LIMITING FACTORS IN OPTICAL WDM SYSTEMS

2.1 INTRODUCTION

This chapter describes the transmission limitations of optical WDM systems using inline optical amplifiers imposed by fibre nonlinearities, optical amplifier noise and fibre dispersion. The main nonlinearities such as stimulated scattering, four wave mixing and carrier induced phase modulation have been discussed. Amplifier noise and polarization mode dispersion have also been detailed.

2.2 FIBRE NONLINEAR EFFECTS

An optical effect is known as nonlinear when its parameters depend on light intensity (power). Fibre nonlinearities are important in optical communications, both as useful attributes and as characteristics to be reduced. These must be considered while designing long-haul high-data rate systems in which signals at multiple wavelengths are transmitted (WDM systems). The consequences of nonlinear transmission can include (1) the generation of additional signal bandwidth within a given channel, (2) modifications of the phase and shape of pulses, (3) the generation of light at other wavelengths at the expense of power in the original signal, and (4) crosstalk between signals at different wavelengths and polarizations, resulting in system degradations (Bass et al, 2001).

The low loss and long interaction length of an optical fibre makes it an ideal medium for stimulating even relatively weak scattering processes. Two important stimulating processes in fibres are: (1) Stimulated Raman scattering (SRS), the interaction of the guided wave with high frequency optical phonons in the material, and (2) Stimulated Brillouin scattering (SBS), the emission, amplification and scattering of low frequency acoustic waves. In four wave mixing (FWM), two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths. An optical nonlinearity that affects only the phase of the propagating signal is the nonlinear refractive index of the fibre material, and it gives rise to carrier induced phase modulation (CIP). In single channel configurations CIP is called self phase modulation (SPM) and converts optical power

fluctuations in a light wave to phase fluctuations in the same wave. In wavelength-multiplexed systems it is called cross phase modulation (XPM) and converts power fluctuations in a particular channel to phase fluctuations in the other channels (Chraplyvy, 1990). XPM is similar to SPM, except that two overlapping but distinguishable pulses (having, for instance, different frequencies or polarizations) are involved.

2.2.1 Stimulated Raman Scattering (SRS)

Stimulated Raman scattering (SRS) is an interaction between light and vibrations of silica molecules which causes frequency conversion of light and results in excess attenuation of short-wavelength channels in wavelength multiplexed systems. SRS is one of the significant nonlinear effects in dense wavelength division multiplexed (DWDM) based fibre communication systems. In it, the coupled light in the fibre interacts with the molecular vibrations, due to which scattered light is generated at a wavelength longer than that of the coupled light. If another signal is also present having this longer wavelength, it undergoes amplification at the expense of the original signal. This leads to the degradation of the Signal to Noise Ratio (SNR) and hence the overall system performance.

The gain coefficient of SRS increases approximately linearly with pump-probe frequency separation up to a separation of about 500 cm^{-1} [1 cm^{-1}=30 GHz]. This means that the channels which are separated by less than 15000 GHz will be coupled via SRS. In case of single-channel lightwave system only one wavelength of light is injected into the fibre. However, spontaneous Raman-scattered light is generated by this signal which can be amplified. It is known that SRS will not be a factor in single channel silica fibre based light wave systems. In wavelength-multiplexed systems the situation is poles apart because channels at different wavelengths are injected into the fibre and the signals at longer wavelengths will be amplified by the shorter wavelength signals. In other words, the probe photons no longer build up from spontaneous Raman noise but are injected in macroscopic quantities as signal channels. This leads to system degradation at lower optical powers than in the single-channel case (Chraplyvy, 1990).

Accurate evaluation of amplification and depletion of optical power due to SRS effect is required. The critical power level at which SRS degrades system performance is given by (Mynbeav and Scheiner, 2006, Agrawal, 2002):

$$P_{th} = 16 A_e / g_R L_e ----(2.1)$$

Where A_e is the effective area of the fibre,

g_R is the gain of Raman scattering having typical value of about 1×10^{-13} m/W at wavelength of 1550nm

and L_e is the effective length of the fibre (km) which is calculated by:

$$L_e = \frac{(1 - \exp(-aL))}{a} ----(2.2)$$

here L is the actual fibre length in km and,

a is fibre loss coefficient in nepers and given by $\alpha/4.343, \alpha$ being wavelength independent fibre loss coefficient in db/km at centre wavelength.

The effect of SRS in DWDM fibre optic system has been treated by many authors under various assumptions. Singh and Hudiara (2004) have given model to calculate SRS without any assumptions ignoring walk off effects given as hereunder:

$$Pm[k] = Pt[k] - Pt[k] \sum_{i=k+1}^{N} D[k,i] + \sum_{j=1}^{k-1} (Pt[j]D[j,k]) ----(2.3)$$

$$for\ k = 1,2,3 \cdots N$$
$$D[k,i] = 0 \quad for\ i > N$$
$$D[j,k] = 0 \quad for\ k = 1$$

$$\left. \begin{array}{l} D[i,j] = \left(\frac{\lambda j}{\lambda i}\right) Pt[j] \left\{ \frac{(fi - fj)}{1.5 \times 10^{13}} \right\} g_{r\max} \left\{ \frac{Le(\lambda j) \times 10^5}{b \times Ae} \right\} \\ \qquad for\ (fi - fj) \leq 1.5 \times 10^{13}\ Hz\ and\ j > i \\ D[i,j] = 0 \\ \qquad for\ (fi - fj) > 1.5 \times 10^{13}\ Hz\ and\ j \leq i \end{array} \right\} ----(2.4)$$

In the equation 2.3, first term gives the total power transmitted to the kth channel, second term gives the total power depleted from the kth channel by the higher wavelength channels and third term indicates the total power received by the kth channel from the lower wavelength channels.

In equation 2.4, g_{rmax} is peak raman gain coefficient (cm/W)

λj, λi are the wavelengths (nm) of jth and ith channels

fi, fj are the centre frequencies (Hz) of the ith and jth channels

A_e is effective core area of optical fibre in cm^2

$L_e(\lambda j)$ is wavelength dependent effective length in Km

and value of *b* varies from 1 to 2 depending upon the polarization state of the signals at different wavelength channels.

For high bit rates and non-zero group velocity dispersion the effects of SRS are reduced by a factor of 2 (Chraplyvy, 1990). SRS arises from a third-order nonlinear susceptibility which has a sub pico second time constant. As this is essentially instantaneous compared to modulation rates in optical systems, the SRS effects will be the same for both the modulated as well as continuous wave (CW) light.

2.2.2 Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin scattering (SBS) is an interaction between light and sound waves in the fibre, and causes frequency conversion and reversal of the propagation direction of light. SBS can yield an even lower stimulated scattering threshold. Acoustic waves in the fibre tend to form a Bragg index grating, and scattering occurs primarily in the backward direction. The Brillouin gain is much higher than Raman gain in fibres. Apparently, SBS is similar to SRS, with a difference that the former involves sound waves rather than molecular vibrations.

Actually, both scattering processes are three wave processes in which the incident (pump) light is converted into light of longer wavelength (Stokes) with a concomitant excitation of a molecular vibration (SRS) or an acoustic phonon (SBS), though there are a number of significant differences between SBS and SRS that lead to markedly different systems consequences. First, the peak SBS gain coefficient in single-mode fibres is over three orders of magnitude larger, that is $g_B = 5 \times 10^{-11}$ m/W (Bass et al, 2001), than the gain coefficient for SRS and under the proper conditions SBS will be the dominant nonlinear process. Second, the optical-gain bandwidth for SRS is of the order of 6000 GHz. Therefore, there is essentially no reduction in Raman gain for pump lasers with large linewidths. The optical bandwidth for SBS in silica is about 20 MHz at 1.55 μm**.** Maximum SBS gain will occur for pump lasers with linewidths less than 20 MHz (Chraplyvy, 1990).

In a single channel the critical power level at which SBS degrades system performance is (Mynbeav and Scheiner, 2006, Vengsarkar, 1998):

$$P_{th} = 21A_e / g_B L_e ----(2.5)$$

Where A_e is the effective area of the fibre,

L_e is the effective length of the fibre

and g_B is the gain of Brillouin scattering.

Due to high value of g_B as compared to g_R the threshold value at which SBS degrades the performance of the system is much less that SRS. Luckily, SBS occurs for a very narrow band of frequencies, hence the damage is reduced. To summarize the discussion, SBS is a strong nonlinear process that exhibits gain in the backward direction. This nonlinearity is most injurious in systems employing narrow bandwidth lasers. In general, encoding pseudorandom data on the optical wave will reduce the effects of SBS. The SBS gain decreases with increasing bit rates (Chraplyvy, 1990).

Stimulated scattering increases fibre attenuation at a high level of transmitted power. SRS has a negligible impact on single channel systems but becomes important for WDM systems. By contrast, SBS is a problem for a single channel system but has almost no effect on WDM systems (Mynbeav and Scheiner, 2006).

2.2.3 Four Wave Mixing (FWM)

In the SRS effect the optical fibre plays an active role through the participation of molecular vibrations. However, in the case of FWM, optical fibre plays a passive role, that is, it simply mediates the interaction among several co-propagating optical signals. In the case of WDM systems, a number of optical waves co-propagate at different wavelengths. Because of the FWM effect, three co-propagating optical signals of frequencies say f_i, f_j and f_k interact and generate a fourth signal at frequency f_{ijk}, where $f_{ijk} = f_i + f_j - f_k$. So in WDM systems many such signals co-propagate with the original signals and grow at the expense of the original signals. This phenomenon is known as FWM and is due to nonlinear response of a dielectric medium (optical fibre) to the intense light (Forghieri et al, 1995).

These newly generated signals can interfere with the original signals if there happens to be some frequency match between them, which leads to cross talk and degradation of the system performance. Probability of this frequency match increases if the channels are equally spaced (Forghieri et al, 1994 a, 1994 b, 1995, Hamazumi et al, 1996). The efficiency of FWM depends on the channel spacing and the fibre dispersion. The interacting and generated waves have different group velocities due to fibre chromatic dispersion. This destroys the phase matching of the interacting waves and lowers the efficiency of power generation at new frequencies (Chraplyvy, 1990). The FWM efficiency decreases with increasing group velocity mismatch. As a result, larger channel spacing and greater group velocity dispersion lead to lower efficiencies. Effect of FWM is even more rigorous in the systems with inline amplification, because due to inline amplification the effective length of the fibre, over which nonlinear interaction takes place, increases.

FWM power generated at the frequency f_{ijk} in this case, that is, with inline amplifiers, is (assuming equal signal power P launched in all the wavelength channels) as under (Maeda et al, 1990, Mahony et al, 1995):

$$P\left(f_{ijk}\right) = k^2 P^3 e^{-a.l} \left[\frac{\{(M+1)L_e\}}{A_e} \right]^2 \eta_{ijk} d_{ijk}^2 \; ----(2.6)$$

$$where \, k = \frac{32 \Pi^3 X}{n^2 c \lambda}$$

$$\eta_{ijk} = \left[\frac{a^2}{\left(a^2 + \Delta\beta_{ijk}^2\right)} \right] \times \left[1 + \left\{ \frac{4e^{-al}}{\left(1 - e^{-al}\right)} \right\}^2 \right] \times \sin^2\left(\frac{\Delta\beta_{ijk} l}{2} \right) ----(2.7)$$

$$\Delta\beta_{ijk} = \left(2\pi\lambda^2 / c\right)\left(\left|f_i - f_k\right|.\left|f_j - f_k\right|\right)\left\{D + dD/d\lambda(\lambda^2 / 2c)\left(\left|f_i - f_k\right| + \left|f_j - f_k\right|\right)\right\} ----(2.8)$$

Where n is refractive index of the fibre

λ is centre wavelength

c is velocity of the light

X is third order nonlinear electric susceptibility

P is power injected in the channel

M is number of amplifiers

l is the optical amplifier spacing

L_e is the fibre effective system length of single amplifier spacing

A_e is effective area of fibre

d_{ijk} is degeneracy factor

$\Delta\beta_{ijk}$ is phase mismatch factor

D is dispersion of fibre

$dD/d\lambda$ is dispersion slope

and ηijk is FWM efficiency.

In the conventional fibre only channels with separations less than 20 GHz will mix efficiently. On the other hand, in dispersion-shifted fibres FWM efficiencies are greater than 20% for channel separations up to 50 GHz. The effects of FWM are bit rate independent (Chraplyvy, 1990).

2.2.4 Self Phase Modulation (SPM)

Self-phase modulation (SPM) is able to occur every time a signal having time-varying amplitude is propagated in a nonlinear material. The origin of the effect is the refractive index of the medium, which will change with the instantaneous signal intensity. The refractive index of most transparent solids, including silica, has the form (Chraplyvy, 1990):

$$n = n_0 + n_2 I ----(2.9)$$

where n_o is the ordinary refractive index associated with the material

n_2 is the intensity-dependent refractive index

and I is the optical intensity.

Hence the phase of light after propagating through a fibre with length L (relative to the phase of the injected light) and effective length L_e is (Chraplyvy, 1990):

$$\phi(L) = \frac{2\pi n_o L}{\lambda} + \frac{2\pi n_2 I L_e}{\lambda} ----(2.10)$$

Any changes in optical intensity (I) will produce corresponding changes in the phase and can effect phase shift keying (PSK) systems. Even though the refractive indexes are very small in silica, the long interaction lengths in optical fibres magnify these effects.

In single channel systems the phase change in the received signal due to the nonlinear refractive index is given by (Chraplyvy, 1990):

$$\sigma_\phi = 0.035\sigma_p \ {-}{-}{-}{-}(2.11)$$

where σ_ϕ is the rms phase fluctuation in radians

and σ_p is the rms power fluctuation in milliwatts.

Power fluctuations in InGaAsP injection lasers are quite small (Liu et al, 1983), and increase roughly as the square root of the optical power (Yamamoto et al, 1983). Even for transmitter powers up to 100 mW the power fluctuations (σ_p) will be less than 1 mW. The resultant phase noise is less than 0.04 rd, which is negligibly small in angle-modulated systems (0.15 rd of phase noise corresponds to a power penalty of roughly 0.5 dB) (Prabhu, 1976, Chraplyvy, 1990).

2.2.5 Cross Phase Modulation (XPM)

In wavelength multiplexed systems, in addition to self phase modulation, there are cross phase modulation effects due to power fluctuations in other optical channels. When several optical pulses propagate within a fibre simultaneously, the nonlinear phase shift of first channel depends not only on the intensity (power) of this channel but also on the signal intensities of the other channels.

In a system with N channels, the rms phase fluctuations in a particular channel due to power fluctuations in the other channel are given by the following expression (Chraplyvy, 1990):

$$\sigma_\phi = 0.07\sqrt{N}\sigma_p \ {-}{-}{-}{-}(2.12)$$

where σ_ϕ is in radians and σ_p is in milliwatts. The power fluctuations in all the channels have been assumed to be the same.

XPM degrades the system performance in the same way as SPM; chirping frequency and chromatic dispersion. As is clear from the expressions XPM can damage the system even more than SPM. However by keeping chromatic dispersion low, the effect of XPM can be reduced to negligible values. XPM essentially depends on the transmission technology,

that is, modulation and detection techniques. XPM is a serious limitation in coherent systems.

Like SRS, a third order electric susceptibility gives rise to SPM and XPM. Hence these are essentially instantaneous effects and apply to both continuous and modulated wave. CIP is not a significant nonlinearity in PSK systems using external phase modulators. This affects only the phase of optical signals. Hence only angle modulated systems will be affected by this nonlinearity (Chraplyvy, 1990).

Each of these nonlinear effects will affect specific lightwave systems in different ways. However, SRS, SBS and FWM will deplete certain optical waves and due to frequency conversion, will generate interfering signals for other channels. This will degrade both direct detection and heterodyne systems. SBS will degrade passively multiplexed systems with few channels more adversely than the systems with many channels. On the other hand, CIP affects only the phase of the signals and not a significant nonlinearity in the systems having external phase modulators. Among all these nonlinearities, FWM and SRS are expected to be the dominant nonlinear effects in the amplifier WDM systems with the intensity modulation-direct detection (IM-DD) scheme (Chraplyvy, 1993, Sekine et al, 1994, Taga et al, 1994, Yu and Mahony, 1995).

2.3 OPTICAL AMPLIFIERS

Optical amplifiers have emerged as key elements for optical direct detection systems. The long-established way of compensating for optical loss in lightwave systems has been the exhausting method of regeneration. Regeneration includes photon-electron conversion, electrical amplification, retiming, pulse shaping and back to electron-photon conversion (Olsson, 1989). In many applications direct optical amplification is more beneficial. Optical amplifiers can be used in any system that is loss limited. There are two main types of optical amplifiers: semiconductor and fibre. The most thriving is the erbium doped fibre amplifier (EDFA), a category of fibre amplifier. The advent of EDFAs accelerated the pace of deployment of high capacity lightwave systems (Giles and Li, 1996). EDFAs have attracted significant attention because of features such as polarization-independent gain, low noise and very low coupling losses (Giles et al, 1989, Rasmussen et al, 1991).

High performance of EDFA has been the major factor in developing long distance transmission systems. These amplifiers can boost the power of lightwave signals without the need of optoelectronic conversion followed by electronic amplifications as in conventional lightwave repeaters. This simple but elegant function is independent of the operating data rate and can simultaneously accommodate many WDM channels.

In amplified fibre systems, fibre loss limitation is overcome by periodically spaced inline optical amplifiers. An optical amplifier magnifies the signal noise along with the signal itself. To make the situation even worse, it generates its own noise as well (Mynbeav and Scheiner, 2006). Amplified spontaneous emission (ASE) is the dominated factor in the generation of noise by an optical amplifier. The majority of excited carriers are made to fall to the lower level by stimulated emission. However, some of these carriers fell down to lower level spontaneously. In the process of decay, these carriers radiate photons spontaneously. These spontaneously emitted photons are in the same frequency range as the transmitted signal, but their phase and directions are random. The spontaneously emitted photons that are in the same direction of as that of the transmitted signal are amplified by an active medium. These spontaneously emitted and amplified photons compose amplified spontaneous emission. As these are random in phase, they do not contribute to the information signal. The problem is that they generate noise within the bandwidth of the signal (Mynbeav and Scheiner, 2006).

2.3.1 Amplified Spontaneous Emission (ASE) Noise

Inline optical amplifiers generate ASE noise, which is propagating along the fibre together with the signal. The total amount of ASE noise power at the receiver increases with the number of inline optical amplifiers. The influence of ASE noise has been studied by a number of authors (Giles et al, 1989, Olsson, 1989, Marcuse, 1990, Humblet and Azizoglu, 1991, Yu and Mahony, 1995, Giles and Li, 1996). It has been renowned that for long-distance amplified transmission systems where numerous inline optical amplifiers are used, the dominant noise source is ASE noise and thus bit-error rate (BER) performance is mainly determined by optical signal to noise ratio (defined as the ratio of optical signal power to ASE noise power after pre detector optical filtering) rather than the received signal power as in conventional systems without inline optical amplifier repeaters (Marcuse, 1990, Humblet and Azizoglu , 1991).

It is necessary to maintain certain level of optical signal power to ensure a certain SNR and hence a particular BER ratio. In long-distance amplified systems, where ASE noise dominates other noise sources such as shot noise and thermal noise, the required optical *SNR* can be estimated from a simple Gaussian approximation (Marcuse, 1990) as given below:

$$Q = \frac{2SNR}{\sqrt{(4SNR+1)}+1}\sqrt{\frac{B_o}{B_T}} ----(2.13)$$

where B_o is the bandwidth of the optical filter before receiver

B_T (bit rate) = *1/2T*, with *T* being the bit time interval

and *Q* is a parameter related to *BER* given by Marcuse (1990) as below:

$$BER = \frac{e^{-(Q^2/2)}}{\sqrt{(2\pi)}Q} ----(2.14)$$

The SNR is defined as ratio of the average (not the peak) signal power to the ASE noise power after optical filtering before the detector. The total amount of ASE noise reaching the detector is proportional to the number of amplifiers, optical gain, amplifier noise figure and the optical filter bandwidth. Chraplyvy (1993) gave expression for calculation of total ASE noise as under:

$$Pase = 2\, n_{sp}\, (G-1)\, h\, f\, B_o\, M ----(2.15)$$

where *h* is Planck's constant (6.63×10^{-34} J.s)

f is centre frequency

G is gain of amplifier

B_o is equivalent rectangular optical bandwidth in Hz

n_{sp} is population inversion parameter

and *M* is number of amplifiers.

Under the assumption of equal amplifier spacing (*l*) and that the amplifier gain exactly compensates for the fibre loss, the minimum required power per channel to ensure the required signal-to-noise ratio of *(SNR)$_o$*, can be expressed as given below (Yu and Mahony, 1995):

$$P = 2(SNR)_o\, n_{sp} fhB_o \left(Ee^{\alpha l}-1\right)\frac{L}{l} ----(2.16)$$

where *L* is the total transmission length and,

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E is a factor accounting for possible losses introduced by fibre splice and other possible optical components inserted in the transmission line.

2.4 FIBRE DISPERSION

Dispersion implies change in the velocity of light inside the medium depending on its wavelength. In optical fibres, dispersion, light travelling at different velocities depending on the wavelength, causes pulse spread. The degree of pulse spreading, denoted as Δt_{total}, comprises of two types, modal dispersion Δt_{modal} and chromatic dispersion Δt_{chrom}. The relationship is as follows (Mynbeav and Scheiner, 2006):

$$\Delta t_{total}^2 = \Delta t_{mod\,al}^2 + \Delta t_{chrom}^2 ----(2.17)$$

The sum of squares appears because of the assumption that both components of total dispersion are linear independent. Modal dispersion is comprised of two types: intermodal dispersion, caused by the presence of many modes within a fibre and intramodal dispersion, caused by the effects occurring due to the actions of components within a single mode. As compared to multimode fibre, a single mode fibre (SMF) is having an advantage of the absence of intermodal dispersion. SMFs are the dominant optical links in the field of communication.

The mechanisms that cause dispersion in SMF are chromatic dispersion and polarization mode dispersion (PMD). Theoretically, chromatic dispersion can be eliminated by choosing an operating wavelength equal to zero dispersion wavelength. But there are no such means to exclude PMD. Hence PMD is one of the major limiting factors of ultra-high bit rate optical fibre communication systems (Mynbeav and Scheiner, 2006).

2.4.1 Polarization Mode Dispersion (PMD)

Pulse spreading caused by a change of fibre polarization properties is called polarization mode dispersion (PMD). Actually SMF carries two modes under one name. These modes are linear polarized waves propagating within a fibre in two orthogonal planes. In case of perfect fibre, both of them propagate at the same velocity and reach at the fibre end concurrently. In this case these modes are called degenerate modes and the effect of their presence at the output signal is not seen. However, practically due to exposure of modes to

the fibre property changes along the two planes of their propagation, the velocity of the modes will be affected.

They will then travel with different velocities and cause pulse spreading. If the pulse has different propagation constants β_x , β_y and different group delays τ_{gx} and τ_{gy} respectively in x and y directions, then a delay difference $\delta\tau_g$, called PMD , will occur between the two waves (Rashleigh and Ulrich, 1978) as given hereunder:

$$\delta\tau_g = \tau_{gx} - \tau_{gy} ----(2.18)$$

The range of the values of PMD varies from 1 picosec/km (conventional SMF) to 1 nanosec/km (high birefringence polarization maintaining fibres) (Mochizuki et al, 1981). In a spun fibre, a specific low birefringence fibre, PMD is negligible (Sasaki et al, 1984).

For a fibre of length L, the 3dB bandwidth B is given by (Kitayama et al, 1988):

$$B = \frac{0.9}{\delta\tau_g L} ----(2.19)$$

The maximum bit rate B_T for digital transmission in relation to PMD is given by (Suzuki et al, 1983):

$$B_T = \frac{B}{0.55} ----(2.20)$$

The pulse spreading Δt_{PMD} can be calculated as follows (Mynbeav and Scheiner, 2006):

$$\Delta t_{PMD} = D_{PMD}\sqrt{L} ----(2.21)$$

Where D_{PMD} is the coefficient of PMD, which does not depend on wavelength, in picosec/km

and L is length of fibre in km.

$\delta\tau_g$ is the relative delay along the two principal states of polarization which denotes an average value. The instantaneous value of $\delta\tau_g$ fluctuates with time over a wide range because of temperature and other environmental factors (Agrawal, 2002). If $\delta\tau_g$ exceeds the bit slot even for a short time interval, the system will stop functioning properly; this is

referred to as fading or outage in analogy with a similar effect occurring in radio systems (Poole and Nagel, 1997, Agrawal, 2002). Using 10% as a conservative criterion, the system length and the bit rate should satisfy the following condition (Agrawal, 2002):

$$B_T^2\, L \leq (10 D_{PMD})^{-2} ----(2.22)$$

In the case of "old" fibre links installed using standard fibres (for D_{PMD}= 1 ps/√km) value, PMD compensation at bit rate 10 Gbps is required if the link length exceeds even 100 km. In contrast, modern fibres have typically D_{PMD}<1 ps/√km. For systems designed using such fibres, PMD compensation is not necessary at 10 Gbps but may be required at 40 Gbps if the link length exceeds 600 km (Agrawal, 2002).

PMD is relatively small compared to chromatic dispersion. However, when one operates at zero dispersion wavelength, chromatic dispersion is decreased to the extent that PMD becomes a significant contributor to the total dispersion. Hence, PMD puts a limit on the minimum degree of dispersion which can be achieved using SMF, and becomes the bandwidth limiting factor.

Fibre nonlinearities such as SPM and XPM have been found to have a significant impact on PMD-induced penalty (Matera and Settembre, 1995, Collings and Boivin, 2000, Khosravani et al, 2001, Sunnerud et al, 2001, Lee et al, 2002, Pan et al, 2002, Xie et al, 2002, Corbel et al, 2003, Xie et al, 2003). It has been reported that the SPM effect can resist PMD-induced pulse broadening in both non return-to-zero (NRZ) (Matera and Settembre, 1995) and soliton (Sunnerud et al, 2001, Xie et al, 2002) transmission systems, and the interchannel XPM-induced polarization scattering in WDM systems affects PMD penalty as well (Collings and Boivin, 2000, Khosravani et al, 2001, Lee et al, 2002, Pan et al, 2002, Corbel et al, 2003, Xie et al, 2003). It has been proved experimentally that the PMD penalty is over-estimated if the PMD impact is evaluated based on a back-to-back system (Zhang et al, 2005). However, the amount of improvement depends on the details of the individual system.

At times, in combination with chirp, a system with both PMD and nonlinearity is less impaired than a system with the same amount of nonlinearity and no PMD (Ibragimov et al, 2000, Möller et al, 2002, Marks and Menyuk, 2003, Menyuk and Marks, 2006). Impact

of fibre nonlinearity on PMD can be quite complex and one cannot simply add the penalties due to PMD and nonlinearity without careful justification (Zhang et al, 2005).

2.5 CONCLUSION

Based upon the analysis of the literature, it can be concluded that FWM and SRS are the dominant nonlinearities for the intensity modulation-direct deduction (IM-DD) systems. The ASE noise is a chief contributor to the total optical noise for long haul transmission systems. The PMD is the most important bandwidth limiting factor in the high rate optical DWDM systems although the collective effect of fibre nonlinearities and PMD is not always catastrophic. They generally appear separately in communication systems, interacting with ASE noise and chromatic dispersion respectively to limit the transmission distance and the data rate per channel.