Analysis of FWM Effect on an Optical WDM System having Unequal Channel Spacing and Nonuniform Chromatic Dispersion

by

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APPROVAL CERTIFICATE

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Dedicated to my beloved parents

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List of Symbols

α	attenuation constant
β	phase constant of single mode fiber
η	efficiency of FWM generation
$\Delta\beta$	phase difference for single mode fiber
$\Delta\beta'$	phase mismatch for EDFA
D_c	chromatic dispersion coeeficient
γ_{tf}	nonlinearity coefficienmt of single mode fiber
γ_{EDF}	nonlinearity coefficient of EDFA
f_0	zero dispersion frequency
A_{eff}	effective core area of fiber
L_{eff}	effective length of fiber
N	number of channels
n_o	fiber refractive index
c	speed of light
N_{th}	thermal Noise
N_{sh}	shot noise
Q	quality factor
P_e	probability of error
μm	micrometer

List of Abbreviations

ASE	Amplifier Spontaneous Emission
ASK	Amplitude Shift Keying
BER	Bit Error Rate
dB	deciBel
DMUX	Demultiplexer
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ES	Equal Channel Spacing Scheme
FDM	Frequency Division Multiplexing
FWM	Four Wave Mixing
GHz	GigaHertz
km	Kilometer
Laser	Light Amplification by Stimulated Emission of Radiation
SMF	Single Mode Fiber
LD	Laser Diode
LED	Light Emitting Diode
MHz	MegaHertz
nm	Nanometer
NES	Nonuniform Dispersion with Equal Channel Spacing Scheme
NUS	Nonuniform Dispersion with Unequal Channel Spacing Scheme
Pf	Power Penalty

RUS	Repeated Unequal Channel Spacing
SBS	Stimulated Brillouin Scattering
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
TDM	Time division multiplexing
US	Unequal channel spacing
WDM	Wavelength Division Multiplexing
MUX	Multiplexer
XPM	Cross phase modulation
THz	TeraHertz

Abstract

With the increase in demand for higher data rate wavelength division multiplexed (WDM) system is becoming increasingly popular day by day. WDM system effectively utilizes the enormous bandwidth of an optical fiber by multiplexing many channels and by transmitting them through the same fiber. However, a number of nonlinear effects can seriously degrade system performance of such a system. Among these nonlinear effects, four wave mixing (FWM) is found to be the most serious cause of performance degradation in long haul WDM systems.

In this work the effect of four wave mixing on the performance of a long distance optical WDM network is analyzed using an analytical approach. Performance criterion like bit error rate, power penalty and allowable input power are estimated. It is observed that the WDM system suffers seriously from performance degradation caused by four wave mixing particularly when system length or number of channels is large. Therefore some scheme is necessary to reduce its effect. Various schemes to reduce the adverse effect of four wave mixing are examined. The schemes are unequal channel spacing, repeated unequal channel spacing, nonuniform chromatic dispersion and dispersion compensation. New schemes are proposed, which are the combinations of either unequal channel spacing or repeated unequal channel spacing and either nonuniform dispersion or dispersion compensation. It is seen that such combinations give much better results compared to the existing schemes. The four wave mixing process in fiber amplifiers is included in the analysis to obtain a complete picture of the effect of four wave mixing on

WDM system. It is found that the influence of four wave mixing in fiber amplifiers can be quite significant and should be taken into careful consideration while evaluating system performance. Finally a design guideline is developed to select a best scheme that gives the best performance with minimum system complexity.

Chapter 1

INTRODUCTION

1.1 Communication System

Communication is the process of transfer of information from one point to another. The block diagram of a general communication system is shown below.

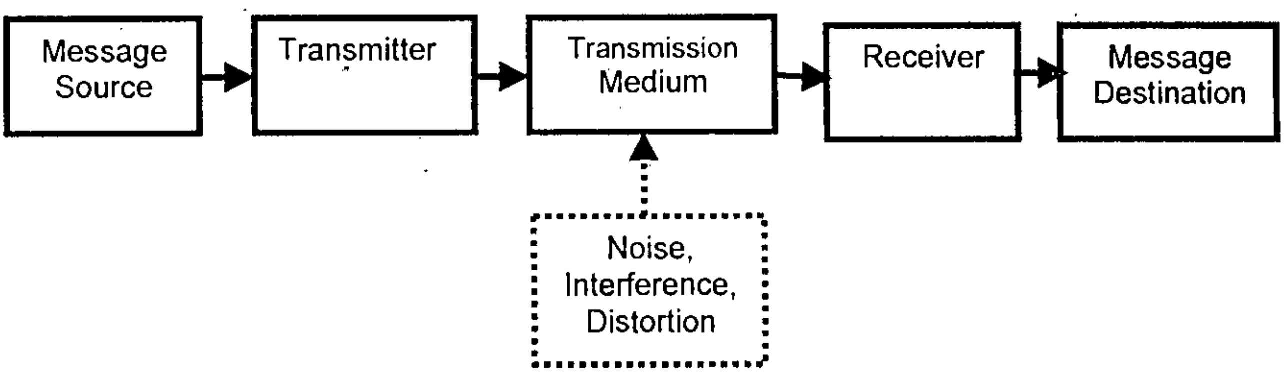


Figure 1.1: Block diagram of a general communication system [Senior, 2000]

As can be seen from figure 1.1, any communication system is composed of the following basic components:

(1) Transmitter: It manipulates the information from the message source and couples it into a transmission channel in the form of a signal, which matches the transfer properties of the channel.

(2) Channel: It bridges the distance between the transmitter and the receiver. As the signal propagates through the channel, it gets attenuated due to transmission loss and distorted due to various nonlinear effects and interference.

(3) Receiver: It extracts the weakened and distorted signal from the channel, amplifies it and restores it to its original form and then passes it into the message destination.

In general the information carrying capacity should be high so that it can meet the requirement of the user. The information carrying capacity is closely related to the bandwidth supported by the communication system. The greater the bandwidth, the higher is the information carrying capacity of the communication system. The system should be such that the information can be carried at an affordable cost and the quality of the message received at the destination is sufficiently free from noise and interference. In this respect, optical fiber communication system has been developed, which offers a huge bandwidth at a relatively low cost.

1.2 History of Optical Communication

Throughout the communication history the chief carrier of information has been electromagnetic waves. Especially the use of visible light has been common for thousands of years. Ancient people used signal fires, reflecting mirrors etc. for the purpose of communication. However, the history of modern optical communication is relatively short. Some efforts were made from time to time to utilize the visible light as a carrier of information but it was limited to short distance and low capacity links only. The reason behind this was the lack of suitable light source and the fact that transmission of light is seriously affected by snow, rain, fog and other environmental factors. Lower frequency electromagnetic waves (radar and microwaves) show much smaller attenuation and hence were preferred as the means of communication in the earlier days.. Attempts to guide the light appear to have been as early as in 1854 by producing reflections in a curved stream of water coming out of a hole in the side of a pail. In 1880, Alexander Graham Bell reported the transmission of speech using a light beam. But such attempts were limited to low capacity short distance communication. Also it was possible for anyone to intercept the signal. A better light wave communication system would certainly need a light guided to help preserve the signal and so increase the reliability, security and distance of transmission. Then in 1910, a solid cylinder was envisaged to guide a wide range of electromagnetic waves including the upper limits of visible light. Another light guide was developed consisting of a hollow tube with a highly reflective metal coating on its inner surface. However, these devices had high signal loss.

Experiments on glass fibers were carried out in 1930s for use as light guide. Optical fibers were used for other purposes also, such as light conduits for card readers, in material endoscopes, in photography etc. The possibility of fiber optic communication was stimulated in the early 1960s with the invention of the laser. The proposal of optical communication via dielectric waveguides or optical fibers was made by Kao, Hockham and Werts in 1966. However at that time the idea that a block of glass may be used for long haul communication seemed somewhat ludicrous because of the large attenuation of normal glass. The early fibers were extremely lossy (typical loss~1000 dB/km). However, the situation changed drastically around the seventies. Nippon Glass Company of Japan first developed graded index fibers in 1968. Corning Glass Works of US produced fibers in 1970 with sufficient purity for use in telecommunication industry, having a loss of less than 20 dB/km. Since 1970, tremendous improvement has been made leading to silica-based fiber having very low attenuation. Progress in the fabrication technology resulted by 1979 in a loss of about 0.2 dB/km near the 1.55 μm wavelength [Miya, 1979], a loss level limited mainly by the fundamental processses like Rayleigh scattering. By 1980s, these activities have led to the development and worldwide installation of practical and commercially feasible optical fiber communication systems that can carry telephone, cable television, voice, data and other telecommunication traffics. The increasing demand of utilizing higher frequencies led to the rapid development of optical communication in the last two decades. Because the optical frequencies are of the order of 10^{14} Hz, so optical communication has a theoretical information capacity exceeding that of microwave communication by a factor of 10^{5}.

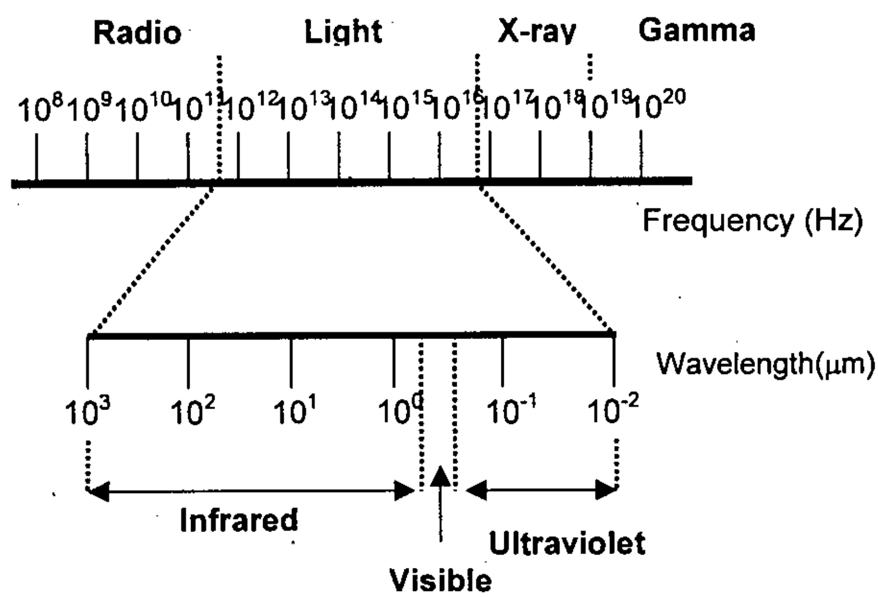


Figure 1.2: Spectrum of electromagnetic waves [Senior, 2000]

Rapid progress has been made in both lowering the attenuation loss in fiber and increasing the wavelength it can handle. Early interest in the fiber was in the 800-900 nm wavelength region, where fibers exhibited a local attenuation minimum. Later interests extended over a wider range of wavelengths up to 1300 nm, the second low attenuation

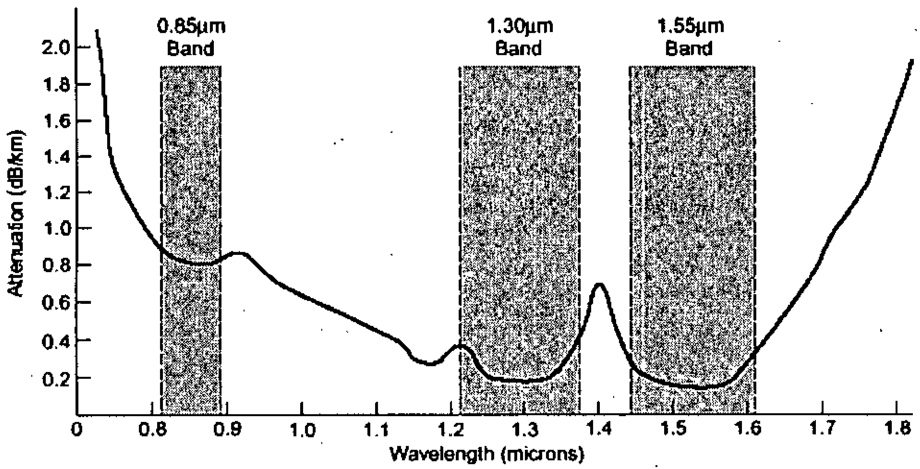


Figure 1.3: Variation of attenuation with wavelength [Senior, 2000]

window in optical fiber. (The first window near 850 nm was used almost exclusively for multimode fiber applications.) In order to optimize the fiber's performance in the 1310 nm window, the fiber dispersion was designed to be very close to zero near that wavelength. That gave the fiber very low dispersion and consequently very high potential bandwidth. As optical fibers became more widespread and the need arose for more bandwidth and distance, the third window near 1550 nm was exploited to provide for single mode fiber operation. The 1550 nm region offers much lower attenuation (0.2 dB/km at 1550 nm vs. 0.5 dB/km at 1310 nm), but it has quite a bit of dispersion (17 ps/nm-km), which seriously limited bandwidth. This could be overcome by using lasers with narrower linewidth. The advancement in laser technology made such narrow linewidth high power lasers readily available. Now-a-days almost all WDM systems operate in the 1550 nm wavelength region employing single mode fiber for operation.

The last two decades were a period of revolutionary development for optical fiber technology. The introduction of fiber amplifiers, especially erbium doped fiber amplifier was the first major step toward making long-haul wavelength division multiplexed system economically possible. This with the combination of modern laser source and the development of coherent detection scheme, has made the optical fiber based communication system the major competitor of microwave and satellite communication systems in present world.

The present is such that in the near future optical fiber communications will be the heart of information and communication technology all over the world. The explosive growth of internet traffic provides strong incentives to exploit the huge bandwidth of fiber optic networks. Such requirements are presently met by synchronous network technology/synchronous digital hierarchy (SONET/SDH) and in near future are most likely to be met by ideally suited WDM and its improved version, dense wavelength-division multiplexing (DWDM) technology. And after one or two decade when the total silica based fiber will be replaced by fiber made up with photonic band gap material or even better technology, the communication system will overcome its limitation imposed by today's fiber properties. Nevertheless, not only the fiber but also with the improvement of coherent source (e.g., LASER) and detector technology, amplification, modulation and switching specially in all optical domain, the optical fiber communication system is becoming the system of choice throughout the world.

1.3 Features of Optical Communication

Optical communication provides a number of attractive features, several of which were not apparent when the technique was originally conceived. Furthermore, the advances in the technology to date surpassed even the most optimistic predictions, creating additional advantages.

(1) ***Enormous optical bandwidth:*** The optical carrier yields a far greater potential transmission bandwidth than metallic cable systems (~500 MHz) or even millimeter wave radio systems (~700 MHz). The low loss transmission characteristics of optical fiber can provide as large as 50 THz bandwidth. This bandwidth is sufficient to meet the demand not only at present but also in the foreseeable future.

(2) ***Small size and weight:*** Optical fibers have very small diameters which are often no greater than that of a human hair. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellite and even ships.

(3) ***Electrical isolation:*** Optical fibers, which are fabricated from glass or sometimes plastic polymer, are electrical insulators and therefore they do not exhibit earth loop and

interference problems. Thus fibers are suited for communication in electrically hazardous environments.

(4) ***Immunity to interference and crosstalk***: As the fibers are dielectric waveguide, they are free from electromagnetic interference, radio frequency interference or switching transients giving electromagnetic pulses.

(5) ***Signal security***: As the light from fibers does not radiate, fibers provide a high degree of signal security.

(6) ***Low transmission loss***: The research and development works over the last twenty years have resulted in the production of optical fibers which exhibit very low attenuation compared to other transmission media. Fibers with losses as low as 0.2 dB/km are in use, which facilitates the implementation of long haul communication link with extremely wide repeater spacing.

(7) ***Ruggedness and flexibility***: Fibers are manufactured with high tensile strengths and , therefore, are superior in terms of storage, transportation, handling and installation.

(8) ***System reliability and ease of maintenance***: With fewer repeaters, the optical system reliability is enhanced. Also the system requires very less maintenance. This property has made use of optical fibers in long haul applications like under ocean cable quite attractive.

(9) ***Potential low cost***: The raw material for glass fiber is made from sand, which is not a scarce resource. The overall system costs for long haul link are substantially less than those of equivalent electrical systems because of low loss and wide band properties of the optical fiber. With the introduction of fiber amplifiers and the implementation of multichannel systems like WDM the cost of transmitting data has become even lower.

1.4 Limitations of Optical Communication:

Though optical fiber has lots of advantages, it is not without limitations. The chief sources of these limitations are attenuation, dispersion and nonlinear behaviour of the fiber. In this section we discuss these effects briefly.

1.4.1 Attenuation

The low attenuation of optical fiber is one of the most important reason behind the wide acceptance of optical fibers. Where the metallic conductors have attenuation around 5 dB/km optical fiber with attenuation less than 0.2 dB/km is readily available. However some attenuation is present in all optical fibers. The measured loss spectrum for an ultra low loss single mode fiber with the calculated attenuation spectra for some of the loss mechanisms is shown in the figure 1.5 [Miya, 1979]. Here the solid line shows the measured value of attenuation and the dashed and dotted lines show calculated attenuation spectra for some of the loss mechanisms contributing to the total fiber attenuation.

The loss mechanisms in optical fibers are

1) ***Intrinsic Loss:*** An absolutely pure silicate glass has little its basic material structure in the near infrared region. However it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 μm wavelength range as shown in the figure1.4 which shows a possible optical attenuation against characteristics for pure glass.

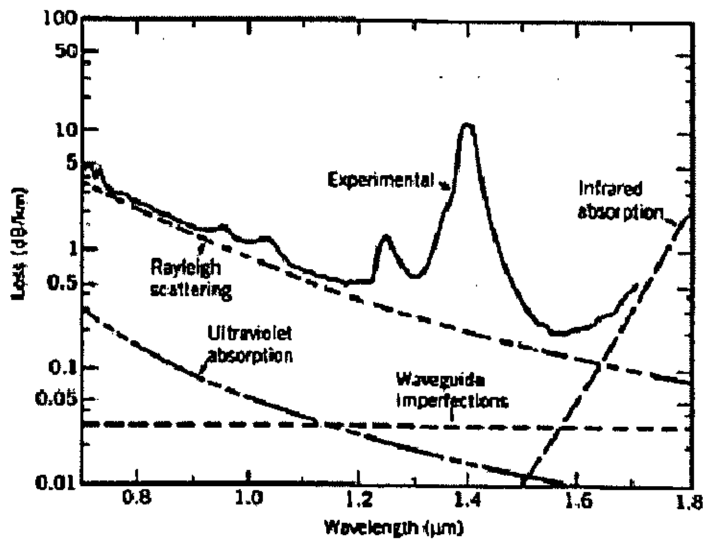


Figure 1.4: The measured attenuation spectrum for an ultra-low-loss single mode fiber [Senior, 2000]

1) ***Extrinsic Losses***: In a practical optical fiber prepared by conventional melting techniques a major source of attenuation is the extrinsic absorption from transition

metal element impurities. Even a relatively small amount of impurities can lead to significant absorption in the wavelength window 0.2-2 μm. The most important impurity that affects the fiber loss is the OH ion, which has a fundamental vibration peak at about 2.73 μm. The overtones of OH absorption peak are responsible for dominant peak near 1.37 μm and a smaller peak near 1.23 μm. Narrow windows exist in the longer wavelength around 1.3μm and 1.55 μm which are essentially unaffected by OH absorption once impurity level has been reduced below one part in hundred million.

2) ***Linear Scattering Losses:*** Linear scattering losses cause transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportional to the mode power) into a different mode. The process tends to result in attenuation of the transmitted signal as the transfer may be to a leaky or radiation mode, which does not continue to propagate within the fiber core. Linear scattering may be categorized into two major types: *Rayleigh scattering* and *Mie scattering.*

Rayleigh scattering is the dominant scattering mechanism in the low absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light.

Mie scattering is another scattering phenomenon that occurs at inhomogeinities that are comparable in size to the guided wavelength. This may result from the cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core cladding interface, core cladding refractive index difference along the fiber length etc.

1.4.2 Dispersion

Velocity of propagation of light is influenced by interaction of the waves with the atoms of the material, where the interaction is a function of frequency. This dependence is expressed by the following equation

$$v_g = \frac{c}{n - \lambda \frac{dn}{d\lambda}} \tag{1.1}$$

where v_g is the group velocity, n is the refractive index, λ is the wavelength of the light, c is the velocity of light in vacuum. The refraction index of silica is dependent upon the signal wavelength as shown in figure 1.5. Thus the velocity of propagation becomes a function of wavelength and so different components will travel at different velocities. The time delay between different spectral components causes spectral broadening of the optical signal and overlapping of adjacent pulses. After certain overlap, the adjacent pulses can no longer be individually distinguishable. This is known as intersymbol interference (ISI) as is illustrated in figure 1.6. Chromatic dispersion can severely limit information capacity of an optical fiber transmission system. Dispersion effect becomes significant in single mode fibers for bit rates higher than 4 GHz.

There are basically two types of dispersion:

1) ***Intermodal dispersion:*** In a multimode transmission system, as each mode has a different group velocity at a single frequency, this sort of dispersion results. In a purely single mode fiber this type of dispersion is absent.

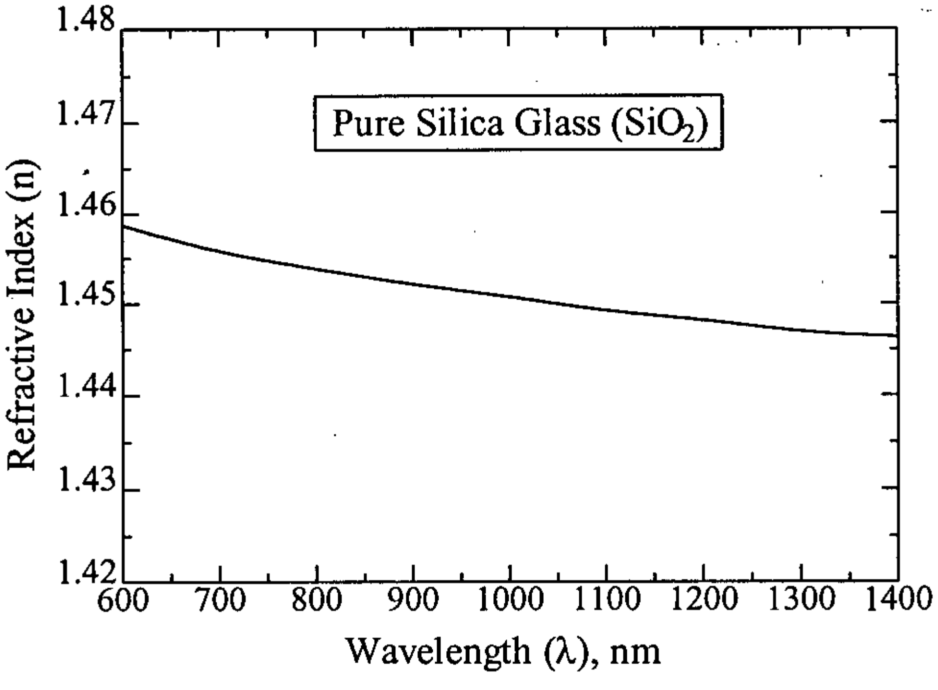
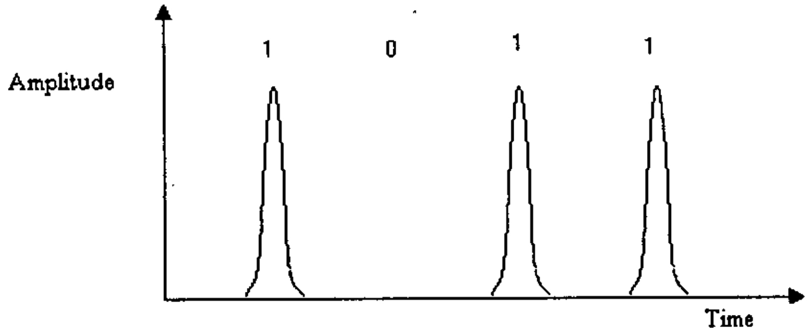
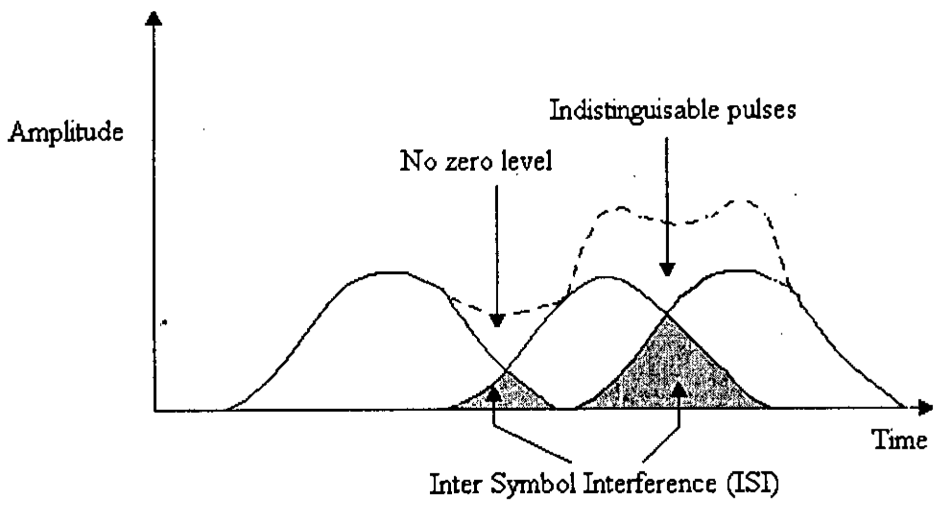


Figure 1.5: Wavelength dependence of refractive index of pure silica glass (SiO_2) [Gowar, 1993]

2) ***Intramodal dispersion:*** Within a single mode, because of group velocity being a function of wavelength this type of dispersion takes place. This is commonly known as the chromatic dispersion.



(a)



(b)

Figure 1.6: Effect of dispersion

Chromatic dispersion again can be separated into three parts:

1) ***Material dispersion(D_M)*** : It arises from the variation of the refractive index of the core material as a function of the wavelength . It occurs when the phase velocity of a plane wave propagating in the fiber varies nonlinearly with the wavelength. It is the principal factor causing dispersion.

2) ***Waveguide dispersion (D_W):*** It results from the variation in group velocity with wavelength for a particular mode. Multimode fibers where the majority of modes propagate far from cut off are almost free from waveguide dispersion. However in single mode fibers this kind of dispersion can be quite significant.

3)***Profile dispersion:*** It originates from the refractive index profile of the fiber. Its contribution is usually quite insignificant and usually neglected in practice.

The total dispersion can be determined by combining the different dispersion effects. The material and waveguide dispersions, to a first approximation, can be added algebraically. The interplay of various contributions in the total dispersion of a standard single-mode optical fiber is shown in figure 1.7 [Gowar, 1993]. The fact that the waveguide dispersion has opposite sign compared to the material dispersion is of considerable practical interest, which can be utilized to develop special fibers. The wavelength λ_0 is termed as the zero-dispersion wavelength. It is the point of inflection in n vs. λ curve, at which the group velocity is a maximum and the pulse transit time is a minimum [Keiser, 1983]. However, the wavelength λ_0 is better described as the wavelength of minimum dispersion from a practical point of view, because a real pulse contains a spread of wavelengths and these propagate with a range of group velocities even though the longest and shortest wavelengths may travel at the same speed. This indicates that there remains a residual dispersion. In any case, the information capacity of the fiber would be much higher if the laser frequency is accurately tuned to the wavelength λ_0.

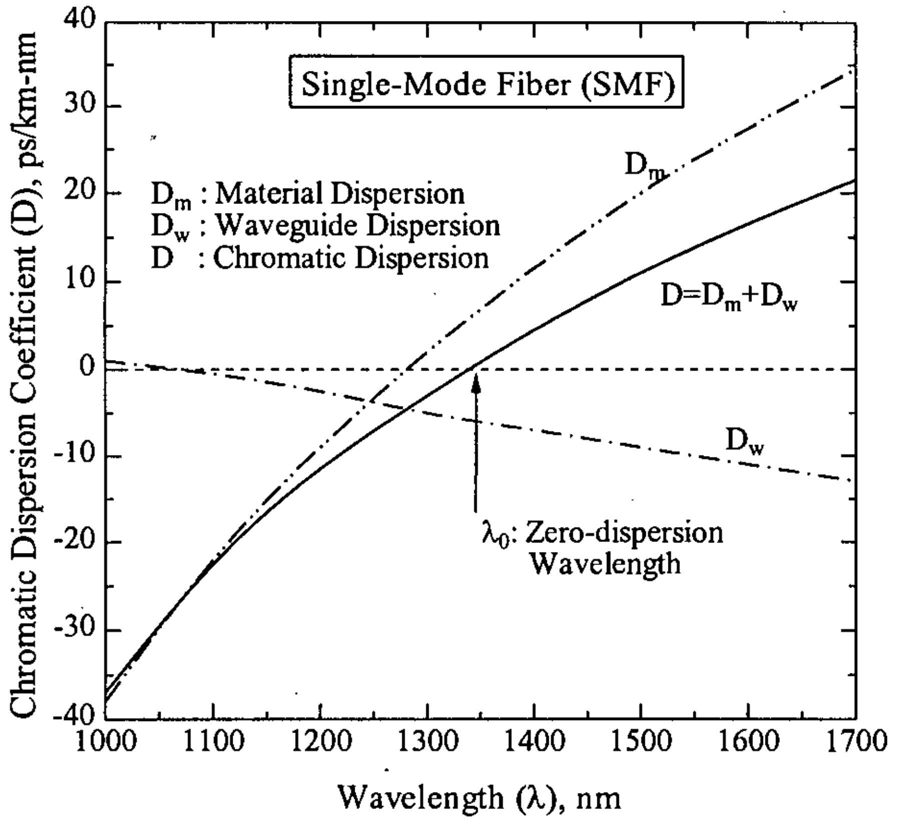


Figure 1.7: Chromatic dispersion characteristics of standard single-mode fiber (SMF) [Gowar, 1993]

1.4.3 Nonlinear Effects

As the data rate on optical fiber increased and transmission lengths increased and the number of wavelengths increased and the optical power levels increased, a whole host of nonlinear fiber effects, just laboratory curiosities a few years earlier, suddenly became very important. In the early days of fiber, one had to worry most about fiber attenuation and to some extent fiber dispersion. As the fiber performance envelope stretched, dispersion became more important, but is generally well understood and can be dealt with using a variety of techniques. What is less well known are a host of optical fiber nonlinearities that have previously not been seen in field deployments other than specialized applications such as undersea installations. Fiber nonlinearities that now must be considered in designing state-of-the-art fiber optic systems include stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing FWM), self-phase modulation (SPM) and cross phase modulation (XPM).

Origin of Fiber Nonlinearities

Fiber nonlinearities arise from two basic mechanisms. The first, and most serious, is the fact that the refractive index of glass is dependent on the optical power going through the material. The general equation for the refractive index of the core in an optical fiber is:

$$n = n_0 + n_2 P / A_{eff} \tag{1.2}$$

where n_0 is the refractive index of the fiber core at low optical power levels, n_2 is the nonlinear refractive index coefficient. It is equal to 2.35×10^{-20} m^2/W for silica, P is the optical power in watts, A_{eff} is the effective area of the fiber core in square meters.

Figure 1.8 shows the relationship of the refractive index versus optical power. It can be seen that the magnitude of the change in refractive index is relatively small. It becomes important since the interaction length in a real fiber optic system can be hundreds of kilometers. The power-dependent refractive index of silica gives rise to the SPM, XPM and FWM nonlinearities.

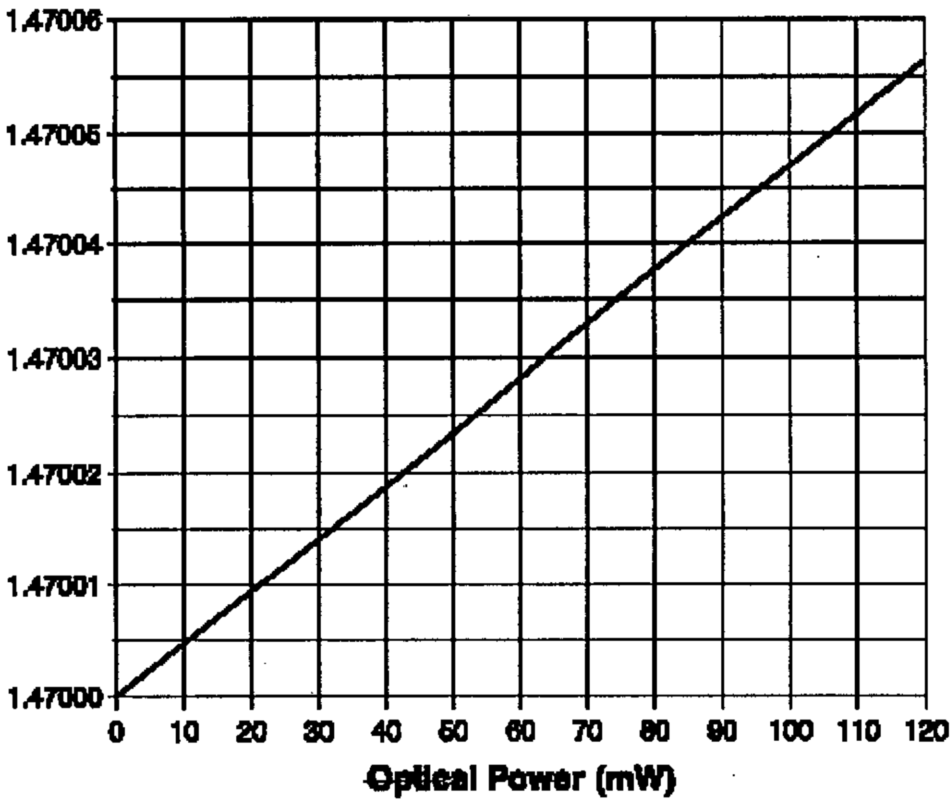


Figure 1.8: Input power dependence of refractive index of pure silica glass (SiO_2)

The second mechanism for generating nonlinearities in fiber are scattering phenomena. These mechanisms give rise to SBS and SRS effects.

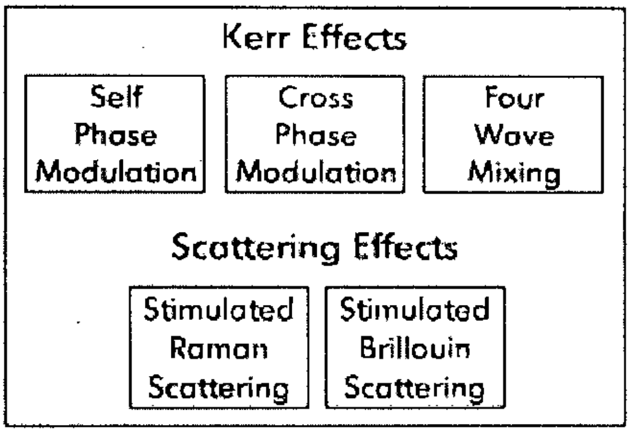


Figure 1.9: Nonlinear effects in fibers

Fiber nonlinearities that now must be considered in designing state-of-the-art fiber optic systems include stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing FWM), self-phase modulation (SPM) and cross phase modulation (XPM). Different fiber nonlinearities are discussed shortly here:

Stimualated Brillouin Scattering (SBS)

Stimulated Brillouin scattering (SBS) is a fiber nonlinearity that imposes an upper limit on the amount of optical power that can be usefully launched into an optical fiber. The SBS effect has a threshold optical power. When the SBS threshold is exceeded, a significant fraction of the transmitted light is redirected back toward the transmitter. This results in a saturation of optical power that reaches the receiver, as well as problems associated with optical signals being reflected back into the laser. The SBS process also introduces significant noise into the system, resulting in degraded BER performance. As a result, controlling SBS is particularly important in high speed transmission systems employing external modulators and continuous wave laser sources. It is also of vital importance to the transmission of 1550 nm-based CATV transmission, since these transmitters often have the very characteristics that trigger the SBS effect.levels that can be carried over the fiber.

Stimulated Raman Scattering (SRS):

Stimulated Raman Scattering occurs when a large pump wave is coinjected at a lower wavelength than the signal to be amplified. In SRS incident light is scattered at a down shifted(stoke shifted) frequency. This process is strongly dependent on the power of the incident beam, called the pimp. As the pump power increases the scattering increases until the scattered power reaches a threshold level. If the pump power is increased beyond this limit the scattering becomes stimulated and the pump rapidly losses its power to the Stoke-shifted beam. The pump is thus depleted due to SRS.

Self Phase Modulation (SPM):

Like FWM, SPM is a phenomenon that is due to the power dependency of the refractive index of the fiber core. It interacts with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. Whereas increasing the fiber dispersion will reduce the impact of FWM, it will increase the impact of SPM. As an optical pulse travels down the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise causing a blue shift. The falling edge of the pulse decreases the refractive index of the fiber causing a red shift. These red and blue shifts introduce a frequency chirp on each edge which interacts with the fiber's dispersion to broaden the pulse. Self phase modulation is very important for CATV system because the nature of such system is very much suitable for sufficient SPM to occur. It can increase the distortion in such link dramatically.

Cross Phase Modulation(XPM):

Cross phase modulation is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Unlike, SPM, fiber dispersion has little impact on XPM. Increasing the fiber effective area will improve XPM and all other fiber nonlinearities.

Four Wave Mixing:

It is a nonlinear phenomenon in which a number of optical signals interact to give rise to new optical signals. This phenomenon will be discussed in detail in chapter3.

1.5 Background of this Study

During the last thirty years or so the study of nonlinear effects in the optical fibers has led to the advent of a new branch of nonlinear optics, referred to as nonlinear fiber optics. A large number of research projects and developments have been carried out over the years in this field. Parametric four-wave mixing was studied about thirty years ago [Stolen, 1974, 1975]The first detailed study of FWM effect in optical fiber was published by K.O.Hill et al in 1978. However at that time high capacity optical fiber system was not available and the FWM effect was only a topic of academic interest. Situation changed quickly when the long-haul optical systems for which FWM effect is a major limiting factor began to be installed throughout the world. With the increase of use of optical fiber extensive research took place about the influence of FWM effect over WDM systems.

FWM effects in fiber lines with multistage optical amplifiers were investigated [Inoue, 1992]. Long-haul WDM systems made the use of fiber amplifiers necessary. Periodic distribution of EDFAs in multiple fiber system further accumulates the FWM signals [Schadt, 1991]. Studies have been made to assess the FWM effect in such amplifiers [Wolfgang, 1996], [Stojan, 2001]. The effect of polarization on FWM efficiency was also examined [Inoue, 1992] . Inter wavelength band FWM process was also studied [Kani, 1999]. The effect of polarization on FWM efficiency was also examined [Inoue, 1992]. Also experiment has been carried out to assess the impact of polarization mode dispersion on FWM induced crosstalk in WDM systems.[Hansryd, 2000]. Equations have been developed describing the performance of WDM systems in presence of FWM [Zheng, 1999], [Inoue, 1994].

Extensive research has also taken place to reduce the FWM effect on WDM systems. Unequal channel spacing has been proposed to ensure that FWM light do not fall on any channel frequency [Forghieri, 1995]. But this not fully solve the problem because it requires a huge expansion in bandwidth and yet the higher order FWM products can degrade system performance especially when power density is high [Song, 2000]. To alleviate the bandwidth expansion problem repeated unequal channel spacing has been proposed [Numai, 2000]. Algorithms have been developed to assess the total number of FWM products in such systems [Chang, 2000].

Another way to reduce FWM effect that gained much attention is to use nonuniform chromatic dispersion.[Nakajima, 1998], [Islam, 2002]. New developments are being made almost regularly in the field of nonlinear fiber optics. Investigations have been made to assess the influence of different factors like channel spacing, input power and number of channels on the performance of WDM system [Islam, 2001]. The effect of power depletion due to FWM was also analyzed [Wu, 1995]. Attempts have also been made to evaluate the performance of complete DWM system in presence of FWM [Islam, 2002] The conventional long haul systems usually uses single mode fibers. But recently multi-mode fibers having with large core area has also been made which have much higher area and therefore reduce power density and FWM effect significantly. However none of these efforts has been completely successful in completing the FWM process in long haul WDM systems. Also the complete evaluation of performance of a WDM system in presence of FWM is yet to be reported.

1.6 Objective of this Study

The objective of this work is to study the effect of four wave mixing on the performance of an optical WDM system. The system limitations imposed by the FWM effect will be evaluated. Next different schemes will be investigated in reducing the effect of FWM. The schemes include unequal channel spacing, repeated unequal channel spacing, nonuniform dispersion and dispersion compensation. The effectiveness of different schemes in FWM reduction will be compared. Then combinations of these schemes will be investigated for the same purpose. New schemes will be a combination of either unequal or repeated unequal channel spacing and either nonuniform dispersion or dispersion compensation. This investigation will propose the best scheme in reducing the effect of FWM with maximum information capacity and minimum system complexity. Finally the effect of FWM process in the EDFAs of transmission link will be included in the study so that the ultimate performance characteristics evaluated in the work gives a complete picture of the FWM effect in optical WDM communication system.

1.7 Brief Introduction to the Thesis

The dissertation consists of nine chapters.

Chapter one is the preliminary chapter where a brief introduction to optical fiber communication along with the historical background is discussed. Recent developments in this field and the limitations are also discussed. The background of this topic and objective of this work is introduced.

In chapter two optical communication system is examined in a greater detail. The receiver configuration, modulation schemes and multichannel optical systems are discussed. A brief introduction to optical amplifiers especially Erbium Doped Fiber Amplifier is also presented.

In chapter three nonlinear optical phenomenon are discussed. The origin of four wave mixing is explained with necessary mathematical models . How the FWM process degrades system performance is also discussed.

Chapter four evaluates the performance of a typical WDM system in presence of FWM. The effects of different system parameters like fiber length, number of channels on system performance are also discussed.

Chapter five introduces the unequal channel spacing and repeated unequal channel spacing scheme for FWM reduction. The performance is evaluated under both the schemes.

Chapter six discusses the effect of chromatic dispersion on FWM performance. Method of nonuniform chromatic dispersion has been examine and performance evaluated under this schemes.

Chapter seven discusses new methods of FWM reduction, which are combinations of the methods, discussed in chapter five and six. The improvement of performance is compared with the results of the earlier chapters.

Chapter eight discusses the FWM process in EDFA. System performance is evaluated taking the FWM process in consideration and the result is compared to those of earlier chapters.

A brief conclusion along with suggestions for future work is given in chapter nine.

Chapter 2

OPTICAL COMMUNICATION SYSTEMS

2.1 Introduction

In this chapter a brief description of the overall optical system is given. Different components used as optical source, modulator and optical amplifiers will be discussed. Different types of multichannel optical systems will also be discussed.

2.2 General Optical Communication System

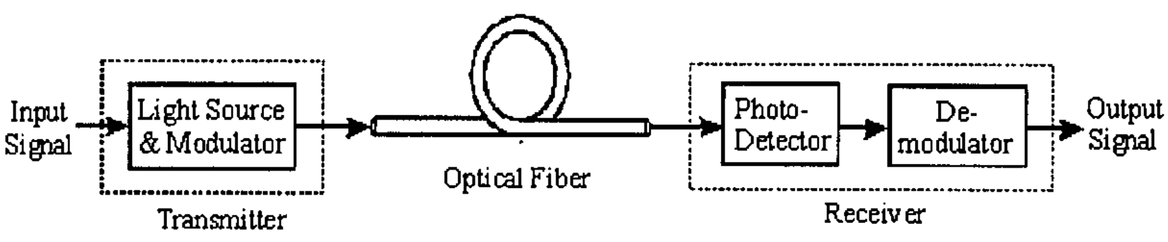


Figure 2.1: Basic configuration of an optical communication system

The block diagram of an optical communication system is shown in figure 2.1. Here the information source provides an electrical signal to a transmitter comprising an electrical stage that drives an optical source to give modulation of light wave carrier. The optical source that provides the electrical to optical conversion may be a semiconductor laser or light emitting diode (LED). The transmission medium consists of optical fiber cable and the receiver consists of a n optical detector which drives a further electrical stage staeg and hence provides demodulation of the optical carrier. Photodiodes and in some instances phototransistors and photoconductors are used as detector.

2.3 Components of Optical Communication System

As is clear from the above discussion an optical communication system consists of the following main components:

1. Optical source,
2. Optical modulator,
3. Optical fiber as transmission wave guide,
4. Optical detector,
5. Demodulator.

In addition, some other components like fiber amplifiers are also used in modern optical communication systems. In the following section some of these components are discussed briefly.

2.3.1 Optical Source

In an optical communication system electrical signals are first converted into optical signals by modulating an optical source such as light emitting diode (LED) or laser diode (LD).

The advantages of LED are as follows:

(i) Less sensitive to retro reflection

(ii) Possess no interference problem

(iii) Less sensitive to temperature variation

(iv) High reliability

(v) Simple electronic excitation

(vi) Less costly.

But the main disadvantages are:

(i) Low coupling efficiency between an LED and a fiber

(ii) Low modulation bandwidth, typically limited to 100 MHz to 200 MHz

(iii) Wide spectral width of about 50-100 MHz around 1550 nm.

The advantages of LD are:

(i) High conservation gain i.e. with small bias current relatively high power output

(ii) Low numerical aperture and as a result high coupling efficiency.

(iii) High modulation bandwidth

(iv) Narrow spectral width (10-50 MHz).

The main disadvantages are:

(i) Highly sensitive to temperature variation

(ii) Produce supplementary to return reflected power

(iii) Less reliable

(iv) More costly.

In summary, for short links (<10 km) LED is suitable, but for medium and long links LD is to be used.

2.3.2 Optical Fiber

The most important part of an optical communication system is the optical fiber. Optical fiber is essentially a thin filament of glass that acts as a waveguide. A waveguide is a physical medium or path that allows the propagation of electromagnetic waves such as light. The concepts of reflection and refraction can be interpreted most easily by considering the behavior of light rays associated with plane waves traveling in a dielectric material. When a light ray encounters a boundary separating two different media, part of the ray is reflected back into the first medium and the remainder is bent or refracted as it enters the second medium. The bending or refraction of light ray at the interface is a result of the difference in the speed of light in two materials having different refractive indices. The relationship at the interface is governed by the Snell's law, as stated below.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

or

$$n_1 \cos\theta_1 = n_2 \cos\theta_2 \qquad (2.1)$$

n_1 and n_2 are the refractive index of the two materials and $n_2 < n_1$. The angles θ_1 and θ_2 are the angles of incidence and refraction respectively. So if a light travels from an optically denser material to a loss dense material, the angle of refraction becomes greater than the angle of incidence. If the angle of incidence reaches a particular value θ_c, the refraction angle becomes 90° and the refracted ray emerges parallel to the interface between the dielectrics. This angle is called the critical angle, which can be found as follows.

$$n_1 \sin\theta_c = n_2 \sin 90° \quad (2.2)$$

$$\theta_c = \sin^{-1}(n_2 / n_1) \quad (2.3)$$

Now if the angle of incidence is greater than the critical angle, all of the incident ray will be reflected back and no refraction will occur. This phenomenon is referred to as the *total internal reflection*. Thus the total internal reflection occurs at the interface between two dielectrics when a light is incident on the dielectric of lower index from the dielectric of higher index and the angle of incidence of the ray exceeds the critical angle as shown in figure 2.2. This is the mechanism by which light at a sufficiently shallow angle (less than 90°– θ_c) may be considered to propagate down an optical fiber with low loss. The fiber consists of a core completely surrounded by a cladding,(both of which consists of glass of different refractive indices. The refractive index of the core is greater than that of the cladding, so the light travels via a series of total internal refractions at the interface of core and cladding as shown in figure 2.3. The light ray is known as a meridional ray as it passes through the axis of the fiber core. However, the above description is an ideal one. In practice, there is always some tunneling of optical energy through the interface. Also there may exist loss of light into the cladding through refraction, rather than total internal reflection, due to any discontinuities or imperfections at the core-cladding interface.

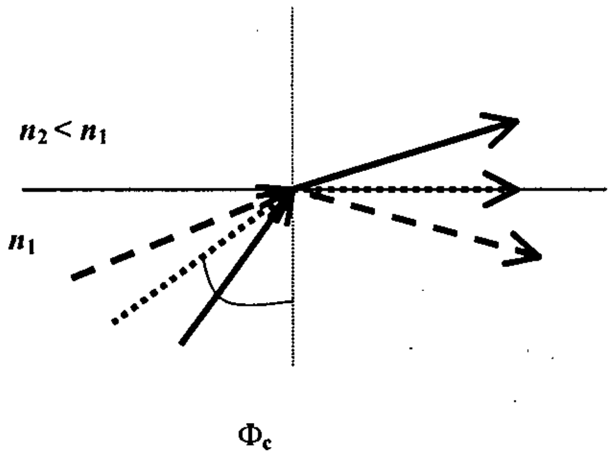


Figure 2.2: Total internal reflection

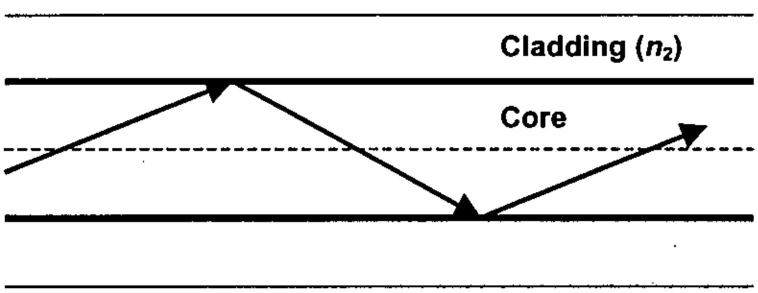


Figure 2.3: Light propagation through fiber

Two major types of fibers are currently in use. They are singl emode fibers and multimode fibers.

Single Mode fiber:

This fiber allows the transmission of only one mode of light through it. The core radius of such a fiber is typically from 2 to 10 μm. They are free from intermodal dispersion. They are suitable for transmission with a large bandwidth and chiefly used for long haul systems like undersea cables.

Multimode fibers:

This type of fiber allows more than one mode to propagate through it. It has larger core areas compared to single mode fibers. It supports smaller bandwidth and chiefly limited to applications where transmission distance is small.

2.3.3 Optical Detectors

After optical signal has been launched into the fiber, it becomes progressively attenuated and distorted with the increasing distance because of scattering, absorption, and dispersion in the fiber. At the receiver the attenuated and distorted optical power is detected by the photodiode. The figure of merit for a fiber is the attenuation and distortion which should be minimum and for a receiver there is a minimum optical power necessary at the desired data rate to attain either a given error probability for a digital system or a specified signal to noise ratio (SNR) for an analog system.

In optical communication systems, two important detection techniques are normally employed. These are as follows.

1. Direct detection,
2. Coherent detection.

In direct detection, a photodetector only responds to changes in the power level (the intensity) of an optical signal, and not to its frequency and phase content. So this is known as intensity modulation (IM). At the receiving end, one then uses direct detection (DD) to convert the optical signal into an electrical signal. The IM/DD systems are simple and less costly but the suffer from limited sensitivity and do not take full advantage of the tremendous bandwidth capabilities of optical fiber due to relatively low optical power output of semiconductor laser diode (SLD). Direct detection optical communication systems have been found very promising for future deep space applications, inter-satellite links and terrestrial line of sight communications. To increase the data rate throughput of all semiconductor free space optical channels, extensive research for bandwidth, power efficient coding and modulation schemes were carried out in the last decade.

Coherent light wave communication systems using heterodyne or homodyne, on the other hand, are becoming more attractive for long haul transmission and wide band data distribution. Two major advantages that coherent systems offer are as follows:

(i) Improved receiver sensitivity (up to 20 dB) relative to direct detection so that either the bit rate or the repeater spacing can be greatly increased.

(ii) A high degree of frequency selectivity on optical wavelength division multiplexing (WDM) system.

2.3.4 Modulation

In order to transmit optical signal via an optical fiber it is necessary to modulate a property of the light with the information signal. This property may be intensity, frequency, phase or polarization with either digital or analog signal. In analog modulation schemes the variation of light takes place in a continuous manner but in case of digital modulation discrete change in light wave is obtained. Although simpler to implement analog communication is less efficient, requiring a far greater signal to noise ratio than digital modulation. Also the linearity needed in analog modulation is not always provided by semiconductor optical sources. For these reasons analog optical fiber systems are generally limited to shorter distance and lower bandwidth than digital links.

In coherent communication system, information can be impressed on the optical carrier in one of the three ways as mentioned below:

i. Phase shift keying (PSK),

ii. Frequency shift keying (FSK),

iii. Amplitude shift keying (ASK).

Depending on the specific application, various modulation and demodulation formats, similar to those of traditional radio frequency communications, are also employed in coherent light wave transmission. These include binary PSK (BPSK), quadrature PSK

(QPSK), orthogonal QPSK (OQPSK), continuous phase FSK (CPFSK), discontinuous phase FSK (DPFSK), binary pulse position modulation (BPPM) etc. Each of the modulation schemes and combinations thereof, with homodyne, heterodyne or diversity receivers has its own merits and demerits and none has emerged as an absolutely preferable.

Actually, the huge transmission capacity of single mode fibers can be exploited efficiently by accessing the fiber bandwidth in the wavelength domain rather than in the time domain. Among WDM systems, DWDM, in which the channel spacing is a few times the bit rate, allows the possibility of transmitting many channels simultaneously, increasing the transmission capacity. A sharp cutoff filter and a modulation scheme with compact spectrum are necessary to construct densely spaced multiplexing system using direct detection scheme.

2.3.5 Optical Amplifiers

Optical fibers attenuate light during propagation like any other material during propagation. In the case of silica fibers the attenuation constant is quite small particularly in the wavelength range of 1.0-1.6 μm where it is less than 1 dB/km with the minimum value of about 0.2 dB/km occurring at 1.55 μm. For applications like local area networks the effect of attenuation can be neglected. But now-a-days optical fibers are heavily used as the transmission medium in long haul communication, which may have length more than several thousand kilometers. In such networks the loss due to attenuation can no more be neglected. In practice the loss limitations are overcome by periodic boosting up of the power level by repeaters. There are two types of repeaters in use now-a-days. The first is regenerators, which converts the optical signal into electrical signal and then, after amplification in the electrical domain, converts it back to optical signal by a transmitter. Such regenerators become quite complex and expensive especially for multichannel lightwave systems. Much more benefit can be obtained if the electric repeaters are replaced by much simpler and potentially less expensive optical amplifiers, which amplify the optical signal directly.

Several kinds of optical amplifiers were studied and developed in the last two decades. A short description of them is given below.

1) ***Semiconductor laser amplifiers:*** Semiconductor laser amplifiers utilize stimulated emission from injected carriers. Several kinds of laser amplifiers have been used in different applications. The most commonly used are Fabry-Perot amplifier which is an oscillator biased below oscillation threshold, the traveling wave (TW) and the near traveling wave (NTW) amplifiers, which are effectively single pass devices and the injection locked laser, which is a laser oscillator designed to oscillate at the incident signal frequency. Such devices are capable of providing high gain (15 to 35 dB) with low power consumption and their single mode waveguide structure makes them particularly suitable for use with single mode fibers. In addition, they are very compact, compatible with IC technology and can be easily coupled with optoelctronic components. They were used initially, but the interest shifted toward fiber based amplifiers because of the

practical issues related to coupling losses, polarization sensitivity and interchannel crosstalk and other application related issues.

2) ***Fiber Amplifiers:*** These amplifiers provide gain from excited dopants or by nonlinear effect like stimulated Raman scattering or stimulated Brillouin scattering.

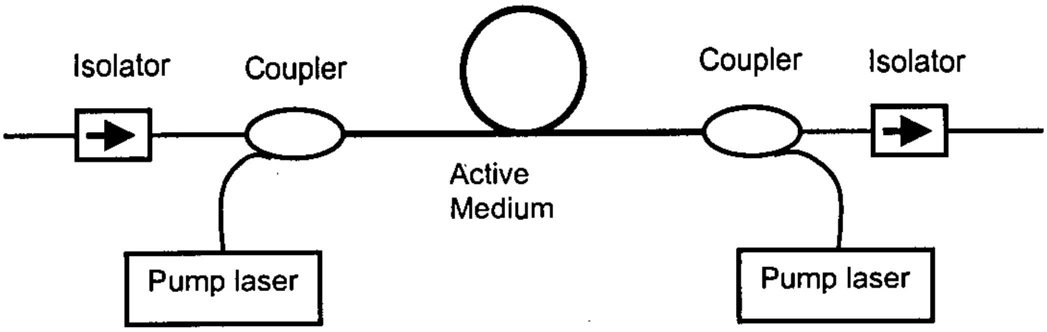


Figure 2.4: Block diagram of a fiber amplifier

A schematic diagram of a general fiber amplifier system is shown in figure 2.4. The gain medium normally comprises of a single mode fiber connected to a dichroic coupler, which provides low insertion loss at both signal and pump wavelengths. Excitation occurs through pumping from a high power laser source, which is combined with the optical input signal within the coupler. The amplified optical signal is therefore emitted from other end of the active medium.

Three common types of fiber amplifiers are listed here.

1) Fiber Raman amplifiers that require high pump powers (0.5 W-1W) that are not readily available from semiconductor lasers.

2) Fiber Brillouin amplifiers that can operate at low power levels but have too small bandwidth to be useful as in-line amplifiers in lightwave systems.

3) A new kind of fiber amplifier based on silica fibers doped with rare earth ions were developed in the late 1980s and turned out to be the most suitable for lightwave system applications. Of these amplifiers the most important one is the erbium doped fiber amplifier (EDFA), which has revolutionized the field of fiber optic communication.

2.3.5.1 Erbium Doped Fiber Amplifier

By making it possible to boost up the power level of the large number of signals that a multichannel optical system has to carry, the erbium doped fiber amplifier (EDFA) has been a key enabling technology in popularizing the WDM systems. It was the first active component used in WDM systems. The use of EDFAs along with WDM technology has made possible a tenfold increase in data rate without increasing system complexity. Erbium is a rare earth element that, when excited, emits light around 1.54 μm. A weak signal enters the erbium doped fiber, into which a 980 nm or 1480 nm light is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550 nm light. As this process continues down the fiber, the signal grows stronger. The key performance parameters of EDFA are gain, gain flatness, noise level and output power. EDFAs are typically capable of gains of 30 dB or more and output power of +17 dB or more. In practice, signals can travel for up to 120 km between amplifiers.

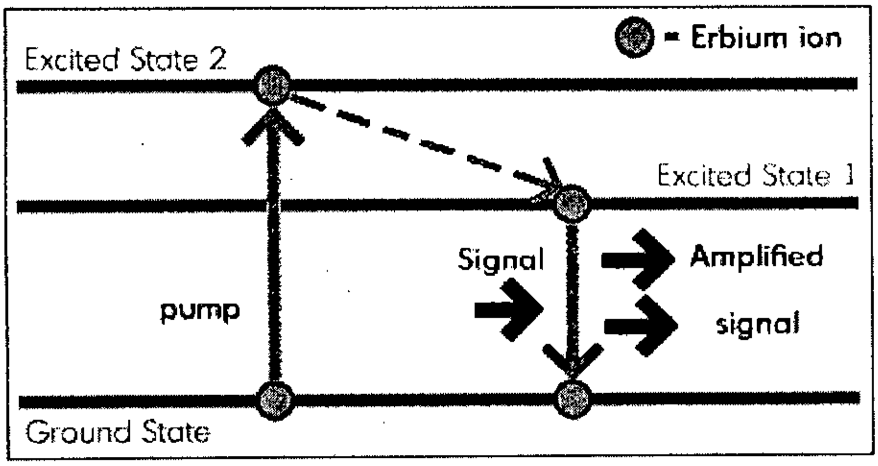


Figure 2.5: Principle of operation of EDFA

Like all optical amplifiers, EDFA also amplify the incident light by stimulated emission, the same mechanism used by lasers. In fact optical amplifier is just a laser without feedback. Figure 2.5 shows an optical amplifier that uses a three level scheme (which is the case for EDFA). Here the dopants are excited to a higher energy state through absorption of pump photons and then relax rapidly to a lower energy state.

Pumping Requirements

The gain characteristics of EDFA strongly depends on the pumping scheme used. Efficient pumping is possible by using semiconductor laser operating near 980 nm and 1480 nm wavelength. It is possible to obtain high amplifier gains within the range of 30-40 dB with only a few miliwatt of pump power. The pump power can be reduced considerably by silica fibers doped with aluminium or phosphorus atoms.Three pumping arrangements are possible with the EDFAs. EDFAs can be designed to operate in such a way that the pump and signal propagate in the opposite direction. This is called backward pumping. When these two propagate in the same direction, it is called forward pumping. The performance is almost the same for the two pumping scheme, when the signal power is small enough for the EDFA to remain unsaturated. In the saturation regime, the power conversion efficiency is generally better in the background pumping configuration. In the bi-directional pumping configuration, the amplifier is pumped in both directions simultaneously by using two semiconductor lasers at the two ends of the fiber. This configuration requires two pumps, but has the advantage that the total pump power and hence the small-signal gain remains relatively constant along the entire amplifier length.

Gain Characteristics

The gain of an EDFA depends on a large number of device parameters such as erbium-ion concentration, amplifier length, core radius and pump power. Considerable efforts have been made to develop an understanding of the gain characteristics through theoretical models. [Agrawal, 1989]. Below is shown some characteristics of typical EDFAs.

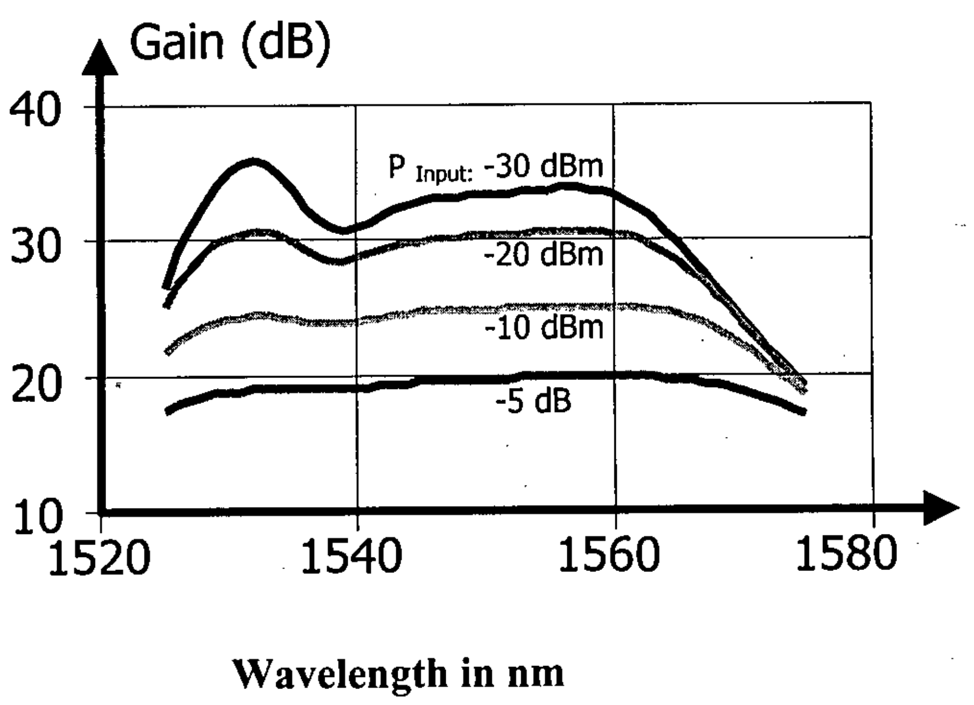


Figure 2.6: Gain versus wavelength of EDFA

Noise in EDFA

As well as providing amplification for an incident light, any gain medium, in which there is a population inversion, is a source of a significant amount of spontaneous emission. Some of that spontaneous emission from any given volume element in the material travels coaxially with the signal and is amplified by the remaining gain medium between its source and the amplifier output facet. Such amplified spontaneous emission (ASE), when mixed with the signal on the detector is a source of noise. Indeed noise associated with the ASE is the limiting factor in determining the ultimate signal to noise ration in any system using optical amplifiers [Agrawal, 1997].

ASE power for a frequency interval from ν to ν+dν is given by

$$P_{ASE}=\mu(G-1)h\nu\, d\nu=\rho_{ASE}\, d\nu \tag{2.4}$$

where μis the population inversion factor, G is the amplifier gain, ν is the frequency and ρ_{ASE} is the spectral power density of the ASE noise.

The total amplifier output power can be determined as

$$P_R=P_S+\rho_{ASE}\, B_0 \tag{2.5}$$

Where P_S is signal power, B_0 is optical bandwidth of the system. ASE noise gives rise to additional noise at receiver over and above signal shot noise. ASE has its own shot noise and it beats both with itself and square law detector. Noise variance is given by

$$\sigma_N=\sigma_{th}+\sigma_{sh}+\sigma_{ASE}+\sigma_{s-ASE}+\sigma_{ASE-ASE} \tag{2.6}$$

Here σ_{th} is the thermal noise, σ_{sh} is the shot noise of signal, σ_{ASE} is the ASE shot noise, $\sigma_{s\text{-}ASE}$ is the signal-ASE beat noise, $\sigma_{ASE\text{-}ASE}$ is the ASE-ASE beat noise

The signal to noise ratio canbe evaluated as

$$SNR = \frac{P_S}{\sigma_N} \tag{2.7}$$

2.4 Multichannel Optical Communication Systems

The large potential bandwidth of optical fiber can be efficiently utilized by transmitting a number of channels simultaneously through the same fiber. The transmission bandwidth of fiber is divided into a number of nonoverlapping frequency (or wavelength) bands and each of these bands is associated to support a single communication channel. Two principal kinds of multichannel systems are common in practical applications, namely, frequency division multiplexing (FDM) and wavelength division multiplexing (WDM). The two schemes differ from each other in respect of receiver configuration, FDM system uses coherent receiver and WDM system uses direct detection receiver.

2.4.1 Wavelength Division Multiplexing (WDM)

Transmitting many different wavelengths of laser light down the same optical fiber at the same time, in order to increase the amount of information that can be transferred is called wavelength division multiplexing (WDM).

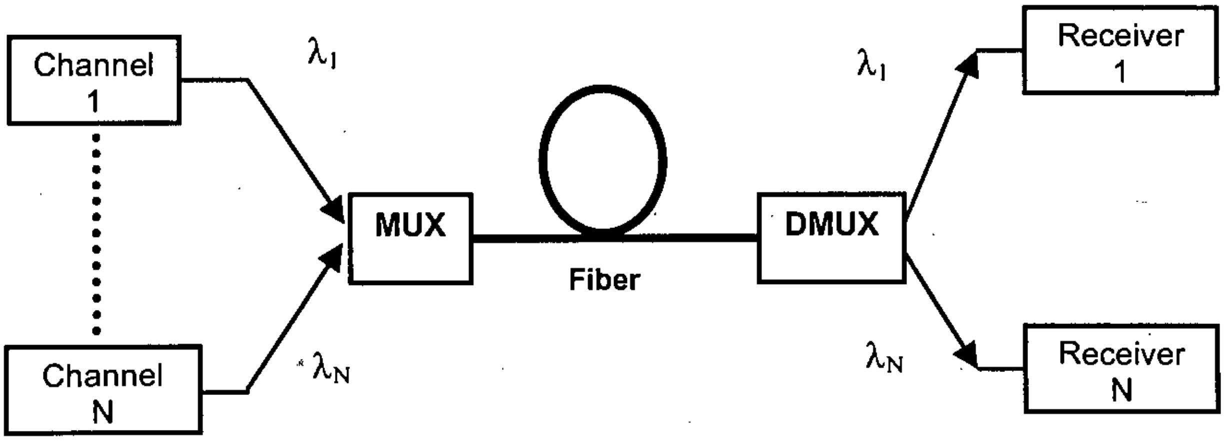


Figure 2.7: Block diagram of a typical WDM system

The block diagram of a WDM system is shown in figure 2.7. In the transmitting end there is a multiplexer using which a number of separate channels are fed through a single optical fiber. In the receiving end there is a demultiplexer which separates the different channels and directs them to different receivers.

Dense Wavelength Division Multiplexed (DWDM) System

The information carrying capacity of the optical fiber system can further be enhanced by using closely spaced wavelengths, which is known as the dense wavelength division multiplexing (DWDM) process. The limits of this spacing are yet to be determined, however, systems are available with a capacity of 128 wavelengths on one fiber.

From both technical and economic perspectives, the ability to provide unlimited transmission capacity is the most obvious advantage of DWDM technology. As demands change, more capacity can be added, either by simple equipment upgrades or by increasing the number of wavelengths on the fiber, without expensive upgrades. Capacity can be obtained for the cost of the equipment only and existing fiber plant investment is retained. DWDM's most compelling advantages can be summarize as follows:

(1) *Transparency*: Because DWDM is a physical layer architecture, it can transparently support both time division multiplexed (TDM) and data formats such as ATM, Gigabit Ethernet, ESCON, and fiber channel with open interfaces over a common physical layer.
(2) *Scalability*: DWDM can leverage the abundance of dark fiber in many metropolitan area and enterprise networks to quickly meet demand for capacity on point-to-point links and on spans of existing SONET/SDH rings.
(3) *Dynamic provisioning*: Fast, simple, and dynamic provisioning of network connections give providers the ability to provide high bandwidth services in days rather than months.

DWDM has become the clear winner in the backbone. It was first deployed in long haul routes at a time of fiber scarcity. Then the equipment savings made it the solution of choice for new long haul routes, even when ample fiber was available. While DWDM can relieve fiber exhaust in the metropolitan area, its value in this market extends beyond this single advantage. Alternatives for capacity enhancement exist, such as pulling new cable and SONET overlays, but DWDM can do more.

DWDM will continue to provide the bandwidth for large amounts of data. In fact, the capacity of systems will grow as technologies advance that allow closer spacing, and therefore higher number of wavelengths. But DWDM is also moving beyond transport to become the basis of all-optical networking with wavelength provisioning and mesh-based protection. Switching at the photonic layer will enable this evolution, as will the routing protocols that allow light paths to traverse the network in much the same way as virtual circuits do today.

2.4.2 Frequency Division Multiplexing (FDM)

In FDM the optical channel bandwidth is divided into a number of nonoverlapping frequency bands and each signal is assigned one of these bands of frequencies. The individual signal can be extracted from the combined signal by appropriate electrical filtering in the receive terminal. Hence FDM is usually done electrically at the transmit terminal prior to intensity modulation of a single optical source.

2.4.3 Comparison of FDM and WDM Systems

Following is a list of comparison between WDM and FDM systems.

1) Both techniques are identical in the sense that optical power from more than one laser travels through a single fiber.

2) For WDM systems, demultiplexing can be done in optical domain using direct detection techniques.

3) Coherent receivers are required for FDM systems and the demultiplexing is done in electrical domain.

4) The channel spacing for a FDM system can be set to a much lower values than that for a WDM system.

5) WDM has simpler and cheaper receiver circuit.

2.5 Conclusion

In this chapter a brief description of the optical communication system is given. Various important components of such a system are discussed. Now a days almost all optical networks are multichannel systems. So different types of multichannel systems are also discussed. Finally a comparison is made between WDM and FDM systems which are the two most popular multichannel systems currently in use.

Chapter 3

FOUR WAVE MIXING

3.1 Introduction

In this chapter a detailed description of the four wave mixing (FWM) phenomenon will be given. The mechanism involved in the generation of FWM components will be discussed. The effects of FWM on WDM system will be described. Finally the expression for evaluating performance of a WDM system in presence of FWM will be developed.

3.2 Origin of FWM

There are in general two types of nonlinear processes. In the scattering processes the fiber plays an active role through the participation of molecular vibrations or acoustic phonons. In many nonlinear phenomenon the fiber plays a passive role except for mediating the interaction among several optical waves through a nonlinear response of bound electrons. Such processes are referred to as parametric processes as they originate from light induced modulation of a medium parameter such as refractive index. FWM is such a parametric process.

The origin of parametric processes like FWM lies in the nonlinear response of bound electrons of a material to an applied electric field. More specifically the polarization induced in the medium is not linear in the applied field but contains nonlinear terms whose magnitude is governed by the nonlinear susceptibilities. The parametric processes can be classified as second order or third order parametric processes depending on whether the second order susceptibility $\chi^{(2)}$ or the third order susceptibility $\chi^{(3)}$ is responsible for them. The second order susceptibility can be neglected in an isotropic medium like silica. For this reason second order processes like second harmonic generation and sum frequency generation are very weak in optical fibers.

The third order parametric processes involve, in general, the interaction among four optical waves and include the phenomenon such as third harmonic generation, four wave mixing and parametric amplification.

The origin of FWM can be understood by considering the third order polarization term given as [Stolen, 1974]

$$P_{NL} = \varepsilon_0 \chi^{(3)} : EEE \tag{3.1}$$

where E is the electric field, P_{NL} is the induced nonlinear polarization and ε_0 is the vacuum permittivity. Let us consider four optical waves oscillating at frequencies ω_1, ω_2, ω_3 and ω_4 respectively linearly polarized along the same axis. The total electric field can be written as

$$E = \hat{x}\frac{1}{2}\sum_{j=1}^{4} E_j \exp[i(k_j z - \omega_j t)] + c.c. \tag{3.2}$$

where $k_j=n_j\omega_j/c$, n_j is the refractive index and all four waves are assumed to be propagated in the same direction z. If we substitute (3.2) in (3.1) and express P_{NL} in the form

$$P_{NL} = \hat{x}\frac{1}{2}\sum_{j=1}^{4} P_j \exp[i(k_j z - \omega_j t)] + c.c. \tag{3.3}$$

we find that P_j for j=1-4 consists of a large number of terms involving the products of three electric fields. For example P_4 can be expressed as [Agrawal, 1995]

$$P_4 = \frac{3\omega_0}{4}\chi^{(3)}_{xxxx}\{[|E_4|^2 + 2(|E_1|^2 + |E_2|^2 + |E_3|^2]E_4 + 2E_1E_2E_3\exp(i\theta_+) + 2E_1E_2E_3\exp(i\theta_-) + ...\} \tag{3.4}$$

where

$$\theta_+ = (k_1 + k_2 + k_3 - k_4)z - (\omega_1 + \omega_2 + \omega_3 - \omega_4)t \tag{3.5}$$

$$\theta_- = (k_1 + k_2 - k_3 - k_4)z - (\omega_1 + \omega_2 - \omega_3 - \omega_4)t \tag{3.6}$$

The term proportional to E_4 is responsible for SPM and XPM effects. The remaining terms are responsible for FWM. How many of these are responsible for a parametric coupling depends on the relative phase between E_4 and P_4 given by θ_+ and θ_- or a similar angle. FWM process becomes significant only if the relative phase nearly vanishes. This requires matching of the frequencies as well as the wave vectors. The latter requirement is often referred to as phase matching. In quantum mechanical terms FWM occurs when photons from one or more waves are annihilated and new waves are created at new frequencies such that the net energy and momentum are conserved during the parametric interaction. The main difference between the parametric processes and the scattering processes is that phase matching condition is automatically satisfied for the scattering processes as a result of the active participation of the nonlinear medium. By contrast the phase matching condition requires a specific choice of frequencies and the refractive indices for a parametric process like FWM to occur.

There are two types of FWM terms in equation (3.4). The second term of the right hand side corresponds to the case in which three photons transfer energy to a single photon at the frequency $\omega_4 = \omega_1 + \omega_2 + \omega_3$. This term is responsible for phenomenon such as third harmonic generation when $\omega_1 = \omega_2 = \omega_3$ or frequency conversion to the wave at $2\omega_1+\omega_3$ when $\omega_1 = \omega_2 \neq \omega_3$. In general it is difficult to satisfy the phase matching condition for such processes to occur in optical fibers with high efficiencies. The last term in (3.4) corresponds to the case in two photons at frequencies ω_1 and ω_2 are annihilated with a simultaneous creation of two photons at frequencies ω_3 and ω_4 such that

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \tag{3.7}$$

The phase matching requirement for this process to occur is that $\Delta k=0$ where

$$\Delta k = k_3 + k_4 - k_1 - k_2$$

$$= (n_3\omega_3 + n_4\omega_4 - n_1\omega_1 - n_2\omega_2)/c \tag{3.8}$$

It is relatively easy to satisfy $\Delta k=0$ for the FWM process described by (3.5) and (3.6) in the particular case in which $\omega_1 = \omega_2$. This partially degenerate case has been studied almost exclusively in optical fibers. Physically it manifests in a way similar to stimulated

Raman scattering. A strong pump wave at ω_1 create two sidebands located symmetrically at the frequencies ω_3 and ω_4 with a frequency shift given by

$$\Omega_s = \omega_1 - \omega_3 = \omega_4 - \omega_1 \tag{3.9}$$

where for definiteness it is assumed that $\omega_3 < \omega_4$.

As can be seen from equation (3.9) the effect of FWM resembles stimulate Raman scattering. In fact the low frequency sideband at ω_3 and high frequency sideband at ω_4 are referred to as Stokes and anti-Stokes bands in direct analogy with SRS. The partially degenerate FWM is also known as three wave mixing as only three distinct frequencies are involved in the nonlinear process.

3.3 Phase Matching in Single Mode Fibers:

As mentioned in the previous section FWM peaks when the wave vector mismatch is close to zero. The wave vector mismatch κ can be expressed in the form

$$\kappa = \Delta k_M + \Delta k_W + \Delta k_{NL} = 0 \tag{3.10}$$

where $\Delta k_M, \Delta k_W, \Delta k_{NL}$ represent mismatching occurring as a result of material dispersion, waveguide dispersion and the nonlinear effects. For SMF significant amount of FWM can occur even when phase matching is not perfect to produce $\kappa=0$. The amount of tolerable wave vector mismatch depends on the relative magnitude of the fiber length L and the coherence length L_{coh} . Assuming that the contribution Δk_M dominate the coherence length can be related to the frequency shift Ω_s an is given by

$$L_{coh} = \frac{2\pi}{|\Delta k_M|} = \frac{2\pi}{|\beta_2|\Omega_s^2} \tag{3.11}$$

In the visible range typically β_2=50-60 ps^2/km resulting in $L_{coh} \geq 1km$ for frequency shifts $\nu_s = \Omega_s / 2\pi \leq 100$ GHz. Such large coherence lengths indicate that FWM can occur in SMF for frequency shifts such that $L \leq L_{coh}$

3.4 Effects of FWM

FWM process can be a serious limiting factor in long haul WDM systems. This is because FWM process becomes stronger when channel spacing is smaller and power per channel is large. This is the case for long haul WDM systems. As the demand for high data rate is increasing day-by-day WDM systems has to transmit more and more channels and all these channels have to be placed within the low attenuation window. Also to make the spacing between the amplifier large, input power per channel has to be large. For these reasons FWM process can become very serious problem particularly in DWDM systems.

FWM process can degrade system performance in two ways:

1) Because of the FWM process a large number of new signals are generated. The number of FWM products because of the interaction of N number of channels is $\frac{1}{2}(N^3$-

N^2). Some of this FWM signal may occupy the same position as the original signals and may degrade system performance by interference.

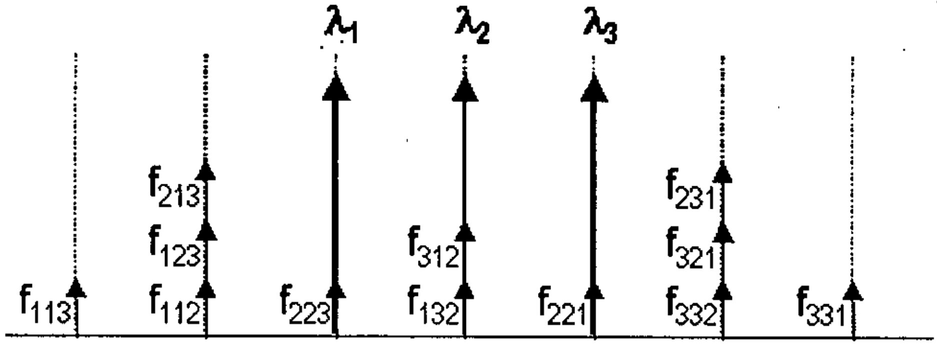


Figure 3.1: Interference caused by FWM products with original signals

For example we take three channels as shown in figure 3.1. Nine FWM products are generated here, of which three falls on the original signal positions and interfere with them.

2) The second problem is that FWM signals take power from the original signals for their generation. As a result the original signals are depleted of power and becomes weaker.

3.5 Evaluation of the Effects of FWM

The effect of FWM is as discussed in the previous section twofold. In this section we shall give analynitical description of these effects. In the first subsection we shall derive a very simple formula which can be used to evaluate the performance of a WDM system quite easily. In the second subsection the necessary formula for evaluating power depletion is given.

3.5.1 Evaluation of Bit Error Rate , Power Penalty and Allowable Input Power

In an optical transmission link, each repeater span is composed of a number of short-length fibers as shown in figure 3.2.

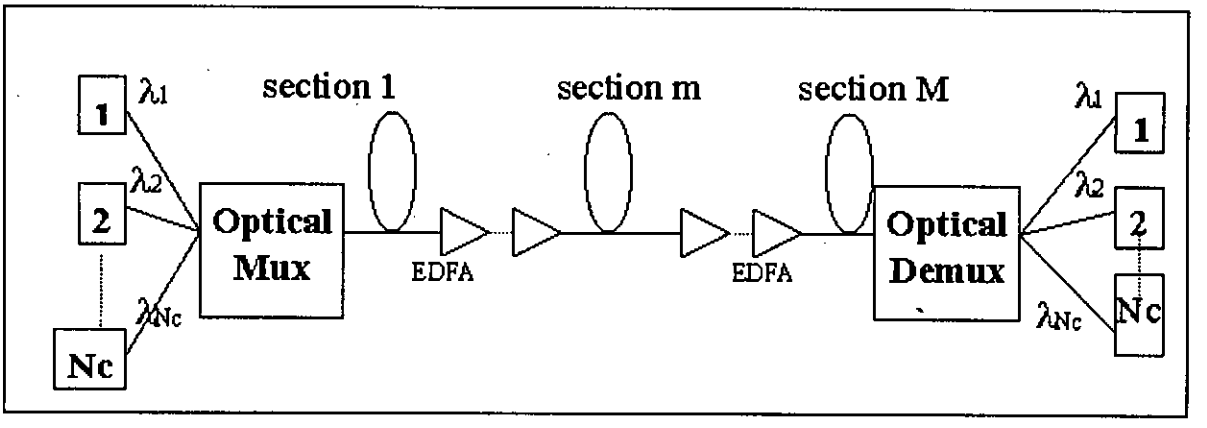


Figure 3.2: Typical WDM system

The total transmission link consists of M sections, where each section has N number of fibers of equal length. There is (M-1) number of amplifiers with equal repeater span throughout the system to compensate for the power loss of the section just before the amplifier. Thus the power input at the beginning of each section is essentially equal. It is assumed that the polarization states of all optical sources are matched throughout the transmission system. For simplicity polarization mode dispersion is ignored.

The probability of error can be determined as [Personic, 1973]

$$P_e = \frac{1}{\sqrt{2\pi}} \int_Q^\infty \exp[-\frac{t^2}{2}]dt \tag{3.12}$$

where, Q is the quality factor and is given by [Schadt, 1991], [Zheng, 1999]

$$Q = \frac{bPs}{\sqrt{N_{th} + N_{sh} + N_{FWM}} + \sqrt{N_{th}}} \tag{3.13}$$

where, $b = \frac{\eta e}{h\nu}$, η is the coupling efficiency of the detector, e is the electron charge, h is the Planck's constant, ν is the light frequency, P_s is the signal power, $N_{sh} = k_s b P_s$ is the shot noise power, k_s is a proportional constant, $N_{th} = \frac{4KT}{R_L} B_e$ is the thermal noise power, K is the Boltzman constant, T is the temperature, R_L is the terminating load resistance, B_e is the electrical bandwidth of receiver and N_{FWM} is the FWM noise power. The signal power can be found as

$$P_s = N_c P_o \exp(-\alpha L) L_r \tag{3.14}$$

where, L_r is the insertion loss before receiver, N_c is the number of channels, P_o is the input power of each channel, L is the section length, α is the attenuation constant.

The power of FWM signal for the general case of chromatic dispersion can be found as [Inoue, 1995] (Appendix B)

$$P_{FWM} = \frac{1024\pi^6}{n_o^4 \lambda^2 c^2}(D\ \chi)^2 \frac{P_a P_b P_c}{A_{eff}^2} e^{-\alpha L} \left| \sum_{M=1}^{M} \exp\left[i \sum_{k=1}^{m-1} \Delta\phi^k \right] \times \sum_{n=1}^{N} \exp\left[\sum_{j=1}^{n-1} \left(-\alpha + i\Delta\beta^{mj}\right) L_0 \right] \times \frac{1-\exp\left[\left(-\alpha + i\Delta\beta^{mn}\right)L_0\right]}{\alpha - i\Delta\beta^{mn}} \right|^2 \tag{3.15}$$

where, A_{eff} is the effective mode area, P_a, P_b and P_c are the input powers of channels a, b and c, n_o is the refractive index, λ is the wavelength, D is the degeneracy factor and L_0 is the length of each fiber so that $NL_0 = L$ is the length of each section. The above expression, however, is derived without taking the FWM process in EDFA into consideration.

The difference in propagation constant of the FWM signal due to chromatic dispersion is given by [Inoue, 1992]

$$\begin{aligned} \Delta\beta^{mn} &= \beta_a^{mn} + \beta_b^{mn} - \beta_c^{mn} - \beta_F^{mn} \\ &= -\frac{\pi\lambda^4}{c^2}\frac{dD_c}{d\lambda}\left\{\left(f_a - f_o^{mn}\right) + \left(f_b - f_o^{mn}\right)\right\} \times \left(f_a - f_c\right)\left(f_b - f_c\right) \end{aligned} \tag{3.16}$$

where, β_a^{mn}, β_b^{mn}, β_c^{mn} and β_F^{mn} are the propagation constants for channel a, b, c and FWM, respectively, of the nth fiber in the mth section, f_o^{mn} is zero-dispersion frequency of nth fiber in mth section, D_c is the chromatic dispersion coefficient, $\phi_a^m = \sum_{n=1}^{N} \beta_a^{mn} L_0$, $\phi_b^m = \sum_{n=1}^{N} \beta_b^{mn} L_0$, $\phi_c^m = \sum_{n=1}^{N} \beta_c^{mn} L_0$ and $\phi_F^m = \sum_{n=1}^{N} \beta_F^{mn} L_0$ are the propagation phases for the channels a, b, c and FWM, respectively, through the mth section. Therefore we get the difference in propagation phase of the FWM signal for mth section

$$\Delta\phi^m = \phi_a^m + \phi_b^m - \phi_c^m - \phi_F^m \tag{3.17}$$

Now if the fibers have uniform dispersion throughout the transmission distance then the equation (3.15) can be rewritten as

$$P_{FWM} = \frac{1024\pi^6}{n_o^4 \lambda^2 c^2}(D\ \chi)^2 \frac{P_a P_b P_c}{A_{eff}^2} e^{-\alpha L} \left| \begin{array}{c} \dfrac{2\exp(i\Delta\phi) - \exp(2i\Delta\phi) - \exp(Mi\Delta\phi)}{1-\exp(i\Delta\phi)} \times \dfrac{1-\exp[(-\alpha + i\Delta\beta)L_0]}{\alpha - i\Delta\beta} \times \\ \dfrac{2\exp[(-\alpha+i\Delta\beta)L_0] - \exp[2(-\alpha+i\Delta\beta)L_0] - \exp[N(-\alpha+i\Delta\beta)L_0]]}{1-\exp[(-\alpha+i\Delta\beta)L_0]} \end{array} \right|^2$$

(3.18)

Finally, N_{FWM} can be estimated as [Zheng, 1999]

$$N_{FWM} = \frac{1}{4} b^2 P_s P_{FWM} \tag{3.19}$$

Putting the equation (3.19) in equation (3.13) we get

$$k_s + \frac{1}{4} b P_{FWM} = \frac{b P_{SF}}{Q^2} - \frac{2}{Q}\sqrt{N_{th}} \tag{3.20}$$

and in absence of FWM

$$k_s = \frac{b P_{s0}}{Q^2} - \frac{2}{Q}\sqrt{N_{th}} \tag{3.21}$$

where, P_{SF}, P_{S0} are the received signal powers with and without FWM, respectively, at a certain value of Q. Thus the power penalty, $P_p = P_{SF} / P_{S0}$, at a given value of Q_o can estimated as

$$P_p = \frac{1}{1 - \frac{1}{4}\frac{P_{FWM}}{P_{SF}} Q_0^2} \tag{3.22}$$

The allowable input power is evaluated using the above equation.

3.5.2 Evaluating the Power Depletion:

Let us assume that we are transmitting three channels with input powers $P_1(0)$, $P_2(0)$, $P_3(0)$. If energy is coupled from P_1 to P_2 and P_3 then we can write [Wu, 1995]

$$Q_1 = P_1(0)y \tag{3.23}$$

$$Q_2 = 0.5P_1(0)(1-y) + P_2(0) \tag{3.24}$$

$$Q_3 = 0.5P_1(0)(1-y) + P_3(0) \tag{3.25}$$

Here γ is the nonlinearity coefficient and $P_j = Q_j exp^2(-\alpha z/2)$, α is the attenuation constant, y is a function of distance z. For unequal channel spacing

$$y = \frac{r+1}{r\cosh^2(\sqrt{r+1}f)+1} \tag{3.26}$$

$$f = \gamma P_1(0)[1-\exp(-\alpha z)]/\alpha \tag{3.27}$$

$$r = 2P_2(0)/P_1(0) \tag{3.28}$$

For equal channel spacing , the equation (3.26) can be rewritten as

$$y = \frac{4\bar{r}^2\exp(2\bar{r}f)}{r_0^2\exp(4\bar{r}f) + 2(2+r_2+r_3)\exp(2\bar{r}f)} + r_0^{-2}(r_3-r_2)^2 \tag{3.29}$$

$$r_2 = 2P_2(0)/P_1(0) \tag{3.30}$$

$$r_3 = 2P_3(0)/P_1(0) \tag{3.31}$$

$$\bar{r} = \sqrt{(1+r_2)(1+r_3)} \tag{3.32}$$

$$r_0 = \sqrt{r_3(r_2+1)} + \sqrt{r_2(r_3+1)} \tag{3.33}$$

By solving these equations we can find the power depletion caused by the FWM process.

3.6 Applications of FWM

FWM causes adverse effect in a WDM system and we try to reduce FWM as much as possible. However, it can also be used to serve some useful purpose. A major application of FWM is in the development of parametric amplifier that operates using the principle of FWM. In contrast to other fiber amplifiers, like Raman amplifiers, they have a small bandwidth (around 100 GHz) but the frequency shift can be as large as 100 THz. It permits considerable flexibility in the choice of a pump, while, at the same time the bandwidth is large enough for many applications. The phase-sensitive nature of these amplifiers can have other advantages. For example, the application of such amplifiers in soliton communication systems can solve the timing-jitter problem.

3.7 Conclusion

In this chapter the FWM process is discussed in some detail. The effects of FWM process on system performance is discussed both qualitatively and quantitatively. A number of applications of FWM process is also discussed.

Chapter 4

PERFORMANCE ANALYSIS OF WDM SYSTEM

4.1 Introduction

In this chapter the performance of a multichannel WDM system in presence of FWM will be evaluated. Here a conventional system is taken, which has uniform chromatic dispersion throughout the length. The dependence of performance on various system parameters like number of channels, input power per channel will be examined.

4.2 System Description

The block diagram of a typical WDM system is as shown in figure 3.2. It is assumed that the gains of the in-line amplifiers are such that they exactly compensate for the loss in different fiber sections and the insertion loss at receiver.

Two multi-amplifier optical systems with fifty sections each consisting twenty different fibers is studied. The length of each fiber is 2 km. The total haul of the system considered is 2,000 km and 1000 km. The values of different system parameters are listed in Appendix A.

4.3 Results

4.3.1 Number of FWM Products

The number of FWM products with various number of channels is shown in figure 4.1. With regard to FWM crosstalk, the ultimate factor degrading the WDM system performance is usually the power of FWM signals rather than the total number of FWM products falling onto the operating band of each channel. Nevertheless the later is a useful measure when the zero dispersion wavelength is near the center channel. [Chang 2000]. As can be seen the number of FWM products increases sharply with the increase in number of channels.

4.3.2 FWM Power

The FWM power generated is plotted in figure 4.2 as a function of frequency. As is seen from the figure the FWM power reduces sharply with the increase in channel spacing. This is because when the cannel spacing is made smaller phase matching becomes easier. This shows the importance of FWM reduction schemes, because in modern WDM systems channel spacing is becoming increasingly small. AS a result the performance can become very unsatisfactory even when the system length is small but the number of channels is large and as a result the spacing between the channels is small.

4.3.3 Bit Error Rate

The BER performance is shown in figure 4.3 and figure 4.4. As seen from both figures BER increases with the increase in input power per channel. From figure 4.3 we see that the increase in system length BER also increases. The effect of channel spacing on BER is shown in figure 4.4. Clearly BER increases when channel spacing is made smaller.

4.3.4 Power Penalty

Power penalty is the ratio of power required at the receiver in presence of FWM and in absence of FWM. The power penalty suffered by the system to achieve a BER of 10^{-9} is plotted in figure 4.5 and figure 4.6. Power penalty increases with input power per channel. It also increases with the increase in system length and reduction in channel spacing.

4.3.5 Allowable Input Power

For long haul WDM system we want to inject high power signals at the transmitting end so that the amplifier spacing can be made sufficiently large. The allowable input power as a function of number of channels is shown in figure 4.7 and figure 4.8. Clearly the allowable input power is quite small for the system under discussion. Also the allowable input power reduces rapidly with the increase in number of channels. It also reduces with the increase in system length and reduction in channel spacing.

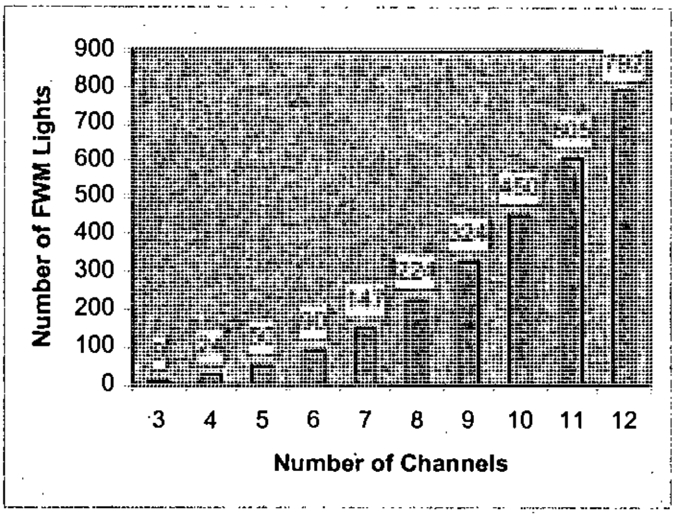


Figure 4.1: Number of FWM lights for varying number of channels

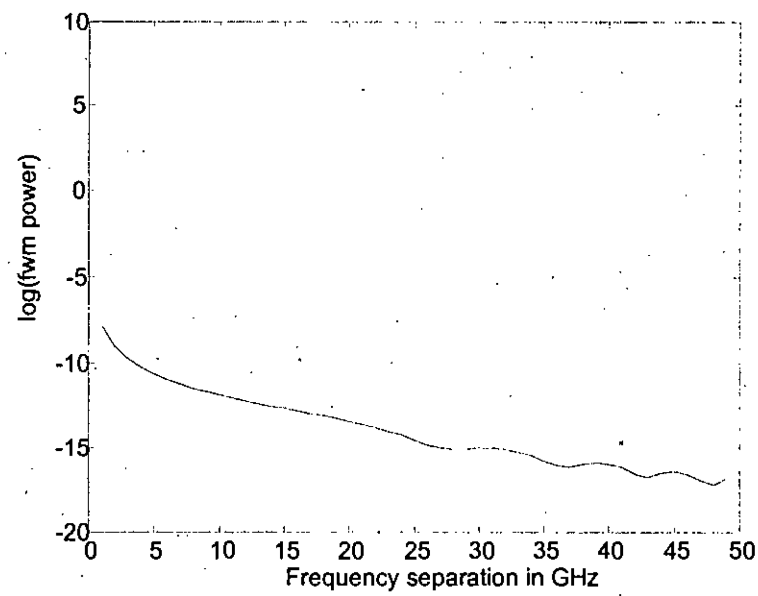


Figure 4.2: FWM power as a function of channel spacing

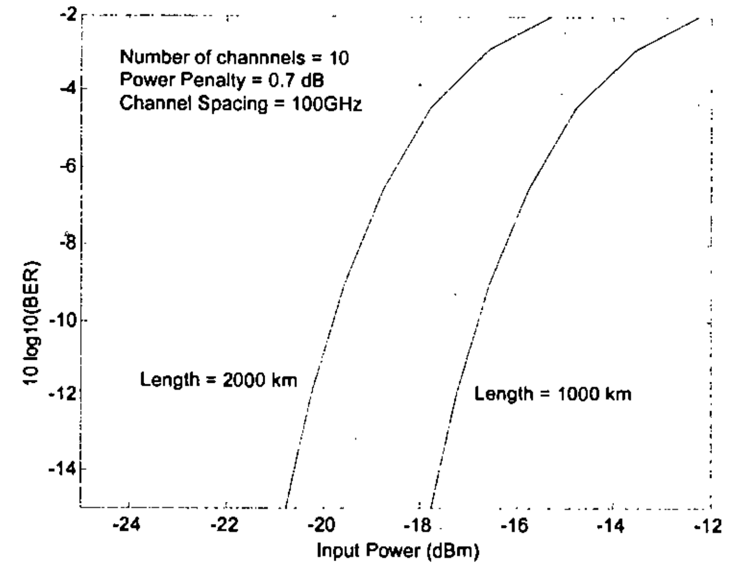


Figure 4.3: BER versus input power for changing length

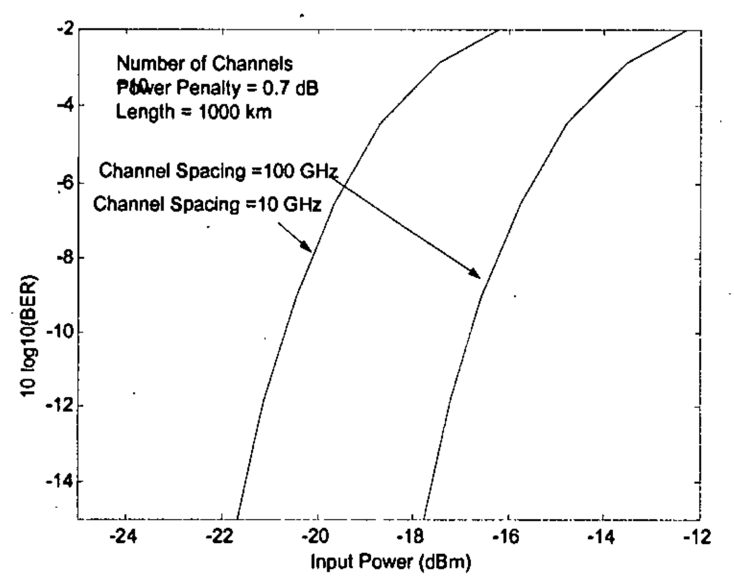


Figure 4.4: BER versus input power for varying frequency spacing

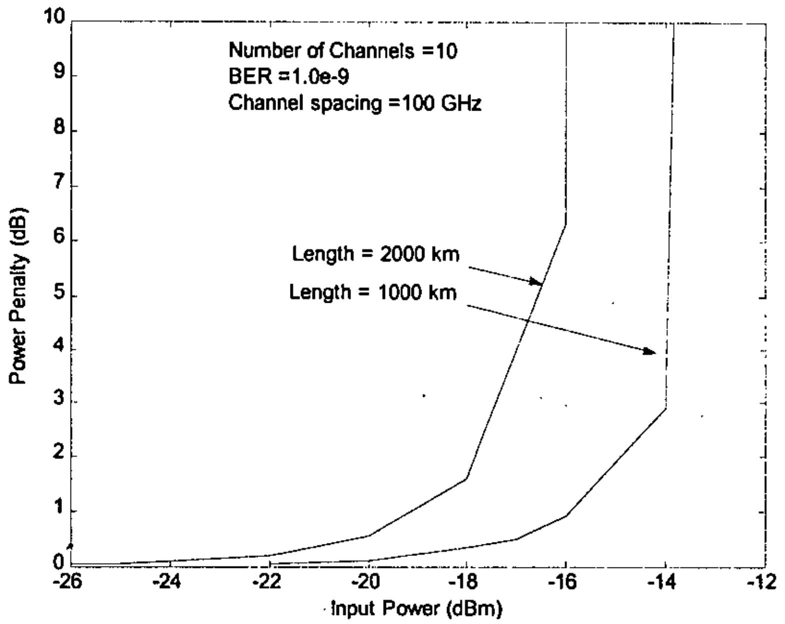


Figure 4.5: Penalty versus input power for changing length

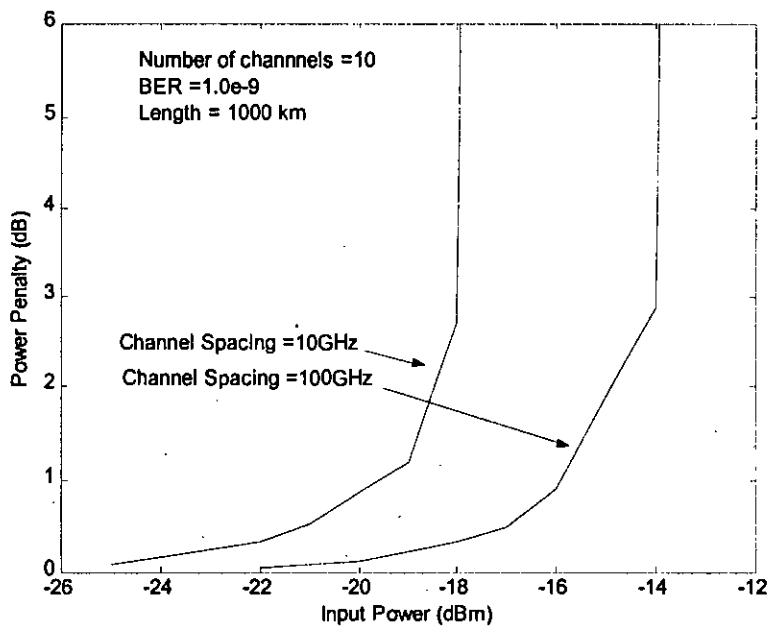


Figure 4.6: Power penalty vs input power for changing frequency

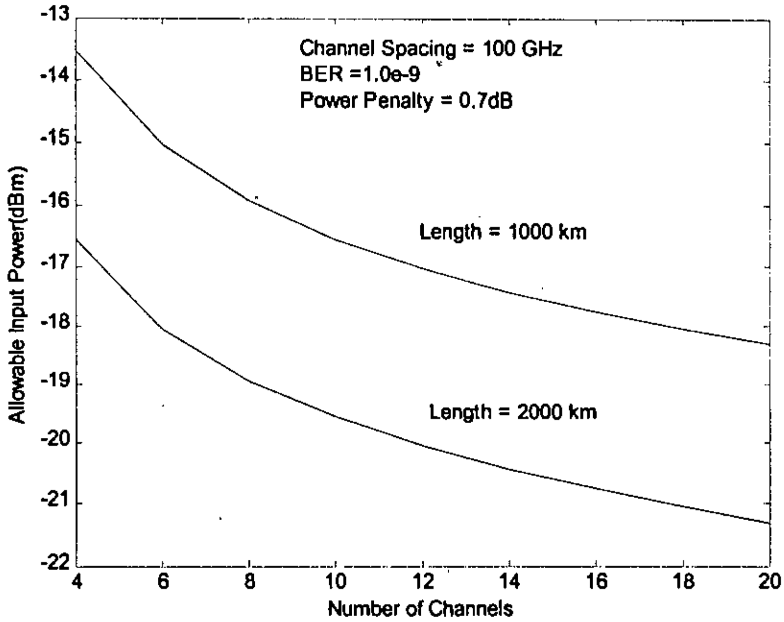


Figure 4.7: Allowable input power versus number of channels for changing length

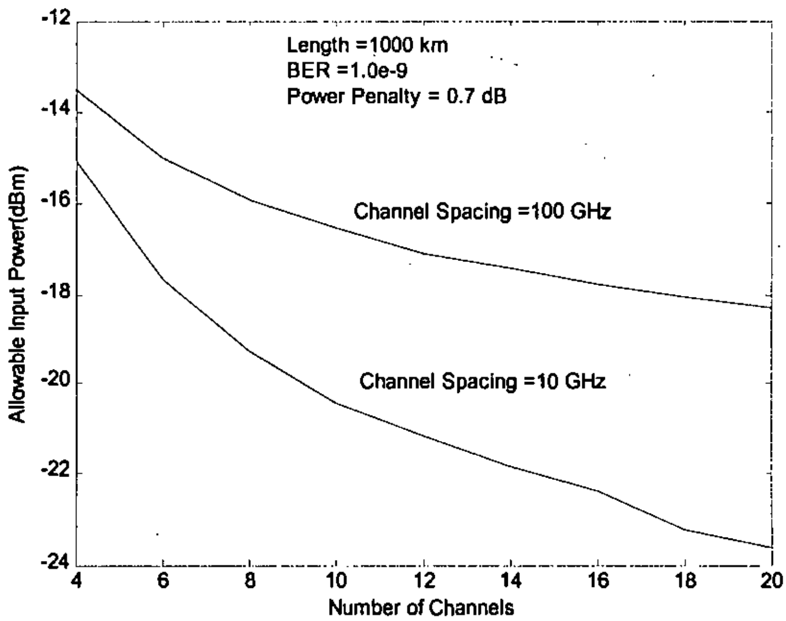


Figure 4.8: Allowable input power versus number of channels for changing channel spacing

4.4 Conclusion

In this chapter we have analyzed the performance of a WDM system that employs uniform dispersion and equal channel spacing scheme. A number of things can be noted from the analysis. First of all it is seen that the number FWM lights increase very quickly with the increase in number of channels. A number of these FWM components may fall on the channel positions and degrade system performance. That is the reason behind the poor performance in BER, power penalty and allowable input power. An important observation is that with the increase in channel power or reduction in channel spacing the performance degrades to a great extent. Therefore some scheme is necessary to improve the performance of the system.

Chapter 5

FWM REDUCTION BY USING UNEQUAL AND REPEATED UNEQUAL CHANNEL SPACING

5.1 Introduction

The major problem caused by the FWM process is that the FWM signals may interfere with the original signals and degrade system performance. Unequal channel spacing scheme can be used to reduce this problem. When the spacing between the channels is unequal the FWM components no more interfere with the original signals. But unequal channel spacing scheme require a huge expansion in bandwidth requirement. To alleviate this problem repeated unequal channel spacing may be used. In this chapter the performance of a WDM system will be investigated under both of these schemes.

5.2 Unequal Channel Spacing Scheme

5.2.1 Principle of Unequal Channel Spacing Scheme

As we know in FWM process three waves with frequencies f_i f_j and f_k ($k \neq i, j$) generate FWM components with frequencies given by

$$f_{ijk} = f_i + f_j - f_k \quad (5.1)$$

The problem of designing a scheme of unequal channel spacing suitable for FWM suppression can be reduced to an integer linear programming (ILP) problem by dividing the optical bandwidth into equal slots of bandwidth Δf large enough to avoid appreciable overlap between adjacent slots. Since the bandwidth occupied by a FWM wave is only slightly larger than the bandwidth of a channel, it is enough to separate them by twice the bit rate [Litchman, 1991]. Given an arbitrary reference optical frequency f_0, the ith slot is centered around the optical frequency $fi=f_0+n_i\Delta f$, where n_i is an integer that can be referred to as the slot number of the ith frequency slot. In terms of slot number (5.1) becomes

$$n_{ijk} = n_i + n_j - n_k \qquad (k \neq i, j) \quad (5.2)$$

If n_{ijk} does not coincide with any of the channel slot numbers for any choice of i,j,k, no FWM wave generated by signal is created in any of the channel slots. If N is the number of channels to be transmitted, it is then sufficient to choose N slots (with increasing slot numbers), $(n_1,n_2,\ldots\ldots,n_N)$, such that

$$\forall i, j, k \in 1 \ldots N(k)(k \neq i, j), \qquad n_{ijk} \notin (n_1, n_2, \ldots, n_N) \quad (5.3)$$

The above condition can be shown to be equivalent to requiring that for any two different pairs the frequency separation between the two channels in each pair cannot be the same [Forghieri, 1994] The FWM problem has then reduced to the ILP problem of finding a vector of N-1 positive integers (m_1, $m_{2,...}m_{N-1}$) which represent the channel spacing, such that the *N(N-1)/2* partial sums of adjacent elements

$$s_{jk} = \sum_{j}^{k} m_j (1 \le j \le k \le N) \qquad (5.4)$$

are all different from each other.

At the receiver optical filters must be used to separate the channels before detection. A minimum frequency spacing $\Delta f_c = n\Delta f$ between slots used for the channels must be provided to allow an adequate amount of rejection of the undesired channels. This imposes on the ILP problem the additional constraint $m_i \ge n$ where $n\Delta f$ is the minimum permitted frequency separation between adjacent channels.

There is no unique solution to the ILP problem described above and no efficient method to solve it is known. An optimum solution can be found only by an exhaustive search.

5.2.2 Limitations of Unequal Channel Spacing Scheme

1) Expansion of Bandwidth Requirement

A problem of this scheme is the expansion of bandwidth. This scheme requires much wider bandwidth compared to equal channel spacing scheme. A lower bound to the total optical bandwidth required B_{un} can be found [Forghieri, 1995] . Let us suppose that the spacing between adjacent channels in terms of number of slots is m_i. The minimum allowable spacing between channels is $n_i\Delta f$. Then the condition for choosing m_i is that each m_i must be different from any other m_i and

$$m_i - n \geq 0 \tag{5.5}$$

In such a case, the lower possible values for $(m_i\text{-}n)$ are 1,2,3,......., (N-1). Thus we get

$$\sum_{i=1}^{N-1} m_i = \sum_{i}^{N-1} n + [1+2+3+.......+(N-1)] = (N-1)n + \frac{(N-1)(N-2)}{2} \tag{5.6}$$

Therefore the optimized bandwidth is given by

$$B_{un} \geq \Delta f \sum m_i = [(N-1)n\Delta f + \frac{(N-1)(N-2)}{2}]\Delta f$$

$$= (1 + \frac{N/2-1}{n})(N-1)n\Delta f$$

$$= (1 + \frac{N/2-1}{n})B_{eq} \tag{5.7}$$

where B_{eq}=(N-1)Δf is the total optical bandwidth of conventional WDM system with the channels equally spaced by Δf.

2) Influence of Higher Order FWM Products

Unequal channel spacing ensures that none of the FWM products generated by the channels will fall on any channel frequency. But newly produced FWM products can mix with channel signals or between themselves to produce higher order FWM products. It has been shown [Song, 2000] that these higher order products can overlap with channels and result in crosstalk. For example if we take a two-channel system as shown in figure 5.1 we see that some of the higher order terms do coincide with channel frequencies.

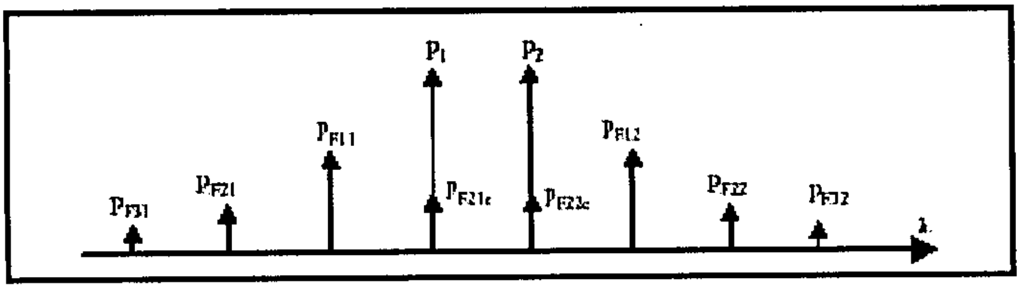


Figure 5.1: Higher order FWM products produced from two signals [Song, 2000]

Here P_1 and P_2 are the input channel. P_{F11} and P_{F12} are the first order FWM powers, P_{F21} and P_{F22} are the second order FWM powers. P_{F31} and P_{F32} are the third order FWM products.P_{F21c} and P_{F22c} are second order FWM products falling on the channels. The effect of these higher order terms may be serious especially when channel power becomes large or channel spacing becomes narrow. Figure 5.2 illustrates this more clearly [Song, 2000]. This is a plot of Q value versus input channel power. When channel power is low (<5 dBm) no significant degradation of Q value occurs. But when channel power increases more than 5 dBm to about 10 dBm, Q value begins to drop sharply.

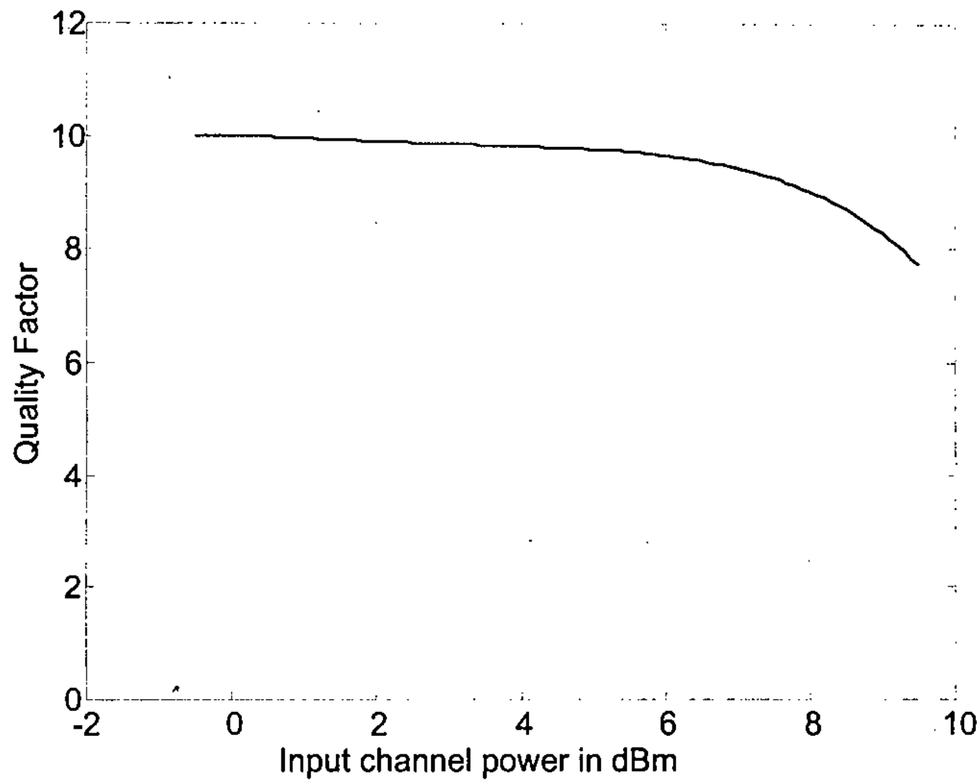


Figure 5.2: Plot of quality factor as a function of input power [Song, 2000]

3) Although the FWM lights do not interfere with the channel frequencies the channels are depleted of power because of the FWM process. This can cause serious performance degradation especially when power level of signals is high or the number of channels is large. But this problem is usually not as serious as the problem of interference caused by the FWM components.

5.3 Repeated Unequal Channel Spacing Scheme

5.3.1 Principle of Repeated Unequal Channel Spacing Scheme

As has already been discussed, ES channels have a lot of FWM lights with the frequencies coincident with those of signals, and US channels have a wide signal bandwidth for a large number of channels. In contrast to these problems, RUS channels analyzed here can simultaneously achieve a few FWM lights interfering with the channel signals and a narrow signal bandwidth even for a large number of channels.

In the case of repeated unequal channel spacing, first a base scheme of unequal spacing for a number of channels is fixed. Let such a base scheme be $\tilde{n}_{us}$. US frequency allocation with number of channels $\tilde{N}_{us}$ and an adjacent spacing $\tilde{d}_{us} = \{d1, d2, d3........d_{N_{US}-1}\}$ is found. Now this base allocation will be repeated as many times as it requires for the desired number of channels to get the RUS allocation [Numai, 2000].Suppose the desired RUS spacing vector be $\tilde{d}_{rus} = \{d1, d2, d3........d_{N_{US}-1}, d1, d2, d3........d_{N_{US}-1},..........\}$. Then from here a number of spacings independent from each other is obtained by extracting consecutive *(N_{US}-1)* elements from $\tilde{d}_{rus}$ as shown here.

$$\tilde{d}^{[1]} = \{d1, d2, d3........d_{N_{US}-1}\}$$

$$\tilde{d}^{[2]} = \{d2, d3........d_{N_{US}-1}, d1\}$$

$$..........................$$

$$\tilde{d}^{[N_{US}-1]} = \{d_{N_{US}-1}, d1, d2, d3........, d_{N_{US}-2}\} \quad (5.8)$$

Then these allocations are to be checked if all of them are US. If so, $\tilde{d}_{us}$ may be considered as a base unit for RUS and the required RUS allocation may be obtained by repeating $\tilde{d}_{us}$ as $\tilde{d}_{rus}$. If all of these allocations are not US then other US allocation for the same number of base channels are to be considered until a suitable one as above may be found.

5.3.2 Limitations of Repeated Unequal Channel Spacing Scheme

1) Repeated unequal channel spacing improves system performance significantly compared to equal channel spacing scheme. But the performance is somewhat worse compared to unequal channel spacing scheme. This is because some FWM light now falls on channel frequencies.

2) Power depletion can cause serious problem especially for DWDM systems where number of channels and power density is quite high. But usually this problem is not as serious compared to the problem of interference.

5.4 Results for Unequal and Repeated Unequal Channel Spacing

5.4.1 Interference of FWM Components with Original Signals

Many of the FWM lights generated coincide with the transmitting channels, specially in case of equal spacing (ES) scheme. Though the FWM lights in repeated unequal spacing (RUS) scheme are semi-suppressed, i.e. not absolutely filterable from the intelligence lights, they produce very small interaction with intelligence lights as compared to the Equal Spacing (ES) scheme. This observation is illustrated in figure 5.3 in terms of the number of FWM lights generated in various channel positions. We have considered ES frequency allocation with 20 number of channels and a channel spacing of 125 GHz. The total BW of system is 2375 GHz. Again for the RUS scheme, a base unit of 6 channels and minimum 90 GHz channel spacing with base bandwidth of 630 GHz is considered. The RUS frequency allocation has 20 channels and hence the total BW being 2358 GHz. It can be observed that the center channels suffer the most as the number of interfering FWM lights is the highest. The same situation is observed in RUS scheme, however, with comparatively a very small number of interfering lights.

5.4.2 Bandwidth Requirement

Unequally Spaced Channels requires much higher BW which is not feasible when large number of channels are considered. Also there is variation in BW requirements in case of different RUS base schemes. If we increase the number of base channels the ultimate BW will increase. In figure 5.4 this is illustrated considering 100 channels by plotting the number of base channels and required BW.

In the graph given in figure 5.5 we have considered three schemes, scheme 1 having 4 base channels, scheme 2 having 5 base channels and scheme 3 having 6 base channels. As the number of base channels increases the performance will improve quite satisfactorily though the BW requirement increases. The BW expansion factor considering the above said three RUS schemes and US has been shown. It appears from the graph that the BW expansion factor for the US increases linearly where the BW expansion factor increases slightly at start for the RUS but becomes almost flat then showing much less BW requirement as compared to US.

5.4.3 Bit Error Rate

The bit error rate performance for the US and RUS scheme has been depicted in figure 5.6 and figure 5.7. As can be seen that compared to ES the performance is much better for US and the performance of RUS is far better than ES but not as good as US. This is because in US none of the FWM signals coincide with any of the original signals but in case of RUS some of the FWM signals may interfere with the original signals.

5.4.4 Power Penalty

The penalty suffered by the systems to achieve a BER of 10^{-9} is determined and shown in figure 5.8 and figure 5.9. The performance of US is far batter and the performance of RUS is little bit worse compared to ES.

5.4.5 Allowable Input Power

For a given power penalty of 0.7 dB at a BER of 10^{-9} the maximum input power is found to be restricted due to the accumulation of FWM powers. The allowable input power with varying number of channels for different systems under investigation are evaluated and shown in figure 5.10 and figure 5.11. It can be observed that the effect of FWM can be managed w`ell by US and RUS schemes.

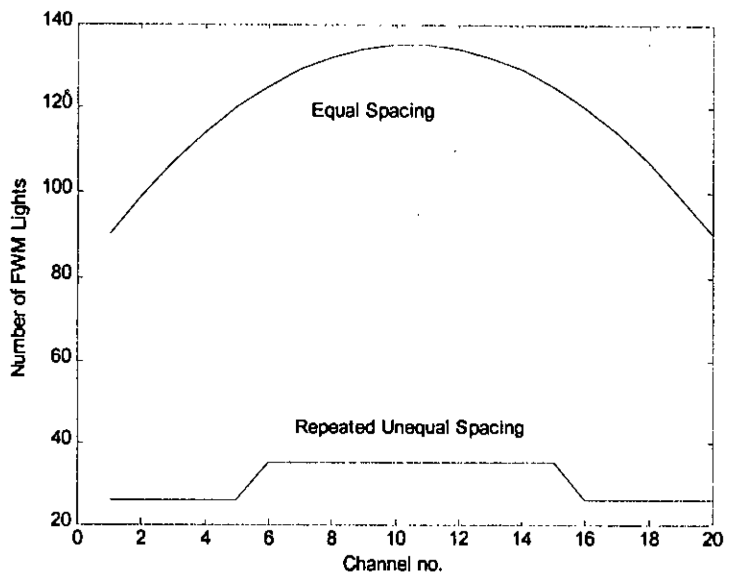


Figure 5.3: Number of FWM lights produced in different channels for ES and RUS

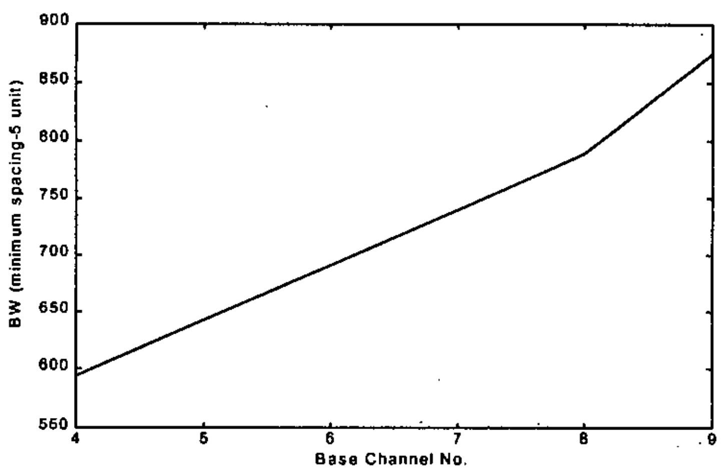


Figure 5.4: Required BW for increasing RUS base channel number

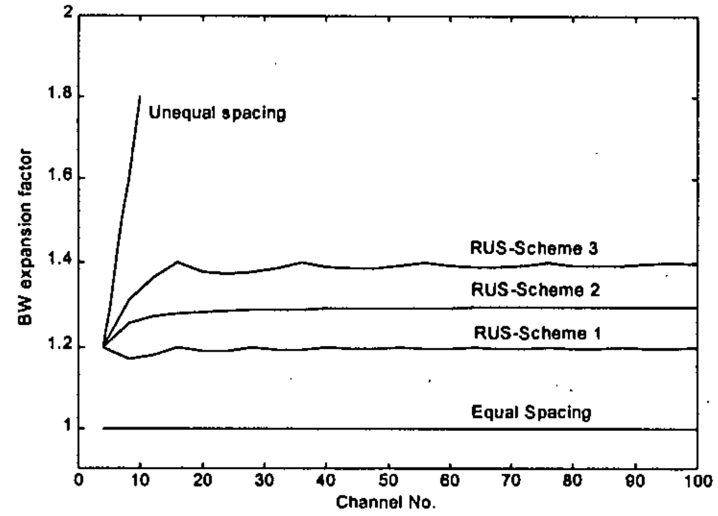


Figure 5.5: Effect on BW expansion factor with increasing number of channels

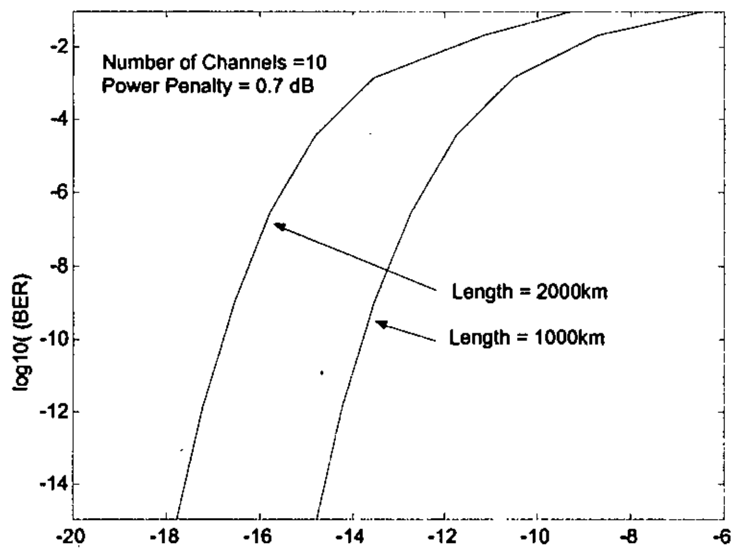


Figure 5.6: Variation of BER with input power under RUS scheme

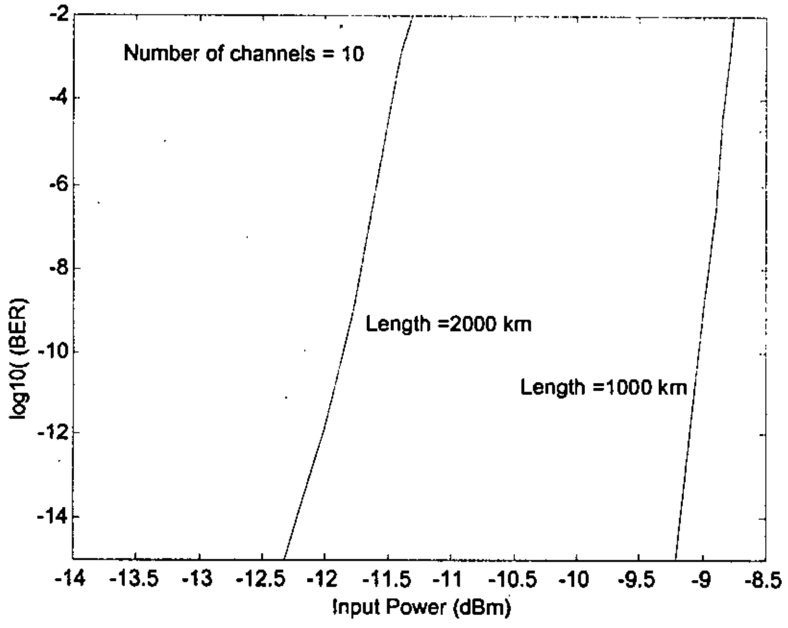


Figure 5.7: Variation of BER with input power under UUS scheme

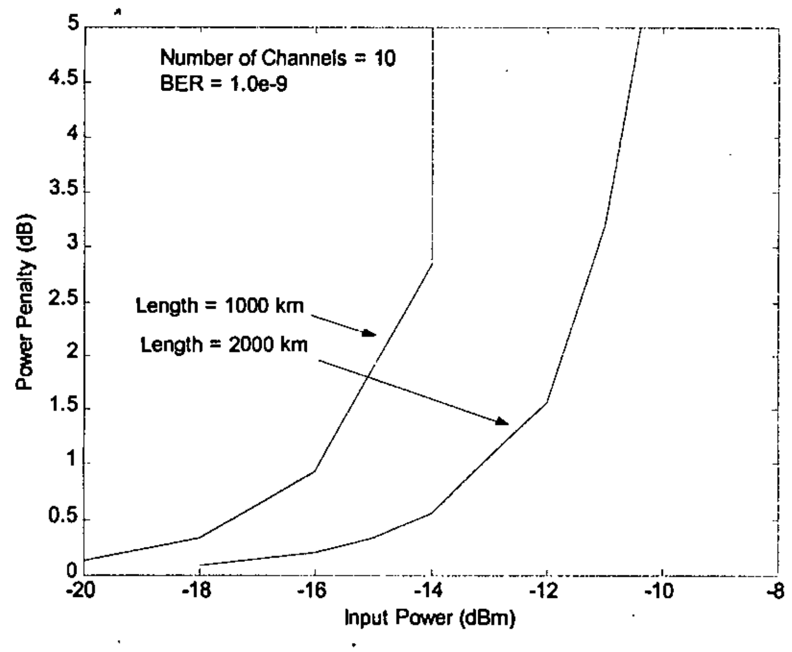


Figure 5.8: Power penalty for varying input power under RUS scheme

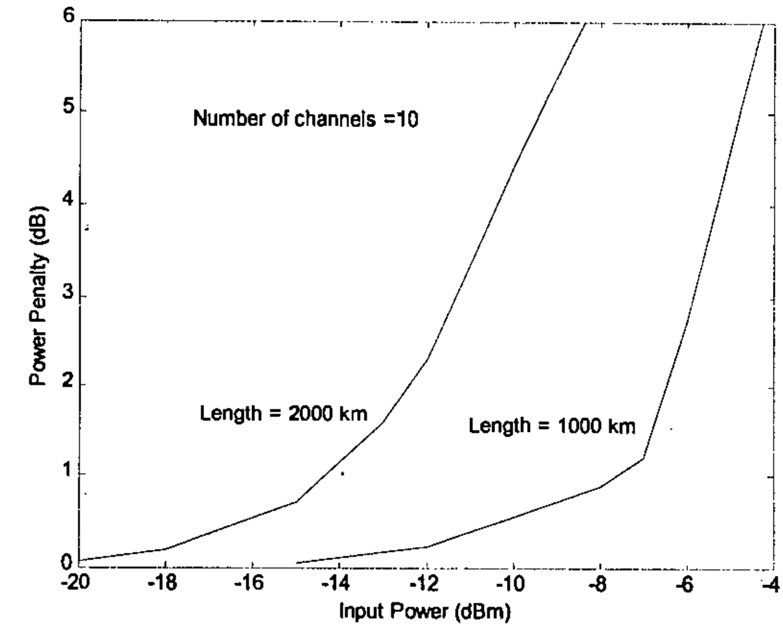


Figure 5.9: Power penalty versus input power for UUS scheme

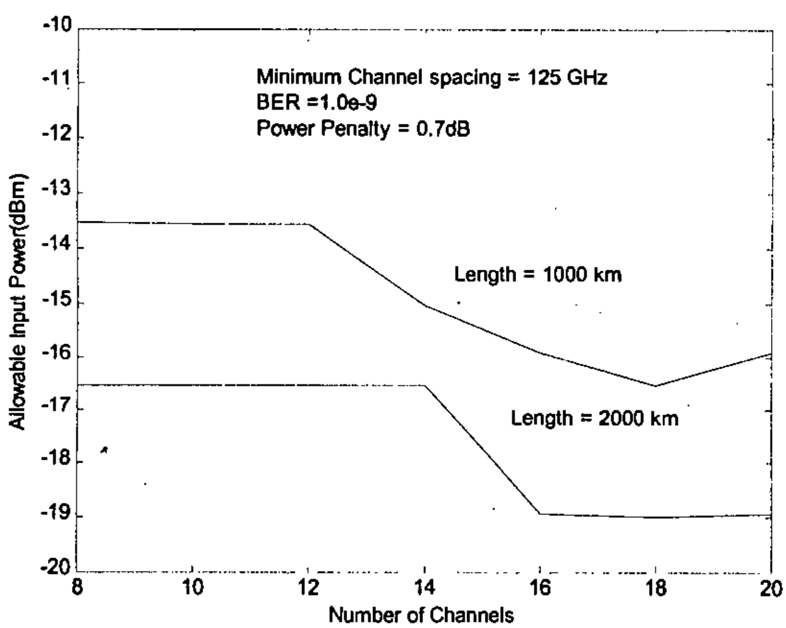


Figure 5.10: Allowable input power for varying number of channels for RUS scheme

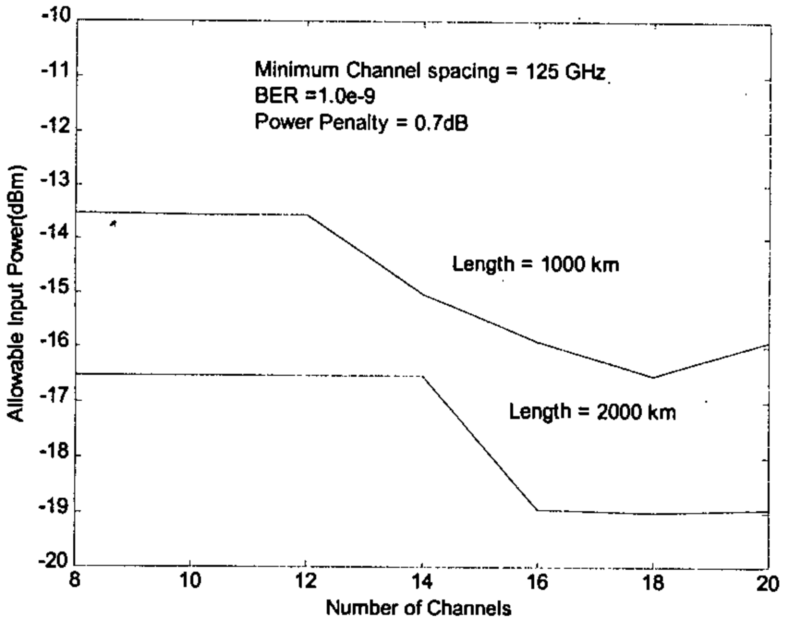


Figure 5.11: Allowable input power for varying number of channels for UUS scheme

5.5 Conclusion

In this chapter the performance of a WDM system is investigated under unequal channel spacing and repeated unequal channel spacing schemes. It is found that the unequal channel spacing scheme results in a significant improvement in system performance but requires extremely large bandwidth and is not suitable for systems with large number of channels. Performance under repeated unequal channel spacing scheme is not as good as unequal channel spacing scheme because inference is present to some extent. Both these schemes may suffer performance degradation when the input power per channel is high. So a better method should be sought which can reduce the FWM effect to a greater extent without causing design complications.

Chapter 6

FWM REDUCTION BY DISPERSION MANAGEMENT

6.1 Introduction

Present WDM systems usually use uniform dispersion throughout the entire system and the dispersion is kept at a minimum to avoid performance degradation caused by dispersion. FWM process becomes quite severe under such condition. In this chapter investigation has been made about the schemes that reduces the FWM process by the management of dispersion.

6.2 Effect of Chromatic Dispersion on FWM process

The efficiency of the FWM process depends strongly on phase mismatching. Chromatic dispersion is a key parameter that determines the phase mismatching in optical fibers. [Shibata, 1987]. To avoid performance degradation caused by chromatic dispersion WDM channels are now-a-days placed around the zero dispersion wavelength region. So the situation when the zero dispersion is at the center of the transmitting channels will also be discussed.

Expression for power of the FWM light is given by [Inoue, 1992]

$$P_F(L) = \frac{1024\pi^6}{n_0^4 \lambda^2 c^2}(D\chi)^2 \frac{P_i(0)P_j(0)P_k(0)}{A_{eff}^2} e^{-\alpha L} \frac{(1-e^{-\alpha L})^2}{\alpha^2} \eta \tag{6.1}$$

Here A_{eff} is the effective mode area, $P_i(0)$, $P_j(0)$ and $P_k(0)$ are the input powers of channels a, b and c, n_o is the refractive index, λ is the wavelength, D is the degeneracy factor and L_0 is the length of each fiber so that $NL_0 = L$ is the length of each section. η represents the dependence of the FWM efficiency on the phase mismatching $\Delta\beta$, which is written as

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2}[1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{\{1-\exp(-\alpha L)\}^2}] \tag{6.2}$$

with

$$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_F) \tag{6.3}$$

where β is the propagation constant. Efficiency η takes a maximum value of 1 for $\Delta\beta=0$. In this situation the phase matching condition is satisfied. Phase mismatching $\Delta\beta$ around a frequency f_0 can be expressed as follows

$$\beta(f) = \beta(f_0) + (f-f_0)\frac{d\beta}{df}(f_0) + \frac{1}{2}(f-f_0)^2\frac{d^2\beta}{df^2}(f_0) + \frac{1}{6}(f-f_0)\frac{d\beta^3}{df^3}(f_0) \tag{6.4}$$

where f is the frequency. The expression for chromatic dispersion D_c is given by

$$D_c = -\frac{2\pi f^2}{c}\left[\frac{d^2\beta(f_0)}{df^2}\right] \tag{6.5}$$

Using this relation the expression for $\beta(f)$ can be written as

$$\beta(f) = \beta(f_0) + (f - f_0)\frac{d\beta}{df}(f_0) - (f - f_0)^2\frac{\lambda^2\pi}{c}D_c(f_0) + (f - f_0)^3\frac{\lambda^4\pi}{3c^2}\{\frac{2}{\lambda}D_c(f_0) + \frac{dD_c}{d\lambda}(f_0)\} \tag{6.6}$$

This expression can be used in the wavelength range within which the dispersion is linear ie second order dispersion is constant. Thus the following treatment is valid for that wavelength region.

Generally D_c dominates and contribution of $dD_c/d\lambda$ can be neglected at the wavelength far from zero chromatic dispersion. At the zero dispersion wavelength $D_c=0$ and the dispersion slope $dD_c/d\lambda$ must be included.

When f_0 is chosen at the zero dispersion wavelength $\Delta\beta$ can be written as(by using the fact that $D_c(f_0)=0$) as

$$\Delta\beta = -\frac{\lambda^4\pi}{3c^2}\frac{dD_c}{d\lambda}\{(f_F - f_0)^3 + (f_k - f_0)^3 - (f_i - f_0)^3 - (f_j - f_0)^3\}$$
$$= -\frac{\lambda^4\pi}{3c^2}\frac{dD_c}{d\lambda}\{(f_i - f_0) + (f_j - f_0)\}\{(f_i - f_0) - (f_k - f_0)\}\{(f_j - f_0) - (f_k - f_0)\}$$
$$= -\frac{\lambda^4\pi}{3c^2}\frac{dD_c}{d\lambda}\{(f_i - f_0) + (f_j - f_0)\}(f_i - f_k)(f_j - f_k) \tag{6.7}$$

where the relation $f_F= f_i+f_j -f_k$ is used. The above equation describes the phase mismatching in the zero dispersion wavelength region. It is noted that the phase matching condition is always satisfied when the zero dispersion wavelength is positioned at the middle between two lights of f_i and f_j ie

$$f_i - f_0 = -(f_j - f_0) \tag{6.8}$$

In this situation since

$$f_F = f_i + f_j - f_k = 2f_0 - f_k \tag{6.9}$$

So f_k-f_0=-(f_k-f_0).Thus FWM light is generated at the side opposite the f_k frequency light wavelength with the zero dispersion wavelength as the center point.

When two of three input lights are degenerate as f_i=f_j , $\Delta\beta$ can be written as

$$\Delta\beta = -\frac{\lambda^4\pi}{c^2}\frac{dD_c}{d\lambda}2(f_i - f_k)^2(f_i - f_0) \tag{6.10}$$

It is noted that the phase matching condition is always satisfied when f_i coincides with the zero dispersion wavelength.

6.3 FWM Reduction by Management of Dispersion

6.3.1 FWM Reduction Using Nonuniform Chromatic Dispersion

As has been discussed in chapter 3 a condition for sufficient FWM to occur is that the signals must be closely phase matched. When the chromatic dispersion is high the difference in group velocity among the different signals is high and as a result phase matching becomes difficult. So one way to reduce FWM efficiency is to use fibers with high chromatic dispersion. However chromatic dispersion also degrades system performance. Therefore we can use nonuniform dispersion scheme in which the different fibers have different chromatic dispersion coefficient but the overall dispersion is a minimum to ensure that the system performance is not degraded much. The general expression for FWM power in a WDM system employing nonuniform dispersion is given by [Inoue, 1995]

$$P_{FWM} = \frac{1024\pi^6}{n_o^4 \lambda^2 c^2} (D\ \chi)^2 \frac{P_a P_b P_c}{A_{eff}^2} e^{-\alpha L} \left| \sum_{m=1}^{M} \exp\left[i \sum_{k=1}^{m-1} \Delta\phi^k \right] \times \sum_{n=1}^{N} \exp\left[\sum_{j=1}^{n-1} \left(-\alpha + i\Delta\beta^{mj} \right) L_0 \right] \times \frac{1 - \exp\left[\left(-\alpha + i\Delta\beta^{mn} \right) L_0 \right]}{\alpha - i\Delta\beta^{mn}} \right|^2 \tag{6.11}$$

where, A_{eff} is the effective mode area, P_a, P_b and P_c are the input powers of channels a, b and c, n_o is the refractive index, λ is the wavelength, D is the degeneracy factor, M is the number of sections, N is length of fiber in each section, and L_0 is the length of each fiber so that $NL_0 = L$ is the length of each section, α is the attenuation constant of fiber, Δβ is the phase mismatch in fiber n in section m,$\Delta\varphi^{(k)}$is the propagation phase difference of the lights a,b,c in section k.

6.3.2 FWM Reduction by Dispersion Compensation

Another way to reduce FWM and improve overall system performance is to use dispersion compensation. A dispersed fiber is used in each section so that the lights at the end of the fiber are highly phase mismatched and the FWM effect is reasonably reduced. To compensate for the high value of dispersion, another opposite polarity dispersion compensating fiber is used in cascade so that the overall dispersion is minimum.

In such compensating fiber model each span of length $L^{(m)}$ consists of two fibers I and II characterized by attenuation $\alpha_{1,2}$, dispersion $D_{1,2}$, dispersion slope $dD_{1,2}/d\lambda$ and length $L_0{}^{(m1,2)}$, such that $L_0{}^{(m1)} + L_0{}^{(m2)} = L^{(m)}$ and $D_1 L_0{}^{(m1)} + D_2 L_0{}^{(m2)} = 0$. In that case the pulse dispersion at each signal wavelength is approximately equal in magnitude but opposite in sign for the two fiber sections providing the desired compensation. Thus equation (6.7) becomes as follows:

$$\begin{aligned}\Delta\beta^{mn} &= \beta_a^{mn} + \beta_b^{mn} - \beta_c^{mn} - \beta_F^{mn} \\ &= (f_a - f_c)(f_b - f_c)\frac{2\lambda_r^2\pi}{c} \times \left[D_{1,2}(\lambda_r) - [(f_a - f_c) + (f_b - f_c)]\frac{\lambda_r^2}{2c}\frac{dD_{1,2}(\lambda_r)}{d\lambda} \right]\end{aligned} \quad (6.12)$$

$D_{1,2}$ is the chromatic dispersion coefficients in fiber 1 and 2.

The equation for FWM power for this scheme can be written as

$$P_{FWM} = \frac{1024\pi^6}{n_o^4 \lambda^2 c^2} (D\ \chi)^2 \frac{P_a P_b P_c}{A_{eff}^2} \exp(-[\alpha_1 L_1 + \alpha_2 L_2]) \left| \sum_{M=1}^{M} \exp\left[i \sum_{k=1}^{m-1} \Delta\phi^k \right] \times \sum_{n=1}^{N} \exp\left[\sum_{j=1}^{n-1} \left(-\alpha^{mj} + i\Delta\beta^{mj}\right) L_0{}^{mj} \right] \times \frac{1 - \exp\left[\left(-\alpha^{mn} + i\Delta\beta^{mn}\right) L_0{}^{mn}\right]}{\alpha^{mn} - i\Delta\beta^{mn}} \right|^2 \tag{6.13}$$

The expression for received power is

$$P_s = P_o \exp\left(-[\alpha_1 L_0^1 + \alpha_2 L_0^2]\right) L_r \tag{6.14}$$

6.4 Results for Nonuniform Chromatic Dispersion

The system parameters are as described in the previous chapter. However here instead of uniform dispersion throughout the system nonuniform chromatic dispersion has been used. The chromatic dispersion of the fibers in a section is all made different. The zero-dispersion wavelengths of the fibers are assumed to be distributed over a 8 nm width around 1550 nm such that the average zero-dispersion wavelength is maintained at 1.55 µm.

For the compensating fiber system each section consists two different fibers, transmitting and compensating. Two systems with different compensation schemes are investigated.

The first compensating system has 42 sections each consisting of two fibers of length 43 km with D = -2 ps/km-nm (dispersion shifted fiber) and 4.6 km with D = 20 ps/km-nm (single mode fiber). The second system has 50 sections each consisting of two fibers of length 6.957 km with D = -95 ps/km-nm (dispersion compensated fiber) and 33.043 km with D = 20 ps/km-nm (single mode fiber).

6.4.1 Average FWM Efficiency

Figure 6.1 shows the FWM efficiency calculated for various chromatic dispersion, however, having uniform dispersion throughout the length. The solid line represents the efficiency in case of equal spacing of 100 GHz between channels, which shows that the FWM effect reduces with the increase in chromatic dispersion. The dotted curve represents the calculation for unequal channel spacing with minimum separation between channels is 100 GHz so that no FWM frequency will interfere with any of the transmitting channels. The FWM efficiency is found to decrease significantly with unequal channel spacing.

6.4.2 Bit Error Rate

The BER performance for various channel spacing and system lengths is shown in figure 6.2 and 6.3. The BER performance shows a significant improvement with the use of nonuniform dispersion scheme. Also a sis with conventional WDM system here too performance degrades seriously with the increase in system lengths or decrease in channel spacing.

6.4.3 Power Penalty

The penalty suffered by the systems to achieve a BER of 10^{-9} is determined and shown in figure 6.4 and figure 6.5. Nonuniform dispersion improves the performance to a great extent as can be seen from the figure. Like BER the performance is degraded when channel spacing is reduced or input power per channel is increased.

6.4.4 Allowable Input Power

For a given power penalty of 0.7 dB at a BER of 10^{-9} the maximum input power is found to be restricted due to the accumulation of FWM powers form figure 6.6 and 6.7. It can be observed that the effect of FWM can be managed well by nonuniform chromatic dispersion.

6.5 Dispersion Compensation Scheme

The performance for the dispersion management scheme is shown in figure 6.8, figure 6.9 and figure 6.10. Clearly the performance improvement is great with dispersion compensating scheme.

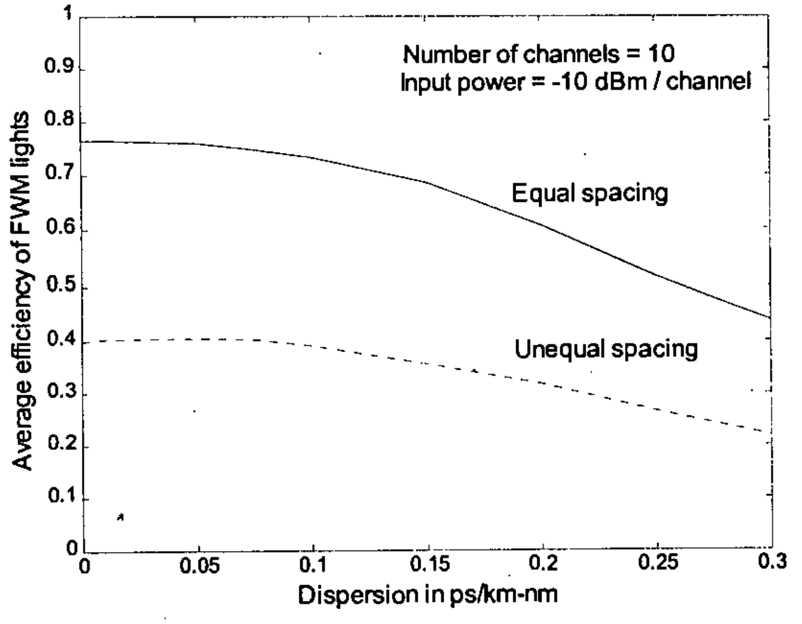


Figure 6.1: Variation of average FWM efficiency with dispersion

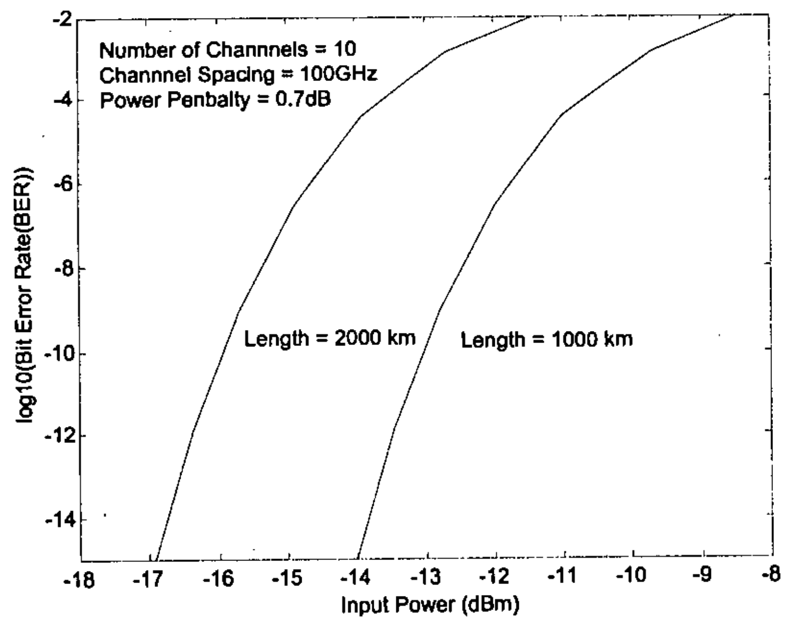


Figure 6.2: BER versus Input Power per channel for NES for various system lengths

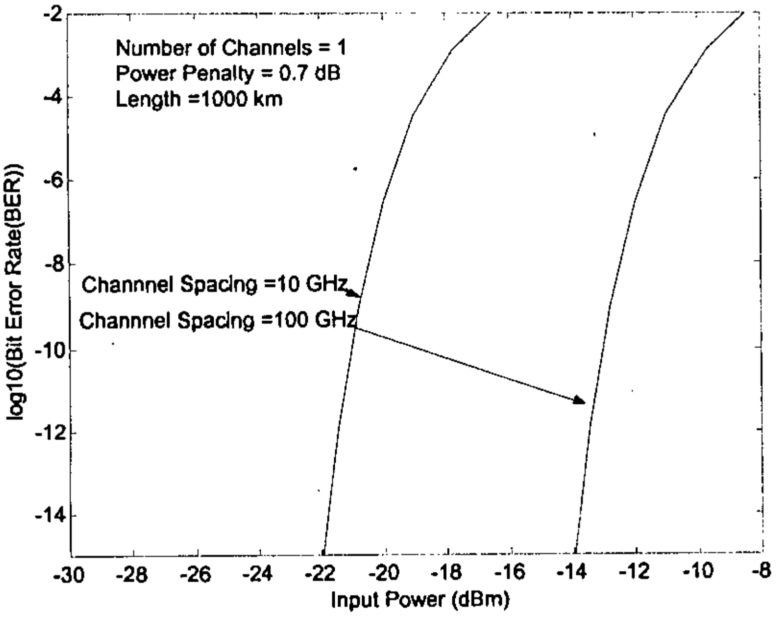


Figure 6.3: BER versus Input Power per channel for NES for various channel spacing

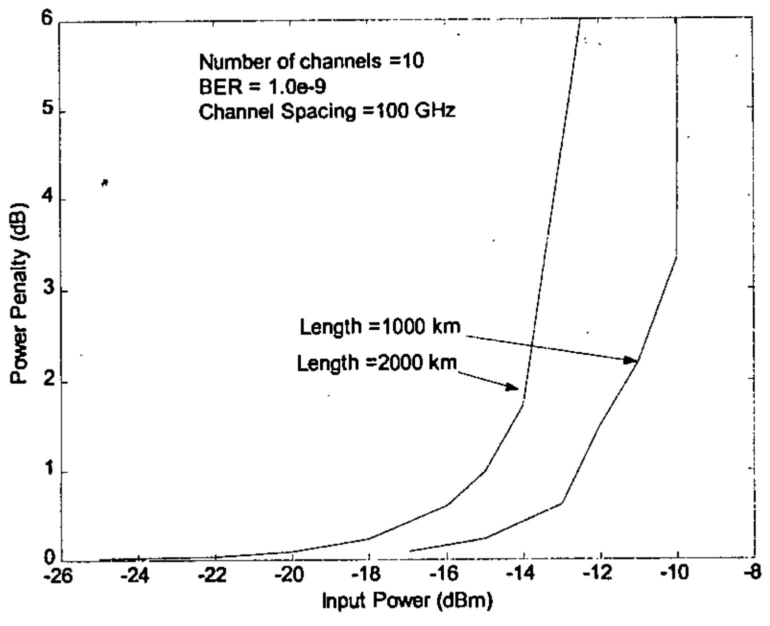


Figure 6.4: Power penalty versus input power for different system lengths

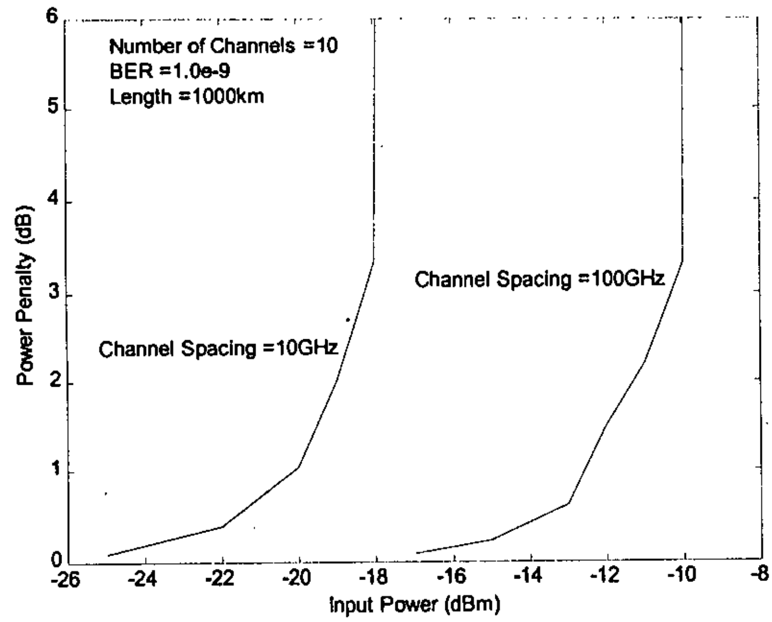


Figure 6.5: Power penalty versus input power for different channel spacing

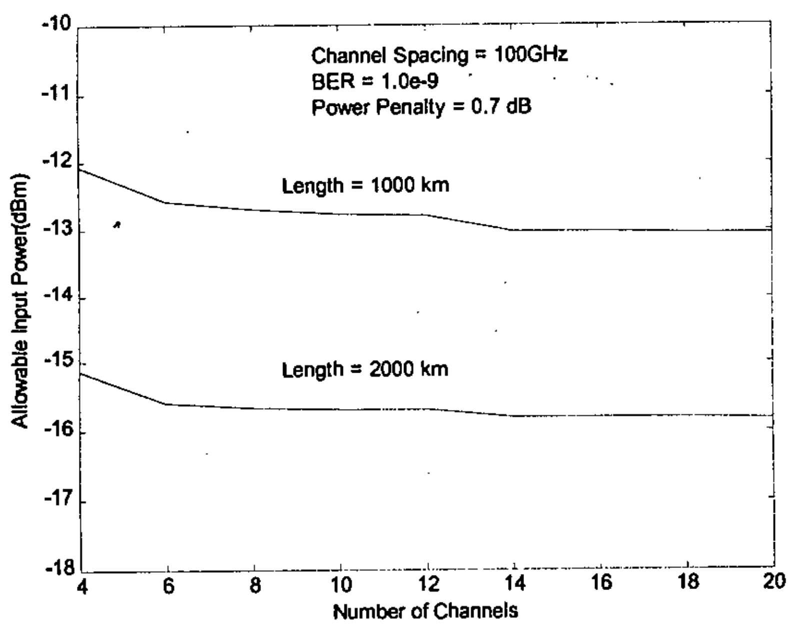


Figure 6.6: Allowable input power versus number of channels for varying system lengths

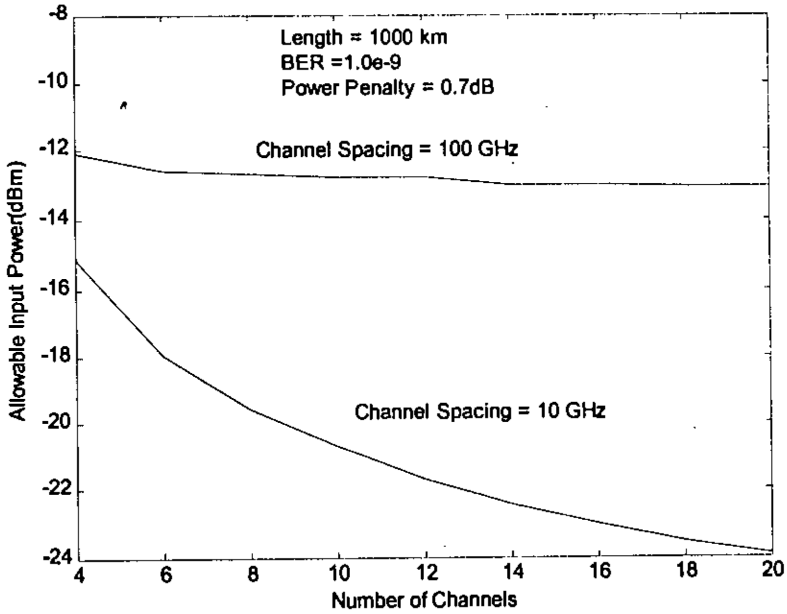


Figure 6.7: Allowable input power versus number of channels for varying channel spacing

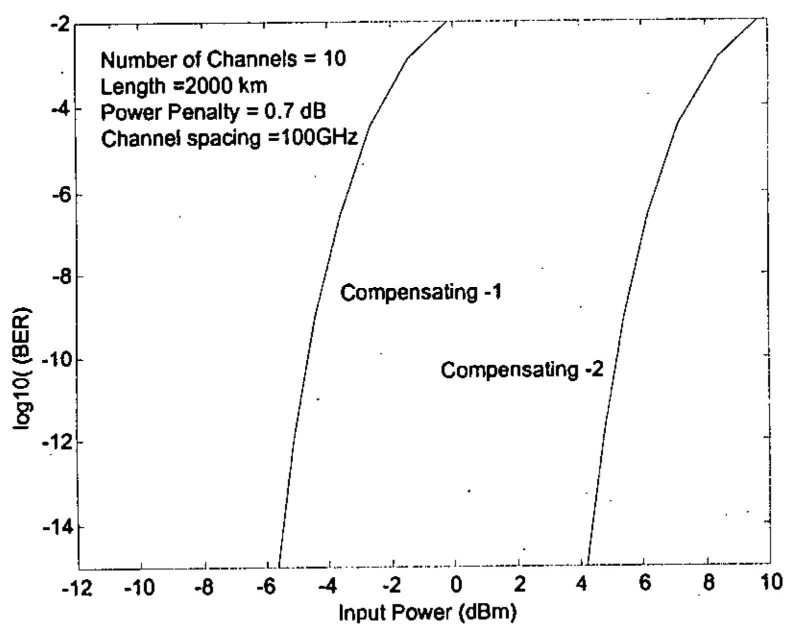


Figure 6.8: BER versus input power for various compensating schemes

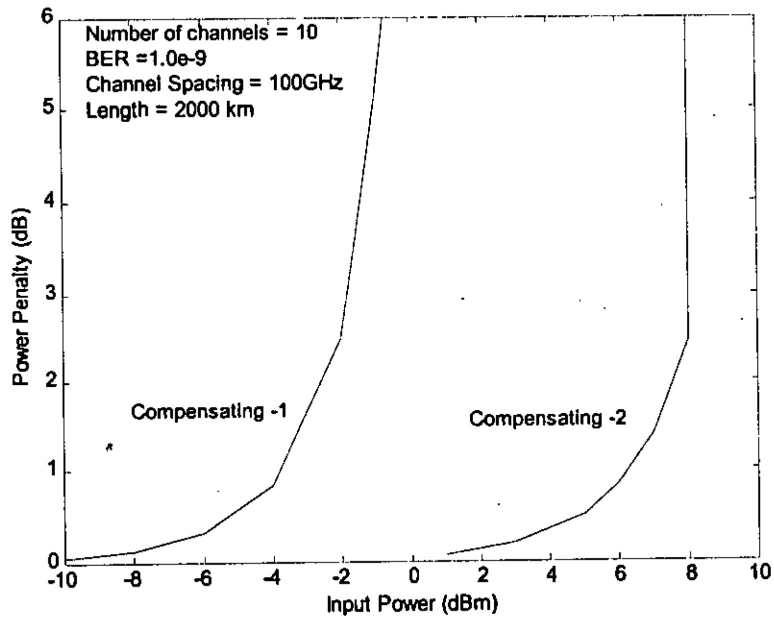


Figure 6.9 : Power penalty versus input power for various compensating schemes

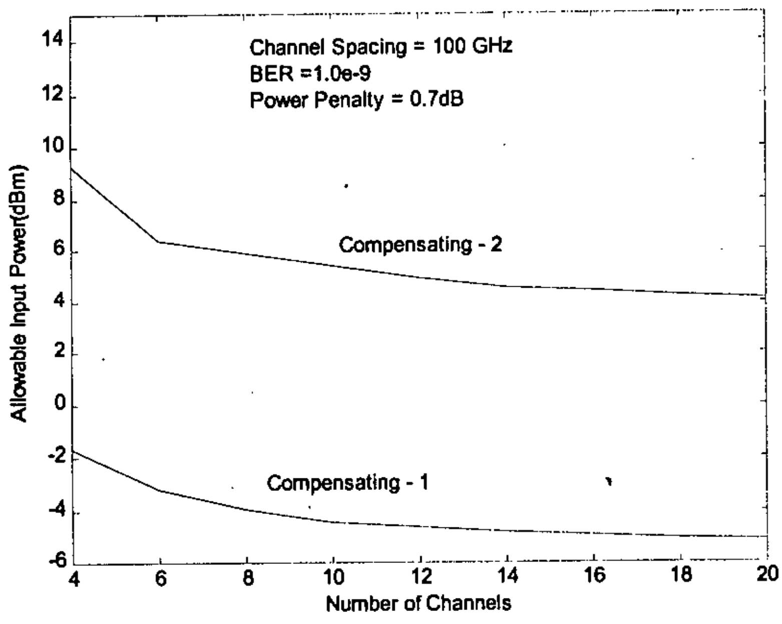


Figure 6.10: Allowable input power versus number of channels for compensating schemes

6.6 Conclusion

As seen form the results above the FWM performance of a WDM system is significantly improved if we use nonuniform dispersion. The improvement is even better when dispersion compensating scheme is used. But this sort of FWM reduction schemes also have some limitations. Although FWM efficiency is reduced under these schemes, the FWM components can occupy the same position as the original signals. So performance can degrade, especially for DWDM systems. Therefore, a better scheme is necessary which will reduce the FWM efficiency and at the same time reduce the problem of interference of the FWM components with the original signals.

Chapter 7

FWM REDUCTION BY A COMBINATION OF UNEQUAL CHANNEL SPACING AND NONUNIFORM CHROMATIC DISPERSION

7.1 Introduction

As has been seen in the previous chapters the techniques so far used for reducing the FWM effect cannot fully serve the purpose because interference or power depletion is present. In this chapter a combination of either unequal channel spacing or repeated unequal spacing with either nonuniform dispersion or dispersion compensation will be examined. The performance will be compared to that of other systems discussed in earlier chapters.

7.2 Reason Behind the Better Performance

In this chapter we shall investigate an FWM reduction scheme by using a combination of unequal channel spacing and nonuniform chromatic dispersion. This scheme should provide a much better performance. The reason behind it is that when we use this scheme interference is minimized because eof unequal channel spacing and at the same time power depletion is reduced because of nonuniform chromatic dispersion. The performance of the proposed system is analyzed and presented in the next section.

7.3 Results

The performance of the WDM system with unequal channel spacing and nonuniform dispersion is shown in figure 7.1, figure 7.2 and figure 7.3. Clearly the performance is very good. The system can handle very high input power and large number of channels with little degradation in performance.

7.3.1 Comparison of Performance of different schemes

In this work we have assessed the performance of different schemes for reduction of adverse effects of FWM. Now we make a comparison of the performance under various schemes.

7.3.1.1 Bit Error Rate

The effect of input power on Bit Error Rate (BER) has been illustrated in figure 7.4 where the power penalty is considered to be 0.7 dB. The figure lists the BER curves for various systems under consideration. It can be observed that repeated unequal channel spacing gives better performance compared to equal spacing. Similarly, use of nonunifrom chromatic dispersion helps in reducing the FWM effect significantly as compared to uniform dispersion. Use of dispersion compensation offers the best result.

7.3.1.2 Power Penalty

The penalty suffered by the systems to achieve a BER of 10^{-9} is determined and shown in figure 7.5. The worst penalty is found to be suffered by the system with equal channel spacing and uniform chromatic dispersion. The dispersion compensated system offers better environment than the other systems.

7..3.1.3 Allowable Input Power

For a given power penalty of 0.7 dB at a BER of 10^{-9} the maximum input power is found to be restricted due to the accumulation of FWM powers. The allowable input power with varying number of channels for different systems under investigation are evaluated and shown in figure 7.6. It can be observed that the effect of FWM can well be managed by using nonuniform dispersion and either unequal or repeated unequal channel spacing scheme. The performance improvement is most remarkable in case of compensating scheme and some sort of unequal channel spacing scheme as shown in figure 7.7, figure 7.8 and figure 7.9. The performance is degraded only at extremely high value of input power. This in fact means that the FWM process is almost absent under such schemes.

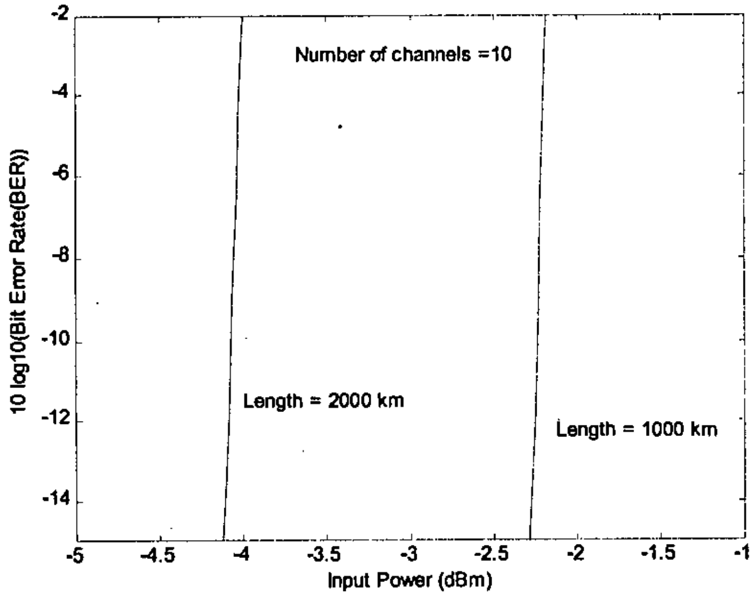


Figure 7.1: BER versus input power for NUS scheme

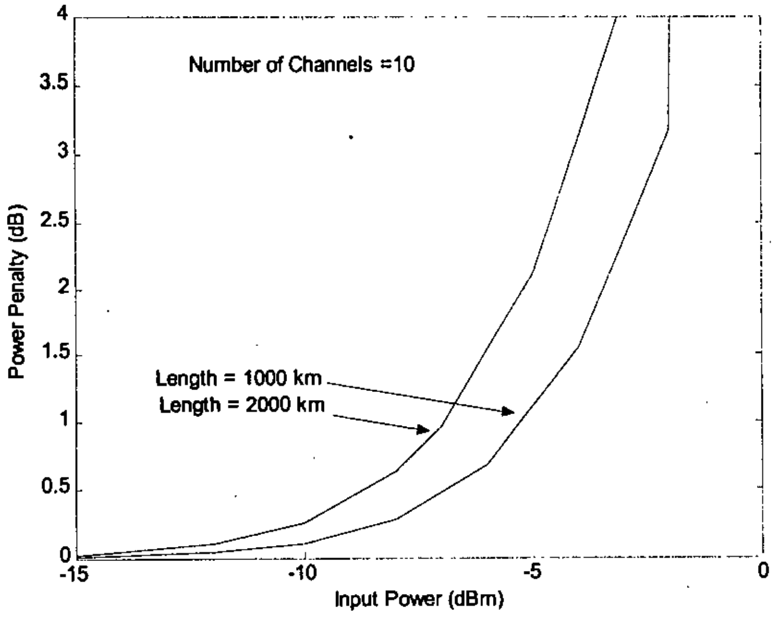


Figure 7.2: Power penalty versus input power for NUS scheme

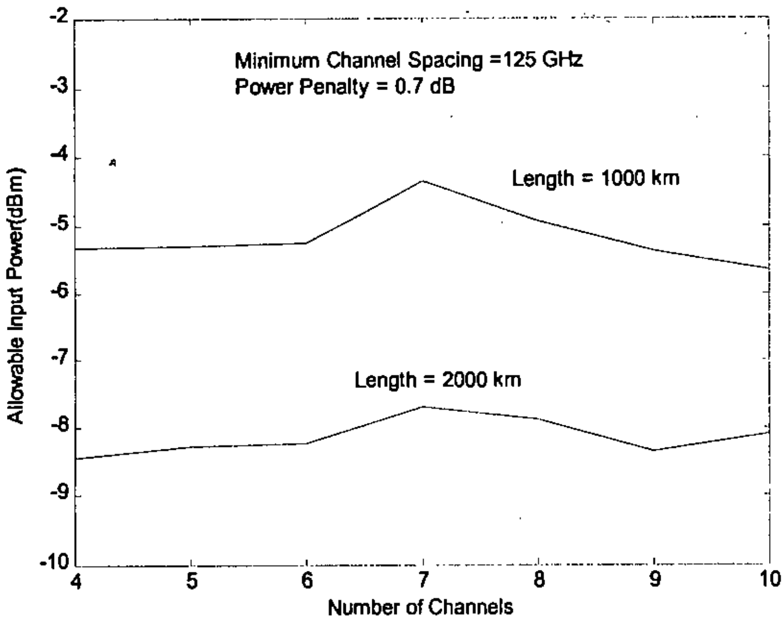


Figure 7.3: Allowable input power versus number of channels for NUS scheme

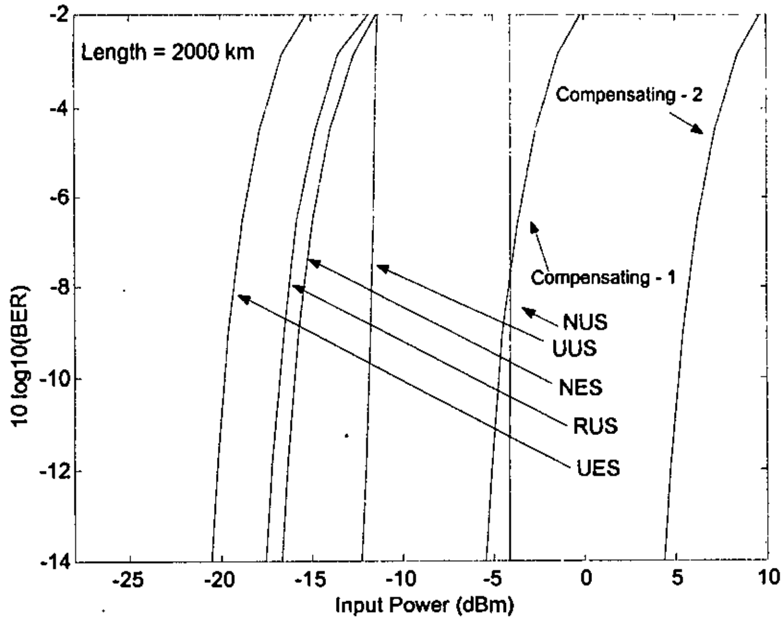


Figure 7.4: BER versus input power for various schemes

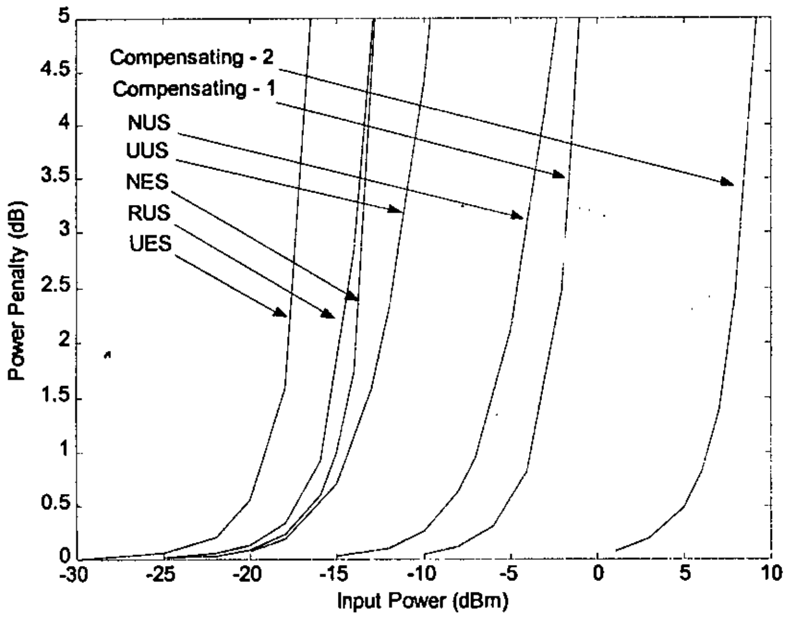


Figure 7.5: Power Penalty versus input power for various schemes

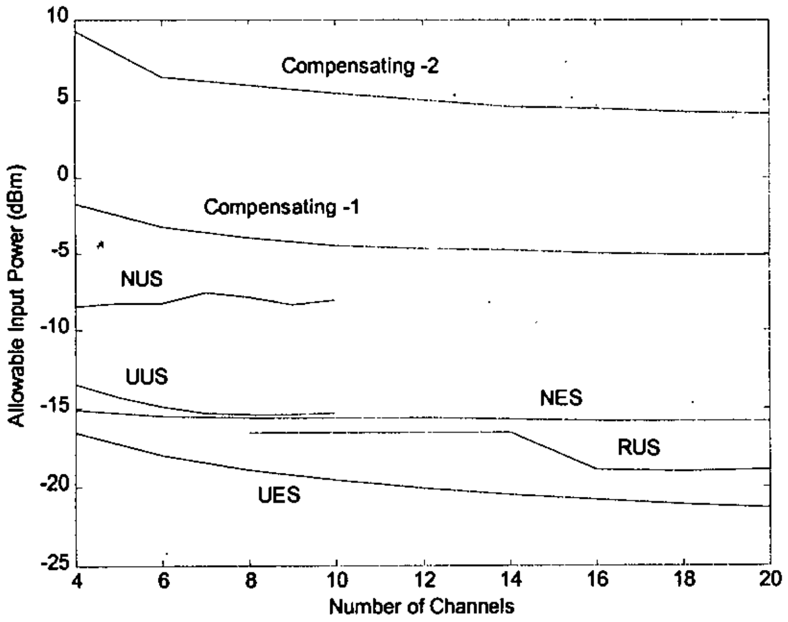


Figure 7.6: Allowable input power versus input power for various schemes

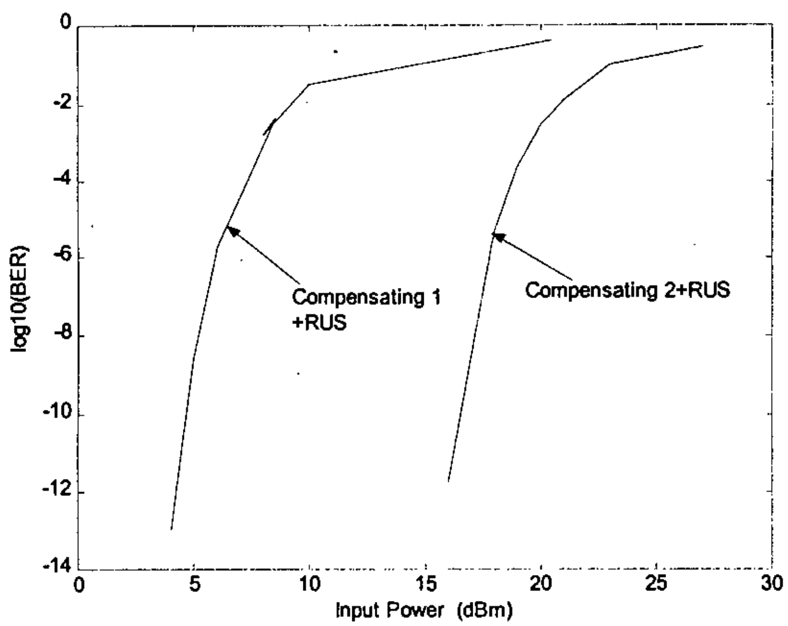


Figure 7.7: BER versus input power for dispersion compensation with RUS scheme

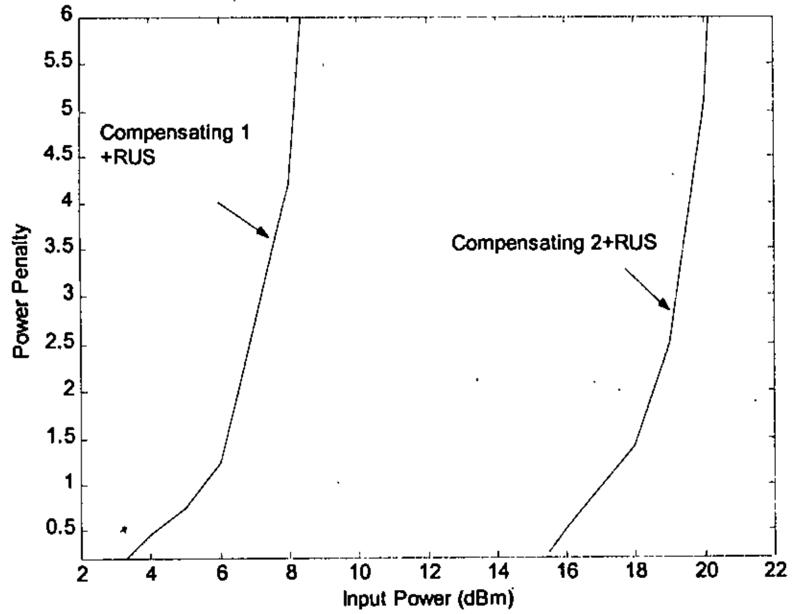


Figure 7.8: Power penalty versus input power for dispersion compensation with RUS scheme

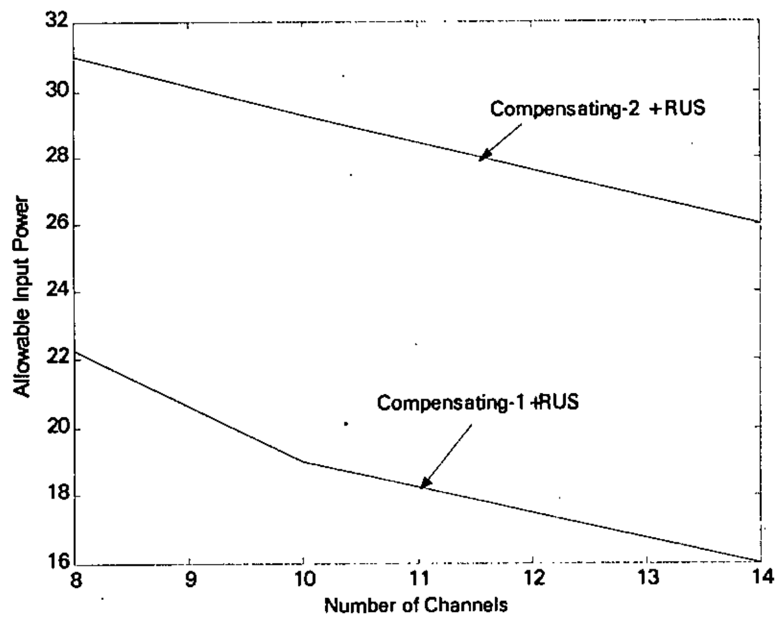


Figure 7.9: Allowable input power versus number of channels for dispersion compensation with RUS scheme

7.4 Conclusions

In this chapter the performance of a WDM system under various combinations of previous schemes has been analyzed. The performance is compared with the results obtained in earlier chapters. It is seen that the schemes proposed in this chapter give very satisfactory results.

Chapter 8

PERFORMANCE EVALUATION OF WDM SYSTEM TAKING FWM PROCESS IN EDFA INTO ACCOUNT

8.1 Introduction

Now-a-days WDM systems make extensive use of EDFAs. The FWM process in EDFA is usually not taken into account while evaluating system performance. Modern WDM systems usually operate in the L band where EDFA s with longer lengths are used. As a result the optical signals get sufficient time for nonlinear interaction within the fiber amplifier. The FWM process can be quite significant in such amplifiers. In this chapter the performance of WDM system is evaluated taking the FWM process into EDFA into account.

8.2 Expression for FWM power considering EDFA

The evolution of the electrical field amplitude of the FWM wave due to the nonlinear interactions of three waves in EDFA or passive transmission fiber can be written as

$$\frac{dE_F(z)}{dz} = \frac{g_F(z)}{2} E_F + i(\frac{D_{ijk}}{3})\gamma E_i^*(z) E_j(z) E_k(z) \exp(-i\beta_F z) \tag{8.1}$$

here $g_F(z)$ represents the gain coefficient of EDFA or loss coefficient impassive transmission fiber, D_{ijk} is the degeneracy factor, γ is the nonlinearity coefficient of EDFA (γ_{EDF}) or the transmission fiber(γ_{TF}).

Assuming that the evolution of amplitude of each applied field $E_q(z)$ ($q=i,j,k$) through the fibers are solely governed by the gain distribution of EDFA or by the loss in the passive transmission fiber the electrical field amplitude of the input signal can be written as

$$E_q(z) = E_{q0}(z)\exp[\frac{1}{2}\int_0^z g_q(z')dz' + i\beta_q z] \tag{8.2}$$

and the gain (or loss) evolution in EDFA(or transmission fiber) can be written as

$$G_q(z) = \exp[\int_0^z g_q(z')dz'] \qquad q=i,j,k,F \tag{8.3}$$

To simplify the solution of (8.1) without losing any significant features, it is farther assumed that each amplifier has an identical gain spectrum within the signal band, and that the span loss in each section is fully compensated by the first inline amplifier. Under these assumptions the power of the FWM wave generated from the multispan transmission line can be given by [Song, 2000]

$$P_{ijk}(N_{amp}(l+L)) = (\frac{D_{ijk}}{3})P_{i0}P_{j0}P_{k0}[\frac{\sin(N_{amp}(\Delta\beta l+\Delta\beta' L)/2)}{\sin((\Delta\beta l+\Delta\beta' L)/2)}]^2 \times \{|\gamma_{EDF}\sqrt{G(l)}\int_0^l G(z)e^{i\Delta\beta z}dz|^2 + \gamma_{TF}^2 G(l)^2$$

$$\times\frac{(1-e^{-\alpha L})^2+4e^{-\alpha L}\sin^2(\beta' L/2)}{\alpha^2+(\Delta\beta')^2} + 2\gamma_{EDF}\gamma_{TF}G(l)^{3/2}\times[\int_0^l G(z)\cos(\Delta\beta z)dz\int_0^L e^{-\alpha z}\cos(\Delta\beta l+\beta' z)dz$$

$$+\int_0^l G(z)\sin(\Delta\beta z)dz\times\int_0^L e^{-\alpha z}\sin(\Delta\beta l+\Delta\beta' z)dz]\}$$

(8.4)

8.3 Results

In our analysis we have included the FWM process in the EDFAs. To evaluate the FWM power in EDFA we need an idea about the gain function of the EDFA. We have found the gain function of a particular EDFA[Giles, 1991] by a fourth degree polynomial. The original experimental data and the polynomial fit curve is shown in figure 8.1.The polynomial approximation of the gain function of the amplifier is

$$G(z) = 0.4965 + 0.2372\times z + 0.1634\times z^2 - 0.0017\times z^3 + 0.0002\times z^4 \quad (8.5)$$

Where $G(z)$ is the gain in dB for a length of z.

8.3.1 FWM Power Variation with Channel Spacing

The FWM power in EDFA is considered in the analysis in this research work. To emphasize its importance we have compared the calculated FWM power at first including FWM process in EDFA and then without considering FWM power in EDFA. The result is shown in figure 8.2. Clearly the FWM process in EDFA can be quite significant as can be seen from the above figure.

8.3.2 FWM Power Variation with Amplifier length

The total FWM power generated is shown as a function of EDFA length in figure 8.3. As can be seen that the FWM power increases with the increase in amplifier length. Another important observation is that the FWM power is a periodic function of EDFA length.

8.3.3 Bit Error Rate

The BER performance is also significantly different when the FWM process in EDFA is taken into consideration. To illustrate this BER curves as a function of input power per channel has been plotted. Two cases has been taken as examples. Figure 8.4 is for the case of uniform dispersion and equal channel spacing and figure 8.7 is for uniform dispersion with repeated unequal channel spacing. As can be seen that the BER is significantly worse when the FWM process in EDFA is taken into consideration.

8.3.4 Power Penalty

The power penalty is plotted as a function of input power per channel in figure 8.5 and figure 8.8. As can be seen that the power penalty is much higher when the FWM process in EDFA is taken into account.

8.3.5 Allowable Input Power

The allowable input power is significantly lower when FWM process in EDFA is taken into account as can be seen from figure 8.6 and figure 8.9.

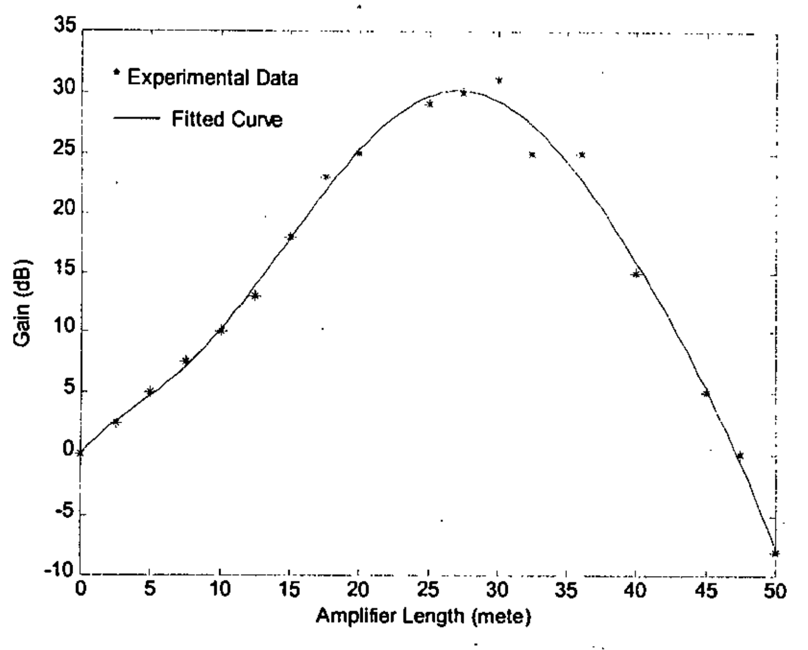


Figure 8.1: Approximation of gain function of EDFA by polynomial fit

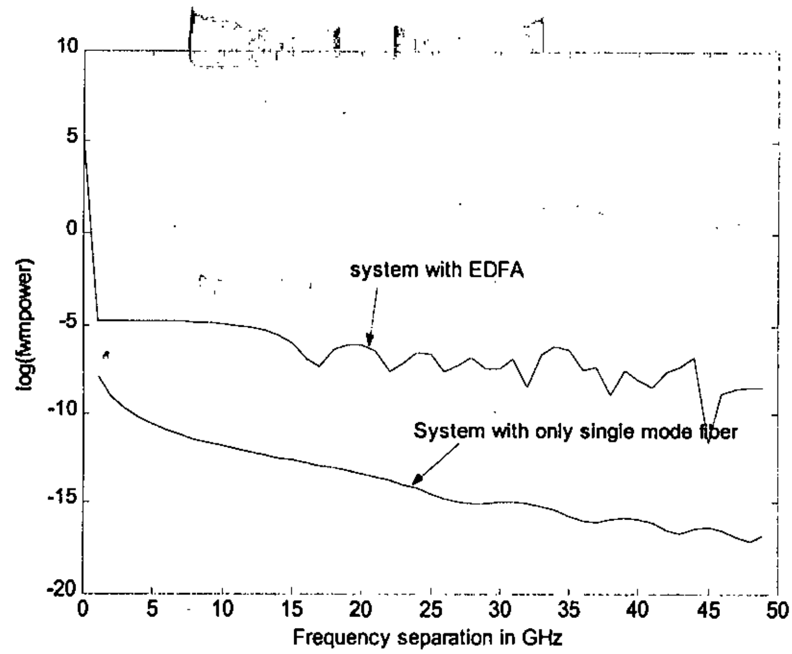


Figure 8.2: FWM power as a function of channel spacing

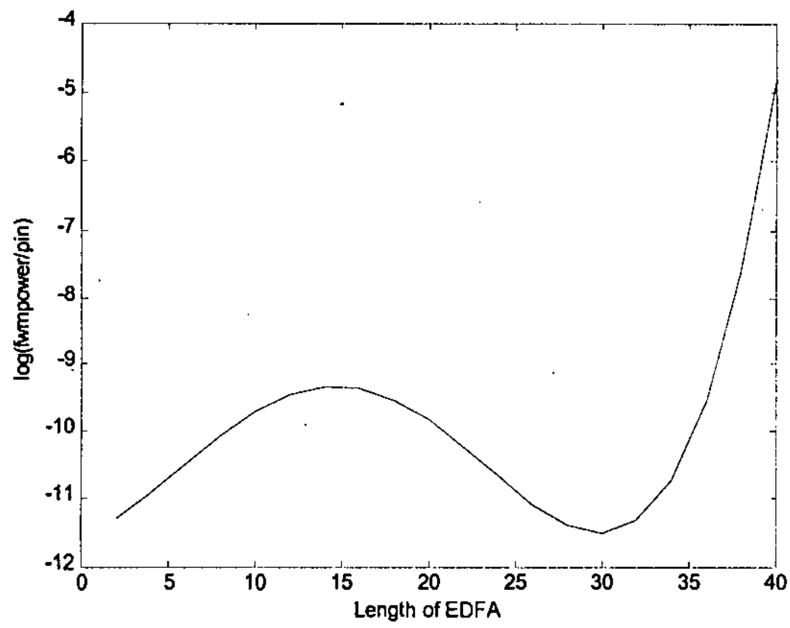


Figure 8.3: Variation of FWM power with EDFA length

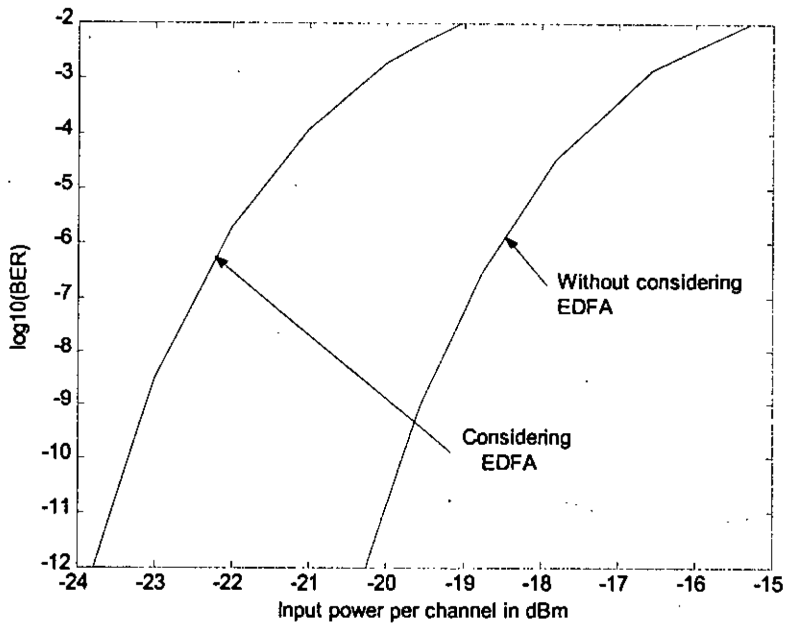


Figure 8.4: Comparison of BER with UES scheme

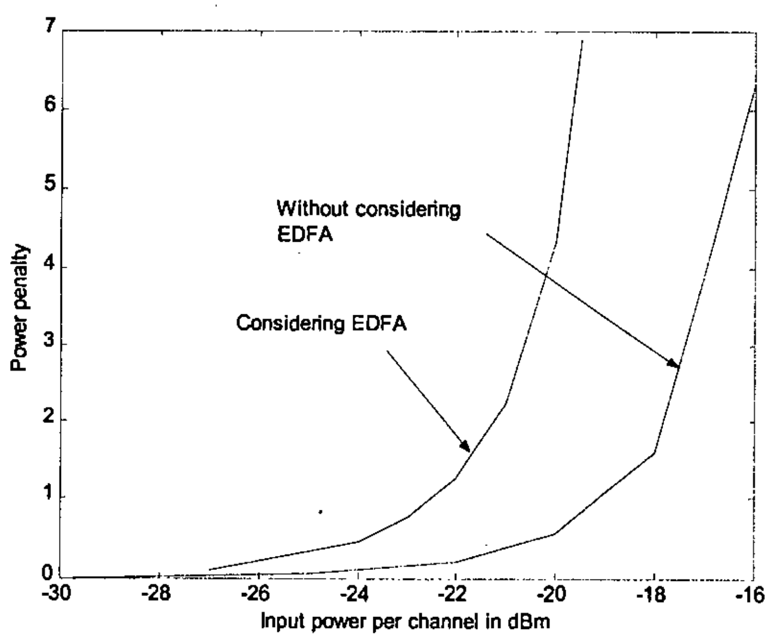


Figure 8.5: Comparison of power penalty with UES scheme

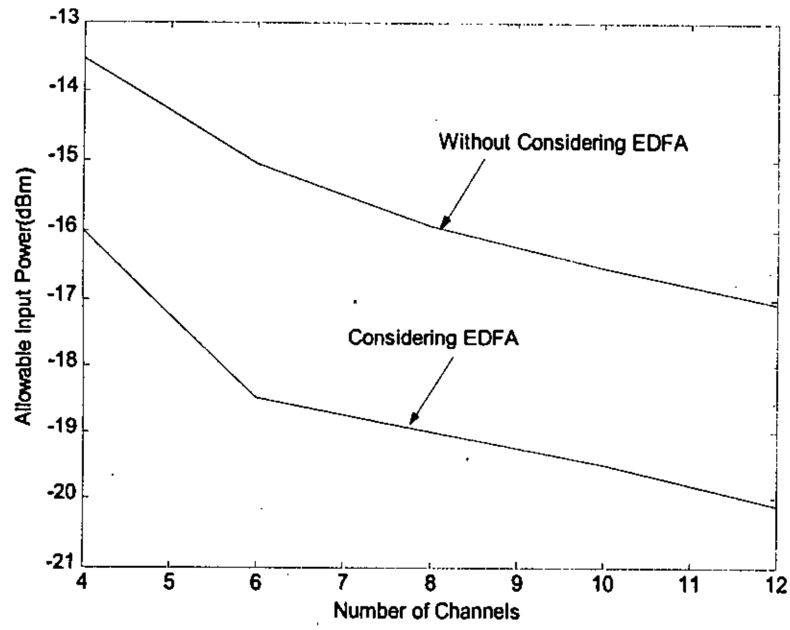


Figure 8.6: Comparison of allowable input Power for UES scheme

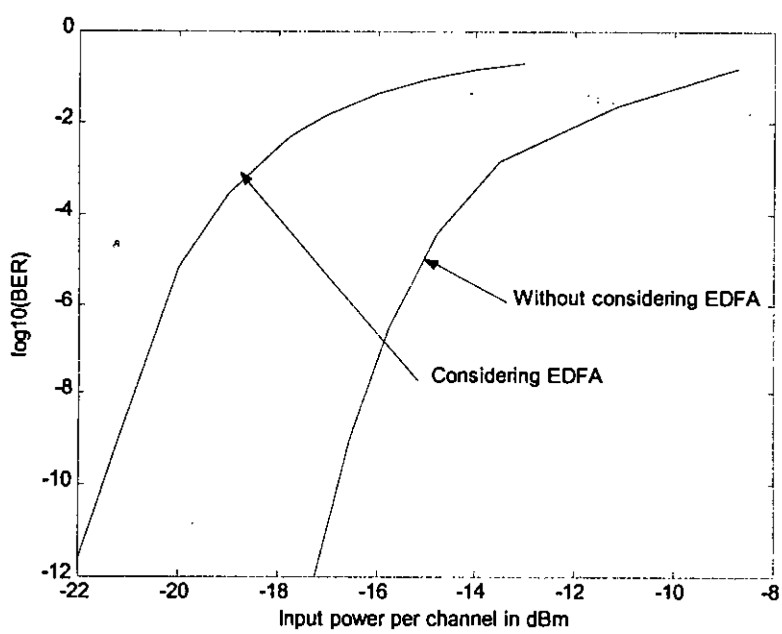


Figure 8.7: Comparison of BER with URS spacing

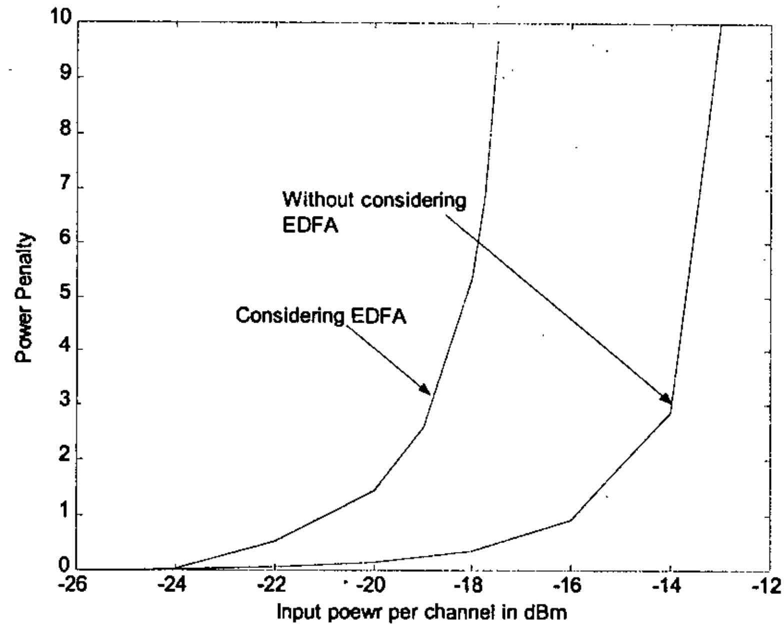


Figure 8.8: Comparison of power penalty with URS scheme

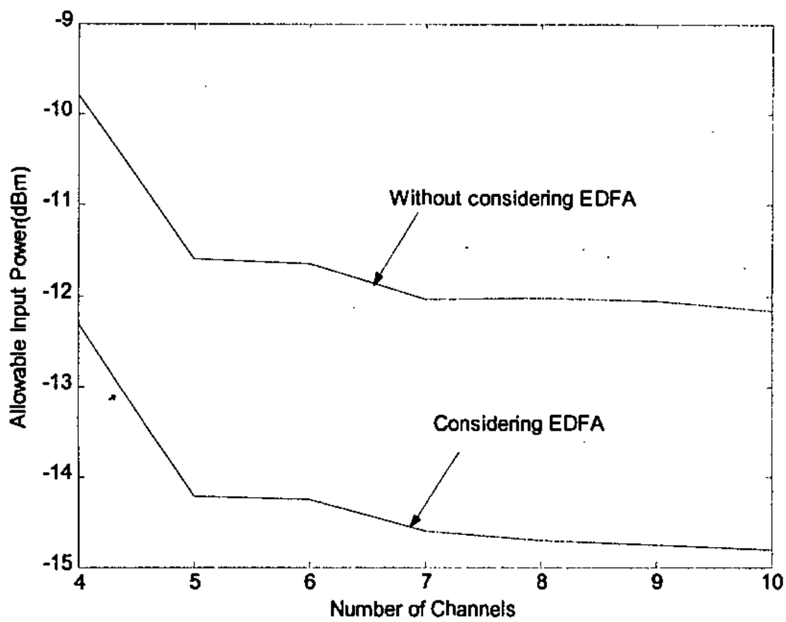


Figure 8.9: Comparison of allowable input power for URS scheme

8.4 Conclusion

In this chapter the importance of FWM process in EDFA is examined. The effect of channel spacing and amplifier length on the FWM process is examined. It is found that FWM power increases sharply when EDFA length is increased. BER, power penalty and allowable input power is significantly different when the FWM process in EDFA is taken into account. Therefore this effect should always be considered during performance evaluation of a WDM system that makes use of long EDFAs.

Chapter 9

CONCLUSIONS

9.1 Conclusions of this Study

A detailed study has been made to evaluate performance of a WDM system in presence of FWM. It is observed that the performance is not satisfactory for conventional WDM system when the number of channels is large or the input power per channel is high. The performance improvement is significant when unequal channel spacing, nonuniform dispersion or dispersion compensation is used. However to obtain the best performance a combination of the above schemes should be used. The possible combinations that can be used are either unequal or repeated unequal channel spacing with either nonuniform dispersion or dispersion compensation.

The following guideline is proposed for the selection of a suitable FWM reduction scheme in a WDM system.

1) Use some sort of FWM reduction scheme in designing WDM system. Avoid using uniform dispersion and equal channel spacing scheme at the same time to avoid the adverse effect of FWM.

2) Use repeated unequal channel spacing when the input power per channel is moderately high or number of channels is large.

3) When the number of channels is large (which is the case for DWDM system) and input power per channel is high (that is the case for a long haul WDM system with large amplifier spacing) use nonuniform dispersion with repeated unequal channel spacing scheme. Use nonuniform dispersion or dispersion compensation with unequal channel spacing only when the amplifier spacing or the number of channels is very large.

The FWM process in EDFA is taken into account in the analysis. It is found that this process should be taken into consideration to fully understand the effect of FWM on WDM systems.

9.2 Suggestions for Future Works

In our work we have assumed that the loss in each fiber section is exactly compensated by the fiber amplifier that follows that section. Future works can be carried out for a general system, where the loss in a section may or may not be fully compensated by the fiber amplifier. We have considered only FWM noise in EDFA. But study should be made that includes the amplifier spontaneous emission noise into account to attain a more accurate picture of the noise produced by EDFA. Future studies should also include not only the FWM effect but also other nonlinear phenomenon into account to obtain a complete picture of the system performance. Finally the additional cost incurred when the identical fibers in uniform dispersion scheme is replaced by the various types of fibers in nonuniform dispersion or dispersion compensating scheme, should also be assessed. Also other possible solutions to the problem should be investigated.

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Appendix A

List of Parameters

n_o	$= 1.45$
λ	$= 1.55\ \mu m$
A_{eff}	$= 50\ \mu m^2$
χ	$= 4 \times 10^{-15}$ esu
α	$= 0.21$ dB/km
$dDc/d\lambda$	$= 0.07$ ps/km-nm^2
γ_{EDF}	$= 3.69\times 10^{-3}$ /mw-km
γ_{TF}	$= 1.2\times 10^{-3}$ /mw-km

Appendix B

Expression for FWM power

An intense light beam propagating through a glass induces a nonlinear polarization in the medium which gives rise to nonlinear effects. Since silica is a symmetric molecule second order susceptibility vanishes for silica glasses. The lowest order nonlinear effects in optical fibers originate from third order nonlinear susceptibility $\chi^{(3)}$. The nonlinear polarization is given by

$$P_{NL} = \chi^{(3)} \mathrm{M} EEE \tag{C.1}$$

The electric field E(t,z) and the nonlinear polarization $P_{NL}(z,t)$ can be written in terms of their Fourier amplitudes as

$$E(z,t) = \int_{-\infty}^{\infty} E(\omega, z) \exp[-i(\omega t - kz)] d\omega \tag{C.2}$$

$$P_{NL}(t,z) = \int_{+\infty}^{-\infty} P_{NL}(\omega, z) \exp(-i\omega t) d\omega \tag{C.3}$$

In this section we obtain the four wave mixing component of a particular channel frequency. To do this we start with the inhomogeneous wave equation

$$\frac{\partial^2}{\partial z^2}E(z,t)-\frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}E(t,z)-\frac{\alpha n}{c}\frac{\partial}{\partial t}E(t,z)=\frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}P_{NL}(t,z) \tag{C.4}$$

Substituting equation (C.2) and (C.3) in equation (C.4) and equating Fourier amplitudes of equal frequencies we obtain the first order differential equation

$$\frac{d}{dz}E(\omega,z)=-\frac{1}{2}\alpha E(\omega,z)+i\frac{2\pi\omega}{nc}P_{NL}(\omega,z)\exp(-ikz) \tag{C.5}$$

Suppose we have four monochromatic light frequencies ω_j (j=1,...,4) where the spacing between the frequencies is very small. We can write for each of the waves

$$E(\omega_j,z)=\frac{1}{2}E_j(z)\delta(\omega_j-\omega)+\frac{1}{2}E_j^*(z)\delta(\omega_j+\omega) \tag{C.6}$$

where the amplitude of $E_j(z)$ depends only on the z coordinate, δ is the Dirac δ function,. Similarly the monochromatic nonlinear polarization P_{NL} for frequency ω_4 is

$$P_{NL}(\omega_4,z)=\frac{1}{2}A_1(z)\delta(\omega_1-\omega)+\frac{1}{2}A_1^*(z)\delta(\omega_1-\omega) \tag{C.7}$$

It has been proved [Hill,1978] that

$$P_{NL}(\omega_4^*, z) = \chi \int_{-\infty}^{\infty} d\omega_1 \int_{-\infty}^{\infty} d\omega_2 \times E(\omega_1, z) E(\omega_2, z) E(-\omega_3, z) \qquad \text{(C.8)}$$

Substituting (C.6) and (C.7) in (C.8) we obtain

$$A_1(z) = \frac{1}{4} \chi E_1(z) E_2(z) E_3^*(z) \qquad \text{(C.9)}$$

It is known that

$$\frac{1}{4}\chi = D\chi_{1111} \qquad \text{(C.10)}$$

where D is the degeneracy factor. D=1,3,6 depending whether three,two or none of the frequencies ω_1, ω_2 , ω_3 are the same. Now we substitute equation (C.6) and (C.7) in equation (C.5) to obtain the first order monochromatic plane wave amplitude at frequency ω_4

$$\frac{d}{dz} E_4(z) = -\frac{1}{2} \alpha E_4(z) + i \frac{2\pi\omega_4}{n_4 c} (D\chi_{1111}) \times E_1(z) E_2(z) E_3^*(z) \exp(ik_4 z) \qquad \text{(C.11)}$$

In general eq(10) is required to describe the depletion of field $E_j(z)$ at frequency ω_j (j=1,2,3) due to transfer of energy from frequency ω_j to frequency ω_4.However we are considering the case when the transfer of energy is really small(very small conversion efficiency) and we assume that the amplitude of the fields $E_j(z)$(j=2,3,4) is diminished solely by fiber attenuation. Under this condition the electric field can be written in the form

$$E_j(z) = E_j \exp(-\frac{1}{2}\alpha z - ik_j z) \tag{C.12}$$

Substituting (C.12) into (C.11) and integrating over the fiber length L we get

$$E_4(L) = i\frac{2\pi\omega_1}{n_1 c}(D\chi_{1111})E_1 E_2 E_3^* \times \exp(-\frac{1}{2}\alpha L)(\frac{\exp(-\alpha L + i\Delta k L) - 1)}{i\Delta k - \alpha}) \tag{C.13}$$

where

$$\Delta k = k_3 + k_4 - k_1 - k_2 \tag{C.14}$$

is the amount of phase mismatch.

To obtain the FWM power at frequency ω_4 we need to take account of the transverse distribution of teh light intensity HE_{11} mode. The time averaged power is given by

$$P_4 = -\mathrm{Im}[\frac{1}{2}\omega_4 \int\int\int E^*(\omega_4, x, y, z) P_{NL}(\omega_4, x, y, z) dxdydz] \tag{C.15}$$

where the Fourier amplitudes are now functions of three coordinate variables and the integrals are taken over the volume of the fiber. The Fourier amplitudes at ω_4 can be expressed as a product

$$E(\omega_4,x,y,z)= E(\omega_4,z)N(x,y) \tag{C.16}$$

where N(x,y) is the normalized mode profile of the HE_{11} mode such that N(0,0)=1; $E(\omega_4,z)$is the electric field amplitude defined earlier. Similarly P_{NL} can be expressed as

$$P_{NL}(\omega_4,x,y,z)= P_{NL}(\omega_4,z)N^3(x,y) \qquad (C.17)$$

where it is assumed that the mode profiles for the four frequencies ω_j(j=1,..,4) are identical. Substituting (C.!7) and (C.!6) in (C.15) we get

$$P_4 = -\mathrm{Im}[\frac{1}{2}\omega_4 \int E^*(\omega_4,z)P_{NL}(\omega_4,z)dz] \times \int N^4(x,y)dxdy \qquad (C.18)$$

An approximate value for the first factor of equation (C.18) can be obtained by replacing this factor with the power in a wave of amplitude $E_4(L)$ and area $\int N^2(x,y)$. Then (C.18) reduces to

$$P_4 = \frac{n_4 c}{8\pi}|E_4(L)|^2 \int N^2(x,y)dxdy \int N^4(x,y)dxdy \qquad (C.19)$$

For a sufficiently small range of frequencies (C.12) we may take Δ kL≈0 and get

$$|E_4(L)|^2 = \frac{4\pi^2\omega_4^2}{n_4^2 c^2}(D\chi_{1111})^2|E_1|^2|E_2|^2|E_3|^2 \times \exp(-\alpha L)L_{eff}^2 \qquad (C.20)$$

where

$$L_{eff} = [1-\exp(-\alpha L)]/\alpha \tag{C.21}$$

Putting the value of $|E_4(L)|^2$ from equation (C.20) into equation(C.18) we obtain

$$P_4 = \frac{256\pi^4\omega_4^2}{n_1 n_2 n_3 n_4 c^4}(D\chi_{1111})^2 L_{eff}^2 \exp(-\alpha L)\frac{P_1 P_2 P_3}{A_{eff}^2} \tag{C.22}$$

where

$$A_{eff} = \frac{\left|\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} N^2(x,y)dxdy\right|^2}{\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} N^4(x,y)dxdy} \tag{C.23}$$