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SOLITON BASED OPTICAL COMMUNICATION

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Abstract—The group velocity dispersion (GVD) imposes severe limit on information carrying capacity of optical communication systems. By choosing appropriate pulse shape highly stable light pulses known as solitons are generated when effect of GVD is balanced by self-phase modulation (SPM). The application of solitons in communication systems opens the way to ultrahigh-speed information superhighways. Transmission speed of order of Tbit/s can be achieved if optical amplifiers are combined with WDM in soliton based communication systems.

1. INTRODUCTION

The need of communication is an all time need of human beings. For communication some channel is needed. Fiber is one channel among many other channels for communication. The dispersion phenomenon is a problem for high bit rate and long haul optical communication systems. An easy solution of this problem is optical solitons–pulses that preserve their shape over long distances. Soliton based optical communication systems can be used over distances of several thousands of kilometers with huge information carrying capacity by using optical amplifiers.

2. SELF-PHASE MODULATION

Self-phase modulation (SPM) 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 an optical pulse encounter a higher refractive index of the fiber compared with the lower intensity portions. The leading edge will experience a positive refractive index gradient (dn/dt) and trailing edge a negative refractive index gradient ($-dn/dt$). This temporally varying index change results in a temporally varying phase change. The optical phase changes with time in exactly the same way as the optical signal [1,15]. Different parts of the pulse undergo different phase shift because of intensity dependence of phase fluctuations. This results in frequency chirping. The rising edge of the pulse finds frequency shift in upper side whereas the trailing edge experiences shift in lower side as shown in Figure 1. Hence primary effect of SPM is to broaden the spectrum of the pulse, keeping the temporal shape unaltered.

For a fiber containing high-transmitted power, the phase (ϕ) introduced by a field $E = E_0 \cos(\omega t - kz)$ over a fiber length L is given by [2,15],

$$\phi = \frac{2\pi}{\lambda}(n_l + n_{nl} I) L_{eff} \tag{1}$$

where effective length $L_{eff} = \frac{(1-\exp(-\alpha L))}{\alpha}$. Linear and nonlinear refractive indices are n_l and n_{nl} respectively and α is attenuation coefficient. The first term on right hand side refers to linear portion of phase constant (ϕ_l) and second term provides nonlinear phase constant (ϕ_{nl}). This variation in phase with time is responsible for change in frequency spectrum.

For a Gaussian pulse, the optical carrier frequency ω (say) is modulated and the new instantaneous frequency becomes,

$$\omega' = \omega_0 + \frac{d\phi}{dt} \tag{2}$$

The sign of the phase shift due to SPM is negative because of the minus sign in the expression for phase i.e., ($\omega t - kz$). Using equations (1) and (2) ω' can be written as,

$$\omega' = \omega_0 - \frac{2\pi}{\lambda} L_{eff} n_{nl} \frac{dI}{dt} \tag{3}$$

At leading edge of the pulse $\frac{dI}{dt} > 0$;

$$\omega' = \omega_0 - \omega(t) \tag{4}$$

And at trailing edge $\frac{dI}{dt} < 0$;

$$\omega' = \omega_0 + \omega(t) \tag{5}$$

where,

$$\omega(t) = \frac{2\pi}{\lambda} L_{eff} n_{nl} \frac{dI}{dt} \tag{6}$$

Thus chirping phenomenon (frequency variation) is generated due to SPM, which leads to the spectral broadening of the pulse without any change in temporal distribution. The SPM induced chirp can be used to modify the pulse broadening effects of dispersion. SPM phenomenon also can be used in pulse compression. In the wavelength region where chromatic dispersion is positive, the red-shifted leading edge of the pulse travels slower and moves toward the center of pulse. Similarly, the blue shifted trailing edge travels faster, and also moves toward the center of the pulse. In this situation SPM causes the pulses to narrow. Another simple pulse compression scheme is based on filtering self-phase modulation-broadened spectrum [14, 15].

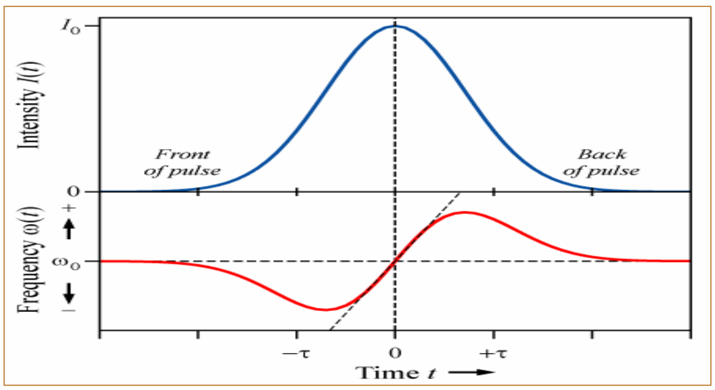


Figure 1. Spectral broadening of a pulse due to SPM.

The performance of self-phase modulation-impaired system can be improved significantly by adjusting the net residual (NRD) of the system. For SPM-impaired system the optimal NRD can be obtained by minimizing the output distortion of signal pulse. The NRD of SPM-impaired dispersion-managed systems can be optimized by a semi analytical expression obtained with help of perturbation theory. This method is verified by numerical simulations for many SPM-impaired systems [12, 13].

3. GROUP VELOCITY DISPERSION

Any information-carrying signal, by necessity, contains components from a range of wavelengths. The group velocity of a signal is function of wavelength, therefore each spectral component can be assumed to travel independently and to undergo a group delay, which ultimately results in pulse broadening [2]. This GVD will eventually cause a pulse to overlap with neighboring pulses. After a certain amount of overlap, adjacent pulses can not be identified at the receiver and error will occur. In this way the dispersive characteristics determine the information carrying capacity of fibers.

The group delay (τ_g) per unit length in direction of propagation is given by

$$\frac{\tau_g}{L} = \frac{1}{v_g} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \tag{7}$$

where, L is the distance traveled by the pulse, β is the propagation constant along fiber axis, wave propagation constant $k = 2\pi/\lambda$ and group velocity $v_g = c\left(\frac{d\beta}{dk}\right)^{-1}$.

The delay difference per unit wavelength can be approximated as $d\tau_g/d\lambda$ if taken optical source is not of too vide spectral width. For spectral width $\delta\lambda$, total delay difference $\delta\tau$ over a distance L, can be written as

$$\delta\tau = \frac{d\tau_g}{d\omega}\delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega \tag{8}$$

where ω is angular frequency. The factor $\beta_2 \equiv \frac{d^2\beta}{d\omega^2}$ is the GVD parameter, which determines how much a light pulse broadens in time as it is transmitted over the fiber.

4. EVOLUTION OF SOLITON

The nonlinear Schrödinger equation (NLSE) is an appropriate equation for describing the propagation of light in optical fibers [3, 4]. Using normalization parameters such as: the normalized time T_0, the dispersion length L_D and peak power of the pulse P_0 the nonlinear Schrödinger equation in terms of normalized coordinates can be written as,

$$i\left(\frac{\partial u}{\partial z}\right) - \frac{s}{2}\left(\frac{\partial^2 u}{\partial t^2}\right) + N^2|u|^2u + i\left(\frac{\alpha}{2}\right)u = 0 \tag{9}$$

where $u(z,t)$ is pulse envelope function, z is propagation distance along the fiber, N is an integer designating the order of soliton and α is the coefficient of energy gain per unit length, with negative values it represents energy loss. Here s is -1 for negative β_2 (anomalous GVD–Bright Soliton) and $+1$ for positive β_2 (normal GVD-Dark Soliton) as shown in Figures 2 and 3 and $N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}$ with nonlinear parameter γ and nonlinear length L_{NL}.

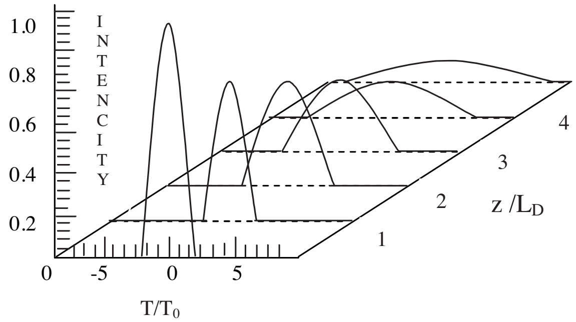


Figure 2. Evolution of soliton in normal dispersion regime.

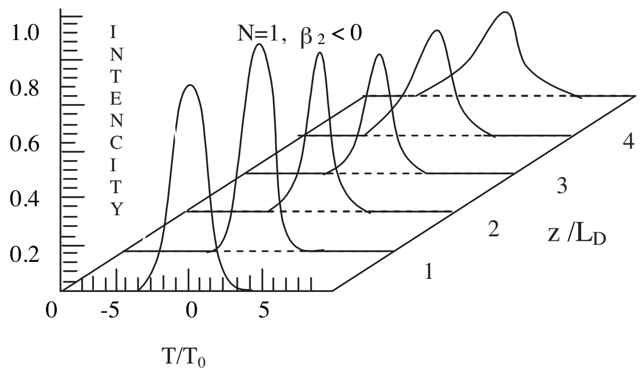


Figure 3. Evolution of soliton in anomalous dispersion regime.

It is obvious that SPM dominates for $N > 1$ while for $N < 1$ dispersion effects dominates. For $N \approx 1$ both SPM and GVD cooperate in such a way that the SPM-induced chirp is just right to cancel the GVD-induced broadening of the pulse. The optical pulse would then propagate undistorted in the form of a soliton [5, 9].

By integrating the NLSE, the solution for fundamental soliton $(N = 1)$ can be written as

$$u(z,t) = \sec h(t) \exp(iz/2) \tag{10}$$

where sech (t) is hyperbolic secant function. Since the phase term exp $(iz/2)$ has no influence on the shape of the pulse, the soliton is independent of z and hence is nondispersive in time domain [23, 24]. It is this property of a fundamental soliton that makes it an ideal candidate for optical communications. Optical solitons are very stable against perturbations; therefore they can be created even when the pulse shape and peak power deviates from ideal conditions (values corresponding to $N = 1$).

5. INFORMATION TRANSMISSION

A digital bit stream can be generated by two distinct modulation formats i.e., non-return-to-zero (NRZ) and return-to-zero (RZ). The solution of NLS equation for soliton holds only when individual pulses are well separated [5, 6]. This can be ensured by keeping soliton width a small fraction of the bit slot. To achieve this, RZ format (Figure 4) has to be used instead of NRZ format when solitons are used as information bits.

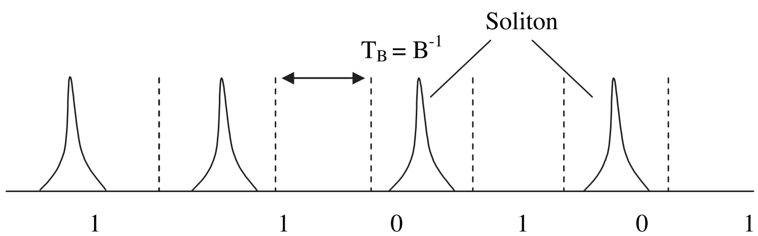


Figure 4. Soliton bit stream in an RZ format.

The bit rate B and the width of the bit slot T_B can be related as

$$B = \frac{1}{T_B} = \frac{1}{2s_0 T_0}$$

where $2s_0 = T_B/T_0$ is the normalized separation between neighboring solitons.

6. 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 [16–18]. A problem with the gain switching technique is that each pulse becomes chirped because of the refractive-index changes governed by the linewidth enhancement factor.

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 grating also offers a self-tuning mechanism that allows mode-locking of the laser over a wide range of modulation frequencies [19]. Such a source produces soliton like pulses of widths 12–18 ps at a repetition rate as large as 40 Gb/s [8].

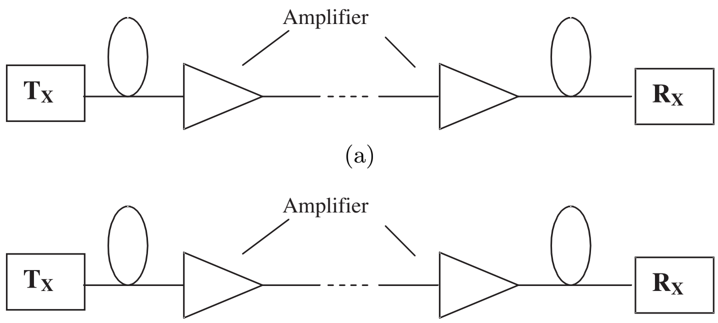
A compact, synchronously diode-pumped tunable fiber Raman source of subpico second solitons can also be used which employs synchronous Raman amplification in dispersion shifted fiber [20]. Wavelength tunability of 1620–1660 nm is exhibited through simple electronic variation of the gain-switching repetition 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.

However, with the femtosecond optical pulses, it is necessary to control their propagation characteristics. In the femtosecond pulse duration regime, the main higher order nonlinear contribution comes from stimulated Raman scattering. The Raman self-frequency shift that results from the energy exchange between the propagating pulses and optical vibrational modes of the glass precludes the stable propagation of subpicosecond solitons along the fiber, leading to rapid displacement of the pulse spectrum to the red (lower frequency side) as it propagates. As a result, practical solitons in fibers often have durations of 1 ps or longer. A shorter pulse suffers self-frequency shifts of $\Delta\omega = L/T_0^2$, where L and T_0 are as defined as earlier.

An adaptive feedback can be used to control the Raman frequency shift of the output pulse, preserving its duration and intensity [21]. 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 [22] which generates 30 ps pulses.

7. AMPLIFICATION OF SOLITONS

In long distance soliton propagation, the energy of soliton decreases because of fiber losses. This would produce soliton broadening because a reduced peak power weakens the SPM effect necessary to counteract the effect of GVD. Therefore, to overcome the effect of fiber losses soliton must be amplified periodically using either lumped or distributed amplification scheme [5, 7]. Lumped amplification is useful provided the spacing between amplifiers L_A is less than dispersion length L_D ($L_A \ll L_D$). For systems having bit rates greater than 10 Gb/s, the condition $L_A \ll L_D$ can not be satisfied. In such situation distributed amplification scheme is a better alternative. This scheme



(b)

Figure 5. (a) Lumped and (b) Distributed amplification of solitons.

is inherently superior to lumped amplification because it compensates losses locally at every point along fiber link. Raman fiber amplifiers can be used for distributed gain when fiber carrying the signal is pumped at wavelength about 1480 nm. Another way is to dope lightly the transmission fiber with erbium ions and pump periodically to provide distributed gain. Solitons can be propagated in such active fiber over long distances.

8. CONCLUSION

Soliton based optical fiber communication systems, using EDFA's, are more suitable for long haul communication because of their very high information carrying capacity and repeater less transmission. These systems are still to be developed for field applications. When transmission demand will increase and device technology will improve, they will be certainly employed in field. By using soliton based optical switches multi GBPS data rate can be achieved for optical computation also.

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