scott Russell is the father of this novel idea. In 1834 when the boat in which he was traveling across the Union Canal connecting Glasgow and Edinburgh was suddenly stopped, he observed a lump of water leaving the barge of the boat and moving without changing its

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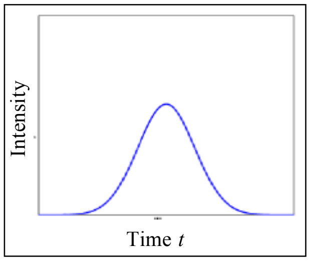

Figure 1. Solitary wave.

shape and speed. He could see this lump moving without any change over a distance of 2 miles. He called such a wave as solitary wave (*Figure* 1). Later on, this exciting phenomenon was observed in different branches of science through both analytical and experimental methods. Soliton in optics refers to a situation where light beam or pulse propagates through a nonlinear optical medium without any change in its shape and velocity. In this article, we will see that this happens because the tendency for the pulse to spread, caused by dispersion in the medium, is compensated by the nonlinear dependence of the refractive index on the amplitude, which causes the pulse to compress. Solitons in nonlinear optical fibers have important applications in communication, optical computing, optical switching, etc.

2. Group Velocity Dispersion

Optical fiber communication has great advantages over the conventional cable communication system. The most important advantage is the availability of enormous communication bandwidth which is a measure of the information carrying capacity. Some of the other advantages are: i) less weight, ii) no hazards of short circuits, iii) low cost and iv) immunity to adverse temperature and moisture conditions. But there are limitations to the distance over which the information can be conveyed without any distortion. The inevitable distortion is due to the optical phenomenon called dispersion which causes an optical signal to get dispersed as it passes through the fiber. This actually limits the transmission capacity of the system. There are mainly two types of dispersion, one due to intramodal dispersion and the other due to intermodal delay effects. These dispersions cause the spreading of the pulse passing through a fiber and the effects can be quantified by considering group velocities of the guided modes. Group velocity gives the speed at which energy in a particular mode travels along the fiber. The intramodal dispersion can be due to material

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and waveguide dispersions.

Material dispersion, also known as chromatic dispersion, arises due to the variation of refractive index of the core of the fiber as a function of wavelength. However, waveguide dispersion which occurs in single mode fibers is due to the fact that only 80% of the optical power is confined to the core while 20% of the optical power is confined to the cladding, resulting in distortion as the velocities of the pulse in the cladding and that in the core have different values. Distortion due to intramodal delay occurs in multimode fibers as each mode has different values for the group velocities. The full effects of these three distortions are seldom observed in practice because of other factors such as nonideal index profiles, optical power-launching conditions, nonuniform mode attenuation, etc. An immediate effect of dispersion is that as the light pulse travels through the fiber, its shape gets broadened. The group velocity, the velocity at which the energy in a pulse travels in a fiber, is given by

$$V_{\mathrm{g}} = \frac{\mathrm{d}\omega}{\mathrm{d}k}, \qquad (1)$$

which can also be called as the velocity of the envelope wave. In a nondispersive medium, the component waves and their superposition (the envelope) will travel with the same velocity which implies that the shape of the pulse (envelope) remains unchanged as the pulse propagates through the medium. But this is a rare situation and in an optical medium the velocity depends on the refractive index which in turn depends on the frequency (wavelength) of the wave. The velocity (phase velocity) of a wave is $\omega/k = v = c/n$, where c is the velocity of the wave in vacuum and n is the refractive index of the medium. As the signal propagates along the fiber, each spectral component can be assumed to travel independently and to undergo a time delay per unit wavelength. We define the propagation time over

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a distance L for a given group velocity V_g as $\tau = L/V_g$. If the spectral width of the pulse is not wide, it may be approximated that the delay difference per unit wavelength along the propagation path is given by $d\tau/d\lambda$. If the wavelengths of spectral components are spread over a wavelength range $\delta\lambda$, the total delay difference $\delta\tau$ over a distance L is given by

$$\delta\tau = \frac{d\tau}{d\lambda}\delta\lambda = -\frac{L}{c}\lambda\frac{d^2n}{d\lambda^2}\delta\lambda. \qquad (2)$$

Thus the spread in arrival times depends on $(d^2n/d\lambda^2)$. This means that the pulse gets spread out as it moves along the fiber, because different component waves which constitute the pulse have different phase velocities. This phenomenon is known as Group Velocity Dispersion (GVD). We introduce a quantity called mode propagation constant $\beta = n(\omega)\omega/c$ and give a Taylor series expansion:

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + ..., \qquad (3)$$

where $\beta_m = (d^m\beta/d\omega^m), m = 1, 2, 3,...$. A little bit of algebra will show that

$$\beta_2 = \frac{d\beta_1}{d\omega} = \frac{\lambda^3}{2\pi c_0^2}\frac{d^2n}{d\lambda^2}. \qquad (4)$$

In the normal dispersion regime the high frequency components (blue shifted) of an optical pulse travel slower than the low frequency components (red shifted). The opposite occurs in the anomalous regime.

Here β_2 is known as GVD parameter. Another quantity known as total dispersion parameter widely used in the literature is defined as,

$$D_\lambda = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2. \qquad (5)$$

From *Figure* 2, it can be seen that D_λ increases as λ increases and vanishes at a wavelength around 1310 nm. This wavelength is called zero dispersion wavelength λ_D. For $\lambda < \lambda_D$, $\beta_2 > 0$, and the fiber is said to exhibit normal dispersion, while for $\lambda > \lambda_D$, $\beta_2 < 0$, and the fiber

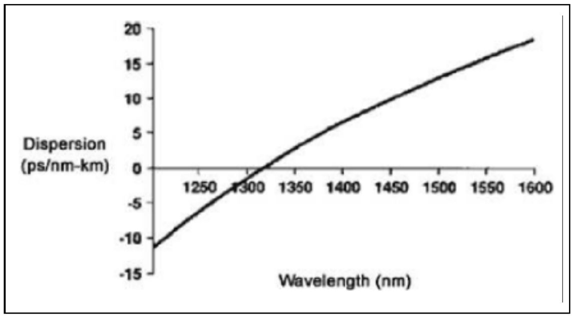

Figure 2. Wavelength dependence of the dispersion parameter D for standard fiber.

is said to exhibit anomalous dispersion. In the normal dispersion regime the high frequency components (blue shifted) of an optical pulse travel slower than the low frequency components (red shifted). The opposite occurs in the anomalous regime. The anomalous regime plays an important role in nonlinear fiber optics, in particular, for the formation of highly stable and distortionless solitons.

3. Fiber Nonlinearities

The other factor which puts a limit on the performance of optical fibers regarding the length over which an optical pulse could be transmitted, arises from the nonlinear processes taking place in the fiber. The major nonlinear processes to be considered are: i) Self Phase Modulation (SPM), ii) Stimulated Raman scattering (SRS) and iii) Stimulated Brillouin Scattering (SBS). SPM gives rise to spectral compression, an effect opposite to that due to GVD and limits the maximum achievable information transfer rate. SRS limits the maximum operational power levels or gives rise to information loss and introduces noise into the system. In SBS, acoustic phonons rather than high frequency optical phonons give rise to frequency-shifted scattering radiation.

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The polarizability of a dielectric medium in a normal situation is proportional to the electric field strength, but if the strength of the light beam is sufficiently high, which is possible if we use a laser beam, it is found that the above relationship is no longer valid and the polarizability of the medium depends on higher powers of the electric field strength and the medium is said to be nonlinear.

The invention of lasers in the 1960s led to a new branch in optics called nonlinear optics. The polarizability of a dielectric medium in a normal situation is proportional to the electric field strength, but if the strength of the light beam is sufficiently high, which is possible if we use a laser beam, it is found that the above relationship is no longer valid and the polarizability of the medium depends on higher powers of the electric field strength and the medium is said to be nonlinear. Thus, we can write the polarizability of a nonlinear medium as:

$$P = \epsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + ...), \qquad (6)$$

where ϵ_0 is the vacuum permittivity and $\chi^{(j)}(j = 1, 2, 3, \ldots)$ is the jth order susceptibility tensor. The linear susceptibility $\chi^{(1)}$ contains the dominant contribution to P. Its effects are included through the refractive index n. The second order susceptibility $\chi^{(2)}$ is responsible for such nonlinear effects as second harmonic generation and sum and difference frequency generation. However, it is nonzero only for media which lack an inversion symmetry at the molecular level. As SiO_2 is a symmetric molecule, $\chi^{(2)}$ or in general, even powered terms in E in (6) vanish for silica glasses. As a result, optical fibers do not normally exhibit second order nonlinear effects. The lowest order nonlinear effects in optical fibers originate from the third order susceptibility $\chi^{(3)}$, which is responsible for the phenomena such as third harmonic generation, four-wave mixing and nonlinear refraction. The refractive index and the susceptibility for a nonlinear medium are related through the relation

$$n = (1 + \chi^{(1)} + \chi^{(2)}E + \chi^{(3)}E^2 + ...)^{\frac{1}{2}}. \qquad (7)$$

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For an optical fiber, this relation takes the form

$$n = (1 + \chi^{(1)} + \chi^{(3)}E^2)^{\frac{1}{2}} = n_0 + \frac{1}{2}\chi^{(3)}E^2 = n_0 + n_2 I. \qquad (8)$$

This equation says that the refractive index of the medium depends on the intensity of light propagating through it. Light is influencing its own velocity as it travels – light can interact with light in a nonlinear medium. For fused silica, $n_0 \sim 1.46$ and $n_2 \sim 3.2 \times 10^{-20}\,\mathrm{m^2W^{-1}}$. If we consider the propagation of a mode carrying 100 mW of power in a single mode fiber with a core diameter of $5\,\mu$m, the change in refractive index due to nonlinear effects is $\Delta n = n_2 I = 1.6 \times 10^{-10}$. This shows that we require pico or femto second lasers to excite nonlinearities in optical fibers. The intensity dependence of refractive index has a number of interesting applications like self phase modulation (SPM) and cross phase modulation (XPM).

The refractive index of the medium depends on the intensity of light propagating through it.

Self Phase Modulation: The most interesting application of intensity dependent refractive index is SPM which refers to a situation where an optical pulse passing through an optical fiber experiences an additional phase shift. Its magnitude can be obtained by noting that when the optical pulse travels over a distance L through an optical fiber, its shift in the phase is given by

$$\varphi = \frac{2\pi}{\lambda} nL = \frac{2\pi}{\lambda}(n_0 + n_2 I\ )L. \tag{9}$$

The intensity dependent nonlinear shift is $(2\pi/\lambda)\, n_2 I L$ and is due to SPM. I is time dependent and hence φ is also time dependent. Therefore, an additional frequency term $\omega = \mathrm{d}\varphi/\mathrm{d}t$ is introduced into the dynamics of the optical pulse resulting in a change in the frequency spectrum and this change in frequency is known as SPM. This will result in the shape of the pulse, pulse broadening or pulse compression can be achieved under appropriate conditions. If the original frequency of the pulse is ω_0, as a result of SPM, the instantaneous frequency of the pulse becomes $\omega' = \omega_0 + (\mathrm{d}\varphi/\mathrm{d}t) = \omega_0 - (2\pi/\lambda)\, z n_2\, (\mathrm{d}I/\mathrm{d}t)$, where we have assumed that the pulse is propagating in the positive z-direction through a

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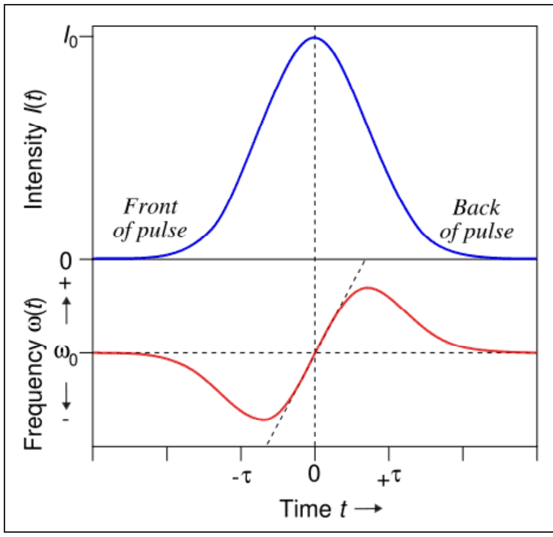

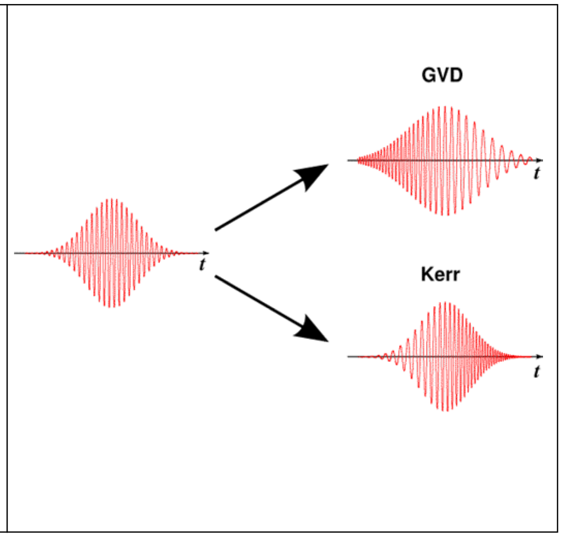

Figure 3.(left) Self-phase modulation.

Figure 4. (right) Linear and nonlinear effects on Gaussian pulses.

distance z. At the leading edge of the pulse $(\mathrm{d}I/\mathrm{d}t) > 0$ while at the trailing edge of the pulse $(\mathrm{d}I/\mathrm{d}t) < 0$. Hence the pulse is said to be chirped, i.e., the frequency varies across the pulse (*Figure* 3).

We have now two independent phenomena occurring in nonlinear optical fibers and these two phenomena independently distort the shape of the optical pulse as it passes through the fiber. But it is found that under appropriate conditions these two phenomena can be made competing such that the effect due to one can be canceled by the effect due to the other. This will result in a situation where the optical pulse can be sent through a nonlinear optical medium without any distortion; the optical pulse is then said to be an optical soliton (*Figure* 4).

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4. Wave Propagation Through an Optical Fiber

The wave equation that can describe propagation of optical pulses along an optical fiber can be derived starting from Maxwell's equations. The study of nonlinear effects in optical fibers involves the use of short pulses with widths ranging from ~ 10 ns to 10 fs. When such pulses propagate through the fiber both dispersive and nonlinear effects influence the shape and spectrum. If $A(z,t)$ is the slowly-varying amplitude of the pulse envelope, then it can be seen that the differential equation which describes the wave propagation through the optical fiber can be cast in the form:

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \gamma \left|A\right|^2 A = 0. \qquad (10)$$

This equation represents an optical pulse passing in the z-direction through an optical fiber exhibiting GVD and SPM, while other effects like absorption, higher order nonlinearities, higher order dispersion, SRS, SBS have not been taken into consideration. If these effects were taken into account, the equation would not have been as simple as given by (10). Equation (10) is referred to as Nonlinear Schrödinger (NLS) equation because it resembles the Schrödinger equation with a nonlinear potential term (variable z playing the role of time and vice-versa). In (10) the second term represents dispersion while the third term accounts for the nonlinearity of the fiber. β_2 is the GVD parameter while the parameter γ is a measure of the third order nonlinearity of the medium. The NLS equation is a fundamental equation in soliton theory and appears in many branches of science. There exist different analytical methods to solve nonlinear partial differential equations. Inverse scattering method is one among them. Only certain nonlinear partial differential equations can be solved by inverse scattering method and NLS equation belongs to this special category. Zakharov and Shabat in 1971 solved NLS equation using inverse scattering method. Introducing dimensionless variables, $U = (A/\sqrt{P_0})$, $\xi = (z/L_{\mathrm{D}})$, $\tau = (T/T_0)$, (10) can be written as,

$$i\frac{\partial U}{\partial \xi} = \beta_2 \frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2 \left|U\right|^2 U, \qquad (11)$$

where P_0 is the peak power, T_0 is the width of the incident pulse and the parameter N is introduced as

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$N^2 = (L_D/L_{NL}) = (\gamma P_0 T_0/|\beta_2|)$. For anomalous dispersion regime $\beta_2 < 0$, while for normal dispersion regime $\beta_2 > 0$. The dispersion length L_D and the nonlinear length L_{NL} are defined as $L_D = (T_0^2/|\beta_2|)$, and $L_{NL} = (1/\gamma P_0)$.

For the anomalous dispersion regime, (11) now takes the form, putting $u = NU$,

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0. \qquad (12)$$

The solution of this equation is given by $u(\xi, \tau) = \mathrm{sech}(\tau) \exp(i\xi/2)$, it is called fundamental soliton solution of (12) and has a bell-shaped form (*Figure* 5). These types of solitons are called bright solitons. In the context of optical fibers, this solution indicates that if a hyperbolic-secant pulse whose width T_0 and the peak power P_0 is launched into an ideal lossless optical fiber, the pulse will propagate undistorted without any change in shape for arbitrarily long distances. It is this fundamental property of solitons that makes them attractive for optical communication systems. This remarkable idea was first proposed in 1973 by Hasegawa and Tappert. However, the non-availability of suitable picosecond lasers and low-loss fiber delayed experimental confirmation of this result. The peak power to support the fundamental soliton inside an optical fiber is given by $P_0 = (|\beta_2|/\gamma T_0^2) \approx (3.11\,|\beta_2|/\gamma T_{\mathrm{FWHM}}^2)$, where the FWHM of the soliton is:

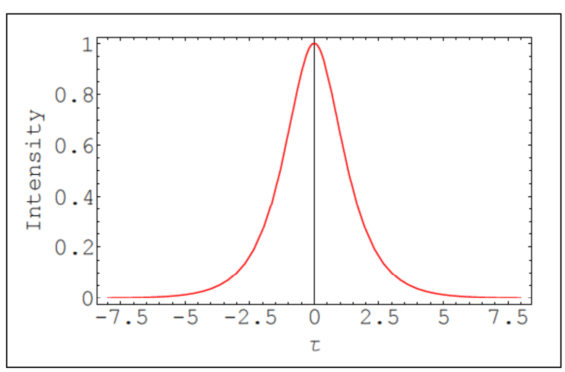

Figure 5. Bright soliton.

$T_{\rm FWHM} \approx 1.76T_0$. Using typical parameter values: $\beta_2 = -1\,{\rm ps}^2/{\rm km}$, $\gamma = 3\ {\rm W}^{-1}/{\rm km}$ for dispersion-shifted fibers near the 1.55μm wavelength, P_0 is $\sim$ 1W for $T_0 = 1$ ps but reduces to 10 mW when $T_0 = 10$ ps. This shows that optical solitons can form in optical fibers at power levels available from semiconductor lasers.

Mollenauer and his group in 1980 first observed solitons in optical fibers.

Mollenauer and his group in 1980 first observed solitons in optical fibers. They used a mode-locked color-centre laser capable of emitting short pulses ($T_{\rm FWHM} \sim 7$ ps) near 1.55 μm. The pulses were propagated through an optical fiber of length 700 m, the core diameter of the fiber being 9.3 μm. If we consider high dispersion, higher order nonlinearities, SRS, SBS, fiber loss, etc., the wave equation takes a complicated form and to analyze the resulting equation through inverse scattering techniques may not be sufficient and we have to use other analytical methods.

If we consider normal dispersion regime instead of anomalous regime, in place of (12) we have,

$$i\frac{\partial u}{\partial \xi} - \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0. \qquad (13)$$

The solution of this equation is given by $u(\xi,\tau) = \tanh(\tau)\exp(i\xi)$. The intensity profiles associated with such solutions show a dip in a uniform background and thus the solutions are called dark solitons (*Figure* 6).

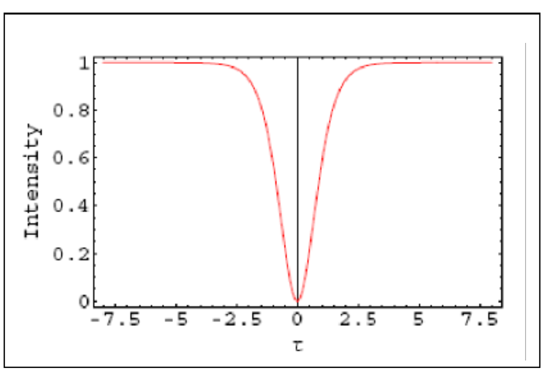

Figure 6. Dark soliton.

In 1988, Mollenauer and his group succeeded in propagating a soliton over 6000 km without any repeaters.

The experimental verification of soliton phenomena in optical fibers by Mollenauer *et al* in 1980 and the experimental demonstration of soliton reshaping by optical amplification and the long distance transmission by means of Raman amplification in 1985 by the Mollenauer group have led people to believe that solitons could be used for ultra high speed transmission purposes. In 1988, Mollenauer and his group succeeded in propagating a soliton over 6000 km without any repeaters. Later on, solitons have been propagated without deterioration over many thousand of kilometers.

5. Other Types of Optical Solitons

Dispersion-Managed Solitons: As we have discussed earlier, Group Velocity Dispersion (GVD) in a nonlinear optical fiber plays a very crucial role in the shaping of the pulse propagating through the fiber. When the NLSE and its solutions are studied, it is assumed that the GVD parameter is constant throughout the length of the fiber, but it is not so. To meet this challenge, a technique called dispersion management is often used in the design of modern fiber optic communication systems. This technique consists of connecting fibers having various values of dispersion parameters such that the average value of GVD in each period is quite low. The ensuing nonlinear stationary pulse generated by the balance between effective dispersion and the averaged nonlinearity is termed as dispersion-managed soliton. In addition to this, suitable theoretical equations have been developed to study the dynamics of optical solitons propagating through dense wavelength-division multiplexed (WDM) systems with dispersion-management, damping and amplification. Recent studies provide an in-depth understanding of the soliton propagation in various types of nonlinear optical fibers such as polarization preserving fibers, birefringent fibers, dispersion-flattened fibers, etc. Very recently, experimental observation of the soliton dispersion management in a fiber with sine-wave variation of the core diameter along the longitudinal direction of propagation of the dispersion oscillating fiber, has been reported. Research studies on soliton dispersion management have been initiated by Hasegawa and his group and ever since various research groups have pursued studies showing rich variety of properties.

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Solitons in Photonic Crystal Fiber: In recent years, photonic crystal fibers (PCFs) (*Figure* 7) have received a great deal of scientific attention because of their numerous and invaluable nonlinear applications in sensor and communication fields. The arrangement of air holes in the cladding region gained more importance due to optical properties of PCFs such as highly nonlinear, highly birefringent, large mode field area, high numerical aperture, ultra flattened dispersion, adjustable zero dispersion, etc. The microstructure of the cladding can be varied in order to tailor the effective refractive index and so the propagation properties of PCF. In PCF, the refractive index difference between core and cladding is much higher than in conventional fibers, which can be obtained by changing the size of the air hole. This significant variation of air hole diameter, pitch and design of the PCF have several applications like wavelength conversion using four wave mixing, optimization of the pump spectra to achieve flat-Raman gain, minimization of noise figure of the PCF amplifier, Raman lasing characteristics, narrow or broad band pass filters, etc. The recent widespread research on PCF was mainly motivated by their nonlinear optical applications such as supercontinuum generation, pulse compression, optical switching, fiber laser, parametric amplifier, soliton

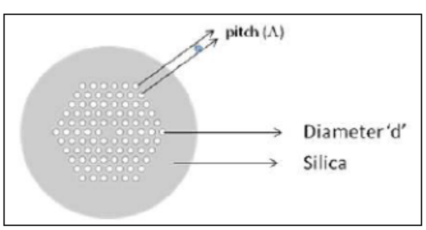

Figure 7. Schematic diagram of photonic crystal fiber.

Much of the recent work has been motivated by experiments in PCFs, where the combination of engineered dispersion-induced frequency chirp and elevated nonlinearity-induced frequency has led to the soliton pulse propagation.

propagation, modulational instability, etc. Among these applications, soliton propagation in PCF with different structure is attracting many researchers, and a great deal of numerical simulation work has already been done in this emerging technological area. Much of the recent work has been motivated by experiments in PCFs, where the combination of engineered dispersion-induced frequency chirp and elevated nonlinearity-induced frequency has led to the soliton pulse propagation, that have found many important applications. For instance, the soliton with variation of both dispersion and nonlinear parameters has been investigated by employing the exact solution of nonlinear Schrödinger equation. Researchers have studied elaborately the nontopological soliton wave solution through gas-filled PCF with newly designed structures. Recent literature also provide supercontinuum generation and pulse compression up to 6 fs using optical soliton in PCF. Besides, Raman-induced soliton pulse propagation has been predicted in PCF combining with higher order nonlinear effects. On employing femtosecond solitons in PCF, energy exchange between the solitons and polarization instability have been demonstrated. In addition to this, pioneering experiments on bound soliton pairs in a highly nonlinear PCF have been successfully conducted. Apart from the soliton in PCF, the stability of the pulse due to the influence of frequency shift has been analyzed in detail (*Figure* 8).

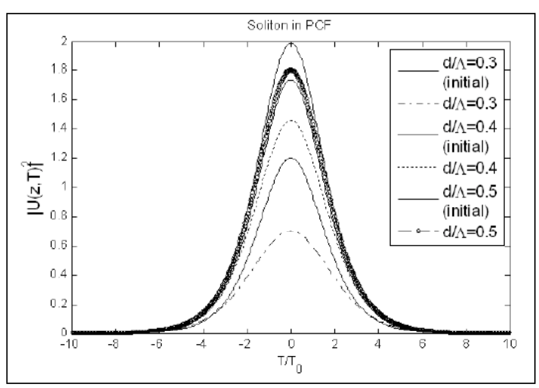

Figure 8. Soliton pulse propagation through photonic crystal fiber for different design parameters.

6. Applications of Optical Solitons

Soliton Amplification: In real situations, one has to consider the loss of energy as the pulse propagates through a fiber due to the absorption of energy by the fiber and this effect is usually termed as fiber loss. Fiber losses lead to broadening of solitons and this is a drawback for many practical applications, especially optical communications. This loss in energy can be restored by amplification of the optical pulses and usually two schemes are employed for soliton amplification. These are known as lumped and distributed amplification schemes. In the lumped scheme, an optical amplifier boosts the soliton energy to its input level after the soliton has been propagated through a certain distance. Two methods, stimulated Raman scattering or erbium-doped fibers are used in the distributed amplification scheme. Both methods require periodic pumping along the fiber length. Since erbium-doped fibers became available commercially after 1990, they have been used widely for loss compensation.

Pulse Compression: An important application of nonlinear fiber optics consists of compressing optical pulses. Pulses shorter than 5 fs have been produced by using dispersive and nonlinear effects occurring in optical fibers. There are two types of pulse compressors based on nonlinear fiber optics: grating-fiber and soliton-effect compressors. A soliton-effect pulse compressor consists of only a piece of fiber whose wavelength is suitably chosen. Pulse compression takes place as a result of an interplay between GVD and SPM. This method has been used since 1983. Dispersion-decreasing fibers (DDFs) are found to be useful for achieving pulse compression. Using DDF pulse compression mechanism, it is possible to generate a train of ultrashort pulses.

An important application of nonlinear fiber optics consists of compressing optical pulses.

Soliton Bit Rate: Solitons, if used with suitable care, would replace the traditional non-return to zero (NRZ)

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and return to zero (RZ) modulations, which are widely used in almost all commercial terrestrial wavelength division multiplier (WDM) systems. NRZ is a binary modulation with square pulses in which the signal is off for a 0 bit and on for a 1 bit. RZ is the same, except that one pulse is shorter than the bit time. Although Kerr nonlinearities (SPM, Cross Phase Modulation (XPM) and Four-Wave Mixing (FWM)) exist in NRZ and RZ systems, they are undesirable effects limiting the performance and distorting signals at high speeds. Typically the design of a conventional WDM system involves increasing the power as much as possible (to counteract attenuation and noise) without introducing too much nonlinearity. Thus, NRZ and RZ systems are often called linear systems. The main difference between encoding digital signals with solitons and with NRZ is that in the latter case if two 1s are close together, the signal intensity does not drop back to 0 between the individual bits as it does with solitons. For the past two decades or so, many leading research groups in USA, Japan, France, Germany, UK and Sweden have been working on soliton technologies for high-bit-rate, long haul communications, even while a heated debate took place over whether solitons were appropriate or even feasible for these networks. For this purpose, many billions of dollars are being invested and active research is in progress, mainly on solitons. Many argued that the conventional NRZ or RZ modulation formats were a better choice than the soliton-based technology.

In recent years, after the invention of dispersion-managed solitons, the debate changed as theoretical understanding improved, network distances increased, bit rates climbed and certain technologies became commercially practical. NRZ experiments worked very well because of dispersion management. In this way, it is possible to have both high local and low average dispersion in the system. The high local dispersion tends to reduce an effect known as four-wave mixing (which tends to distort signals and produce intersymbol interference) and disrupts the phase matching of the different optical frequencies making up a signal, thus reducing the interactions among them. Moreover, the low average dispersion reduces its net cumulative effects over long spans of optical fiber. Because of this, solitons have gradually emerged as a viable candidate for the next generation of terrestrial transport systems. Soliton light can be used to transmit data at rates in excess of 50 Gbit/s over distances greater than 19,000 km of Dispersion-Shifted Fiber, requiring no repeaters and with no errors. Interestingly however, a form of RZ modulation called chirped RZ (CRZ) has emerged as the chosen candidate for the next generation undersea systems. Solitons and the CRZ modulation format, like other 'hard optic' technologies, are just one step forward in creating the next generation of optical networks. Research scientists are actually working on other technologies that improve components in optical networks. And at the same time, advances in optical networking software, or 'soft optics' continues to be the umbrella that harnesses and manages the light created by hard optics and will be used to build future all-optical networks. Systems employing solitons have also been able to exploit WDM to increase the total bit rate, but not yet to the extent obtained with NRZ. Mollenauer's team has transmitted eight separate 10Gbit/s channels using solitons, for a total of 80 Gbit/s, and Nakazawa of NTT Laboratories has achieved five separate 20-Gbit/s channels, for a total capacity of 100 Gbit/s and, very recently, because of the constant efforts, several groups have enormously increased the number of channels and bit rates.

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Timing Jitter: The existence of an ideal soliton in a fiber demands that soliton pulses should be well separated from each other. Thus if each soliton pulse is designated to carry one digit of information, in order

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to identify each information bit, it should be separated sufficiently from adjacent digits. This is possible only when the soliton pulse width becomes much shorter than the bit rates, thereby demanding a much larger bandwidth when compared with a linear pulse having the same bit rate. As a testimony to the experimental realization on information transmission by optical solitons, the Japanese firm NTT has implemented information transfer through all optical soliton communication lines in the Tokyo Metropolitan Network and observed that the rate of information transmission through this network was as high as 40 Gbit/s while operating on the soliton mode, whereas while operating on an ordinary linear mode using the same network, the information rate was only about 2.4 Gbit/s. In addition to this, in laboratory conditions, the same Japanese firm was able to increase the transmission bit rate to terabits per second. The major detrimental factor to the use of all optical soliton communication lines is the occurrence of soliton timing jitter which is due to amplifier noise or due to interactions with neighboring solitons and thus is responsible for bit rate error. Soliton jitter can be effectively controlled by exploiting the robust nature of solitons and by reducing the average dispersion close to zero by means of dispersion compensation.

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Soliton Photonic Switches: As with optical regeneration, the need to convert optical data back to base band electrical signals is tremendously cumbersome and slow. New techniques hold out the hope that it will soon be possible to execute logic circuits at the optical level in the form of switches or binary logic gates such as NOR and NAND gates. Although this technology still lies in the realm of the laboratory, a most interesting application of solitons can be seen in the SOLITON NOR GATE. It does not take too much imagination to see what could be achieved if this approach to optical logic circuits can be commercialized in the near future. So, how does this optical logic work? Again, it is based on erbium-doped fiber. Not only does this fiber enable the laser generation of high-power solitons and amplify low-power optical data streams, but it can act as a logic gate as well! It is hard to believe that all this can be achieved from a piece of passive glass! Erbium fiber is an attractive medium to make all-optical logic gates, because such gates have an almost instantaneous response. By using long lengths of inexpensive fiber, low switching energies can be achieved. The technology is called soliton-dragging logic gates and can satisfy all the needs for logic gates or switches in an optical computer or digital communications data switch. It is possible to cascade gates, connect the output of one gate to inputs of many others and vice versa. It is also possible to perform the complete range of Boolean logic operations including addition and subtraction.

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In recent years, an even newer type of optical soliton has been discovered. These solitons are created with a very strong nonlinear effect found in some crystals in which two light fields can 'shake hands' and cooperate by traveling together without dispersion. These are much more stable than previously known solitons, because they are adapted to travel in many other types of environment rather than just inside optical fibers. For example, they can travel stably in the surface region of an optical integrated circuit. Because of the very strong nonlinear effect (which is several thousand times larger than the previous nonlinear effect), optical solitons of this type can also be produced with extremely low laser powers. Possible applications include optical information storage of enormous quantities of data, all-optical switches, much faster optical devices than any known electronic devices, etc.

7. Spatial Solitons

When optical beams travel, say along z-direction, through

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a bulk homogeneous optical medium, there exists every possibility that the beam diffracts along x and y directions. However, if this diffraction can be compensated by an increase of the refractive index of the material in the transverse directions occupied by the beam, which is possible if the medium is nonlinear, the medium becomes an optical wave guide confining the wave in the high index region. There has been tremendous growth in the field of optical spatial solitons since the first observation of self-trapping of light. A laser beam when focused onto the edge of a photosensitive material can write its own waveguide and then gets guided by this waveguide. In this process, the beam of light which initially diffracts, changes the refractive index of the medium. As time passes on, the beam dynamically creates a channel that counteracts diffraction and guides the beam through the material. When an optical beam propagates in a suitable nonlinear medium, solitons can be formed and can be propagated without any diffraction effect. Spatial solitons with various dimensionality have been observed in various nonlinear media. Below, we discuss spatial solitons formed in photorefractive materials and photopolymers because of their practical importance.

When illuminated, a space-charge field is formed in the photorefractive material which induces nonlinear changes in the refractive index of the material by the electro-optic (Pockels) effect. This change in refractive index can counter the effect of beam diffraction and form a PR soliton.

Photorefractive Solitons: The study of spatial solitons is considered to be important because of possible applications in optical switching and routing. Segev *et al* proposed a new kind of spatial soliton, the Photorefractive Soliton (PR) in the year 1992. When illuminated, a space-charge field is formed in the photorefractive material which induces nonlinear changes in the refractive index of the material by the electro-optic (Pockels) effect. This change in refractive index can counter the effect of beam diffraction and form a PR soliton. The light beam effectively traps itself in a self-written waveguide. As compared to the Kerr-type solitons, these solitons exist in two dimensions and can be generated at low power levels of the order of several microwatts. The PR soliton has been investigated extensively by various groups as it has potential applications in all-optical switching, beam steering, optical interconnects, etc. At present, three different kinds of PR solitons have been proposed: quasi-steady state solitons, screening solitons and screening photovoltaic solitons. The screening PR solitons are one of the most extensively studied solitons. They are possible in steady state when an external bias voltage is applied to a non-photovoltaic PR crystal. This field is partially screened by space charges induced by the soliton beam. The combined effect of the balance between the beam diffraction and the PR focusing effect results in the formation of a screening soliton. A new kind of PR soliton, the photorefractive polymeric soliton, has been proposed and observed in 1991 in a photorefractive polymer made from a mixture of two dicyanomethylenedihydrofuran (DCDHF) chromospheres. Since then it has attracted much research interest owing to the possibility of using them as highly efficient active optical elements for data transmission and controlling coherent radiation in various electro-optical and optical communication devices when compared to PR crystals.

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Solitons in Self-Writing Waveguides: Light induced or self-written waveguide formation is a recognized technology by which we can form an optical waveguide as a result of the self-trapping action of a laser beam passed through a converging lens or a single mode fiber. Self-writing is a relatively new and emerging area of research in optics and the first experiment was demonstrated by Frisken in 1993. Since then the phenomenon of self-writing has been reported in a number of photosensitive optical materials including UV-cured epoxy, germano-silicate glass, planar chalcogenide glass, etc. The physics of self-writing in all cases is very similar to that of spatial solitons discussed above, which occur due to balance between linear diffraction effect and nonlinear self-focusing effect. These waveguides offer a number of

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advantages in comparison with other methods of fabricating waveguides such as epitaxial growth, diffusion methods and direct writing.

The self-written waveguides so formed are of particular interest as these waveguides can be formed at low power levels and the material response is wavelength sensitive; therefore a weak beam can guide an intense beam at a less photosensitive wavelength. These waveguides evolve dynamically, and they experience minimal radiation losses due to the absence of sharp bends. Many processing steps are needed to form buried waveguides. But, if the buffer layer is transparent at the writing wavelength, self-writing can be used to form these buried waveguides. Another application of self-written waveguides is in telecommunication. The major obstacles in the widespread use of single mode fibers in the telecommunication industry are problems associated with effective low cost coupling of light into single mode optical fibers and the incorporation of bulk devices into optical fibers. A self-written waveguide structure induced by laser-light irradiation is considered as a candidate for convenient coupling technique between the optical fiber and waveguide .

Polymer optical waveguides have attracted considerable attention for their possible application as optical components in future optical communication systems; because fabricating waveguides from polymers is much easier than fabricating them from inorganic materials. In recent years, experiments with photopolymerizable materials have produced promising results. Self-trapping and self-focusing phenomena in photopolymerizable materials (a liquid diacrylate photopolymer) have been demonstrated both experimentally and theoretically. These phenomena have been observed after an initial diffraction period lasting approximately 20 s. A directional coupler using a three-dimensional waveguide structure has been fabricated. Recently, successful fabrication of artificial ommatidia (imaging unit of insect's compound eyes) by use of self-writing and polymer integrated optics has been reported. These biomimetic structures were obtained by configuring micro lenses to play dual roles for self-writing of waveguides (during the fabrication) and collection of light (during the operation).

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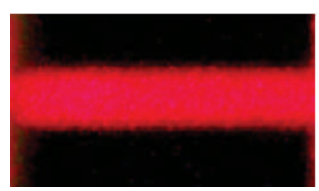
When the photopolymer is illuminated with light of appropriate wavelength (632.8 nm), the polymer chains begin to join. The length of these chains determines the density of these polymers. As a result, the refractive index of the exposed part of the material changes. The change in refractive index occurs both due to photo bleaching of methylene blue and the photo polymerization effect. Photo bleaching is a term that applies to techniques of exposing dye-doped materials to light whose wavelength lies within the spectral absorption bands of the composite dye-polymer system. The change in refractive index so produced is much larger than that of traditional nonlinear optical phenomena such as Kerr or photorefractive effects. However, the index change upon illumination is not instantaneous as compared to these two effects. In recent years, many types of photopolymerizable systems have been developed as holographic recording media. These materials have characteristics such as good spectral sensitivity, high resolution, high diffraction efficiency, high signal to noise ratio, temporal stability and processing in real time, which make them suitable for recording holograms. Because of these properties, photopolymer materials are useful in applications such as optical memories, holographic displays, holographic optical elements, optical computing and holographic interferometry. The most widely used photopolymer recording medium consists of acryl amide and poly (vinyl alcohol). Very recently (C P Jisha *et al*, *Applied Optics*, Vol. 47, pp6502-07, 2009), a self-written waveguide inside a bulk methylene blue sensitized poly/vinyl alcohol)/acrylamide photopolymer material has been observed (*Figure* 9).

Figure 9. Propagation of the beam through the medium with no diffraction.



9. Conclusion

The use of solitons (both temporal and spatial) as information carriers in optical systems is still being heavily researched. As the pulses broaden, neighboring solitons will overlap and this overlap is not fully understood. Systems, which allow the propagation of envelope solitons, operate in the region of negative GVD. However, it has been recently found that dark solitons can propagate through optical fibers. The characteristics of these fibers are currently being investigated. Some of the topics like higher order nonlinear and dispersive effects, cross phase modulation, SRS and SBS, polarization effects, birefringence have not been discussed in this article. Interested readers can look into the references cited below for more information on optical solitons. This article discusses some of the directions that theoretical and experimental investigations have taken over the last few decades in this rapidly growing field. It is clear that solitons will play a major role in the next generation of optical communication systems.

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Suggested Reading

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