Solitons in the context of optical fibre communications: A review

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Resilience to Group Velocity Dispersion (GVD) and Polarization Mode Dispersion (PMD) makes optical solitons attractive for multigigabit data transmission by exploiting the ultimate capacity of the optical fibres. In optical fibres solitons can evolve by choosing appropriate pulse and fibre parameters to obtain a counter balancing of GVD and Self Phase Modulation (SPM). This paper provides a thorough review of the optical solitons giving emphasis to the developments in optical communications, highlighting all important milestones over the last few decades.

1. Introduction

The advances in nonlinear optics has led to the fabrication of new nonlinear materials [1], harmonic generations, optical solitons, parametric amplification [2], stimulated Raman scattering [3], self-induced transparency, modulation instability [4], which find a myriad of applications ranging from high speed data transmission [5-6] in optical communication [7], switching [12], amplifiers, pulse reshaping, pulse compression [3], tunable lasers to encoded message transmission. The notable phenomenon of optical solitons has revolutionized the scope of telecommunication world [8].

The soliton pulses are so stable that their shape and velocity are preserved while travelling long distances along a medium. This means that soliton pulses do not spread in optical fibre after propagating thousands of kilometres. In an optical fibre, solitons pulses are generated by counter balancing the effect of the dispersion with the Self-Phase Modulation (SPM) [1]. A soliton has to retain its power between specified levels to preserve its dispersion resilient nature in an optical link. It becomes necessary to compensate for fibre loss periodically. This can be done by using lumped Erbium Doped Fibre Amplifier (EDFA) repeaters. Experimental demonstration and numerical investigations depict that soliton based systems exploit ultimate capacity of single mode optical fibres. Design and analysis of soliton links have been carried out experimentally in late 1990's. The capacity of such systems is limited due to many reasons. The limit is imposed mainly by Amplified Spontaneous Emission (ASE) noise and dispersive wave radiations. ASE noise results in fluctuations of soliton central frequency. Due to this different solitons travel with different speeds resulting in Gordon-Haus (GH) jitter [7]. Experimental studies are carried out by the pioneers in this field to attain a very high speed for long distance transmission systems. Obstacles in the realization of high bit rate (>100Gbps)

soliton systems are identified. They include the Soliton Self Frequency Shift (SSFS), GH jitter and the soliton-soliton interaction. Many solutions to these effects are explored both experimentally and analytically in the past few decades. The influence of nonlinear effects such as Four Wave Mixing (FWM) and Cross Phase Modulation (XPM) in the performance of soliton based systems are investigated. Solitons are found to be resilient to Polarization Mode Dispersion (PMD) and there exists an optimal value of Group Velocity Dispersion (GVD) for which the solitons are most resistant to the effect of PMD [33].

2. Theoretical Investigations

The concept of solitary waves was first introduced in 1834 by Russell [9]. Hasegawa and Tappert were the first to use soliton in optical fibre system in 1973 and they demonstrated the stability of solitons by numerical calculations [10]. In 1981 Hasegawa et al. studied analytically the behaviour of the envelope soliton equation in optical fibres in the presence of loss where solitons represent a solution of Nonlinear Schrödinger Equation (NLSE) [11].

The stability of the solitons with its resistance to dispersion makes them very good candidate for optical communication. The soliton pulses are superior to Non Return to Zero (NRZ) optical pulses in the following manner [12].

- Solitons can be generated in the loss minimum region at around 1550 nm.
- Soliton pulse transmission is possible over long distance. Solitons can be both time and polarization multiplexed.
- There is no waveform distortion over long distances, which is useful for long distance communication.

- Solitons are dispersion free, and the collision of the solitons are elastic in nature, after collision their amplitude and frequency remain unchanged, only position and phase change.
  - Two counter propagating solitons pass each other without affecting each other's motion.

The main obstacles that affect propagation of stable soliton pulses are fibre loss and chromatic dispersion. For long distance optical transmission systems, optical amplifiers must be used to compensate for fibre loss. A common technique consists of doping the silica fibre with rare-earth ions and pumping them optically to realize the optical gain. The propagation of soliton through a nonlinear dispersive medium can be analysed [13-15] by numerically solving NLSE (1a-1d)

$$\frac{\partial u}{\partial x} = j\frac{1}{2}\frac{\partial^2 u}{\partial T^2} + B\frac{\partial^3 u}{\partial T^3} + j|u|^2 u - \Gamma u \qquad (1a)$$

where

$$B = \frac{\beta_3}{6|\beta_2|\, t_0} \qquad (1b)$$

$$\Gamma = \frac{\alpha\, t_0^2}{2\,|\beta_2|} \qquad (1c)$$

$$\beta_i = \frac{\partial^i \beta}{\partial \omega^i} \quad (i = 2, 3) \qquad (1d)$$

The equation (1a) includes second and third order dispersions, fibre nonlinearity, and loss. $u(x,T)$ is the normalized complex amplitude of the soliton pulse, x is the normalized distance along the direction of propagation, T is the normalized time, β is the propagation constant, B is the third order dispersion coefficient, Γ is the normalized loss factor, α is the fibre loss, and t_0 is the $1/e$ times the width of initial pulse. The first, second and the third terms of equation (1a) represent the self phase modulation, first and second order dispersions respectively. Solitons evolve because of the dynamic balance between the GVD and SPM. In optical communications, fundamental solitons ($N=1$) are preferred to higher order solitons. N is the order of the soliton defined by

$$N^2 = L_D\big/L_{NL}$$

where L_D and L_{NL} are the dispersion and the nonlinear lengths respectively. L_D and L_{NL} are defined by equations (2) and (3) respectively

$$L_D = \frac{T_0^{\,2}}{|\beta_2|} \qquad (2)$$

$$L_{NL} = \frac{1}{\gamma P_0} \qquad (3)$$

where T_0 is the pulse width, β_2 is the group-velocity dispersion coefficient, P_0 is the peak power of the pulse and γ is the nonlinearity coefficient.

The exact shape of the input pulse used to launch the fundamental soliton is not critical. Moreover, since the fundamental solitons can be formed for values of N in the range $0.5<N<1.5$, even the width and the peak power of the input pulse can vary over a wide range without hindering soliton formation. It is this relative insensitivity to the exact value of the input parameter that makes the use of solitons feasible in practical application. The fundamental soliton requires the lowest value of peak power and retains its pulse shape at every step of its propagation, where as solitons of higher order restores its shape only at regular intervals of soliton period and requires higher peak power.

The soliton period, Z_{sp} is the length of the propagating nonlinear medium at which a soliton of higher order repeats its shape. Z_{sp} is given by equation(4) [6],

$$Z_{sp} = \frac{\pi^2 c \tau^2}{\lambda^2 |D|} \qquad (4)$$

where D is the dispersion parameter, λ is the wavelength, τ is the normalizing time ($\tau = t_{FWHM}/1.76$) and c is the speed of light in vacuum. t_{FWHM} is the full width half maximum of the pulse. Soliton pulse evolution through a passive fibre can be simulated by numerically solving NLSE. The pulse evolution in an Erbium Doped Fibre (EDF) or Praseodymium Doped Fibre (PDF) can be analysed by solving Max-Bloch equations [74]. Fig. 1 shows the evolution of a 125 ps pulse with a peak power of 0.32 mW through a lossless passive monomode fibre of dispersion parameter $\beta_2 = -20\ ps^2/km$. In this case as $L_D\big/L_{NL} \ll 1$, the dispersive effects dominates over the nonlinear effects leading to the broadening of the pulse in the time domain.
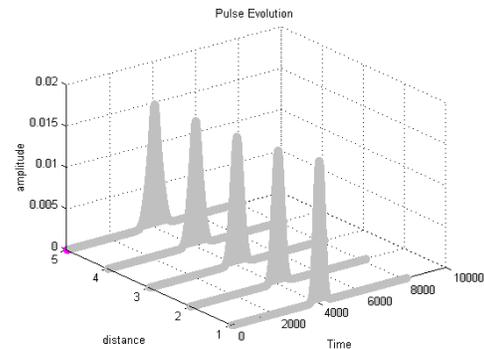

Fig. 1. Soliton pulse evolution through a monomode lossless fibre when dispersive effects dominate over nonlinear effects ($P_0 = 0.32 mW$, $\alpha = 0$, $\beta_2 = -20\ ps^2/km$, $\gamma = 0.003\ /W/m$).

Fig. 2 shows the propagation of 125 ps pulse through same fibre but with peak power $1W$. These values of β_2, pulse width and peak power are such that the ratio $L_D/L_{NL} \gg 1$ and the nonlinear effects dominates over the dispersive effects leading to the compression of the pulse.
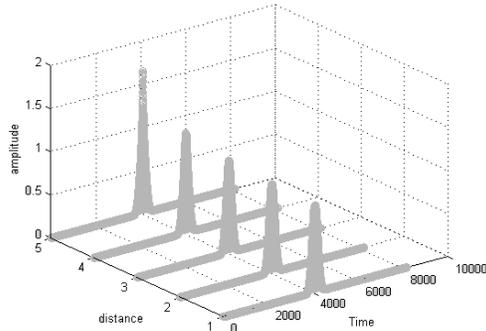

Fig. 2. Soliton pulse evolution through a monomode lossless fibre when nonlinear effects dominate over dispersive effects ($P_0 = 1W$, $\alpha = 0$, $\beta_2 = -20 ps^2/km$, $\gamma = 0.003/W/m$).

In Fig. 3, the peak power of the pulse is kept at 0.64mW for which L_D becomes equal to L_{NL}. The GVD and SPM effects compensate each other leading to soliton pulse evolution. In all the above cases fibre was assumed to be lossless, but optical fibres are inherently lossy. The basic attenuation mechanisms in the fibre are absorption, scattering and excessive bending [11]. The attenuation imposes an upper limit on the distance over which light can be transmitted. The power of the first order soliton reduces when it travels a few soliton periods due to fibre loss. Fig. 4 shows the propagation of a soliton pulse when the fibre loss parameter is 0.06 db/km over a distance of twice the dispersion length. As the soliton peak power decreases along the fibre due to the loss, the nonlinear effect is no longer strong enough to cancel the group velocity dispersion effects. Thus, unlike the lossless case, the dispersion effect is dominant.
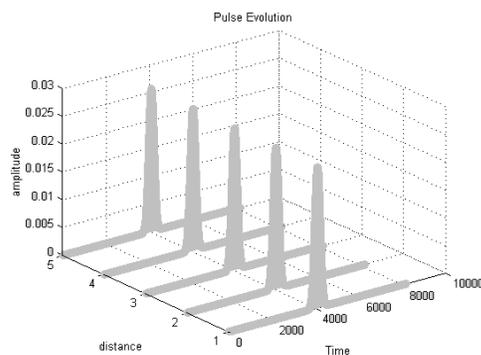

Fig. 3. Soliton pulse evolution through a monomode lossless fibre when nonlinear effects and dispersive effects are counter balanced ($P_0 = 0.64mW$, $\alpha = 0$, $\beta_2 = -20 ps^2/km$, $\gamma = 0.003/W/m$).
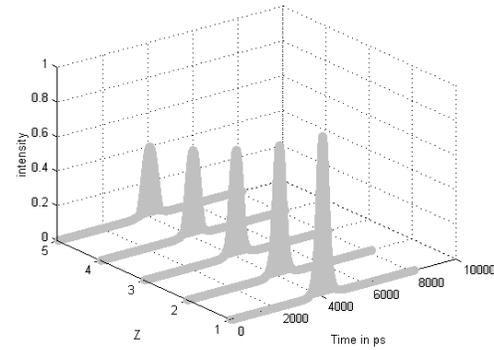

Fig. 4. Soliton propagation in a lossy fibre ($P_0 = 0.64mW$, $\alpha = 0.06 db/km$, $\beta_2 = -20 ps^2/km$, $\gamma = 0.003/W/m$).

The plots (Fig. 1-Fig. 4) are obtained by numerically solving NLSE using the Split Step Fourier Method (SSFM) [13]. The propagation may be analysed using other methods like inverse scattering method (ISM), perturbation method (PM), Finite difference method [16], Fourier series analysis technique (FSAT)[14], Fuzzy Mesh Analysis Technique (FMAT) [17] and Coupled amplitude phase modulation[18].

Inverse Scattering Method (ISM) gives an analytic solution to the propagation of soliton in a lossless optical fibre. Soliton pulses propagate unchanged over long distances in the absence of loss. If fibre loss is to be considered, then an exact analytical solution cannot be obtained by ISM. For higher order solitons the complexity and difficulty of finding the exact solutions using ISM is greatly increased. Hence a perturbation technique should be used to take the effect of the fibre loss into account. The limitation of using PM is that the loss factor in the soliton equation cannot be greater than a certain value (normalized loss factor should be smaller than 0.015), otherwise inaccurate results will be obtained. SSFM is a pseudo spectral numerical method with which fibre loss can be taken into consideration. However, the disadvantages of using SSFM are the requirement of large number of sampling points and the use of the Fast Fourier transform (FFT) many times at each propagation step. It is also noted that for a propagation distance of one soliton period FFT are to be used as many as 3000 times and the cumulative errors are unavoidable.

FSAT is a novel method proposed by P.Shum and H. Ghafouri-Shiraz in 1995[14] to solve the NLSE, and the results were in complete agreement with those produced by other methods like the Split Step Fourier Method (SSFM). It was found that for a given computational accuracy in order to obtain the same results we need fewer sampling points for FSAT compared with SSFM. M. C. Lee et al. had applied FSAT to solve the NLSE and investigate the soliton propagation in a distributed EDFA system taking into account the frequency dependent gain, which is effectively used to compensate for the Soliton Self Frequency Shift (SSFS) [19,22]. With FMAT it is

possible to vary the mesh size with the shape of the soliton pulses along the propagation distance such that the computational efficiency can be enhanced and the number of sampling points can be greatly reduced. It was shown that the mesh analysis technique is capable of analyzing the propagation phenomena of high power solitons, pulse compression and soliton interaction in an efficient manner

With coupled amplitude phase modulation method the fundamental soliton solutions were obtained for both anomalous dispersion regimes and normal dispersion regimes without using the inverse scattering or the Backlund transform [18]. By considering the amplitude and phase of the complex solution separately, a set of amplitude-phase coupled nonlinear equations were derived from NLSE. The characteristic equation satisfied by the envelope amplitude were obtained for the fundamental soliton and soliton-modulated wave. The conditions to be satisfied by the phase propagation constant and soliton power give rise to useful criteria for the design of optical soliton communication systems. Numerical simulations were found to agree well with theoretical results.

An obstacle in realizing ultra high speed (>100 Gb/s) optical communication system over long distance links is the SSFS caused by Intra Pulse Stimulated Raman Scattering (ISRS) [23,24]. Raman effect can cause continuous downshift of the mean frequency of pulses propagating in optical fibres [23]. For solitons in silica fibres, the effect varies roughly with the inverse fourth power of the pulse width. At 1500 nm wavelength in a fibre of 15 ps/nm/km time-of-flight dispersion, a soliton of 250-fsec duration is predicted to shift by its own spectral width after about 100 m of propagation. The theory agrees with the experimental measurements [3].

Recently, with the advent and rapid development of the erbium-doped fibre amplifiers, soliton transmission through a chain of fibre amplifiers has attracted widespread attention. Two transmission schemes, namely, "average soliton method" [24] and "preemphasis method" [25] were proposed to propagate solitons through a transmission link [5].

In the average soliton method, the input peak power of the soliton is chosen such that the average power between two adjacent repeater amplifiers equals the fundamental soliton power in the ideal case, where the transmission loss is assumed to be zero. In the case of the preemphasis method the initial pulse amplitude is chosen so that the pulse width at the end of the repeater span is same as that of the launched pulse. This scheme requires that the repeater spacing is much smaller than the soliton period. The two methods had been compared by studying the soliton propagation behaviour along a number of optical amplifier stages. Numerical simulations had shown that the preemphasis method works reasonably well only under certain conditions and requires relatively smaller amplifier spacing. If these conditions are not satisfied preemphasis method leads to soliton deterioration. However the average soliton method maintains quite good soliton transmission stability even when these conditions are somewhat relaxed. The distance between optical

amplifiers in the latter method can be made considerably longer. The average soliton method provides quite stable transmission even for large pulse amplitudes and even when the one-tenth condition is not strictly satisfied. Hence, amplifier spans of the order of 100 km can be achieved along with high transmission capacity.

The preemphasis method works fairly well when the normalized amplitude A is in the range $1.2 < A < 1.4$ and when the condition of amplifier spacing being smaller than one-tenth of soliton period is satisfied.

For an optical soliton communication system with lumped amplifiers the expression for Bit Error Rate (BER) was obtained as equation (5) [26]

$$BER = Q\left(\frac{S}{\sqrt{M} + \sqrt{2S + M}}\right) + 2Q\left(t_w/\sigma_t\right) \qquad (5)$$

where $Q(\ )$ denotes the Marcum-Q function defined as

$$Q(a) = \frac{1}{\sqrt{2\pi}} \int_a^\infty \exp\left(-x^2/2\right)dx$$

S is the signal-to-noise ratio, $2M$ is the dimensionality of the space of the detected optical field, σ_t^2 is the variance of the soliton arrival time and $2t_w$ is the detection window size.

For an optical soliton communication system with lumped amplifiers, a simple analytical expression was proposed for the optimal fibre dispersion which yields minimum bit error rate as [26]

$$D_{opt} = 3.2086 \frac{\tau\, t_w[1 + 0.5\sqrt{M/(X)}]}{\lambda^2 Z} \qquad (6)$$

where, $X = \sqrt{S/2}(t_w/\sigma_t)$, λ is the operating wavelength in μm and Z is the transmission distance in kms.

The maximum rate-distance product of the system is limited by the energy fluctuation and the timing jitter resulting from the accumulated ASE noise of the amplifiers. It was shown both analytically and by numerical simulation, that solitons can traverse great distances through a chain of lumped amplifiers connecting dispersion shifted fibre spans [7]. The fibre spans can also have large fractional variations. The resultant pulse distortions and dispersive wave radiation tend to be negligible, as long as the length scale of the variations in energy and dispersion are short relative to the soliton period.

The soliton propagation regime could prove the most appropriate for very high capacity systems even though the soliton system could appear complicated for the presence of optical filters which are used to avoid the Gordon-Haus effect and for the necessity of short amplifier spacing (L_a) to preserve the soliton nature [27]. The performance improvements of soliton links using lumped EDFA repeaters were evaluated from the view point of BER and the aspects for the upgrade of soliton

communication systems and the trade offs involved between the fibre parameters and the inter amplifier spacing were explored [28].

GVD compensation in in-line amplifier systems was evaluated from the view point of improving the transmission distance [29]. The NLSE was numerically solved to study the optical pulse propagation in the fibre and to clarify the optimum configuration for GVD compensation. It was shown that the optimum amount of GVD compensation is about 100% of the GVD experienced by the transmitted signal. The optimum compensation interval was found to be a function of the bit rate, signal power, and dispersion parameter. For dispersion parameter values ranging from -0.1 ps/nm/km to -10 ps/nm/km, and an amplifier noise figure of about 6 dB, the optimum compensation configuration can eliminate the GVD from in-line amplifier systems, thus improving transmission distances to those limited by SPM and higher-order GVD. The propagation behaviour of optical solitons in a distributed gain medium with finite bandwidth, such as EDFAs which are widely used as fibre amplifiers was studied [30]. The way the solitons react to energy losses depends strongly on the relative magnitudes of dispersion length L_D and amplifier spacing L_A. When $L_A << L_D$, a soliton is not distorted, despite energy losses [31]. The distributed amplification scheme is inherently superior to lumped amplification, since its use provides a nearly lossless fibre link. Numerical simulations show that distributed amplification scheme considerably benefits high capacity soliton communication systems. Fig. 5 shows the evolution of a fundamental soliton for lumped and distributed amplification using $L_A = 100 kms$ and $L_D = 50 kms$. Lumped amplification fails to maintain the soliton even over 500 kms where as soliton can propagate over a distance more than 5000 kms when distributed amplification is used.
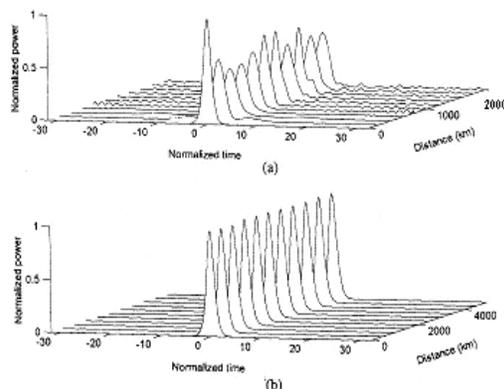

Fig. 5. Evolution of a fundamental soliton for (a) lumped (b) distributed amplification schemes [31].

The technique of synchronous regeneration of wavelength-division multiplexed (WDM) soliton signals opens up the perspective of transoceanic systems having 10-20 Gbit/s line rates and 80-160 Gbit/s aggregate capacities [80]. The principles of WDM signal synchronization were generalized to systems with dispersion slope compensation. Quantization and analysis of the WDM collisions were detailed for systems either with or without dispersion slope compensation (DSC). The potentials of the synchronous WDM soliton regeneration associated with exponential dispersion management were investigated in both cases through extensive numerical simulations of realistic transoceanic systems with up to 160 Gbit/s capacity. Moreover, such regenerated WDM soliton systems were proven to be robust to fluctuations of some key parameters of the system. These studies represent an assessment of the ultimate capacities of regenerated soliton transmission.

S. Kumar et. al obtained the optimal dispersion profiles for a WDM soliton system by minimizing the radiative noise and the collision induced frequency shift [82]. It was shown that the two step optimal profile with out dispersion slaving to the ideal exponential profile allows a large increase in the amplifier spacing with no significant deterioration of the system performance.

Ultra fast all-optical signal processing techniques are expected to play major role in future ultrafast single-carrier soliton systems, because they can remove the electronics bottleneck.

The influences of chromatic dispersion, coupling length, and soliton energy on the soliton robustness to Polarization-Mode Dispersion (PMD) were investigated numerically [33]. It was found that both chromatic dispersion and soliton energy have significant effects on the soliton robustness to PMD, and by optimizing chromatic dispersion and soliton energy, soliton pulse broadening can be depressed to within 10% even when the differential group delay is about twice the input pulse width. The BER degradation of conventional soliton systems due to PMD was investigated [34] by Chongjin et. al. It was found that the interplay between the dispersive waves generated by PMD and adjacent soliton pulses will seriously degrade the BER of soliton systems, and make them even worse than linear systems if all other transmission impairments are neglected. In order to achieve soliton robustness to PMD, some techniques to eliminate or reduce the dispersive waves must be employed, such as soliton control methods or dispersion-managed solitons.

Dark solitons were predicted as early as 1973 [85] by finding the solution to the equation (1) for the case of normal GVD($\beta_2 > 0$). Such solitons are characterized by an intensity profile with a dip in a uniform background, the term dark soliton is used to describe such pulses.

The application of self-similarity techniques to the study of nonlinear pulse propagation has been the subject of much recent interest in the context of parabolic pulse generation in optical fibre amplifiers with normal GVD. Such pulses also called optical similaritons, present a new class of solutions to NLSE with gain. They are asymptotically generated in the amplifier, independent of the shape or noise of the input pulse [87], and propagate self-similarly subject to exponential scaling of their pulse amplitude, temporal duration and spectral width [86].

A new method to generate dark soliton trains by exploiting the interaction between two time-delayed optical similaritons with the same wavelength [35] was proposed very recently by Christophe Finot et al. The temporal overlap of two similariton pulses creates a sinusoidal beating which subsequently evolves into an ultrahigh repetition-rate train of dark solitons through the combined effects of normal dispersion, nonlinearity, and adiabatic Raman gain. The experimental results were found to be in good agreement with numerical predictions. The dependence of the repetition rate of the dark soliton train on the time separation between the initial pulses, the initial pulse energy, and the Raman gain was investigated. The numerical study of the interaction between three similaritons of the same wavelength was carried out.

Y. J. He and H. Z. Wang demonstrated that soliton phase jitter can be efficiently suppressed by both Butterworth filters and nonlinear gain for ultra short solitons with higher-order effects, as well as for long duration solitons [36]. The nonlinear gain added to the system is to suppress not only background instability but also phase jitter, whereas the Butterworth filters are used to reduce both self-frequency shift and phase jitter. This scheme especially exploits a possibility for achieving a higher-speed soliton communication system using ultrashort solitons based on Differential Phase-Shift Keying (DPSK) and longer distance soliton communication systems based on DPSK [36].

Modulation instability is the well-known tendency in anomalous dispersion fibres for small variations in an almost constant power level to grow exponentially. Modulation instability is a nonlinear effect that can lead to temporal modulation of intense continuous wave laser fields. For an erbium doped fibre soliton laser, although it operates in the anomalous dispersion regime of the fibre used and a strong internal gain exits in it, because a soliton pulse is inherently stable against modulation instability, normally no modulation instability can be observed [4].

3. Experimental studies

Mollenauer succeeded in the first experiment of soliton propagation in optical fibre in 1980 [37]. Experimental demonstration of soliton propagation in long fibres with the loss being compensated by Raman gain was demonstrated by L. F. Mollenauer and R. H. Stolen [38]. It was proved that with sufficient gain to compensate for net fibre energy loss, a distortion less propagation of 10-ps FWHM pulses at a wavelength of 1560 nm over a 10 km length of single-mode fibre is possible and the same was demonstrated.

The fibre loss induced pulse broadening in long distance communication systems were counter balanced by amplifying the solitons periodically by using EDFA. This method was demonstrated experimentally by Suzuki et al. in 1990, when error free data transmission at 5 Gbit/s over a distance of 250 km using EDFAs as repeaters was reported [39].

In 1991, Nakazawa [40] demonstrated the remarkable stability of the optical soliton for 1 million km of transmission. Later in 1993 10 Gb/s optical signal was transmitted over 180 million kms and suggested that error free transmission is possible over unlimited distances [83]. In late 1991, Mollenauer [41] showed "error-free" transmission of solitons at 25 Gb/s for as long as 14, 000 km. Nakazawa demonstrated the stable transmission of optical signal at 10 Gb/s over 180 million km, and suggested that error-free transmission over unlimited distance was possible [42]

10 Gbits/s optical soliton transmission in a recirculation loop was demonstrated by S. Kawai et. al [8]. The signal frequency sliding technique was employed to reduce the accumulation of ASE noise and timing jitter. Error free (BER<10^{-9}) soliton transmission over 30000 km was achieved. F. M Mitschke and L. F Mollenauer experimentally studied the propagation of sub picosecond pulses through several lengths of single mode, polarization preserving fibre [3]. For 120-fsec pulses, a net self frequency shift as great as 10 % of the optical frequency was observed. The principle effect was much stronger and qualitatively different from those predicted. By means of Raman effect, there was a steady flow of energy from higher to lower frequency components of the soliton.

A femtosecond non-frequency shifted solitons with peak powers greater than 5 Mw was generated in a Xe-filled, hollow core, Photonic Band Gap Fibre (PBGFs) by Dimitre G. Ouzounov et. al. This was the first observation of temporal solitons with no self frequency shift. The PBGFs were made utilizing the standard techniques with a transmission gap in the near infrared region. The nonlinear and dispersion properties of these fibres were such that the dispersion in the transmission window was primarily anomalous and relatively large as compared to conventional glass fibres, which made the structure suitable for supporting solitons [45].

Hirokazu Kubota and Masataka Nakazawa presented the preemphasis method for soliton transmission [6]. Using preemphasis method the initial soliton pulse width could be preserved after propagation over long distance despite the existence of fibre loss. The key to success was the use of a combination of the dynamic range of the $N=1$ soliton, fibre loss, and lumped gain media which were installed into every soliton-width recovery length. It was shown that with lumped gain, the soliton pulse could propagate over more than 9000 km when the repeater spacing was 31 km and fibre loss was 0.22 dB/km [25]. It was found that for a given amplifier spacing, by increasing the input normalised pulse intensity up to a maximum of 1.4 the emphasis method was very successful in sending solitons over long distances. This system could be constructed with conventional optical fibres and rare-earth doped fibre amplifiers pumped by laser diodes. This method was a promising alternative to the Raman amplifier for soliton transmission which required relatively high pump powers.

The distributed erbium doped fibre amplifiers offered very attractive prospects for the realization of ultralong

lossless transmission lines. Use of ultralong dispersion shifted Erbium-doped fibre amplifier in soliton transmission was experimented by Nakazawa et al. during 1990 [43]. Distributed, dispersion-shifted EDFAs with doping concentrations as low as 0.1-0.5 ppm were fabricated and their gain characteristics were studied for the purpose of soliton amplification for the first time. A 9.4 km dual-shape-core type amplifier with a 0.5 ppm concentration had a gain of more than 20 dB at 1535 nm and 10dB at 1552 nm with a forward pumping configuration, and could successfully amplify and transmit a 20 ps soliton pulse train at 2.5 GHz repetition rate. Soliton transmission characteristics of an 18.2 km long fibre amplifier were studied using backward and forward pumping. It was found that A=1.5 soliton pulses with a pulsewidth of 20 ps could be amplified over 18.2 km at a repetition rate of 5 GHz, where soliton narrowing to 16 ps was observed.

An experimental observation of modulation instability in a passively mode-locked fibre soliton ring laser was reported in [4]. It was shown that due to modulation instability, dispersive waves of the laser could become unstable and consequently resulted in the generation of new spectral components in the soliton spectrum. Modulation instability was observed in the laser when dispersive waves of the laser became strong enough. Experimentally it was found that the strength of dispersive waves in the laser was the cavity energy in excess of the total soliton pulse energy. Before a new soliton pulse was created or an existing soliton pulse was destroyed, changing the strength of pump power could efficiently control the strength of dispersive waves in the laser. Fig. 6 shows typical soliton spectra observed in the laser. It was found that as the pump power was increased, new spectral components suddenly appeared in the soliton spectrum. Initially two new spectra were visible in the soliton spectrum, one appeared close to the centrum of the soliton spectrum, and the other one appeared near the high frequency sideband of the soliton spectrum. As the pump power was increased, other spectra also appeared in the soliton spectrum as shown in Fig. 6(c).

No significant changes in soliton pulse's peak power and duration were observed. This experimental result further confirmed that modulation instability affected only the dispersive waves of the laser and had no effect on the soliton pulses.

Raid de la Fuente and Alain Barthelemy had shown that spatial solitons were able to induce the stable guiding of a weak probe beam in a homogeneous Kerr type nonlinear media through XPM [77]. The modes of the induced waveguide were derived from the propagation equation of the probe. Experimental results were reported, demonstrating the stable confinement of a green probe beam induced by an IR spatial soliton. In the paper [32] by Sebastein et al., two all-optical devices, the Nonlinear Optical Loop Mirror (NOLM) and the Kerr Fibre Modulator (KFM), were used to achieve major functions related to high bit rate soliton links. At the interface with existing networks, conversions from data at the NRZ

format to RZ and soliton data, and vice-versa were required. These two conversions were demonstrated through NOLMs, and their limitations were investigated. The paper focuses on in-line soliton regeneration through synchronous modulation. All-optical modulation could be done either with intensity or phase modulators. They initially proposed the NOLM as all-optical intensity modulator. A modified configuration of the NOLM, having two optical controls, removed some limitations pertaining to the single-control configuration, yielding even higher performance. The other all-optical synchronous modulator considered was the KFM, which was a pure phase modulator. Its potential was demonstrated in a 20-Gb/s soliton transmission experiment, when driven by an optoelectronic optical clock generation device. Issues specific to the implementation of both types of all-optical fibre-based modulators were discussed. A true all-optical synchronous regenerator, combining all-optical clock recovery circuit and KFM, was tested in an actual soliton transmission experiment at 20 Gb/s.
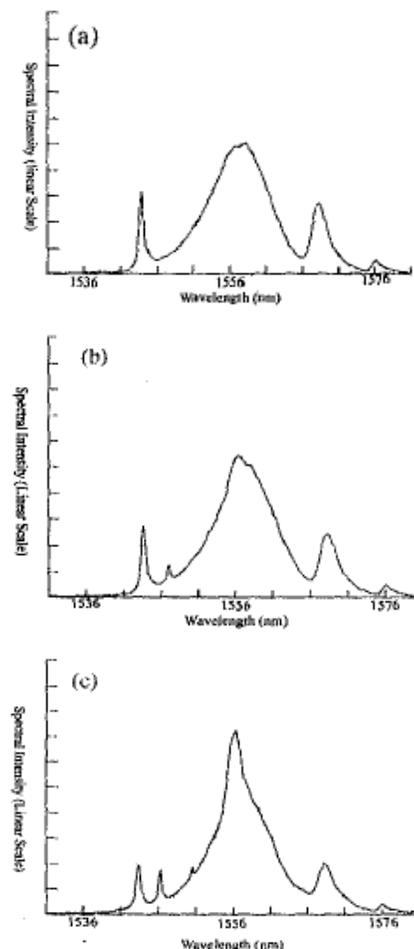

Fig. 6. Soliton spectra observed in the laser. a): Before occurrence of modulation instability. b) and c): under modulation instability [4].

F. Pitel et. al showed that the operating wavelength range of a 10 Gbit/s single channel soliton system using sliding-frequency guiding filters over a 18 Mm distance reduced from 1.3 to 0.2 nm, when the system was upgraded to 20 Gbit/s with a second wavelength channel [81]. An experimental study of 2×10 Gbit/s WDM soliton transmission, an error free distance > 18 Mm was achieved with a 0.17 nm margin for the multiplex. This margin extended up to 0.85 nm for 10 Mm propagation distance. In a simple WDM system configuration without dispersion management and after fine tuning optimisation of the multiplexed wavelengths a record error free distance in excess of 19 Mm was obtained.

It was shown that soliton propagation and spectral filtering can be used to reduce the intensity noise of solitons in optical fibres to below the quantum mechanical shot noise limit [79]. The experimental investigations of the use of soliton spectral filtering in the spatial domain was investigated. The transmission of solitons through a spectral filter after propagation was energy dependent leading to nonlinear input-output energy transmission relationship. By operating at zero slope points on the input-output curve it was possible to squeeze the noise of 2.7 ps solitons to 3.7 dB below the shot-noise level. Experiments with 160-fs pulses had demonstrated greater than 4.5-dB squeezing [79].

Soliton robustness to polarisation dispersion pulse broadening in a 400 km installed optical fibre was experimentally demonstrated by B. Bakhshi et al. [46]. With 10 ps input pulses and a differential group delay of 7.6 ps, the soliton pulsewidth at the receiver was maintained within 10–11 ps when the input polarisation was changed, while the corresponding range for dispersion-compensated linear pulses was 10.5–15.5 ps. In yet another work [47] they experimentally demonstrated a new technique for measurement of the differential group delay (DGD) in optical fibres using polarization-division multiplexed (PDM) solitons. The change in the separation of orthogonally polarized solitons propagating along different principal axes in a fibre equals the DGD at the signal wavelength was demonstrated. Based on this principle, they used PDM solitons to measure the accumulated DGD at different distances along a 400-km installed fibre. The measured DGD exhibited the expected square-root-of-length dependence, corresponding to a polarization-mode dispersion of $0.26\,ps/km^{1/2}$. The results were in excellent agreement with those obtained by a commercial instrument utilizing Jones matrix eigen analysis. This work showed that PDM solitons, which were proposed as a way to reduce soliton interaction, might in fact be inappropriate for real life communication purposes as the PMD induced change in the pulse separation might become too large.

Both numerical and experimental studies of groups of dissipative solitons in a fibre laser cavity were done by N. Akhmediev et. al. [44]. It was found that two solitons could be coupled into a stable pair that had a group velocity different from the velocity of a single soliton. The collision of the pair with a single soliton produced various scenarios. The collision destroyed the bound state and the formation of another pair of solitons moved way with the same velocity, leaving one of the solitons of the previously-moving pair at rest was observed. Soliton triplets were formed as a result of a collision [44].

C. Finot et. al carried out experiments for the generation of dark soliton train at high repetition rates [35]. They had also confirmed the evolutions of the repetition rate of the dark solitons as a function of the initial pulse temporal separation, pulse energy and integrated gain. These evolutions were both affected by the intrinsic properties of the similaritons and the relative velocities of the dark solitons. Although the experimental results were obtained using Raman amplification, it could be extended to other amplification process with normal dispersion, in the regime of adiabatic amplification.

Period-doubling of dispersion-managed solitons in an Erbium-doped fibre ring laser operating at the near zero net cavity group velocity dispersion region was experimentally observed by L. M. Zhao et al. [78]. The generated dispersion-managed solitons of the laser were characterized by their near Gaussian spectral profiles and had no sidebands. Numerical simulations were carried out to verify the experimental observations and it was shown that the period-doubling could occur both in the positive and negative near zero net cavity group velocity dispersion regions, which suggested that the occurrence of the period-doubling was an intrinsic feature of the mode-locking fibre lasers and was found to be independent of the concrete mode-locked pulse profile.

4. Issues in soliton transmission using

Lumped EDFA repeaters

Several issues were found to influence the performance of soliton link using lumped EDFA repeaters. In order to compensate for the loss of the fibre, a common technique is to use the silica fibre doped with rare-earth ions and pumped optically to realize the optical gain. But such amplification schemes introduce noise to the signal which degrades the Signal to Noise Ratio (SNR), thus imposing a fundamental limit on the system bit error performance. ASE noise present in doped fibre amplifiers cause fluctuations in the central carrier frequency of soliton. This leads to a random fluctuation in the soliton arrival time (GH jitter) which deteriorates BER performance.

For high bit rate transmission, the use of ultra short pulses induce higher order effects like the higher order dispersion, self steepening and the SSFS. One of the factors limiting the full utilization of bandwidth offered by the soliton communication system is the interaction between adjacent soliton pulses. In the femtosecond regime, a slight difference between the amplitude of two solitons causes a significant change in the soliton-soliton interaction as a result of SSFS. The non instantaneous response of the nonlinear medium that is the SSFS causes amplitude asymmetry between two adjacent solitons and

also modifies the soliton interaction. In order to minimize the soliton – soliton interaction, it becomes necessary to keep the temporal pulse separation below five times the width of the pulses [63].

For handling more channels it is necessary to achieve wavelength division multiplexing using optical solitons by propagating different carrier frequencies through a channel. The lower order nonlinearities in such systems manifests as Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) which involves multiple channel interfering with each other.

In soliton links using lumped EDFA repeaters, the gain of the amplifiers is set exactly equal to the fibre loss between the amplifiers. The gain of such amplifiers is to be kept stable using optical feed back methods, otherwise leads to link instability resulting in vanishing of fundamental solitons or appearance of higher order solitons.

Issues and challenges faced in the performance improvements of soliton links and the efforts for minimizing the adverse effects over the last few decades are discussed below.

4.1   Soliton self frequency shift

High speed communication system involves sub picosecond or femtosecond soliton transmission and the spectrum of the soliton pulse becomes so wide (> 5 THz) that ISRS can take place.
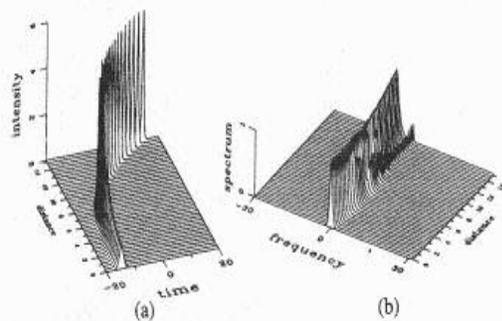

Fig. 4. Soliton amplification for $T_0 = 100 fs$ showing the effects of Raman - induced frequency shift on (a) pulse shape and (b) pulse spectrum (Ref. [1]).

The main effect of ISRS is to transfer energy from the high frequency components to the low frequency of the same pulse [48]. Therefore, the pulse spectrum is shifted towards longer wavelengths as soliton propagates through the fibre. This shift in the carrier frequency reduces the group velocity and slows down the soliton. Fig. 4 shows the effects of SSFS in both the time and frequency domains.

A solution to the SSFS was suggested by Ferreira, Mario F. S. [19]. The SSFS was compensated by the frequency dependent gain in Distributed Fibre Amplifiers (DFA) leading to what is known as soliton trapping.

Adiabatic soliton trapping was observed under the effect of nonresonance between the carrier and the maximum gain frequency [20]. The pulse width of the soliton became narrower with a moderate optical gain, which can be realized for distributed fibre amplifiers. By increasing the gain destroyed the trapping of soliton pulse and the carrier frequency of the soliton began to increase due to SSFS. Also the soliton amplitude increased with propagation distance to a point where SSFS dominated. At this point, the soliton trap was broken and the carrier frequency drifted away from the centre line. This frequency drift can be compensated for by the linearly frequency-dependent term.

Adiabatic soliton trapping was observed due to the frequency-dependent gain in fibre amplifiers [21]. The soliton pulse width was practically unaffected by the non resonance of the carrier frequency, while the soliton self-frequency shift became very sensitive to this non resonance. It was shown that the effective component of the gain spectrum for the SSFS compensation was the linearly frequency dependent gain with a positive slope and an optimal compensation condition was identified. The stability of the steady state solution for the perturbed NLSE was also studied using phase-plane formulae. The combined effects of inter pulse Raman scattering and XPM from a pump pulse on the propagation of picosecond signal pulses in an optical fibre was studied by C. S. Aparna et. al. [49]. It was shown that although interpulse Raman scattering can suppress the frequency downshifts, it is XPM that has a more significant effect. They made a more complete and accurate study of the effects of a pulsed pump on the propagation of the signal, considering the effects of XPM, SPM and ISRS. A new expression for XPM in the presence of Raman scattering was derived. The co propagation of a bright and dark pulse in the so-called reverse or inverted case, in the presence of Raman scattering was also studied. A dark pulse was seen to stabilize the bright pulse against the frequency downshifts.

4.2   Gordon-Haus Jitter

For a soliton transmission system which uses lumped optical amplifiers with a fixed amplifier spacing and a fixed bit rate, the optimum input pulse width and input amplitude were presented by H. Kubota and M. Nakazawa to maximize the soliton transmission distance [50]. In a 10 Gbits/s soliton system with a repeater spacing of 40~50 km, a pulse width of 20ps, and normalized amplitude of about 1.4 ~1.8, the limitation owing to mutual soliton interaction was negligible compared with that resulted from the interaction between the amplifier noise and the soliton pulse, and the soliton pulse could propagate up to the Gordon-Haus (GH) limit [7].

In long distance optically amplified soliton communication systems, the limit to channel bit-rate arises from timing jitter in the soliton arrival times due to the GH effect [27]. Error free, single-channel, soliton data transmission at 10 Gb/s over ultra-long distance were achieved by incorporating in-line components to control

the effects of amplifier noise [51-52]. In the case of unlimited propagation, soliton transmission control was implemented using a combination of fixed frequency filters and synchronous modulators [53]. In the other experiment GH jitter was suppressed by sliding frequency, guiding filters [54], whose inclusion was demonstrated to be compatible with wavelength division multiplexing unlike that of synchronous modulation. In straight-line systems, however, both these approaches had implementation problems associated with the remote control and reliability of the required in-line components.

An alternative, non system-invasive technique for GH jitter reduction was based on post-transmission dispersion compensation [55]. This technique took the advantage of the dependence of GH jitter on the sign of dispersion to reverse its growth at the end of a transmission line by appending a dispersion compensating element. However, the potential jitter reduction was limited by associated pulse broadening, to a small fraction of the improvements available through in-line techniques [55].

Dispersion compensation was one method of equalization for propagation effects in linear lightwave systems. An alternative equalization scheme utilizes Optical Phase Conjugation (OPC) midway down the system span [56-57]. There was considerable interest in the latter technique, particularly with regard to short-haul propagation in standard, step-index fibre [58-61]. Moreover, recently it was pointed out that mid-system OPC is equally applicable to long-haul systems [62] and in particular, that it could compensate for composite dispersive-nonlinear effects. Consequently it was suggested that the potential capacities of all optical non soliton light wave systems could be increased, using mid-system OPC, to rival the demonstrated capability of soliton systems. However, since the governing propagation equation is identical, mid-system OPC was equally applicable to long haul, soliton lightwave systems and it was demonstrated that within the domain of validity of the average soliton model [62,24], mid-system OPC could reverse soliton interactions and reduce rms GH jitter by one-half. W. Forysiak and N. J. Dorau considered in great detail the effect of OPC on GH jitter in long-haul, soliton communication systems, including in a simple way the effects of finite conjugator efficiency [64]. The effect of optical conjugation on GH jitter in long-distance soliton communication systems was considered. In-line optical phase conjugation at an optimal point two-thirds of the way down the system reduced the rms jitter by a factor of three. A post-transmission-line compensation scheme based on optical phase conjugation and soliton-supported dispersion compensation reduced the rms jitter by a factor of two.

4.3 Soliton - soliton interaction

One of the important issue which affects the performance of a high speed soliton based system is adjacent soliton-soliton interaction [13]. Analysis of femtosecond soliton interactions in a lossless transmission line, was done by Kenji Kurokawa et al. in 1994. [65] Fig. 4 shows waveforms and spectra of output pulse pairs under inphase condition. The input pulses are $N = 1$ solitons with a pulse width of 400 fs. When the input pulse pair was in phase, soliton interaction (collision) occured at around $Z/Z_{sp} = 6$ as shown in Fig. 5, where Z_{sp} is the soliton period. It was found that when soliton interaction occurred, the output pulse narrowed and the spectral width broadened. Pulse narrowing due to the soliton interaction greatly accelerated the SSFS. The SSFS is clearly seen in the longer wavelength region. The narrower soliton with a higher intensity at $Z/Z_{sp} = 20$ had a longer wavelength carrier, and two solitons propagate with different frequencies. After the interaction, the output pulse separation increases along the fibre because of the different group velocities, as shown at $Z/Z_{sp} = 20$ in Fig. 5. Nakazawa et. al presented numerical simulations of the 80 Gbit/s soliton transmission experiment operating in a regime beyond average soliton limit and pointed out that the dispersive waves and soliton interaction limited the total transmission distance to ~500 kms in agreement with experimental results [67].
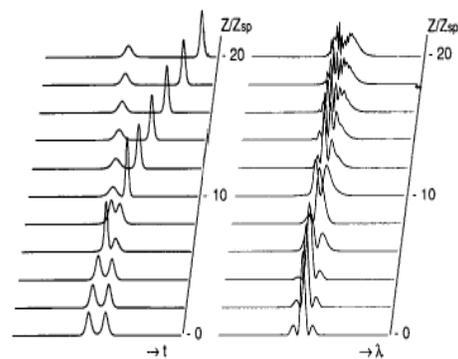

Fig. 5. Femtosecond soliton interaction with the SSFS under in phase condition in a lossless transmission line [65].

The limitations to the maximum transmission capacity in a long distance soliton transmission system with sliding guiding filters were studied in the year 1993 [66]. It was shown that sliding the centre frequency of the filters may substantially stabilize the soliton even in the case of strong resonance overlap with the radiation that originates from the periodic amplification. This permitted a considerable reduction of both the minimum pulse width and pulse-to-pulse separation in the transmission.

High bit rate, soliton-based lightwave systems are attracting considerable interest as they are expected to significantly increase the capacity of fibre-optic communication links. However, until 1993 [67], stable transmission of solitons was achieved in the so called average-soliton [68] (or guiding centre-soliton [69]) regime characterized by the amplifier spacing being much smaller than the soliton period. Higher bit rates with practical amplifier spacing required the use of shorter solitons having a soliton period shorter than the amplifier

spacing. In such a case the concept of average solitons is not valid for describing soliton propagation as 'quasi-adiabatic'. Numerical simulations proved that the system performance was affected not only by soliton-soliton interaction but also by the interaction between solitons and dispersive waves [70].

Two ways of improving the system performance were presented and discussed [70]. The use of fast saturable absorbers could eliminate interaction between solitons and dispersive waves and increase the transmission distance above 1000 km. It was found that the soliton-soliton interaction could be made virtually ineffective by using synchronous modulation. Such a lightwave system could transmit a high bit-rate (50-100 Gbit/s) soliton signal over transoceanic distances while keeping amplifier spacing larger than the soliton period.

4.4   Amplifier gain stability

In a soliton link using lumped EDFA repeaters the EDFA gain is set equal to fibre loss between two successive repeaters. The gain of such amplifiers are to be stabilized using optical feedback methods. The amplifier gain fluctuation can lead to dispersive wave radiation which in turn will deteriorate the BER performance. It had been reported in the literature that environmental temperature affects EDFA gain [72]. An analytical approach to describe the light pulse amplification using resonant pumped Erbium Doped Fibre Amplifiers (EDFAs) by incorporating the temperature dependence of gain was proposed in [73]. Models based on rate equations fail when the light pulse width becomes very narrow and comparable to the dipole relaxation time. The model which describes the amplification of light pulses ranging from sub picoseconds to hundreds of picoseconds is based on Maxwell-Bloch equations [74]. Light pulse amplification in resonant pumped Erbium doped fibre was described by incorporating temperature dependence of gain using modified Max-Bloch equations [73].

In multigigabit, long distance soliton links, the gain fluctuations were suppressed to very low desirable levels using optical feedback methods. This is to prevent the link instability due to the vanishing of the fundamental soliton or the appearance of the soliton of higher order depending on whether cumulative effect of gain fluctuations leads to a decrease or an increase of power level in the link.

4.5   The influence of other nonlinear effects

FWM is a nonlinear process arising from a Kerr type nonlinearity in which three waves interact through the third-order electric susceptibility of the optical fibre to generate the fourth wave with a new frequency. FWM in fibre may be very strong due to large field intensities in the core and the long interaction length. FWM is likely to occur in a high bit-rate signal transmission system and had been extensively studied [71,75]. The dispersion-shifted fibre, while allowing high-bit-rate channels to be transmitted over long distance, enhances the efficiency of generation of FWM waves by reducing the phase mismatch naturally provided by the fibre dispersion. For this reason FWM is the important non-linear effect in long-haul WDM system using dispersion-shifted fibre especially in soliton WDM system in which the nonlinearity is utilized.

FWM in a soliton WDM communication system with cascaded lumped amplifiers was studied [75]. The performance degradation of the middle channel caused by the crosstalk was investigated through theoretical analysis and numerical calculation. The results showed that the influence of FWM on a soliton system was different from that on a conventional communication because of the dominant nonlinear feature in soliton communication systems.

The nonlinear contribution to the refractive index, essential for the propagation of solitons, also gives rise to XPM between two overlapping waves of different frequencies (and/or different polarizations) during their common propagation. Thus, a strong wave (the pump) is able to induce a phase shift on a weaker one through XPM when they simultaneously propagate in a Kerr-type nonlinear medium. The resulting effects that have already been considered mainly concerned with propagation of short pulses in fibres with modification of the probe pulse spectrum, temporal shape, or polarization. The occurrence of induced transverse modulation instability and induced focusing had been predicted for focusing as well as for defocusing nonlinear materials. Recently it was shown that through XPM, two superimposed soliton beams of identical size but different colour can propagate as a pair of stationary solitary waves if certain relationships between their respective intensity and wavelength were satisfied [76]. Raid de la Fuente and Alain Barthelemy had shown that spatial solitons were able to induce the stable guiding of a weak probe beam in a homogeneous Kerr type nonlinear media through XPM [76]. The modes of the induced waveguide were derived from the propagation equation of the probe. Experimental results were reported, demonstrating the stable confinement of a green probe beam induced by an IR spatial Soliton [77].

The wavelength division multiplexed optical soliton had made way to the next generation optical high capacity optical communication systems. The WDM solitons were strongly affected by inter channel collisions, as the different channels travel at different velocities [83]. These different wavelengths hence overlap periodically along the transmission length. During the collisions nonlinear effects like XPM and FWM induced frequency shifts to the soliton pulse which were converted into timing jitter. The collisions were particularly important in lumped amplification schemes because it could   lead to asymmetric collisions which were an important source of timing jitter. Hence it was necessary to have a collision management scheme for WDM solitons systems [83]. Three techniques were implemented for collision management, through the introduction of an initial delay among pulses of different channels, optimization of channel spacing and amplifier spacing.

5. Conclusion

Theoretical investigations and experimental studies in the area of soliton based fibre optic communications are presented in this paper. The issues and challenges involved in realizing multigigabit long distance soliton links are reviewed. The research progress which explores the impact of non linear effects in the performance of single and multichannel (WDM soliton systems) systems are discussed.

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