ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 5.2
IJAR 2015; 1(2): 275-280
www.allresearchjournal.com
Received: 03-11-2014
Accepted: 08-12-2014

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Evolution of solitons in single mode fiber

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DOI: https://doi.org/10.22271/allresearch.2015.v1.i2d.9281

Abstract
This paper describes propagation of optical pulses inside a dispersive and non-dispersive single mode fiber. It gives a brief description about Group-velocity dispersion (GVD) and Self-phase modulation (SPM). These effects play the main role in the formation of soliton pulses. It also describes the combined effects of GVD and SPM that results in evolution of solitons.

Keywords: Group-velocity dispersion, self-phase modulation, soliton transmission, optical fiber communication

Introduction
The information carrying capacity of optical fiber communication systems are limited by propagation losses and pulse broadening phenomenon which results due to group velocity dispersion (GVD). With the advent of erbium-doped optical amplifier (EDFA), the limiting effects of losses can be overcome easily. The effect of GVD can be nullified with self phase modulation (SPM) which arises due to fiber non-linearities. The SPM produces the inverse effect of GVD, that is, pulses contracts on propagation. Thus when a high power short duration pulse is transmitted inside a single mode fiber it does not broadens and its pulse width remains constant. This leads to a phenomenon known as evoluation of solitons. Thus soliton based optical fiber systems have large information carrying capacity.
Further, by combining WDM and soliton techniques, the information carrying capacity of optical fiber systems can be increased to a great extent. The experiments show that the use of WDM solitons has the potential of realizing transoceanic lightwave systems capable of operating with a capacity of 1 Tb/s or more.

Propagation of optical pulses inside single mode fiber
The propagation of optical pulses inside single mode fiber is governed by the nonlinear Schrödinger (NLS) equation. For pulse width > 5 ps, this equation is given as [1]

$$i\frac{\partial A}{\partial z} = -\frac{i\alpha}{2}A + \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \gamma|A|^2 A \qquad (1)$$

where A is the slowly varying amplitude of the pulse envelope. It is measured in a frame of reference moving with the pulse at the group velocity v_g , i.e. $T = t - z/v_g$. Parameters α, β_2 and γ are attenuation coefficient of fiber, GVD parameter and nonlinear parameter respectively. The three terms on right hand side of eq. (1) govern the effects of fiber losses, dispersion and nonlinearity respectively. Depending on the initial width T_0 and the peak power P_0 of the incident pulse, either dispersive or nonlinear effects may dominate.
In terms of normalized time scale τ ($=T/T_0$) and normalized amplitude U [$A(z,\tau) = \sqrt{P_0}\, e^{-\alpha z}\, U(z,\tau)$], the eq. (1) can be written as

$$i\frac{\partial U}{\partial z} = \frac{\mathrm{sgn}(\beta_2)}{2L_D}\frac{\partial^2 U}{\partial \tau^2} - \frac{e^{-\alpha z}}{L_{NL}}|U|^2 U \qquad (2)$$

where P_0 is the peak power of the incident pulse, sgn (β_2) = ±1 (depending on the sign of GVD parameter β_2) and

$$L_D = \frac{T_0^2}{|\beta_2|},\ L_{NL} = \frac{1}{\gamma P_0} \qquad (3)$$

The dispersion length L_D and nonlinear length L_{NL} provide the length scales over which dispersive or nonlinear effects become important for pulse evolution. When fiber length L is such that L << L_{NL} and L << L_D, neither dispersive nor nonlinear effects play a significant role and therefore pulse maintains its shape during propagation. The fiber plays a passive role in this regime and acts as a mere transporter of optical pulses except for reducing the pulse energy because of fiber losses. For L ~ 50 km, L_D and L_{NL} should be larger than 500 km for distortion free transmission. At λ = 1.55 μm, for standard telecommunication fibers ($|\beta_2| \cong 20 ps^2 km^{-1}$ and $\gamma \approx 3\ w^{-1}km^{-1}$), this condition is achieved if T_0 > 100 ps and P_0 ~ 1 mW. L_D and L_{NL} become smaller as pulses become shorter and more intense. For example, L_D and L_{NL} are approximately 100 m for T_0 ~ 1 ps and P_0 ~ 1 W. For such pulses both the dispersive and nonlinear effects must be considered if fiber length exceeds a few meters.

When L << L_{NL} but L ~ L_D, pulse evolution is governed by GVD and the nonlinear effects play an insignificant role. The dispersive dominant regime is applicable whenever

$$\frac{L_D}{L_{NL}} = \frac{\gamma p_0 T_0^2}{|\beta_2|} << 1 \qquad (4)$$

For L << L_D but L ~ L_{NL}, pulse evolution is governed by the SPM. This nonlinearity dominant regime is applicable when

$$\frac{L_D}{L_{NL}} >> 1 \qquad (5)$$

When the fiber length L is larger or comparable to both L_D and L_{NL}, both dispersion and nonlinearity act together. Their interplay leads to a qualitatively different behaviour compared with that expected from GVD or SPM alone. Their combined effect leads to formation of solitons in anomalous-dispersion regime (β_2 < 0) and pulse compression in normal- dispersion regime (β_2 >0).

Effect of group-velocity dispersion

Any information or signal which is transmitted through the optical fiber travels at the group-velocity. The group-velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. As a result, different spectral components of the pulse travel at slightly different group velocities and do not arrive simultaneously at the output and leads to the pulse broadening. If Δω is the spectral width of the pulse, the extent of pulse broadening (Δt) for a fiber of length L is given by

$$\Delta t = L\frac{d^2\beta}{d\omega^2}\Delta\omega = L\beta_2\Delta\omega \qquad (6)$$

Where β is propagation constant. The parameter $\beta_2 = \frac{d^2\beta}{d\omega^2}$ is known as the GVD parameter.

The effect of GVD on optical pulses propagating in a linear dispersive medium can be calculated by setting α = γ = 0 in eq. (1). In terms of normalized amplitude U (z, T) it can be written as

$$i\frac{\partial U}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 U}{\partial T^2} \qquad (7)$$

The above equation is readily solved by using the Fourier transform (F.T.) method. If Ũ (z, ω) is F.T. of U (z, T), such that

$$U(z,T) = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(z,\omega)e^{-j\omega T}d\omega \qquad (8)$$

then eq. (7) becomes

$$i\frac{\partial U}{\partial z} = -\frac{1}{2}\beta_2\omega^2 U \qquad (9)$$

and its solution may be given by

$$\tilde{U}(z,\omega)=\tilde{U}(0,\omega)\exp(\frac{i}{2}\beta_2\omega^2 z) \qquad (10)$$

Equation (10) shows that GVD changes the phase of each spectral component of the pulse. The amount depends on both the frequency and the propagated distance. Such phase changes do not affect the pulse spectrum but modify the pulse shape. By substituting eq. (10) into eq. (8), the general solution of eq. (7) is given by

$$U(z,T) = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(0,\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 z - i\omega T\right)d\omega \qquad (11)$$

where Ũ (0, ω) is the F.T. of the incident pulse, i.e.

$$\tilde{U}(0,\omega)= \int_{-\infty}^{\infty} U(0,T)e^{-j\omega T}dT \qquad (12)$$

In this section the GVD effect is considered for Gaussian (both unchirped & chirped) and hyperbolic-secant pulses. Gaussian pulses are considered because the pulses emitted from many lasers can be approximated by a Gaussian shape. Hyperbolic secant pulse is most desirable in the context of optical solitons and some mode-locked lasers also emit such pulses.

Gaussian pulse

For an unchirped Gaussian pulse the incident field is given as

$$U(0,T)=\exp(-T^2/2T_0^2) \qquad (13)$$

where $2T_0$ is temporal width of the incident pulse. It is defined as the time interval between two points at which intensity is $1/e^2$ times the maximum intensity as shown in Fig. 1(a). Substituting the F.T. of U (0, T) in eq. (11), the amplitude at any point z along the fiber is obtained as

$$U(z,T)=\frac{T_0}{(T_0^2-i\beta_2 z)^{1/2}}\exp\left(-\frac{T_0^2}{2(T_0^2-i\beta_2 z)}\right) \qquad (14)$$

Since U (z, T) is also Gaussian, it shows that a Gaussian pulse maintains its shape on propagation but its width T (z) increases by a factor

$$\frac{T(z)}{T_0}=\left[1+\frac{z|\beta_2|}{T_0^2}\right]^{1/2}=\left[1+\frac{z}{L_D}\right]^{1/2} \qquad (15)$$

Here L_D is dispersion length as defined earlier. It is the length at which pulse broadens by a factor of √2. Equation (15) shows that pulse broadens on propagation. Such broadening is shown in Fig. 1(b).

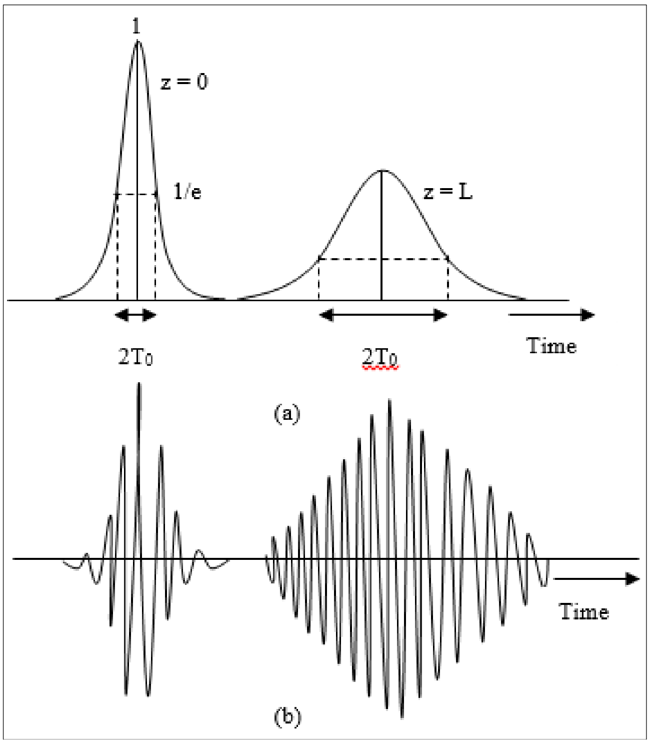


Fig 1: The temporal broadening of a Gaussian pulse. [a] The corresponding intensity variation. [b] The electric field distribution

It can be calculated from equations (13) and (14) that both pulses have same energy. Since energy is conserved on propagation, the amplitude U (z, T) is function of T_0 and it is inversely proportional to T_0.
Equation (13) can be written in the form

$$U(z,T)=|U(z,T)|\exp[i\phi(z,T)] \qquad (16)$$

where

$$\phi(z,T)=-\frac{\operatorname{sgn}(\beta_2)(z/L_D)}{1+(z/L_D)^2}\left(\frac{T^2}{T_0^2}\right)+\frac{1}{2}\tan^{-1}(z/L_D) \qquad (17)$$

The time dependence of the phase $\phi(z,T)$ implies that the instantaneous frequency $\partial\phi/\partial T$ across the pulse does not remain same and differs from the central frequency. This phenomenon is known as pulse chirping. Further, the frequency changes linearly across the pulse. It increases or decreases depending upon whether the dispersion regime is normal or anomalous. Dispersion induced pulse broadening can be understood by the fact that different frequency components of a pulse travel at slightly different speeds. Red components travel faster than blue components in normal dispersion regime while opposite occurs in anomalous dispersion regime.

Chirped Gaussian pulse

In the case of linearly chirped Gaussian pulse, the incident field is written as

$$U(0,T)=\exp\left(-\frac{(1+iC)T^2}{2T_0^2}\right) \qquad (18)$$

where C is chirp parameter. The chirp is known as positive or negative depending upon whether C is +ve or –ve. As defined earlier, the time dependence of instantaneous frequency of the pulse is known as frequency chirping. Since the incident field has time dependent phase component, the instantaneous frequency across the pulse is variable. It can be shown that it increases or decreases linearly from leading to the trailing edge depending upon the chirp is +ve or -ve.
The F.T. and spectral half width of U (0, T) are given by

$$\tilde{U}(0,\omega)=\left(\frac{2\pi T_0^2}{1+iC}\right)^{1/2} e^{-\left(-\frac{\omega^2 T_0^2}{2(1+iC)}\right)} \qquad (19a)$$

$$\Delta\omega=\left(1+C^2\right)^{1/2}T_0 \qquad (19b)$$

The spectral width is thus enhanced by a factor of $(1+C^2)^{1/2}$. In presence of chirp, the spectral width is not transform limited as it does not satisfies the relation $\Delta\omega T_0 = 1$.
The amplitude U (z, T) of the pulse is obtained by substituting equation (19a) and (19b) into eq. (11) and is given by

$$U(z,T)=\frac{T_0}{\left[T_0^2-i\beta_2 z(1+iC)\right]^{1/2}}\exp\left(-\frac{(1+iC)T^2}{2\left[T_0^2-i\beta_2 z(1+iC)\right]}\right) \qquad (20)$$

The above expression shows that a chirped Gaussian pulse also maintains its Gaussian shape on propagation, but the width (temporal) T (z) alters by a factor

$$\frac{T(z)}{T_0}=\left[\left(1+\frac{C\beta_2 z}{T_0^2}\right)^2+\left(\frac{\beta_2 z}{T_0^2}\right)^2\right]^{1/2} \qquad (21)$$

This factor shows that the pulse broadening depends on the relative signs of the parameters β_2 and C. It goes through an initial narrowing stage when $\beta_2 C < 0$ and then after broadens. This initial narrowing is due to the fact that when $\beta_2 C < 0$, the dispersion induced chirp is in opposite direction to that of initial chirp. As a result the net chirp is reduced leading to pulse narrowing. When $\beta_2 C > 0$, pulse always broadens.

Hyperbolic secant pulses
The incident field for the unchirped hyperbolic secant pulse is given by

$$U(0,T)=\text{sech}(T/T_0) \quad (22)$$

The field U (z, T) can be obtained by substituting F.T. of U (0, T) into eq. (11) and evaluating the integral. It can be shown that qualitative features of dispersion-induced broadening are nearly identical for Gaussian and sech pulses.

The effect of self- phase modulation (spm)
Self-phase modulation is the frequency change caused by a phase shift induced by the pulse itself. SPM arises because the refractive index of the fiber has an intensity dependent component. When an optical pulse travels through the fiber, the higher intensity portions of the pulse encounter a higher refractive index compared with the lower intensity regions. This non-linear refractive index (n_2) induces a phase shift that is proportional to the intensity of the pulse. Different parts of the pulse undergo different phase-shifts, which give rise to chirping of the pulse. Pulse chirp in turn broadens the spectrum of the pulse, while keeping the temporal shape unaltered. The spectral broadening of the pulse without a corresponding increase in temporal width leads to a frequency chirping of the pulse fig.(2).The chirping effect is proportional to the transmitted signal power. In silica optical fibers, for which n_2 is positive, the frequencies in the trailing edge of the pulse increases and those in the leading edge decreases with respect to the center frequency of the pulse.

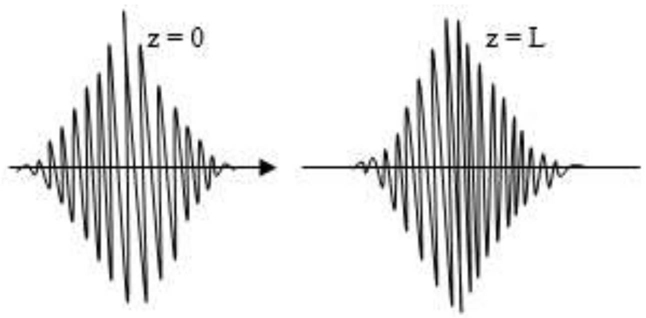


Fig 2: Effect of self phase modulation on the transmitted pulse

The effect of SPM on pulse propagation can be evaluated by neglecting chromatic dispersion (β_2 = 0). Under this condition, the NLS equation (2) in terms of the normalized amplitude U (z, T) becomes

$$\frac{\partial U}{\partial z} = \frac{ie^{-i\alpha z}}{L_{NL}}|U|^2 U \quad (23)$$

The above equation is solved by taking U = V$e^{j\phi_{NL}}$ and equating real and imaginary parts. It is obtained as

$$\frac{\partial V}{\partial z} = 0 \quad (24)$$

$$\frac{\partial \phi_{NL}}{\partial z} = \frac{e^{-\alpha z}}{L_{NL}} V^2 \quad (25)$$

Eq. (24) shows that amplitude V does not change along the fiber length. Solution of eq. (25) for a fiber length L, is obtained as

$$\phi_{NL}(L,T) = |U(0,T)|^2 \left(L_{eff} / L_{NL}\right) \quad (26)$$

Where the effective length L_{eff} is defined as

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$$

In general

$$U\,(L, T) = U\,(0, T)\,\exp\left[i\phi_{NL}(L,T)\right] \quad (27)$$

Equation (27) shows that SPM gives rise to an intensity dependent phase shift keeping the pulse shape unaffected. The nonlinear phase shift ϕ_{NL} increases with L. L_{eff} is smaller than L because of fiber losses. In the absence of losses (α = 0), L_{eff} = L. The maximum phase shift ($\phi_{\max}$) occurs at the pulse centre. With U normalized such that $|U(0,0)| = 1$, it is given by

$$\phi_{\max} = \frac{L_{eff}}{L_{NL}} = \gamma P_0 L_{eff} \quad (28)$$

The physical meaning of L_{NL} is clear from equation (28). It is the effective propagation distance at which $\phi_{\max}$ = 1. The SPM induced spectral broadening is a consequence of the time dependence of ϕ_{NL}. It increases with the propagation distance. In other words, new frequency components are generated continuously as the pulse propagates down the fiber. The extent of pulse broadening also depends on the pulse shape.

Combined effect of GVD and SPM & evaluation of solutions
New qualitative features arise from interplay between GVD and SPM. In the anomalous-dispersion regime, the two phenomena can cooperate in such a way that pulse propagates undistorted. Such pulses are known as optical solution. In the normal dispersion-regime, the combined effects of GVD and SPM can be used for pulse compression.
In presence of GVD and SPM both, the pulse evolution can be obtained by solving the non-linear Schrödinger (NLS) equation [eq. (1) or (2)].
The equation (2) can be further normalized as

$$i\frac{\partial U}{\partial \xi} = \frac{\text{sgn}(\beta_2)}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2 e^{-\alpha z}|U|^2 U \quad (29)$$

where ξ and τ represent the normalized distance and time variables defined as

$$\xi = \frac{z}{L_D} \text{ and } \tau = \frac{T}{T_0} \quad (30)$$

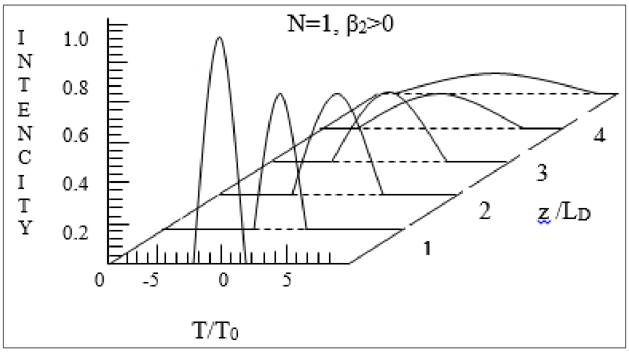
and the parameter N is given by

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} \quad (31)$$

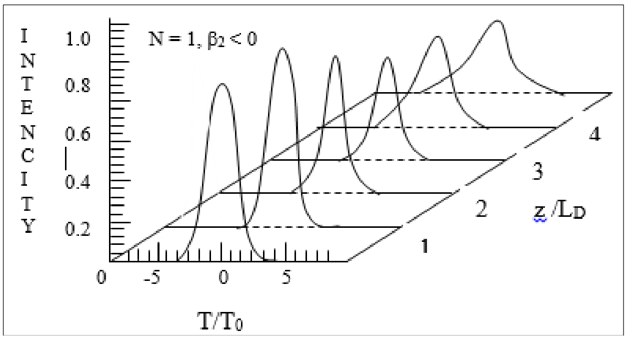
The parameter L_{NL} is known as non-linear length. Dispersion dominates for N<<1 while SPM dominates for N>>1. For N≈1 both SPM and GVD play an equally important role during pulse evolution.

Figure 3(a) shows evolution of the shape of an initially unchirped Gaussian pulse in the normal dispersion. The qualitative behavior is quite different from when either SPM or GVD dominates. The pulse broadens much more rapidly compared with N=0 case; i.e. no SPM.

In anomalous dispersion regime, the pulse broadens at a rate much lower than in the absence of SPM and then appears to reach a steady state for z > $4L_D$, as shown in Fig.3(b). This steady state condition is obtained as SPM induced positive chirp is cancelled by dispersion induced negative chirp. Thus, SPM and GVD cooperate with each other to maintain a chirp free-pulse. This leads to soliton evolution. Initial broadening of the Gaussian pulse occurs because the Gaussian profile is not the characteristic shape associated with a fundamental soliton. But if the input pulse is chosen to be a "sech" pulse, both its shape and spectrum remains unchanged during propagation.



(a)



(b)

Fig 3: Evolution of pulse shapes for an initially unchipped Gaussian pulse propagating in (a) normal dispersion regime (b) anomalous-dispersion regime

Thus by a proper choice of the pulse shape (a hyperbolic secant shape) and power carried by the pulse, one effect can by compensated by the other. In such a case, the pulse would propagate undistorted by a mutual compensation of dispersion and SPM effects. Such a pulse would neither broaden in time domain nor in the frequency domain and is called solution.

When an input pulse having a "sech" shape such that

$$u(0,\tau) = N \operatorname{sech}(\tau) \quad (32)$$

is launched in to a fiber, its shape remains unchanged during propagation for N=1 and follows a periodic pattern for higher integer values of N. The parameter N is known as order of the soliton. The optical pulse corresponding to N=1 is known as fundamental soliton. Pulses corresponding to N>1 are known as higher order solitons. The higher order soliton recover their original shape after a distance known as soliton period, z_0. It is given by $z_0 = (\pi/2)\, L_D$, Both the parameters N & z_0 play an important role in the theory of optical solitons.

In its most general form, the NLS equation for N=1 can be written as [2].

$$u(\xi,\tau) = \eta \operatorname{sech}[\eta(\tau + \delta\xi - q)]\exp\left[-i\delta\tau + i(\eta^2 - \delta^2)\xi/2 + i\phi\right] \quad (33)$$

where the parameters η, q, δ and ϕ represent the amplitude, position, frequency and phase of input pulse at ξ = 0. Substituting η=1, q = 0, δ = 0 and ϕ = 0 in equation (33), the canonical form of a fundamental soliton is obtained as

$$u(\xi,\tau) = \operatorname{sech}(\tau)\exp\left(\frac{i\xi}{2}\right) \quad (34)$$

The above equation shows that the optical pulse acquires a time independent phase shift ξ/2 as it propagates inside the fiber, but its amplitude remains unchanged. It is the property of the fundamental soliton that makes it an ideal candidate for optical communication. Another important property of fundamental soliton is that it is remarkably stable against perturbations. It can be generated even when the pulse shape and peak power deviate from ideal conditions.

Soliton Transmitters

Soliton communication systems require an optical source capable of producing chirp free pico-second pulses at a high repetition rate with a shape closest to the "sech" shape. The source should operate in the wavelength region near 1.55 μm.

Early experiments on soliton transmission used the technique of gain switching for generating optical pulses of 20-30 ps duration by biasing the laser below threshold and pumping it high above threshold periodically [3-5]. The repetition rate was determined by the frequency of current modulation. A problem with the gain switching technique is that each pulse becomes chirped because of the refractive-index changes governed by the line width enhancement factor.

In an experiment [5], by using above technique, 14 ps optical pulses were obtained at a 3 Gb/s repetition rate by passing the gain-switched pulse through a 3.7-km long fiber with β_2 = 23 ps^2/km near 1.55 μm. An erbium-doped fiber amplifier (EDFA) is used to amplify each pulse to the power level required for launching fundamental solitons. In another experiment, gain-switched pulses were simultaneously amplified and compressed after passing them through a narrowband optical filter. It was possible to generate 17 ps-wide, nearly chirp-free optical pulses at repetition rates in the ranging 6-24 Gb/s.

Mode-locked semiconductor lasers can also be used for soliton communication and are often preferred because the pulse train is emitted from such a laser is being nearly chirp-free. The technique of active mode locking is generally used by modulating the laser current at a frequency equal to the frequency difference between two neighboring longitudinal modes.

The grating also offers a self-tuning mechanism that allows mode-locking of the laser over a wide range of modulation frequencies [6]. Such a source produces soliton like pulses of widths 12-18 ps at a repetition rate as large as 40 Gb/s [7]. Mode-locked fiber lasers provide an alternative to semiconductor sources although such lasers still need a semiconductor laser for pumping [8]. An EDFA is placed within the Fabry-Perot (FP) or ring cavity to make fiber lasers. Both active and passive mode-locking techniques have been used for producing short optical pulses. Active mode-locking requires modulation at higher order harmonics of the longitudinal-mode spacing because of relatively long cavity lengths (>1m) that are typically used for optical fiber lasers. Such harmonically mode-locked fiber lasers use an intra-cavity $LiNbO_3$ modulator. A semiconductor optical amplifier can also be used for active mode-locking, producing pulses shorter than 10 ps at a repetition rate as high as 20 Gb/s [9]. Passively mode-locked fiber lasers either use a multiquantum-well device that acts as a fast saturable absorber or employ fiber non-linearity to generate phase shifts that produce an effective saturable absorber.

A compact, synchronously diode-pumped tunable fiber Raman source of subpico second solitons can also be used which employs synchronous Raman amplification in dispersion shifted fiber [10]. Wavelength tunability of 1620-1660 nm is exhibited through simple electronic variation of the gain-switching repetition frequency and solitons as short as 400 fs are obtained. The use of femtosecond pulses enhances the capacity of the soliton systems to a great extent.

An adaptive feedback can be used to control the Raman frequency shift of the output pulse, preserving its duration and intensity [11]. Compact erbium doped fiber lasers are promising sources for pulse generation because of their high stability, ease of use and cost efficiency. One such laser was recently reported which generates 30 ps pulses [12].

Conclusion

It is concluded that solitons in anomalous dispersion regime are formed due to the interplay of GVD and SPM. The effect of GVD is to broaden the transmitted pulse in time domain keeping its spectrum unchanged. On the other hand, SPM broadens the pulse spectrum without changing the temporal behaviour of the pulse. Both these effects counteract each other and the pulse is transmitted keeping its shape unaltered. Hyperbolic secant pulse is most desirable in soliton transmission. The behaviour of Gaussian pulses is quite close to the secant pulses. Soliton based optical fiber communication systems are more suitable for longhaul communication because of their very high information carrying capacity and repeater less transmission. These systems are not fully developed for field applications. When transmission demand will increase and device technology will improve, they will be certainly employed in field.

Acknowledgement

Author is thankful to Prof. N Singh, University of Allahabad for providing computational facilities.

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