Analysis of Raman amplification in DWDM communication systems

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Analysis of Raman Amplification in DWDM Communication Systems

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Abstract

Fiber Raman Amplifier has become one of the key technologies in long-haul and ultra long-haul fiber optic transmission systems. Distributed Raman amplifier offers improvement in noise figure and at the same time, reduction in nonlinear penalties allowing longer amplifier spans, higher traffic capacity (higher bit rates and close channel spacing) as well as operation near zero-dispersion wavelength. Meanwhile, discrete Raman amplifier helps to increase the capacity of fiber optic networks by opening up new windows for Wavelength Division Multiplexing (WDM), such as S-band lumped Raman amplifier. The application of Raman amplifier in Dense Wavelength Division Multiplexing (DWDM) introduces some challenges such as poor gain uniformity within the wide transmission bandwidth, poor pumping efficiency and also additional noise and crosstalk generated due to some nonlinear effects. We address these issues and propose solutions to optimize the use of fiber Raman amplifier in DWDM communication. We start with briefly discussing some fundamental properties of fiber Raman amplifier, including the origin of Raman amplifier, the gain and noise properties. The amplification process can be explained by both classical and quantum theory of the stimulated Raman scattering. In addition, we also briefly discuss the polarization dependence of Raman amplifier.

We present two possible methods to flatten Raman gain profile. First, we introduce the use of optical filter based on fiber loop mirror. High birefringence fiber loop mirror using Sagnac interferometer has some advantages such as its resistance to environmental changes, strong noise rejection ability and more importantly, input polarization independent. We present the detail characterization of this filter and

experimentally demonstrate the use of this particular filter to flatten Raman gain for signal wavelengths within C-band. The filter is located at the end of the distributed Raman amplifier using single mode fiber of 70 km length, generating average 15 dB On-Off Raman gains. We show that by employing two sections of high birefringence fiber loop mirror, we obtain about 38 nm flat gain with gain ripple ± 0.5 dB.

We also report the application of multi-wavelength Raman pump to generate flat Raman gain. We present a new scheme called Alternating Time-Division Multiplexed Raman pump scheme. This method involves the use of multi pump sources with different wavelengths, which are modulated and temporally separated from each other in order to improve gain and noise properties due to avoidance of pump-to-pump interaction effect. We present the necessary operating condition of this new scheme to generate flat Raman gain for signals with C-band wavelength range. By using 100 km Non-Zero Dispersion Shifted Fiber (NZDF), we obtain flat gain with gain ripple ± 0.5 dB and amplifier noise figure -5 dB. We also propose the use of Gaussian pump pulses as a better alternative solution in this TDM Raman pump scheme.

Finally, we report a new method to describe the Raman scattering between channels in DWDM based on Volterra Series. Basically the optical signal in fiber transmission can be represented by the Volterra series containing first order kernel, third order kernel, and fifth or even higher order kernels for the case of high nonlinear system. As part of the nonlinear effects, Raman scattering can also be described by the Volterra Kernels. It was proven that the accuracy of this series for optical signal transmission in single mode fiber is good, compared to the existing split-step Fourier method. Therefore, we propose to use this series to identify the Raman kernels' component within the DWDM

transmission. The model derived can become a method to measure the interference between DWDM channels due to the stimulated Raman scattering, i.e. Raman crosstalk. We investigate the identification of Raman crosstalk between two channels for On-Off Keying Non-Return to Zero (OOK-NRZ) input modulation format. We use the principal of mean square error algorithm to identify the Raman kernels numerically. By correlating input and output signals, we obtain the third order Volterra kernels due to Raman scattering. Our results show good agreement with the one resulting from the split step Fourier method.

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Symbols and Abbreviations

Symbols	Meaning	Units
τ	group delay	ps/m
λ	carrier wavelength	nm
λ_0	zero-dispersion wavelength	nm
D	fiber dispersion parameter	ps/nm-km
S_0	dispersion slope at zero-dispersion wavelength	ps/nm ² -km
V_g	group velocity	m/s
α	fiber attenuation	dB/km
κ_{Ray}	Rayleigh backscattering coefficient	km ⁻¹
$\Delta\omega_p$	bandwidth of pump spectrum	Hz
A_{eff}	effective fiber core area	μm ²
c	vacuum velocity of light	m/s
L_D	dispersion length	m
L_C	length of collision	m
L_B	beat length	mm
T_{FWHM}	Full width at the half intensity-maximum of pulse	μs
T	period	μs
T_p	active pulse period	μs
ρ	pulse duty cycle	-
f	pulse repetition rate	Hz
A	normalized amplitude of input pulse	-

P_0	peak power of input pulse	W
$\tilde{p}$	electric dipole factor	

Abbreviations	Meanings
ASE	amplified spontaneous emission
CW	continuous wave
DRS	double Rayleigh backscattering
DSF	dispersion shifted fiber
DWDM	dense wavelength-division multiplexing
FWM	four-wave mixing
GVD	group-velocity dispersion
i.i.d	independent identically distributed
NZDF	non-zero dispersion shifted fiber
NLSE	nonlinear Schrödinger equation
OOK	On-Off Keying
PCF	photonic crystal fiber
SMF	single mode fiber
SPM	self-phase modulation
SRB	single Rayleigh backscattering
SRS	stimulated Raman scattering
VSTF	Volterra series transfer function
XPM	cross-phase modulation

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CHAPTER 1

Introduction

1.1 Historical Background

The demand for high capacity long-haul telecommunication is expanding at steady rate and expected to grow faster in the next decade. A communication network covering long distance and large areas with large capacity is highly demanded. Reducing loss and increasing communication bandwidth are the keys to improve the communication network. Optic fibers answer this demand with its ability to accommodate high bandwidth data through wavelength division multiplexed system and its low loss at around 1.5 μm windows. Lightwave technology is now advancing at a rate exceeding a factor of 100 in every ten years. Long distance transmission entered a “*Tera*” era in around 1996, where the transmission of Tb/s per fiber was experimentally demonstrated. At this rate, one hair-thin fiber can actually accommodate 40 million data transmission at 28 kb/s, 20 million digital telephony channels, or half million digital television channels.

Lightwave technology was initially introduced by Bell system in 1980 [1], which is known as FT3 system with digital transmission rate of 45 Mb/s and regenerator spacing of about 7 km. It was operated at 0.82 μm centre wavelength on multimode fiber, which was then upgraded to 90 Mb/s per fiber. It was subsequently followed by the lightwave generation using single mode fiber (SMF) operating at low and minimum loss fiber window, i.e. centre operating wavelength on 1.3 μm and 1.55 μm . The FT Series G

System was operating at 417 Mb/s data rates and then 1.7 Gb/s and 50 km regenerator spacing due to lower loss [2].

The new SMF technology operating at 1.55 μm window to achieve long regenerator spans was using high-speed electronic time division multiplexing (ETDM). Using TDM, data is routinely transmitted at 2.5 Gb/s (OC-48) and increasingly at 10 Gb/s (OC-192). The further increases in capacity were achieved by further advances in the enabling technologies such as fiber design, laser technology, high-speed modulator, and sensitive high-speed receiver. Recent advances have resulted in speeds of 40 Gb/s (OC-768). Unfortunately, due to limitation in high-speed electronics, a new approach was defined to combine many wavelengths onto a single fiber, called Wavelength Division Multiplexing (WDM) technology. Without having to lay new fiber, the effective capacity of existing fiber plant can be increased by factor of 16 or 32. System with 128 and 160 wavelengths are in operation today with higher density on the horizon. Despite the dramatic increase in fiber capacity, this technology enables a very large regenerator spacing, i.e. up to 10,000 km, and has opened a new dimension of networking, i.e. adding the dimension of wavelength to the existing dimension of space and time [3].

Fig. 1.1 A WDM Link.

A WDM link involves transmitting data bits into optical lights, multiplexing multiple streams of lights at different wavelengths, which are then coupled into optical fiber, amplifying optical signals, de-multiplexing the multiplexed stream into component stress and receiving transmitted data by optical receiver. Dense WDM (DWDM) spaces the wavelengths more closely than WDM and therefore has a greater overall capacity. Some notable features in DWDM systems are the ability to amplify all the wavelengths at once without converting them into electrical signals, and the ability to carry signals of different speeds and different types simultaneously and transparently over the fiber (protocol and bit rate independence).

Table 1 Evolution of WDM to DWDM.

Time Frame	WDM Type	Channels	Wavelength	Channel Spacing
1980's	Wideband	2	1310 nm, 1550 nm	-
Early 90's	Narrowband	2 – 8	C – Band	200 – 400 GHz
Mid 90's	Dense	16-40	C – Band	100 – 200 GHz
Late 90's	Dense	64-160	C – Band	25 – 50 GHz
Current	Ultra Dense	160-320	C/L – Band	12.5 – 25 GHz

One of the major focuses in DWDM system is on the detection of modulated light signals, therefore optical signal to noise ratio becomes an important parameter. The weak signal at the receiver in many optical communication systems are due to accumulation of fiber loss through long transmission span. One can use in-line repeater and/or pre-amplifier at the receiver input to boost the optical signal power. Conventionally, one can use electronic circuits as in-line repeater, or called regenerative repeaters. However, since this electronic design is highly dependent on modulation format, data bit rate, multiplexing scheme, this in-line repeater becomes inflexible. Thus, direct optical amplification is required to improve the signal power.

1.2 Motivation

Investigation into optical amplifier first began in the mid-1960s with the oscillation of a rare-earth glass laser. Research into optical fiber amplifiers, on the other hand, has centered on fiber lasers doped with rare earths such as Neodymium (Nd) or Erbium (Er). Since later 1980s, researchers had started to study the applicability of Erbium-Doped Fiber Amplifier (EDFA) and some various transmission experiments had been performed. In 1985-1986, an optical amplifier was demonstrated by University of Southampton, by using 3 meter of silicon fiber doped with Erbium. The research team achieved amplifier gain of 125 dB at 1530 nm signal wavelength. Nowadays, commercial EDFA are available for 980 nm or 1480 nm pump wavelengths.

The EDFA, in particular, has been recognized to have wide potential for application, due to its many beneficial characteristics such as coincidence of the amplification waveband and the optical fiber minimum loss window; its high gain, broadband, low-loss and polarization-independent operation; the absence of nonlinear behavior, low coupling loss with optical fiber and the fact that it is optically pumped. However, the capacity of current WDM systems is largely limited by the relatively narrow gain bandwidth of EDFA. Achieving EDFA gain over bandwidths in excess of 4 to 5 THz requires the substantial use of gain equalizing filters that are very costly in terms of optical power budget of the system. One technology to overcome this problem is *Raman Amplifier*.

Fundamental principle behind Raman amplification is Raman effect, which was initially discovered by C. V. Raman in his experiment on scattering by liquids, which occurs at low excitation intensity (C. V. Raman 1928) [4]. Subsequently, Woodbury and Ng (1962) discovered that in addition to the normal spectral content of laser radiation,

frequency-shifted radiation may occur under certain condition. Starting from then, a lot of systematic works were performed to analyze the Raman effect in different type of materials – both micro-physically ordered and disordered systems.

In the early 1970s, R. H Stolen, E. P. Ippen, and A. R. Tynes were among the first to demonstrate Raman scattering for amplification purposes in optical fibers, called Raman amplifier. Raman gain of fused-quartz was plotted from an exciting line at 526 nm and having peak gain at around 440 cm^{-1} frequency shift [5]. However, due to the lack of low-loss fiber and appropriate pump sources, the stimulated Raman scattering (SRS) was less studied during the period of 1970-1980's. In the mid of 1980, many research works promoted Raman amplification as an alternative way to overcome attenuation in optical fibers, i.e. L. F. Mollenauer *et al.* demonstrated the soliton propagation in long fibers whose loss is compensated by distributed Raman amplifier [6]. Nonetheless, due to its poor pump-power efficiency, from mid of 1980 till early 1990, work on Raman amplifiers was abandoned with the commercialization of EDFA. In the mid 1990's, high power lasers become commercially available and subsequently in the years after, a resurged interest in Raman amplifier increased as the need to provide wider amplification bandwidth and longer transmission span beyond the capacity of EDFA. By early 2000's, almost all wide-bandwidth long-haul and ultra long-haul transmission used Raman amplifier including undersea experiment [3], high-capacity transmission [7 - 10], shorter span single channel transmission [11] and soliton systems [6, 12 - 13].

Raman gain arises from transfer of power from one optical beam into another beam by energy of optical phonon. The gain bandwidth is more than 100 nm, which is equivalent to 40 THz bandwidth in the 1500 nm spectral region. Some other fundamental and

beneficial features of Raman amplifier in addition to the wide amplification bandwidth are: *i)* it exists in any fiber which promotes flexible and cost-effective means of upgrading the optical communication system, *ii)* its gain spectrum can be tailored by adjusting the pump wavelengths which enables: a) flat gain over certain bandwidth by employing proper combination of pump wavelengths, b) extended bandwidth of transmission especially in dense wavelength division multiplexing (DWDM) systems, and *iii)* its small gain coefficient imposes possibility of having distributed amplification, which improves the amplifier noise performance.

However, Raman amplifier also faces some challenges to be solved, such as *i)* its poor gain efficiency, *ii)* noises and crosstalk induced by nonlinear effects due to the interaction of high intensities pump power at multi-wavelength Raman pump scheme, *iii)* its fast transient response induces new source of noise and may cause burst error in transmission due to the transient effect during the channel add-drop or cable cuts, owing to the strong nonlinearity at power overshoot and degradation of signal to noise ratio at power undershoot due to pump depletion [14]. These conditions motivated us to look into this problem in greater details and proposed some solutions with detailed analysis. Some major problems we highlighted in our research were how to improve the signal to noise ratio and how to enhance the cost effectiveness of Raman amplification, especially for the long haul optical communication. These correspond to *i)* how to provide uniform and high gain levels for all wavelengths within the desired signal transmission bandwidth and *ii)* how to suppress the noise levels. The gain uniformity can be achieved by using conventional method, such as optical filter, covering certain amplification bandwidth. In addition to that, the use of multi-wavelength pump can also flatten the Raman gain. The use of optical filter would be accompanied by suppression of some gain at certain

wavelength, which reduces the gain efficiency. However, this method is simple to implement and induces less cost, as compared to multi-wavelength pump method. On the other hand, multi-wavelength pump provides more flexibility in designing flattened gain. The drawback of this method is the reduction of gain efficiency due to some energy transfer between the multi-wavelength pump, which propagating simultaneously. In addition, nonlinear interaction among pumps also induces more noise to the system. Therefore based on this condition, in this study, we investigate both the application of optical filter and multi-wavelength Raman pump to flatten Raman gain. The use of high-birefringence fiber loop mirror as an optical filter to flatten the Raman gain is implemented. Subsequently, the analysis of new pumping scheme, Time-Division Multiplexed Raman pumping scheme, is presented in details. The advantages and drawback of both methods are elaborated from the results obtained by some experimental work and/or numerical simulation. Last but not least, the noise generated in transmission system due to Raman crosstalk is also investigated in the last chapter. For details, we provide the objectives and major contributions of our research work in the next section.

1.3 Objectives

In this thesis, we aim to thoroughly analyze the application of Raman amplifier in DWDM communication. We are answering two fundamental issues related to every amplifier, which also applies to Raman amplifier, i.e. gain and noise performance. Fundamental issues related to gain performance of Raman amplifier are non-uniformity of Raman gain coefficient with respect to wavelength and poor Raman gain efficiency. We aim to answer these by proposing two different methods of Raman gain flattening, i.e. by using optical filter and by using multi-wavelength Raman pump. Gain flatness performance is measured in terms of flat gain bandwidth and gain ripple. Improvement of

gain efficiency is also seriously taken into account in both gain flattening processes, such as lowering gain suppression in the application of optical filter, and avoidance of power transfer between pump beams in the multi-wavelength Raman pump.

We also answer some fundamental issues related to the noise performance by investigating several sources of noise, such as amplified spontaneous emission, single and double Rayleigh backscattering noise, and noise due to Four-Wave Mixing effect. Both noise and gain performance in multi-wavelength Raman pump can be improved by using special pump scheme called Time-Division Multiplexed Raman pump scheme. We aim to set certain operating conditions to optimize its performance. We also propose different pump modulation format, i.e. Gaussian pulse, as an alternative solution in addition to the existing square pulse modulation.

Finally, we also conduct investigation on other source of noise to the signal, e.g. Raman crosstalk. We propose the application of Volterra series transfer function to identify the crosstalk between DWDM channels induced by Raman scattering for various input signal modulation formats.

1.4 Major contribution of this Thesis

Generally, there are four major contributions in this thesis. Firstly, we propose a special type of optical filter based on Sagnac interferometer to flatten Raman gain for DWDM communication. We have demonstrated experimentally the application of high birefringence fiber loop mirror at the transmission end to flatten the Raman gain for

signals in C-band window. We propose the use of both single and double sections Hi-Bi fibers with different lengths of polarization maintaining fiber.

Secondly, we investigate the new Raman pump scheme, called Time-Division Multiplexed Raman pump scheme, and present detailed characterization and operating conditions to optimize both gain and noise performance of the amplifier. We use this Raman pump scheme in generating flat Raman gain by using multi-wavelength pump with certain pump wavelength and power configurations, where the latter acts as the weighting function. We focus the investigation on the design of alternating Raman pump scheme, which means two neighboring pump pulses have different pump wavelengths. We include some important factors such as fiber properties (attenuation, dispersion, Raman gain coefficient, Rayleigh scattering coefficient), pump RIN level, pump pulse repetition rate and pulse duty cycle. We optimize the gain and noise performance while still maintaining the avoidance of pump-to-pump interaction among pump pulses. We use the amplifier gain flatness and effective noise figure as the performance parameters.

Thirdly, we propose Gaussian pump pulse to the Time-Division Multiplexed Raman pump scheme. We set some properties of Gaussian pulse in this scheme with the objective of maintaining free-pump-interaction. Subsequently, we present detailed analysis on both single-wavelength and multi-wavelength Gaussian pulse Time Division Multiplexed Raman pump scheme. We use similar approach as in the square pulse modulation to set certain operating conditions that will optimize both gain and noise performance of the amplifier.

Finally, we present the analysis of Raman crosstalk in DWDM communication by using Volterra series transfer function. By using cross-correlation method, we obtain the first, third and possibly fifth order nonlinear kernel that exist in fiber transmission. We focus on the third and fifth order nonlinear kernels induced by Raman scattering phenomena, which we call it Raman kernels. We specifically focus on identifying third order Raman kernels between two channels in DWDM communication for On-Off Keying (OOK) input modulation format. We derive the identification algorithm in OOK by using mean square error algorithm with some approximation. We thus compare the results obtained from this method to the one from the split-step Fourier method.

1.5 Organization of the Thesis

This thesis focuses on the study of Raman amplifier in DWDM Communication and is organized as follows: Chapter one provides a brief introduction of the historical background and the significance of the study, based on which the motivation and objectives of the thesis are derived. Chapter two presents the fundamental of fiber Raman amplifier, including the stimulated Raman scattering based on quantum theory and classical theory, properties of fiber Raman amplifier including gain and noise properties. In Chapter three, we present Raman gain flattening scheme by using high-birefringence fiber loop mirror. Both theoretical works and experimental validation are presented to flatten the Raman gain within C-band signals with good gain bandwidth and gain ripple. The analysis of Raman gain flattening process by using newly developed multi-wavelength Time Division Multiplexed Raman pump scheme is presented in chapter four. In this chapter, we define the necessary operating conditions to optimize the gain and noise performance of TDM Raman amplifier by taking into account some major fiber properties and modulated pump properties. The characteristics of fiber dispersion

profile, pump wavelength configurations, pulse repetition rates and duty cycles, pump RIN level and both bandwidth and gain ripple of flat Raman gain are investigated. The possibility of using Gaussian pulse TDM Raman pump is also studied. Chapter five presents the identification of Raman kernels by using Volterra series transfer function in distributed Raman amplifier. A general set of equations to govern the identification process is derived for On-Off Keying modulation format. The model derived can become an alternative test method to measure the interference between DWDM channels due to stimulated Raman scattering. The accuracy of the model is compared with the existing high accuracy split-step Fourier method by correlating the output and input of Raman amplified transmission system. The interaction between WDM channels are represented by 3rd, 5th, or higher order Raman Kernels, depending on the channel intensity level. Finally, our conclusion and recommendations for future research work are presented in the last chapter.

CHAPTER 2

Fundamental of Fiber Raman Amplifier

2.1 Introduction

Scattering occurs when monochromatic radiation of frequency ω_1 is incident on systems such as dust-free, transparent gases and liquids, or optically perfect, transparent solids, most of it is transmitted without change, but in addition some scattering of the radiation occurs. Elastic scattering causes no frequency shift on the incident radiation unlike the inelastic one. Inelastic scattering produces scattered radiation with additional pair of new frequencies $\omega_1 \pm \omega_M$.

Generally scattering process comprises Raman, Brillouin, Rayleigh and Rayleigh-wing scattering. By definition, those components of the scattered light that are shifted to lower frequencies are known as Stokes components and those components that are shifted to higher frequencies are known as anti-Stokes components.

Raman Stokes scattering consists of transition from the ground state $|g\rangle$ to the final state $|n\rangle$ by means of an intermediate transition to a virtual level associated with the excited state $|n'\rangle$. On the other hand, Raman anti Stokes scattering entails a transition level from level $|n\rangle$ to level $|g\rangle$ with $|n'\rangle$ as intermediate state. In thermal equilibrium, the population of level $|n\rangle$ is smaller than level $|g\rangle$ by Boltzmann constant $\exp(-\hbar\omega_{ng}/kT)$, therefore Stokes generation are more than anti-Stokes.

2.2 Stimulated Raman Scattering

When the incident radiation consists of two overlapping coherent monochromatic beams of frequencies ω_1 and ω_2 with $\omega_1 > \omega_2$, interaction between these two frequencies produces various frequency combinations (harmonic). Two possible harmonic frequencies are $\omega_S = 2\omega_2 - \omega_1$ and $\omega_{AS} = 2\omega_1 - \omega_2$, which are known as Stokes and anti-Stokes frequency component respectively. When ω_2 varies while keeping ω_1 constant, the intensity of Stokes generation increases as $(\omega_1 - \omega_2)$ approaches ω_M . The condition where $(\omega_1 - \omega_2) = \omega_M$ is known as *Raman resonance*, where ω_M is the molecular frequency observable in Raman scattering. When Raman resonance is reached, frequency matching condition is satisfied and thus Stokes radiation relative to ω_2 called coherent Stokes Raman scattering $\omega_S = 2\omega_2 - \omega_1 = \omega_2 - \omega_M$ and anti-Stokes radiation relative to ω_1 called coherent anti-Stokes Raman scattering $\omega_{AS} = 2\omega_1 - \omega_2 = \omega_1 - \omega_M$ are produced, as illustrated in Fig. 2.1. This coherent nature produces highly directional beams of scattered radiation with small divergences, with intensity proportional to the square of the number of scattering molecules and the square of the irradiance of the incident radiation at ω_1 and ω_2 .

Consider an interaction in a material system with radiation of frequencies ω_1 and ω_2 as described above. Suppose that before interaction there are n_1 photons having energy $E_1 = \hbar\omega_1$ each, n_2 photons having energy $E_2 = \hbar\omega_2$ each and molecules with energy E_i . Under Raman resonance condition, the interaction of the radiation with the material involves annihilation of photon with energy E_1 and creation of photon with

energy E_2 . This process is called stimulated Raman Stokes generation as the presence of radiation frequency $\omega_2 = \omega_1 - \omega_M$ stimulates the Stokes generation and produce intensity of radiation at frequency ω_2 .

Fig. 2.1 Energy transition diagram

2.2.1 Quantum Theory of Stimulated Raman Scattering

The probability of a photon to be emitted into Stokes mode S per unit time is postulated to be [15]

$$P_S = Dm_L(m_S + 1) \quad (2.2.1)$$

where m_L, m_S are mean number of photons per mode in the laser radiation and mean number of Stokes photon, respectively, and D is a proportionally constant whose value depends on the physical properties of the material medium. The functional form of P_S in (2.2.1) above represents the linear photon transition rate from laser radiation to both spontaneous scattering, i.e. Dm_L , and stimulated scattering, i.e. $Dm_L m_S$.

By its definition, the time rate of change of the mean photon occupation number in the

Stokes mode can be given by:
$$\frac{dm_S}{dt} = P_S = Dm_L(m_S + 1) \quad (2.2.2)$$

The spatial growth rate of the Stokes mode corresponds to the traveling wave in positive z direction at the velocity of c/n is thus defined as:

$$\frac{dm_S}{dz} = \frac{1}{c/n} \frac{dm_S}{dt} = \frac{n}{c} Dm_L(m_S + 1) \quad (2.2.3)$$

When the occupation number of the Stokes mode is less than unity, i.e. $m_S \ll 1$ and under non-depleted laser field, equation (2.2.3) thus becomes:

$$\frac{dm_S}{dz} = \frac{n}{c} Dm_L \quad (2.2.4)$$

The solution is given by
$$m_S(z) = m_S(0) + \frac{n}{c} Dm_L z \quad (2.2.5)$$

The Stokes generation in (2.2.5) refers to the spontaneous Raman scattering, where the Stokes intensity increases proportionally with respect to the length of the Raman medium and the total molecules contained in the interaction region.

When the occupation number of the Stokes mode is much greater than unity, i.e. $m_S \gg 1$ and under non-depleted laser field, equation (2.2.3) becomes:

$$\frac{dm_S}{dz} = \frac{n}{c} Dm_L m_S \quad (2.2.6)$$

The solution is given by:
$$m_S(z) = m_S(0)e^{Gz} \quad (2.2.7)$$

where:
$$G = \frac{n}{c} Dm_L \quad (2.2.8)$$

Equation (2.2.8) introduces gain coefficient G of the stimulated Raman scattering. The Stokes intensity m_s is seen to grow exponentially with propagation distance through the medium.

Since creation of one Stokes photon results in lost of one laser photon, we can describe

this interaction as:

$$\frac{dm_L}{dz} = -\frac{dm_S}{dz} \quad (2.2.9)$$

By taking into account the total number of Stokes mode that can be radiated M and geometric factor that take into account the non-uniformity angular distribution of the Stokes b , equation (2.2.9) can be modified into:

$$\frac{dm_L}{dz} = -Mb \frac{dm_S}{dz} = -Mb \frac{Dm_L}{c/n} \quad (2.2.10)$$

The factor M above can be expressed as [16]: $M = \frac{V\omega_s^2\Delta\omega}{\pi^2(c/n)^3}$ (2.2.11)

where V denotes the volume of the region in which the Stokes modes are defined and $\Delta\omega$ denotes the linewidth of the Stokes radiation.

The factor b is defined as the ratio of the angularly averaged Stokes emission rate to the directional Stokes rate in which factor D and ultimately gain coefficient G in (2.2.8) is to

be determined, which is described as: $b = \frac{\int |f(\theta, \phi)|^2 d\Omega / 4\pi}{|f(\theta_s, \phi_s)|^2}$ (2.2.12)

where $|f(\theta, \phi)|$ denotes the angular distribution of the Stokes radiation and (θ_s, ϕ_s) is the direction of particular Stokes mode for which D is to be determined.

Conventionally, the rate of loss of laser photons can be described by:

$$\frac{dm_L}{dz} = -N\sigma m_L \quad (2.2.13)$$

where N denotes the molecule density and σ denotes the cross sectional area. By comparing (2.2.10) and (2.2.13), we can express D in term of cross section σ by:

$$D = \frac{N\sigma(c/n)}{Mb} \quad (2.2.14)$$

Substituting (2.2.14) into (2.2.8) gives us the Raman gain coefficient G as:

$$G = \frac{N\sigma\pi^2 c^3 m_L}{V\omega_s^2 \Delta\omega b n^3} \quad (2.2.15)$$

From (2.2.15), we can see some important properties that contribute to the Raman gain coefficient, such as cross-sectional area σ , number density of molecule N , linewidth of the Stokes radiation $\Delta\omega$, mean number of photons per mode (corresponds to field intensity) of both the laser and Stokes, and the volume V of the region in which the Stokes modes are defined. Also, different Stokes frequency results in different Raman gain coefficient. We can also analyze and present this Raman gain coefficient from the classical theory. From this view, we could directly use the gain coefficient into the well-known Maxwell equation, which finally gives us the Stokes and laser pump intensity evolution inside the optical fiber.

2.2.2 Classical Theory of Stimulated Raman Scattering

When an electromagnetic radiation interacts with a material system, a frequency-dependent linear induced electric dipole vector $\tilde{p}^{(1)}$ is given by:

$$\tilde{p}^{(1)} = \alpha \tilde{E} \quad (2.2.16)$$

where $\tilde{E}$ denotes the electric field of the incident, plane wave, monochromatic radiation with frequency ω_i and α is the polarizability tensor of the molecule. Generally, this tensor is a function of nuclear coordinates and hence of molecular vibrational frequencies. When the scattering system is considered to be vibrational system, not rotational, the molecule is space-fixed in its equilibrium configurations, but the nuclei vibrate about their equilibrium positions. Thus the variation of the polarizability with vibration of molecule can be expressed by expanding each component $\alpha_{p\sigma}$ of the polarizability tensor α with respect to normal coordinates of vibration Q as follows:

$$\alpha_{p\sigma} = (\alpha_{p\sigma})_0 + \sum_k \left(\frac{\partial \alpha_{p\sigma}}{\partial Q_k} \right)_0 Q_k + \frac{1}{2} \sum_{k,l} \left(\frac{\partial^2 \alpha_{p\sigma}}{\partial Q_k \partial Q_l} \right)_0 Q_k Q_l + \dots \quad (2.2.17)$$

where $(\alpha_{p\sigma})_0$ denotes the value of $\alpha_{p\sigma}$ at the equilibrium configuration, whilst Q_k, Q_l represent the coordinates of vibration associated with the molecular vibrational frequencies ω_k, ω_l respectively and the summations are to cater all normal coordinates.

The derivatives above are taken at the equilibrium configuration. Using the electrical harmonic approximation, where the higher order term of Q are neglected, the polarizability tensor can thus be expressed as: $(\alpha_{p\sigma})_k = (\alpha_{p\sigma})_0 + (\alpha'_{p\sigma})_k Q_k \quad (2.2.18)$

In order to illustrate the generation of Rayleigh and Raman scattering, assuming that Q_k is in the form of time dependent system of a simple harmonic as given by:

$$Q_k = Q_{k0} \cos(\omega_k t + \theta_k) \quad (2.2.19)$$

By introducing frequency dependence electric field $\tilde{E} = E_0 \cos(\omega_1 t)$, we obtain a set of induced electric dipole vectors $\tilde{p}^{(1)}$ from (2.2.16) in the form

$$\tilde{p}^{(1)} = \tilde{p}^{(1)}(\omega_1) + \tilde{p}^{(1)}(\omega_1 - \omega_k) + \tilde{p}^{(1)}(\omega_1 + \omega_k) \quad (2.2.20)$$

The first term in (2.2.20) represents the induced electric dipole moment due to Rayleigh scattering, whereas the second and third term represents the Raman scattering induced electric dipole moment.

In order to analyze the Raman effect on the signal propagation, we refer to the fundamental Maxwell equation as given by:

$$\nabla^2 \tilde{E} - \frac{1}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \tilde{P}}{\partial t^2} \quad (2.2.21)$$

where $\tilde{P}(z, t)$ denotes the total induced polarization, which accounts for linear polarization $\tilde{P}_L(z, t)$, noise induce polarization $\tilde{P}_N(z, t)$, third order polarization due to Kerr effect $\tilde{P}_K(z, t)$ and Raman effect $\tilde{P}_R(z, t)$. Third order polarization induced by Raman Effect $\tilde{P}_R(z, t)$ is given by $\tilde{P}_R(z, t) = N \tilde{p}^{(1)}(z, t)$, where N is number density of molecules. The spatial evolution of optical fields is described based on (2.2.21) as:

$$\frac{\partial^2 \tilde{E}}{\partial z^2} - \frac{1}{(c/n)^2} \frac{\partial^2 \tilde{E}}{\partial t^2} = \frac{4\pi}{c^2} \frac{\partial^2 \tilde{P}}{\partial t^2} \quad (2.2.22)$$

Chapter 2

Fundamental of Fiber Raman Amplifier

Assuming the vibrational mode can be described as a simple harmonic oscillator of a resonance frequency ω_v and damping constant γ , the molecular vibration can be

represented as [15]:

$$\frac{d^2 Q}{dt^2} + 2\gamma \frac{dQ}{dt} + \omega_v^2 Q = \frac{F(t)}{m} \quad (2.2.23)$$

where m denotes the nuclear mass and $F(t)$ denotes the force acting on the vibrational degree of freedom given by:

$$F(t) = -\frac{d\left\{\frac{1}{2}\langle\tilde{p}^{(n)}.\tilde{E}\rangle\right\}}{dQ} = \frac{1}{2}\left(\frac{\partial\alpha}{\partial Q}\right)_0 \langle\tilde{E}^2\rangle \quad (2.2.24)$$

In the case of stimulated Raman scattering, the total electric field with monochromatic frequencies ω_1 and ω_2 with $\omega_1 > \omega_2$ is assume to be represented as:

$$\tilde{E}(z,t) = A_1 \exp[i(k_1 z - \omega_1 t)] + A_2 \exp[i(k_2 z - \omega_2 t)] + c.c \quad (2.2.25)$$

where A_1 and A_2 are the complex amplitudes; k_1 and k_2 are the propagation constant of electric fields at frequencies ω_1 and ω_2 respectively.

Substituting (2.2.24) into (2.2.23), we obtain:

$$F(t) = \left(\frac{\partial\alpha}{\partial Q}\right)_0 \left[A_1 A_2^* \exp\{i(Kz - \Omega t)\} + A_1^* A_2 \exp\{-i(Kz - \Omega t)\} \right] \quad (2.2.26)$$

where:

$$K = k_1 - k_2 \text{ and } \Omega = \omega_1 - \omega_2$$

Based on (2.2.26), the molecular vibration in (2.2.23) can be approximated as:

$$Q(z,t) = Q(\Omega) \exp[i(Kz - \Omega t)] + Q^*(\Omega) \exp[-i(Kz - \Omega t)] \quad (2.2.27)$$

Substituting (2.2.26) and (2.2.27) into (2.2.23), we find the amplitude of the molecular

vibration as:

$$Q(\Omega) = \frac{(1/m)[\partial\alpha/\partial Q]_0 A_1 A_2^*}{\omega_v^2 - \Omega^2 - 2i\Omega\gamma} \quad (2.2.28)$$

Since the polarization of the medium is given by $\tilde{P}(z,t) = N\tilde{p}(z,t)$, the third order polarization induced by Stokes Raman effect is thus obtained as:

$$\tilde{P}_R^S(z,t) = P(\omega_2) \exp(i\omega_2 t) + c.c \quad (2.2.29)$$

with
$$P(\omega_2) = \frac{(N/m)(\partial\alpha/\partial Q)_0^2 |A_1|^2 A_2}{\omega_v^2 - \Omega^2 + 2i\Omega\gamma} \exp(ik_2 z) \quad (2.2.30)$$

Raman susceptibility can be defined from (2.2.29) as:

$$\chi_R(\omega_2) = \frac{(N/m)(\partial\alpha/\partial Q)_0^2}{\omega_v^2 - \Omega^2 + 2i\Omega\gamma} = \frac{(N/m)(\partial\alpha/\partial Q)_0^2}{\omega_v^2 - (\omega_1 - \omega_2)^2 + 2i(\omega_1 - \omega_2)\gamma} \quad (2.2.31)$$

Equation (2.2.31) can also be expressed as: $\chi_R(\omega_2) = \chi_{R-real} + i\chi_{R-imag}$ (2.2.32)

Where: $\chi_{R-real} = \frac{[\omega_v^2 - (\omega_1 - \omega_2)^2]}{[\omega_v^2 - (\omega_1 - \omega_2)^2]^2 + 4\gamma^2(\omega_1 - \omega_2)^2} [(N/m)(\partial\alpha/\partial Q)_0^2]$ (2.2.33)

$$\chi_{R-imag} = -\frac{2(\omega_1 - \omega_2)\gamma}{[\omega_v^2 - (\omega_1 - \omega_2)^2]^2 + 4\gamma^2(\omega_1 - \omega_2)^2} [(N/m)(\partial\alpha/\partial Q)_0^2] \quad (2.2.34)$$

Substituting (2.2.25) and (2.2.29) into (2.2.22), the spatial evolution of Stokes in slowly-varying amplitude approximation is given by:

$$\frac{\partial A_2}{\partial z} = i2\pi \frac{\omega_2}{nc} \chi_R(\omega_2) |A_1|^2 A_2 \quad (2.2.35)$$

As the imaginary part of Raman susceptibility is negative, the Stokes generation is said to be pure *gain* process. Therefore, Raman amplifier is a Stokes generation process induced by higher frequencies optical field, which automatically fulfill phase matching condition at the Raman resonance frequencies.

2.3 Fiber Raman Amplifier

A very important parameter related to Raman amplifier is Raman gain coefficient g_R , which was derived in previous sections. In general, g_r depends on the composition of fiber core and varies significantly with the use of different dopant. The most significant feature of Raman gain coefficient is that g_r extends over a large frequency range (up to 40 THz bandwidth). Figure 2.2 below shows the Raman gain coefficient g_r as a function of Raman shift at a pump wavelength $\lambda_p = 532$ nm [5].

Fig. 2.2 Raman gain curve of a silica-core single-mode fiber. This curve is normalized to 1.0 at 440 cm^{-1} . The peak gain at 440 cm^{-1} is for a pump wavelength 532 nm is $1.86 \times 10^{-11}\text{ cm/W}$.

Raman frequency shift corresponds to wavelength shift as governed by:

$$\Delta\lambda = \frac{-\lambda_p^2}{c} \Delta f \quad (2.3.1)$$

where $c, \Delta\lambda, \lambda_p, \Delta f$ denote the speed of light ($\approx 3 \times 10^8\text{ m/s}$), wavelength shift, centre wavelength (pump wavelength) and frequency shift, respectively. The frequency shift, as

shown in the Fig. 2.2 can also be represented in a normalized value with respect to the

centre wavelength as:

$$\Delta f = \frac{\Delta \lambda}{\lambda_p^2} \quad (2.3.2)$$

Therefore, Raman frequency shift of the Raman peak gain at 440 cm^{-1} in Fig 2.2 corresponds to 13.2 THz frequency shift from the pump frequency. This also corresponds to 12.45 nm wavelength shift from the pump wavelength, thus peak Raman gain occurs at 544.45 nm.

Based on interaction between pump and signal propagation, fiber Raman amplifier can be classified into Forward, Backward and Bi-directional amplification. Basically, the amplification process is governed by the following coupled equations [17,18]:

$$\begin{aligned} \frac{\partial P_p}{\partial z} + \frac{1}{V_p} \frac{\partial P_p}{\partial t} &= \pm \alpha_p P_p(z, t) \pm \frac{\nu_p}{\nu_s} \frac{g_r}{A_{eff} K} P_s(z, t) P_p(z, t) \\ \frac{\partial P_s}{\partial z} + \frac{1}{V_s} \frac{\partial P_s}{\partial t} &= -\alpha_s P_s(z, t) + \frac{g_r}{A_{eff} K} P_p(z, t) P_s(z, t) \end{aligned} \quad (2.3.3)$$

where g_r , and A_{eff} denote the Raman gain coefficient and effective cross-sectional area, respectively; $P_p(z, t)$ and $P_s(z, t)$ denote the pump and Stokes signal; α_p and α_s denote fiber attenuation at pump and Stokes wavelengths, ν_p and ν_s denote the pump and Stokes signal wavelengths, respectively. The factor K represents the polarization dependent factor of Raman gain coefficient. This factor is an average taken over all states of polarization of the pump. Under this assumption, an explicit treatment of the evolution of the states of polarization of the pump and signals is not required. However, under certain circumstances, this polarization dependent factor may bring a crucial effect to the performance of Raman amplified signal transmission, especially at very high speed data

transmission, thus can not be ignored totally. The $\pm$ sign in the first part of (2.3.3) determines the direction of pump propagation with respect to the Stokes signal propagation. Obviously, the application of multi-wavelength pump with different pump propagation, i.e. bi-directional Raman amplifier, will extend (2.3.3) into more complex coupled equations. This motivates many researchers to investigate and propose an optimized numerical solution for various Raman amplification scheme [19-21].

In the linear amplification region or small signal region, where $P_s \ll \alpha_p / g_R$, pump power is not depleted, therefore, the coupled mode equation can simply be solved as:

$$P_s(z, t) = P_s(0, t) \exp \left[\frac{g_r z}{A_{eff} K} \int_{z'=0}^z P_p(z', t) dz' \right] \exp(-\alpha_s z) \quad (2.3.4)$$

where $P_p(z', t) = P_p(0, t) \exp(-\alpha_p z')$ for forward pumped Raman amplifier,

or $P_p(z', t) = P_p(L, t) \exp\{-\alpha_p (L - z')\}$ for backward pumped Raman amplifier

From (2.3.4), Raman net gain is defined as:

$$\begin{aligned} G_{net} &= \frac{P_s(L)}{P_s(0)} = \exp \left[\frac{g_r z}{A_{eff} K} \int_{z'=0}^L P_p(z', t) dz' \right] \exp(-\alpha_s L) \\ &= \exp \left[\frac{g_r z}{A_{eff} K} P_p(0) L_{eff} \right] \exp(-\alpha_s L) \end{aligned} \quad (2.3.5)$$

Effective length L_{eff} represents the real amplification length in lossless fiber. It can be

measured by:

$$L_{eff} = \int_{z=0}^L \frac{P_p(z, t)}{P_p(0, t)} dz = \frac{1 - \exp[-\alpha_p L]}{\alpha_p} \quad (2.3.6)$$

Raman gain is often quantified in a form of On-Off gain, which is defined as:

$$G_{on-off} = \frac{P_s(L)|^{pump-on}}{P_s(L)|^{pump-off}} \quad (2.3.7)$$

From (2.3.5), we can see that both fiber loss and effective cross-sectional area affect the Raman gain, as also showed in Fig. 2.3.

Fig. 2.3 Raman On-Off gain of a silica-core fiber as function of length and fiber core diameter.

Based on amplification medium, Raman amplifier is generally classified into two types: *distributed* and *discrete* Raman amplifier. Distributed Raman amplifier uses the transmission medium as the amplification medium, whereas discrete Raman amplifier is described as a black-box amplifier, which is typically used as the pre-and post-amplifier in the transmission. We focus our analysis more on the application of distributed Raman amplifier in DWDM communication.

2.3.1. Broad-Band Raman Amplifier

The asymmetry shape of Raman gain spectrum causes non-uniform gain experienced by signal wavelengths within the communication band. This creates problems in receiving signals at the detector, due to the difference in optical signal to noise ratio. Therefore a method to flat Raman gain is required. Basically there are two methods of application for this purpose, i.e. by using optical filter or using multi-wavelength Raman pumps. The spectral flexibility of Raman amplifier allows the gain spectrum to be shaped by combining multiple pump wavelengths to make a polychromatic pump spectrum. Many studies have been done for optimization approaches that give the flattest gain with the fewest number of pumps. The use of both methods to flatten Raman gain will be presented in more details in next chapters.

As high intensity pump beams co-propagate simultaneously, nonlinear effect occurs between pumps, such as power transfer due to stimulated Raman scattering and noises generated by Four-Wave Mixing. These effects can degrade the performance of Raman amplifier. Some studies have been done to investigate the impact of pump-to-pump interaction and how to reduce or eliminate this effect. Further detail about this will be discussed in chapter four.

2.3.2. Noise properties of Raman Amplifier

Noise properties of Raman amplifier are another important property for the application of Raman amplifier in WDM communication. It may degrade the bit-error rate performance of digital transmission system or signal to noise ratio in analog communication system. One parameter to assess the noise performance of discrete amplifier is the amplifier noise figure, which represents the degradation of signal to noise ratio from the input to the

output of the amplifier:

$$F = \frac{(SNR_e)_{in}}{(SNR_e)_{out}} \quad (2.3.8)$$

Signal to noise ratio is the ratio of the square average of the photocurrent induced by the signal at the receiver and the variance of the total current [22]:

$$SNR_e = \frac{I_{sig}^2}{\sigma^2} \quad (2.3.9)$$

In distributed Raman amplifier, the amplifier noise figure is defined as effective noise figure, which includes the exponential decay due to fiber loss α_s as [23]:

$$F_{eff} = F_R \exp(-\alpha_s L) \quad (2.3.10)$$

where: $F_R = \frac{2P_{ASE}}{G_R 2h\nu B_0} + \frac{1}{G_R}$, and G_R is the net Raman gain, which is defined in (2.3.6).

The term effective noise figure is basically to allow us to compare the change in the signal to noise ratio between the distributed Raman amplifier and discrete Raman amplifier. Typical use of noise figure in amplifier usually represents the improvement or degradation of signal to noise ratio due to the gain and additional noise from the amplifier. In distributed Raman amplifier, due to its long amplification length, there are two types of gain: On-Off gain and Net gain, whereas in typical amplifier, such as discrete EDFA or discrete Raman amplification, no significant difference between On-

Off and Net gains, due to low fiber loss. In order to allow us directly compare the noise figures between these two types of amplifier, we use On-Off gain as the reference. This can be done by canceling the effect of fiber loss to the output signal by multiplying the obtained noise figure F_R with the fiber loss term, as shown in (2.3.10).

From (2.3.10), when effective noise figure $F_{eff} = 0$ dB, it refers to the condition that the total additional noise generated by the amplifier effectively does not change the signal to noise ratio, because the amount of On-Off amplification to the signal is in similar level as the noise generation, such that the effective ratio does not differ. However, the fiber loss will still further degrade the signal to noise ratio. This will then create significant difference between distributed and discrete Raman amplification. In discrete Raman amplification, the ultimate noise figure F_R does not differ much from the F_{eff} , due to low fiber loss. However, in distributed Raman amplification, the ultimate noise figure F_R will differ significantly from the F_{eff} . When fiber loss $\alpha_s = 0.22$ dB/km and transmission length $L = 100$ km, the zero F_{eff} in distributed amplification corresponds to 22 dB real noise figure, which means, there is degradation to the signal to noise ratio of about 22 dB due to the fiber loss itself. Based on this fact, as we focus on analyzing the effect of noise generation to the degradation of signal to noise ratio, we use F_{eff} (as a normalized factor, with respect to fiber loss) in order to directly see the effect of total noise generation. Ultimately, for every value of F_{eff} presented in this work, fiber loss effect should be added in order to know the real noise figure of the amplifier.

Common sources of noise in Raman amplified system are amplified spontaneous emission (ASE) and some nonlinear impairment as due to four wave mixing (FWM), self phase modulation (SPM) and cross phase modulation (XPM). Additional noise could also come from Rayleigh scattering, double Rayleigh backscattering and relative intensity noise (RIN) transfer from pump to signal.

2.3.2.1 Amplified Spontaneous Emission Noise

Raman amplified spontaneous emission (ASE) noise can be generated in two directions - backward and forward ASE. The direction classification aligns with the signal propagation direction. The equations governing the propagation of ASE noise in both directions are [24]:

$$\frac{dP_A^+}{dz} = \pm [g_R P_p(z) - \alpha_A] P_A^+ \pm 2h\nu B_0 g_R P_p(z) \quad (2.3.11)$$

$$\frac{dP_A^-}{dz} = \mp [g_R P_p(z) - \alpha_A] P_A^- \mp 2h\nu B_0 g_R P_p(z) \quad (2.3.12)$$

where P_A^+ and P_A^- are the Forward and Backward ASE noise powers respectively, g_R is the Raman gain coefficient, α_A is the ASE loss coefficient, and h, ν, B_0 are the Planck constant, optical frequency and noise bandwidth respectively. We use the typical constant value of fiber loss $\alpha_A = 0.22$ dB/km. The positive-negative sign refers to two possible pump propagations, i.e. positive sign of the right hand term in (2.3.11) refers to counter-propagating Raman pump and vice versa. Both co- and counter-propagating pump can be included in the case of bi-directional Raman pump scheme. As the noise generation is directly induced by the pump beams, any pump power fluctuation may cause additional noise transfer, i.e. relative intensity noise (RIN) transfer, especially

when the phase matching condition is fulfilled or in the case of pump modulation. Pump-RIN can be defined as follow [24]:

$$RIN = 10 \log_{10} \left(\frac{2 \langle \Delta P(t)^2 \rangle}{\langle P(t) \rangle^2 B_0} \right) \text{ (dB/Hz)} \quad (2.3.13)$$

We plot Raman ASE both in the co- and counter-propagating directions with respect to the Raman pump in Fig. 2.4. Raman On-Off gain is set to be 16 dB with Raman pump and signal wavelength are $\lambda_p = 1450$ nm and $\lambda_s = 1550$ nm respectively, fiber dispersion slope $S_0 = 0.078$ ps/nm²km at zero dispersion wavelength $\lambda_0 = 1400$ nm. In backward Raman pump scheme, counter-propagating ASE travels together with the signal light, thus directly affecting the optical signal to noise ratio. This figure shows that in the early state, co-propagating ASE evolution experiences high noise amplification as the pump power is not yet fully depleted by fiber attenuation. Therefore Rayleigh backscattered co-propagating ASE and double Rayleigh backscattered counter-propagating ASE can significantly add up to the total noise to the signal.

Fig. 2.4 Raman Amplified Spontaneous Emission (ASE) noise with respect to fiber length.

In order to accommodate the noise contribution from the co-propagating ASE, (2.3.11) and (2.3.12) can be modified into (2.3.13) and (2.3.14) in the case of backward Raman pump scheme.

$$\frac{dP_A^+}{dz} = [g_R P_p(z) - \alpha_A] P_A^+ + 2h\nu B_0 g_R P_p(z) + \kappa_{Ray} P_A^- \quad (2.3.13)$$

$$\frac{dP_A^-}{dz} = -[g_R P_p(z) - \alpha_A] P_A^- - 2h\nu B_0 g_R P_p(z) - \kappa_{Ray} P_A^+ \quad (2.3.14)$$

where κ_{Ray} ($\approx 10^{-4} / km$) is the Rayleigh backscattering coefficient.

It is defined as $\kappa_{Ray} = \alpha_{Ray} S$, where α_{Ray} is the fiber loss due to Rayleigh scattering and S is the recapture fraction in backward direction. Consider only the single Rayleigh backscattered co-propagating ASE contributing to the counter-propagating ASE, i.e. third term in (2.3.13) is negligible, the counter-propagating ASE evolution is plotted as shown in Fig. 2.5 below.

Fig. 2.5 Counter-propagating ASE including the contribution from co-propagating ASE with Rayleigh backscattering coefficient α_{Ray} equal to 0 (solid lines), $10^{-4} / km$ (dotted lines) and $5 \times 10^{-4} / km$ (dashed lines).

The contribution from Rayleigh backscattering will be more significant at high Raman On-Off gain. From Fig. 2.5, when net Raman gain is as low as -6 dB, the additional noise induced by Rayleigh backscattering is insignificant, however when net gain is increased up to 8 dB, additional noise contributed from Rayleigh backscattering will be up to 7 dB, as seen within 20-40 km distance. However as the noise is also attenuated, the final additional noise incurred due to Rayleigh backscattering process can be as high as 3 dB.

Significant enhancement to the co-propagating ASE noise occurs when there is group velocity matching between ASE and pump beam. Group velocity matching induces Raman gain coefficient enhancement as described in appendix A:

$$g_{RR} = g_R \left(1 + \frac{1}{2} \left[\frac{g_R P_p}{\left| \frac{1}{V_p} - \frac{1}{V_s} \right| \Delta \omega_p} \right]^2 \right) \quad (2.3.15)$$

where P_p and $\Delta\omega_p$ are the pump power and pump laser bandwidth respectively. Based on the linear dispersion profile, we could obtain the group velocity of pump and ASE. The location of zero dispersion wavelength and dispersion slope directly affects the gain enhancement due to group velocity matching. Fig. 2.6 shows the co-propagating ASE under pump-ASE group velocity matching condition (dashed lines) and no group velocity matching (line with circles) for On-Off Raman gain levels 20 dB (A) and 25 dB (B). Pump RIN equals to -110 dB/Hz with band-limited noise bandwidth equals to 25 GHz. The co-propagating ASE ultimately enhances the counter-propagating ASE, which then affects the optical signal to noise ratio of backward Raman amplifier system. A 20 dB Raman gain induces peak ASE enhancement at about 7 dB, whereas 25 dB Raman gain induces about 17 dB ASE enhancement. This ASE enhancement will be transferred to the counter-propagating ASE through the Rayleigh backscattering process.

Fig. 2.6 Co-propagating ASE with the presence of group velocity matching. Dashed lines and line with circles denote the co-propagating ASE with and without group velocity matching, respectively. On-Off Raman gain equal to 20 dB (A) and 25 dB (B).

Performance degradation due to noise enhancement is shown in Fig. 2.7 below. From the figure, we see that when pump noise is as high as -110 dB/Hz, a 25 dB On-Off gain has resulted in a positive effective noise figure, i.e. amplifier noise figure started to degrade. This means, high pump noise increases the noise sensitivity to the gain level. The effective noise figure profile we obtain here almost resembles the profile produced by [24], which is beyond certain gain level, the effective noise figure starts to degrade, and the degradation rate depends on the level of pump noise. The major difference between Fig. 2.7 and the one shown in [24] is that the results shown in [24] included the consideration of the velocity matching condition, which would significantly further degrade the effective noise figure at high gain levels.

Fig. 2.7 Effective Noise Figure vs. Raman On-Off gain.

2.3.2.2 Multiple-Path Interference Noise

Multiple path interference refers to the case when a signal light reaches the optical receiver by more than one optical path. This can be due to discrete reflection at faulty connectors or splices and/or double Rayleigh backscattering (DRS). Rayleigh backscattering occurs when light is elastically reflected by submicron inhomogeneities in fiber refractive index that were frozen into glass when it was solidified. DRS set the fundamental limit to the Raman gain before MPI dominates. DRS induced MPI in Raman amplified system is governed by these following equations [25]:

$$\frac{dP_s}{dz} = [g_R P_p(z) - \alpha_s] P_s \quad (2.3.16)$$

$$-\frac{dP_{SRB}}{dz} = [g_R P_p(z) - \alpha_s] P_{SRB} + \kappa_{Ray} P_s \quad (2.3.17)$$

$$\frac{dP_{DRS}}{dz} = [g_R P_p(z) - \alpha_s] P_{DRS} + \kappa_{Ray} P_{SRB} \quad (2.3.18)$$

where $P_p(z)$ and $P_s(z)$ denote the pump and signal power evolution, g_R denotes the Raman gain coefficient, α_s is the fiber loss coefficient, κ_{Ray} is the Rayleigh backscattering coefficient. The term P_{SRB} and P_{DRS} describe the power evolution of the single Rayleigh backscattered noise and double Rayleigh backscattered noise, respectively. Fig. 2.8 shows the degradation of $OSNR_{MPI}$ as the Raman On-Off gain increases. Similarly, co-propagating gain enhancement due to group velocity matching and pump RIN can enhance the MPI noise quite severely, especially at high On-Off gain. The figure shows that under noisy pump and group velocity matching conditions, the signal to noise ratio experiences degradation as high as 12-13 dB when On-Off Raman gain equals to 25 dB. The group velocity matching conditions contributes dominantly to the enhancement in the MPI noise, especially when Raman gain goes beyond 15 dB. The effect of pump noise (RIN levels) to the MPI enhancement gets more significant when Raman gain is set higher than 25 dB.

Fig. 2.8 Optical Signal to Noise Ratio (OSNR) due to MPI vs. Raman gain.

2.3.2.3 Crosstalk in Fiber Raman Amplifier

As more than one wavelength signals traveling together in WDM system, coupling between modulated signals through nonlinear process induces crosstalk. One of the nonlinear effects that induce crosstalk is the stimulated Raman scattering itself. Generally, crosstalk due to SRS can be classified into two major types: Raman crosstalk with the presence of pump beam and without pump beam. The presence of pump beam indicates the increase of the signal intensities and thus possibly induces higher crosstalk level.

Inter-channel Raman crosstalk is generated between signal wavelengths through stimulated Raman scattering. The channels at longer wavelengths experience gain at the expense of the channels in shorter wavelengths. This tends to tilt the output power spectrum, especially at dense WDM system. Crosstalk will only be generated when two signal wavelengths overlap in space and time. Therefore, this crosstalk level will be much dependent on the bit pattern and walk-off effect introduced by the group velocity difference. Statistically, this crosstalk can be quantified quite deterministically due to the averaging effect in a large number of bits transmitted. At the presence of Raman pump, signal light will not be attenuated exponentially as fast as without Raman pump, thus more crosstalk may be generated.

The presence of Raman pump may create additional crosstalk to the signal through transfer of pump noise to the signal through the SRS or pump mediated signal-signal crosstalk. Pump Relative Intensity Noise (RIN) can be transferred to signals due to the extremely fast response time of Raman process. The application of counter-propagating

pump uses the transit time through the effective length to average the fluctuations of the pump power, thus dramatically reducing the amount of crosstalk. This crosstalk can be reduced by having high pump modulation frequency. Corner frequency is defined as minimum modulation frequency to reduce the RIN transfer by 3 dB [26]. Corner frequencies for counter- and co-propagating Raman pump are defined as:

$$f_{C-counter} = \frac{\alpha V_s}{4\pi} \quad (2.3.19)$$

$$f_{C-counter} = \frac{\alpha}{2\pi S_0(\lambda_s - \lambda_p) \left| \frac{\lambda_s + \lambda_p}{2} - \lambda_0 \right|} \quad (2.3.20)$$

Pump-mediated inter-channel crosstalk amount is significant at co-propagating Raman pump scheme where the interaction time between pump and each signal bits is longer before it walks off. When walk off effect is not considered, which refers to the worst condition of pump-mediated Raman crosstalk, if pump power increases, the signal power level is highly amplified, thus depleting the pump significantly, whilst the pump-mediated crosstalk increases.

The equations governing the two WDM channels and one pump wavelength are written

as:
$$\frac{dP_{s1}(z)}{dz} = [g_{R1}P_p(z) - \alpha_s]P_{s1} \quad (2.3.21)$$

$$\frac{dP_{s2}}{dz} = [g_{R2}P_p(z) - \alpha_s]P_{s2} \quad (2.3.22)$$

$$\frac{dP_p}{dz} = \left[-\frac{\nu_p}{\nu_{s1}} g_{R1}P_{s1}(z) - \frac{\nu_p}{\nu_{s2}} g_{R2}P_{s2}(z) - \alpha_p \right] P_p \quad (2.3.23)$$

where: $P_{s1}(z)$, $P_{s2}(z)$ and $P_p(z)$ are the signal powers of two channels and pump power;

g_{R1} and g_{R2} are the Raman gain coefficient between pump and two signals. Assuming the

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fiber loss α is constant for all wavelengths, and signals and pump power at $z=0$ are defined as: P_{s10} , P_{s20} and P_{p0} , the equation (2.3.21) – (2.3.23) can be solved as (details in

Appendix B):

$$P_{s1}(z) = P_{s10}(t - z/V_{s1}) \frac{1 + \frac{\nu_p}{\nu_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} + \frac{\nu_p}{\nu_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}}}{1 + \frac{\nu_p}{\nu_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R1}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right) + \frac{\nu_p}{\nu_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R2}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right)} \times \exp\left(\frac{g_{R1}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right) \exp(-\alpha z) \quad (2.3.24)$$

$$P_{s2}(z) = P_{s20}(t - z/V_{s2}) \frac{1 + \frac{\nu_p}{\nu_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} + \frac{\nu_p}{\nu_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}}}{1 + \frac{\nu_p}{\nu_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R1}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right) + \frac{\nu_p}{\nu_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R2}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right)} \times \exp\left(\frac{g_{R2}P_{p0}}{\alpha}(1 - e^{-\alpha z})\right) \exp(-\alpha z) \quad (2.3.25)$$

Degradation due to crosstalk is characterized by Signal-Interference Ratio (SIR), which is defined as:

$$SIR(dB) = 10 \log_{10} \left(\frac{P_s(L)}{|I|} \right) \quad (2.3.26)$$

Interference power in channel 1 from channel 2 is simply defined as:

$$I_1 = P_{s1}(L) \Big|_{P_{s20}=0} - P_{s1}(L) \Big|_{P_{s20}>0} \quad (2.3.27)$$

2.3.3. Polarization Dependent Raman Gain

Raman gain coefficient is dependent on the polarization of the pump and Stokes field. In typical long fiber, which does not maintain linear polarization, Raman gain will assume average value, which is taken as half of the linearly polarized gain, as represented by K factor above. Maximum Raman gain actually occurs not only for parallel linear polarizations but whenever pump and Stokes polarizations are the same, for example, the same elliptical polarization [27]. In a depolarizing fiber, both pump and Stokes wave see the same strains and experience the same depolarization for certain distance, but eventually the relative polarization will become random due to the wavelength difference. The distance for which the gain decreases is the distance where the state of

polarization of pump and Stokes wave get out of step. Certain characteristic length is observed beyond which the gain varies between maximum and zero with an average of one-half. Using similar approach by Hellwarth when dealing with wave-front conjugation by stimulated Raman or Brillouin scattering in waveguide, formal derivation of gain in a single-mode birefringent fiber was obtained [28].

Consider pump and Stokes fields co-propagating in birefringent fiber as follows:

$$\tilde{E}_p = [\hat{x}A_{px} \exp ik_{px}z + \hat{y}A_{py} \exp ik_{py}z] \Psi \left(\frac{8\pi}{nc} \right)^{1/2} \exp(-i\omega_p t) \quad (2.3.28)$$

$$\tilde{E}_s = \exp\left(\frac{\gamma z}{2}\right) [\hat{x}A_{sx} \exp ik_{sx}z + \hat{y}A_{sy} \exp ik_{sy}z] \Psi \left(\frac{8\pi}{nc} \right)^{1/2} \exp(-i\omega_s t) \quad (2.3.29)$$

where A_x and A_y denote the complex amplitude along two principal axes of birefringence with subscripts p and s referring to pump and Stokes field respectively, whilst k_x, k_y are the corresponding propagation constants.

The scalar mode field Ψ is assumed to be the same for both pump and Stokes field as well as both polarizations and is normalized so that $\int \Psi^2 r dr d\phi = 1$. From Maxwell equation, it is derived that:

$$ik\gamma\tilde{E}_s = -\frac{4\pi\omega_s^2}{c^2}\tilde{P}_s \quad (2.3.30)$$

where k is the average propagation constant and $\tilde{P}_s$ is the nonlinear polarization in the approximation where the polarized cross section dominates, which is defined as:

$$\tilde{P}_s = -iG\tilde{E}_p(\tilde{E}_p^* \cdot \tilde{E}_s) \quad (2.3.31)$$

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From (2.3.28) - (2.3.31), we obtain a coupled-wave equation as follow:

$$\gamma A_{Sx} = \beta |A_{px}|^2 A_{Sx} + \beta A_{px} A_{py}^* A_{Sy} K \quad (2.3.32)$$

$$\gamma A_{Sy} = \beta A_{py} A_{px}^* A_{Sx} K + \beta |A_{py}|^2 A_{Sy} \quad (2.3.33)$$

The coupling coefficient β contains an inverse integral, which is the inverse of an

effective cross-area:

$$\beta = \frac{32\pi^2 G \omega_s^2}{nkc^3} \int_0^\infty \int_0^{2\pi} \Psi^2 r dr d\phi$$

The factor K is a function of fiber length, birefringence and pump-Stokes frequency

separation, defined as:

$$K = \int_0^L \frac{\exp(i\Delta kz)}{L} dz = \exp\left(i \frac{\Delta k L}{2}\right) \frac{\sin\left(\frac{\Delta k L}{2}\right)}{\frac{\Delta k L}{2}} \quad (2.3.34)$$

where:

$$\Delta k = (k_{px} - k_{py}) - (k_{Sx} - k_{Sy}) = 2\pi \partial n \partial \nu \quad (2.3.35)$$

There are two regimes depending on whether $\Delta k L / 2$ is much greater or less than π , which

defines the polarization length:

$$l_p \approx \frac{1}{\partial n \partial \nu} \quad (2.3.36)$$

If the fiber is excited in one principle axis, i.e. $|A_x|^2 = P$ and $|A_y|^2 = 0$, the gain in the $\hat{x}$ direction is $\gamma = \beta P$ and in the $\hat{y}$ direction is zero regardless the length L greater or less than l_p . However, the gain would be different if both axes are excited, i.e. linearly polarized field $A_x = A_y^*$ and $|A_x|^2 = |A_y|^2 = P/2$. When $L \ll l_p$, the solutions of the coupled wave equation are $\gamma = \beta P$ and $\gamma = 0$, however when $L \gg l_p$, single and independent gain $\gamma = \beta P / 2$ is obtained due to uncoupled condition. Thus, for length $L \gg l_p$, there is a difference of a factor of 2 in gain for the two-excitation condition. This factor is thus commonly adopted to represent the polarization effect to the Raman gain coefficient.

2.4 Summary

Raman scattering involves the molecular transition energy level and produces Stokes and anti-Stokes components as shown in Section 2.1. Stimulated Raman scattering refers to the generation of Stokes components due to the presence of stimulating photons at longer wavelength. This scattering process can be quantified based on both quantum and classical theory, as shown in Section 2.2. One of the important parameters defined in this process is the Raman gain coefficient at the Raman resonance frequency, where coherence is automatically generated due to phase matching condition. Subsequently, various properties of fiber Raman amplifier are discussed in detail in Section 2.3, such as broad band gain property, noise properties and polarization dependence of Raman amplifier. The characterization of the fiber Raman amplifier for the continuous wave Raman pump is done by considering some factors, such as fiber properties (length, dispersion, attenuation, cross-sectional area, Raman gain coefficient, Rayleigh backscattering coefficient and polarization dependent factor) and Raman pump properties (line-width, relative-intensity noise). Optical signal to noise ratio and effective noise figure become important parameters that determine the performance of fiber Raman amplifier. Having understood the fundamental properties of Raman amplification, we will further present some further development on this area and some challenges to be resolved. In the next chapters, we will present our works on Raman amplification, with the focus on how to improve the amplification gain and noise performance.

CHAPTER 3

Raman Gain Flattening by Using High Birefringence Fiber Loop Mirror

3.1 Introduction

The practical implementation of WDM techniques within transport networks requires i) to transfer the data streams at suitable or selected wavelengths, ii) to make the channel multiplex propagate without loss over long distance or through a large number of nodes, iii) to reroute channels according to different network configurations, iv) to add or drop channels inside the network nodes, and finally v) to select the desired channel. The value of optical amplifiers is in the key number ii above, which is to further expand the capacities of the WDM key technologies, i.e. transmitter and receiver. In transmitters, they make it possible to compensate for connection losses due to modulation process, while reducing transmission loss and pre-amplifying signal help to improve the receiving end. Based on this classification, we have pre-amplifiers, in-line amplifiers and post-amplifiers. Different type of application of optical amplifier emphasizes different key performances [29]. For instance, for post-amplifier application, the most significant parameter is the saturation output power. If the transmission rate exceeds several Gb/s, the error rate characteristics will deteriorate due to the patterning effects at gain saturation, so higher saturation level is essential. However, pre-amplifiers emphasize more on high level of signal to noise ratio and polarization independent performance, which will help much on the optical detection process. Meanwhile, in-line amplifiers is expected to produce performance that average those two earlier types of amplification,

and pretty much depend on the intended receiver number and transmission speed. Thus, minimum insertion loss, high saturation output, low noise contribution and polarization independent performance are necessary. The summary of the requirement to different type of amplifiers above is presented in Table 2.

Table 2 Key performance requirement of different type of Optical Amplifiers

Function	Post-amplifier	In-line amplifier	Pre-amplifier	Booster amplifier
High Gain	√	○	○	○
High Saturation Output	○	√ (○)	×	○
Low Noise Characteristics	×	√ (○)	○	√
Polarization Independence	×	○	○	√
Low Insertion Loss	×	√	○	×
Narrow-band Optical Filter	×	×	○	×
Optical Isolator	○	○	○	○

Legend: ○ : Essential, √ : Necessary, × : Unnecessary

Generally, the use of optical amplifier in DWDM communication requires its gain spectrum to be equalized and also covering wide bandwidth. This motivates intensive research works to investigate all possible methods to flatten the gain within the required amplification bandwidth. There are some principle methods that can be used to achieve this purpose, for example by i) modifying the inherent gain coefficient of the amplification medium, ii) designing certain pumping schemes and iii) employing optical filter. In the next section, we will discuss in details all these possible methods together with some research works done on gain flattening process of optical amplification in recent years, especially in Fiber Raman amplification. Subsequently, we proposed the use of optical filter based on the use of high-birefringence optical loop mirror to flatten the Raman amplifier. Detail analysis on both theoretical and experimental results will be presented in this chapter.

3.2 Latest Development on Gain Flattening of Optical Fiber Amplifiers

3.2.1 Rare-Earth Doped Fiber Amplifier

The basic principle for this amplification is using the stimulated emission of optically excited rare-earth ions in the fiber core. This requires high quantum efficiency, efficient pumping, and low loss. Two types of rare-earth ions used are Praseodymium and Erbium ions for 1.3 μm and 1.5 μm amplification, respectively.

Praseodymium doped fiber amplifier (PDFA) is employed in optical transmission system that use the standard 1.3 μm single mode fiber, which is most commonly installed in terrestrial systems, for both digital and analog optical transmission [30-36]. An experimental work on low-noise and high power PDFA by using cascade configuration was able to produce 40.6 dB maximum gain at 1.3 μm and 3 dB bandwidth of 17 nm under small input signal region (≈ -30 dBm) [37]. Under saturation condition, the amplification bandwidth increases up to 34 nm for an input power of -3 dBm. The amplifier noise figure (NF) is measured to be about 4.3 dB. As compared with the Erbium-Doped Fiber Amplifier (EDFA), PDFA has lower quantum efficiency, which thus requires higher pump power.

Erbium Doped Fiber Amplifier (EDFA) has intensively been demonstrated as power amplifier, to increase the transmitter output power, as optical pre-amplifiers, to improve receiver sensitivity, and as in-line amplifiers to replace the traditional regenerative repeaters [38]. In addition to that, the application of distributed Erbium-doped fiber amplifier (d-EDFA) on data transmission with bit rate-distance product of 55 Gb/s.Mm was investigated [39]. As a typical amplifier, some key issues related to EDFA are gain

bandwidth, gain and noise levels, and amplifier reliability. Several methods have been proposed to achieve broadband gain characteristics, such as the use of alumina-co-doping technique [40], fluoride host glasses [41-43], and optical filter [44-47].

3.2.2 Fiber Raman Amplifier

A number of research have been done on utilizing the fiber nonlinear effect for fiber measurement and several useful device functions such as optical frequency generation, wavelength conversion and optical amplification. As mentioned before, stimulated Raman scattering can be employed as fiber amplification with a very much broader bandwidth as compared to conventional Semiconductor Optical Amplifier (SOA) and Erbium Doped Fiber Amplifier (EDFA). There are two classes of Raman amplifier, distributed Raman amplifiers (DRA) and discrete Raman amplifiers. DRA occurs along the transmission fiber, i.e. gain is distributed along transmission fiber. On the other hand, discrete Raman amplification occurs within discrete elements of the transmission.

Similar as EDFA, in order to amplify WDM signal within certain transmission window, it is necessary to flatten the Raman gain with certain level of gain ripple. Basically, similar approaches applied to EDFA can be applied to flatten Raman gain, such as use of optical filter [48], modification of the amplification medium, i.e. fiber properties [49]. Recently, H. Masuda *et. al* designed Tellurite-based Fiber Raman amplifier that provide wide and relatively flat amplification bandwidth [50]. Essentially, they used two designs, i.e. Tellurite-based Fiber Raman Amplifier (T-FRA) with a two stage configuration and hybrid FRA with three stage configuration, to produce about 130 nm bandwidth. However, the gain ripple needs further improvement, as there is only 17% gain ripple for the hybrid FRA and 42% for T-FRA.

As the Raman gain profile is dependent on both pump wavelength and inherent material characteristics, we could use multi-wavelength Raman pump in order to produce flat Raman gain. This allows us to have more flexibilities and also opportunities to design flat Raman gain that fulfill our desired application. There have been intensive research works on the use of multi-wavelength Raman pump, both experimentally [51-56] and theoretically [57-61] to produce different flat Raman gain bandwidth with different gain levels and gain ripples. The use of nonlinearity-broadened pumps in increasing the bandwidth of flattened Raman gain was also reported [62]. In addition, some other problems, such as nonlinear interaction, may occur due to the simultaneous propagation of multi-wavelength pumps, which requires more attention in adopting this method [63-64]. We will address this problem in more details in next chapter.

In this chapter, we would present our work on Raman gain flattening, particularly by using optical filter. The key issue in adopting this method is to use a suitable optical filter that can cover a wide bandwidth and properly equalize the Raman gain to give us good gain flatness. Three parameters need to be observed are i) how wide is the flat gain bandwidth, ii) how flat is the gain, and iii) how high is the average gain obtained. As mentioned above, the use of optical filter to flatten Raman gain previously has been introduced by F. Koch *et al* [48]. The optical filter is formed by using Long Period Grating (LPG) in combination with the use of two Raman pump. The transmission profile of LPG filter is properly compensating the spectral gain fluctuation produced by the two pump sources, such that the resulting gain is relatively flat, i.e. 1.27 dB gain ripple over the spectral range from 1505 nm– 1570 nm. If one pump source and LPG filter are used, the resulting Raman gain will have 1.26 dB gain ripple over a spectral range of 22.8 nm only. In addition to the three challenges mentioned above, the cost of

the optical component accompanying the application of Raman amplification is also important factor to be considered. The use of multi-wavelength pump may give better gain performance as compared to the use of optical filter. However this causes more cost as multi-pump sources are required. F. Koch tried to combine the use of both multi-wavelength pump sources together with the LPG-based optical filter to produce wide flattened Raman gain. This brings out another challenge if we can use any other type of optical filter which is more dynamic and able to cover wider range of amplification band. Therefore, we propose to use another type of optical filter to flatten Raman gain with single-wavelength pump only, which will result in further improvement to the flat Raman gain, as compared to previous published results.

3.3 Raman Gain Flattening Using Hi-Bi Fiber Loop Mirror

Some common types of optical filter and all-fiber wavelength division multiplexer (WDM) are designed based on coupler [65], Mach-Zehnder interferometers [66], birefringent gratings [67], and the birefringence of the fiber [68]. The use of optical filter for wavelength division multiplexer imposes some basic parameters, such as bandwidth, channel isolation and peak-passband insertion loss. Earlier days, narrow band optical filter was used in all-fiber wavelength division multiplexers (WDM), which has advantages of low cost, low loss, small size and better performance as compared to the conventional WDM based on bulk dispersion components. Two main problems when using tapering method for WDM are loss and polarization dependent filter [69]. As the polarization state in ordinary fiber is random, a polarization independent optical filter is preferred. A polarization independent all-fiber tunable WDM was proposed based on Sagnac interferometer and the non-reciprocity of the birefringence to the polarization states [70]. Sagnac interferometer refers to the ring interferometry, where a beam is split

and the two beams are made to follow a trajectory in opposite direction. Thus, in general form, Sagnac birefringence filter refers to a low-loss 3-dB coupler and the Sagnac loop contains an arbitrary chain of birefringence elements. Two basic features of this type of filter are i) the magnitude response of the transfer function is independent of the input polarization state, and ii) the output polarization state is rotationally transformed version of the input state.

The birefringence elements employed in this Sagnac loop can be derived from the conventional Solc and Lyott filters. Fundamental study of these birefringent filters brought in the Jones matrix, as a parameter representing the filtering process and ultimately produced the transfer function [71]. The use of these two filter configuration inside the Sagnac loop was investigated by X. Fang et al [72]. Subsequently, a systematic method to built high-order all-fiber birefringent Sagnac filters was reported, where the filters are composed by fiber couplers, fiber wave-plates and high-birefringence fiber [73]. Various intensity transfer function was produced, such as narrow band-pass and band-stop filter, also rectangular and triangular filter. In addition to that, an investigation on all-fiber tunable comb filter with adjustable channel spacing, based on Lyot-Sagnac interferometer was demonstrated by R. M. Sova *et al* [74].

By setting up this filter such that for certain wavelength ranges it passes the signal with less reluctance; whereas for other wavelength ranges, it induces higher loss to suppress the gain, we could obtain flattened amplified signal power at the receiver. Some advantages using this type of filter are its resistance to environmental changes, strong noise rejection ability and input polarization independent [70]. As compared to the

Mach-Zender Interferometer, the use of Sagnac interferometer for WDM is more resistant to environmental changes because the two light beams travel along a common path. Moreover, it provides greater flexibility in handling different operating conditions and easy to implement. In this chapter, we are going to employ the optical filter characteristic of Sagnac interferometer with high birefringence fiber inside the fiber loop mirror to flatten our Raman gain.

3.3.1 High Birefringence Fiber Loop Mirror Using Sagnac Interferometer

Ideally, in a perfectly isotropic material, two orthogonally polarized modes are degenerated (maintaining perfect cylindrical symmetry along its entire length), thus maintaining identical effective refractive index, i.e. $n_x = n_y$. However, due to unintentional variations in the core shape and anisotropic stresses along the fiber length, fibers exhibit non-identical refractive index $n_x \neq n_y$ and thus *modal birefringence*: $B_m = |n_x - n_y|$. Some methods have been proposed to measure the birefringence of the optical fiber.

Polarization maintaining fiber contains built-in birefringence much larger than random birefringence due to stress and core-shape variations. It contains two principle axes, so-called fast and slow axes based on the speed at which light polarized along those traveling inside the fiber. When low power continuous wave light is launched with its polarization direction oriented at an angle with respect to one axis, the polarization state

changes periodically along the fiber from linear, elliptic and circular over a distance

known as beat length:
$$L_B = \lambda / B_m \quad (3.1)$$

Fiber birefringence is of great importance in many aspects of optical communication and device technology, e.g. signal degradation due to the polarization mode dispersion in high-speed optical communication. Many optical systems depend on the polarization-dependent electro-optic devices, the throughput of which depends on the state of polarization of the input field. The fiber birefringence beat length is the key parameter in determining the operation of interferometer.

Polarization independent optical filter using high-birefringence has attracted many applications, such as narrow band wavelength division multiplexer. In this section, we are employing this method as optical filter for gain flattening. Unlike narrow band WDM, optical filter for gain flattening requires sufficiently wide bandwidth to compensate the non-uniformity of wide bandwidth Raman gain. As described above, this type of filter is ideally polarization independent. Consider a simple basic structure of fiber Sagnac interferometer, as shown in Fig. 3.1 below. In this figure, the solid lines and dashed lines represent the incoming and outgoing lights into and from the fiber loop, respectively.

Fig. 3.1 Basic structure of Sagnac Interferometer.

The Jones matrixes of the fiber along the clockwise and anti-clockwise directions are

given as [70]:
$$J_{cw} = \begin{bmatrix} A & -B^* \\ B & A^* \end{bmatrix} \text{ and } J_{ccw} = \begin{bmatrix} A & -B \\ B^* & A^* \end{bmatrix} \quad (3.2)$$

with: $|J_i| = 1$ for lossless reciprocal system. The coupler we use in this structure is 50:50

coupler, whose Jones matrix is given as:
$$J_{Coup} = \begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2}i \\ \frac{\sqrt{2}}{2}i & \frac{\sqrt{2}}{2} \end{bmatrix} \quad (3.3)$$

In order to observe the input-polarization independent nature of this filter, assuming the input coming into port 1 $\tilde{E}_{1in}$ is polarized light, along with either one of the two coordinate axis of the reference system. First, assume that the polarized light coming into to the input ports are given by: $\tilde{E}_{1in} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $\tilde{E}_{2in} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$. From (3.3), we obtain the lights propagating inside the fiber loop opposite to each other, one clockwise and counter-clockwise, i.e. $\tilde{E}_1'$ and $\tilde{E}_2'$. Both lights pass through the high-birefringence fiber, which is represented by Jones matrix in (3.2). After one loop, the outgoing lights $\tilde{E}_1''$ and $\tilde{E}_2''$ will go through the 50:50 coupler again to both output port 1 and 2. After derivation, we obtain

the output lights as:
$$\tilde{E}_{1out} = i \begin{bmatrix} A \\ \text{Re}(B) \end{bmatrix} \text{ and } \tilde{E}_{2out} = \begin{bmatrix} 0 \\ \text{Im}(B) \end{bmatrix} \quad (3.4)$$

On the other hand, if the lights coming into the input ports are given by: $\tilde{E}_{1in} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and

$\tilde{E}_{2in} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, then after going through similar derivation, we would obtain the output lights

as:
$$\tilde{E}_{1out} = i \begin{bmatrix} -\text{Re}(B) \\ A^* \end{bmatrix} \text{ and } \tilde{E}_{2out} = \begin{bmatrix} \text{Im}(B) \\ 0 \end{bmatrix} \quad (3.5)$$

Chapter 3

Gain Flattening in Fiber Raman Amplifier

From (3.4) and (3.5), we can see that under the two orthogonal linear polarization inputs, the transfer function of the high-birefringence fiber loop mirror is identical and mainly determined by parameter A and B, which is the property of high-birefringence. This shows that the interferometer is input polarization independent.

However, under practical circumstances, when the coupler is not perfectly 50:50, this may affect to the input polarization independent nature of the high-birefringence Sagnac interferometer. To illustrate this, assuming the coupler is $(50 + \delta):(50 - \delta)$ coupler, where δ refers to any value representing the deviation from perfect 3 dB coupler.

The Jones matrix is thus defined as:

$$J_{\text{Coup}} = \begin{bmatrix} \sqrt{\frac{5+\delta}{10}} & \sqrt{\frac{5-\delta}{10}}i \\ \sqrt{\frac{5+\delta}{10}}i & \sqrt{\frac{5-\delta}{10}} \end{bmatrix}.$$

Using similar calculation as before, when the input lights are polarized into $\tilde{E}_{1in} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

and $\tilde{E}_{2in} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, the output lights will be:

$$\tilde{E}_{1out(1)} = i \begin{bmatrix} [(0.5 + 0.1\delta) + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}]A \\ (0.5 + 0.1\delta)B + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}B^* \end{bmatrix} \quad (3.6)$$

$$\tilde{E}_{2out(1)} = \begin{bmatrix} [-(0.5 - 0.1\delta) + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}]A \\ -(0.5 - 0.1\delta)B^* + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}B \end{bmatrix} \quad (3.7)$$

Subsequently, when we change the input polarization state, the output lights will be:

$$\tilde{E}_{1out(2)} = i \begin{bmatrix} -(0.5 + 0.1\delta)B^* - \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}B \\ [(0.5 + 0.1\delta) + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}]A^* \end{bmatrix} \quad (3.8)$$

$$\tilde{E}_{2out(2)} = \begin{bmatrix} (0.5 - 0.1\delta)B - \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}B^* \\ [-(0.5 - 0.1\delta) + \sqrt{(0.5 + 0.1\delta)(0.5 - 0.1\delta)}]A^* \end{bmatrix} \quad (3.9)$$

From (3.6) till (3.9), we can see that as δ increases, the difference in output lights between two different input polarization states will also increase. In order to have a clearer picture, let's assume that the coupler is 60:40, which corresponds to $\delta = 1$. The output lights at port 2, for two different polarization states, will be:

$$\tilde{E}_{2out(1)} = \begin{vmatrix} 0.09A \\ 0.49B - 0.4B^* \end{vmatrix}$$

$$\tilde{E}_{2out(2)} = \begin{vmatrix} 0.4B - 0.49B^* \\ 0.09A^* \end{vmatrix}$$

From the matrices, unlike the case of 50:50 coupler, here we observe a slight change in the intensity of the output light, which means a slight change in the transfer function of the high-birefringence fiber loop mirror. Therefore, under practical circumstances, when we apply this method for optical filter, we could not expect perfectly input polarization independent Sagnac interferometer. Some slight changes to the interferometer transfer function may occur as different polarization state of the input lights entering into this fiber loop.

Using this concept to flatten Raman gain, let us consider a fiber loop containing high-birefringence fiber with length L and birefringence coefficient B with polarization controller as illustrated in Fig. 3.1. The polarization controller is to control the polarization states of the light entering into the interferometer. The intensity of the output light from the loop mirror depends on the phase differences among the interfering beams, which is determined by the birefringence and the lengths of Hi-Bi fibers, and the setting of polarization controller.

Fig. 3.2 High-Birefringence Fiber based Fiber Loop Mirror.

We consider the Jones matrix J to represent the birefringence fiber in the loop. By using 50:50 coupler and applying energy conservation in the system, i.e. $J_{yx} = -J_{xy}^*$, the output $\vec{E}_2$ can be expressed as:

$$\begin{pmatrix} E_{2x} \\ E_{2y} \end{pmatrix} = \frac{1}{2} (J_{xy} - J_{xy}^*) \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} E_{1x} \\ E_{1y} \end{pmatrix} \quad (3.10)$$

The Jones matrix for the loop with a high-birefringence fiber can actually be represented as a product of three matrices: U_L , U_R and D . Matrices U_L and U_R represent the contribution of the linear and circular birefringence of the coupler and orientation of the principal axes of a high-birefringence fiber at the ports 3 and 4. Generally they can be written as:

$$U = \begin{pmatrix} U_{xx} & U_{xy} \\ -U_{xy}^* & U_{xx} \end{pmatrix}$$

where U_{xx} and U_{xy} are complex numbers, and the condition $|U_{xx}|^2 + |U_{xy}|^2 = 1$ is satisfied.

Matrix D represents the linear birefringence of the Hi-Bi Fiber, which is described as:

$$D(\omega, L) = \begin{pmatrix} e^{i\Delta\beta(\omega)L/2} & 0 \\ 0 & e^{-i\Delta\beta(\omega)L/2} \end{pmatrix} \quad (3.11)$$

where: $\Delta\beta(\omega) = \frac{2\pi}{\lambda} B$ and

$$B = n_x - n_y \text{ (Birefringence coefficient)}$$

The Hi-Bi fiber based filter transfer function of the output at port {2} can be defined as:

$$T_2 = \sin^2\left(\frac{\pi BL}{\lambda}\right) \quad (3.12)$$

With spacing of the interfered fringes from the output port of the Sagnac loop filter, $\Delta\lambda$,

is given by:
$$\Delta\lambda = \frac{\lambda^2}{BL} \quad (3.13)$$

The input light from the input port {1} is split into two counter-propagating beams by the 50:50 coupler. The Hi-Bi fiber induces a phase difference between the two orthogonally polarized parts of the fundamental mode traveling in the loop. The polarization controller is set to produce a rotation of 90° in relation to the principle axes of the Hi-Bi fiber for beams coming from both directions. Thus, the slow-axis component of the co-propagating beam is changed to the fast-axis component by the polarization controller and then travels through the Hi-Bi fiber as the fast mode. On the other hand, the slow-axis component of the counter-propagating beam, after traveling through the Hi-Bi fiber as the slow mode changes to the fast-axis mode at the exit of the PC. The slow-axis components of the two counter-propagating beams interfere with each other when they are recombined at the 3 dB coupler, with a phase difference δ . The same applies to the y-axis components of the two beams. This suggests that the transmittivity of the Sagnac loop depends on the phase difference and therefore a periodic function of wavelength, λ , can be achieved. The phase change introduced by the birefringence is defined as:

$$\Delta\Phi = \frac{2\pi L_B}{\lambda} B \quad (3.14)$$

where L_B and B denote the fiber beat length and birefringence coefficient. For every $\Delta\Phi = 2\pi$, the input state of polarization is restored and the length associated with this phase change is polarization beat length. Thus, birefringence coefficient is simply defined as:

$$B = \frac{\lambda}{L_B} \quad (3.15)$$

The reflectivity spectrum of the Hi-Bi fiber loop is independent of the state of polarization of the input beam. And the maximum contrast of the interfered fringes from the output port is achieved when the PC is set to rotate the linearly polarized components of the two counter-propagating beams by 90° . If the rotation is not set to 90° , only part of the beams will interfere and the contrast of the fringes will decrease.

This filter has been employed in WDM communications to select any particular channel. Therefore, the wavelength spacing $\Delta\lambda$ of the filter as defined in (3.13) should agree with the channel spacing of the WDM communication, which is defined by ITU frequency grid. Fig. 3.2 shows an example of filter design with 0.8 nm and 0.4 nm channel spacing by employing Hi-Bi fiber with beat length = 3 mm. By using (3.15), at wavelength 1550 nm the birefringence coefficient is $B = 5.167 \times 10^{-4}$. From the figure, we can see that the extinction ratio of the filter transfer function is nearly over 30 dB. The extinction ratio is defined as the ratio of two optical power levels. In this context, the ratio of peak filter and notch of the filter transfer function defines the filter extinction ratio. This ratio provides us the information how much suppression given to the signal within the band-stop, as compared to the band-pass signal.

Fig. 3.3 Transfer Function of Hi-Bi Fiber Loop Mirror based Optical Filter.

3.3.2 Experimental Setup

In our experiment, we used various lengths of Polarization Maintaining Fiber (PMF) and polarization controllers (PC's) to form a section of High Birefringence Fiber Loop Mirror. We use ASE source operating within 1525 nm to 1575 nm wavelength range as our input signal. The pump beams with wavelength $\lambda_p = 1455$ nm and 1.2 W total pump power are injected through WDM couplers in bi-directional propagating direction. We use 70 km SMF with attenuation coefficient $\alpha = 0.22$ dB/km. At the end of fiber transmission, we measure the signal power level by using optical spectrum analyzer (OSA) with 0.2 nm resolution. The optical isolator prevents backward signals or pump beam reaching the signal source so as to prevent it from being damaged by high power beam. The detailed schematic diagram is shown in Fig. 3.4.

In our experiment, we used the Mickey-mouse type of polarization controller. This PC has a relatively low loss, low cost with a relatively small size so that it is feasible to be implemented in our experiments. The polarization controller introduces about 0.8 dB

insertion loss. We set the composition of fiber round in QWP: HWP: QWP = 3:6:3. With this composition, we expected to have a relatively high birefringence due to the induced stress of the fiber coils. The Raman amplified signal beam is split by the 50:50 coupler into two counter-propagating beams passing through polarization controllers and Hi-Bi fiber. By setting up different lengths of the High-Birefringence fiber and adjusting the polarization controller, we can obtain a flat Raman gain. We measure the intensity of output signal and take the ratio with input signal to get net Raman gain. On-Off Raman gain can thus be obtained by taking away the fiber attenuation factor.

Fig. 3.4 Experimental setup of flattened Raman gain by using Hi-Bi Fiber Loop Mirror.

Initially, we use one Hi-Bi fiber section, which comprises 1 PMF and 2 polarization controllers at each end of the PMF. The high birefringence fiber has a nominal beat length of 3 mm at the wavelength of 1550 nm. The insertion loss due to the Hi-Bi FLM was about 2.7 dB, which is mainly due to splices and polarization controllers. We obtain 3 different filter spectra from different length of PMF and observe its corresponding flat On-Off Raman gain. From (3.13), we know that the wavelength spacing $\Delta\lambda$ of the optical filter is inversely proportional to the length of the Hi-Bi fiber. Thus, if we want to cover wide amplification bandwidth, we should i) have shorter Hi-Bi fiber and ii) tune

the polarization controller so that the optical filter reflectivity spectrum will proportionally compensate the gain spectrum, such that the peak gain is pulled down to certain level and flat gain is obtained. Experimentally, we should try different length of Hi-Bi Fiber and tune the polarization controller and observe the resulted flat Raman gain. This created problem designing the fiber loop mirror, especially when splicing short Hi-Bi fiber to the fiber from the polarization controller. The longer the flat gain spectrum to be achieved, the shorter the Hi-Bi fiber is. This could set the limitation factor, whereby, experimentally it's not possible to set up the fiber loop mirror with very short Hi-Bi fiber. Perhaps getting other Hi-Bi fiber with higher birefringence would help to flatten the Raman gain with wider gain spectra, e.g. S and C band.

We used 5 cm length of Hi-Bi Fiber and plot the measured filter spectrum and its corresponding flat Raman gain in Fig. 3.5 and Fig. 3.6. The peak-to-notch depth in the filter reflection spectrum can be adjusted by more than 5 dB by adjusting the polarization controller. Initial peak Raman gain level is about 16.5 dB at 1555 nm wavelength. Due to this fact, in order to flatten the gain we should adjust the filter in such that at wavelength 1555 nm the gain can be suppressed in such we will obtain a flattened gain. Insertion loss = 7 dB.

Fig. 3.5 The Reflectivity spectrum of single section 5 cm Hi-Bi Fiber Loop Mirror Filter.

Fig. 3.6 Flattened Raman gain profile by using single section 5 cm Hi-Bi Fiber Loop Mirror Filter.

From Fig. 3.6 we see two profiles of flattened Raman gain with two different flattened gain bandwidths. The first flattened gain shows a flattened gain with fluctuation about ± 0.5 dB with 20 nm bandwidth. This does not show much improvement as compared to the original Raman gain profile, which has fluctuation of about ± 0.5 dB with 18 nm bandwidth. By further increasing the notch depth of the filter spectrum up to a certain level, we obtain more flattened gain. Clearly, an optimum level is reached when the

flattened gain bandwidth is maximum and peak gain suppression is minimum. The second curve in Fig 3.6 shows a flattened Raman gain with gain fluctuation about ± 0.5 dB and 43 nm gain bandwidth (i.e. $\cong 5$ THz with 1550 nm centre wavelength). The average Raman On-Off gain within this 43 nm bandwidth is about 11 dB, which is 5.5 dB drop from the original peak gain. This result shows a significant improvement in term of flattened gain bandwidth as compared to the original Raman gain profile.

Secondly, we used 8.5 cm length of Hi-Bi Fiber and plot the results in Fig 3.7 and 3.8. The second plotted curve in Fig 3.8 shows a flattened Raman gain bandwidth of about 32 nm with gain ripple ± 0.5 dB. The average On-Off gain within this 38nm bandwidth is about 13 dB, which is about 3.5 dB drop from the original peak gain. By setting longer Hi-Bi fiber, the birefringence effect is stronger and thus the bandwidth of filter is getting narrower. We can compare Fig 3.5 and Fig 3.7 in that when the Hi-Bi fiber is 5 cm, the reflectivity spectrum shows about 1/4 cycle of the repetition curve within 1525-1572 nm, whereas in fig 3.4, the curve has formed almost $\frac{1}{2}$ cycle of the repetition curve within 1525-1572 nm. This confirms our prediction that as the Hi-Bi fiber is getting longer, the faster is the periodicity of the filter spectrum.

From Fig. 3.8, when PMF length equals to 8.5 cm, the longer PMF will shorten the bandwidth of the flattened gain. However, the gain suppression is reduced as compared to our previous result when 5 cm PMF was used. From this, we may conclude that we could dynamically control the Raman gain to become a flattened profile by using different length of PMF to suit our needs in the optical transmission system. If we require a large bandwidth of flattened gain, we should use 5 cm of PMF, whilst longer PMF is

preferable when we need a relatively wide bandwidth of flattened gain while still maintaining high value of Raman gain.

Fig. 3.7 The Reflectivity spectrum of single section 8.5 cm Hi-Bi Fiber Loop Mirror Filter.

Fig. 3.8 Flattened Raman gain profile by using single section 8.5 cm Hi-Bi Fiber Loop Mirror. Dashed line represents the original Raman gain profile, whereas solid line represents the flattened Raman gain.

Furthermore, we use longer PMF to see the flattened Raman Gain. Fig. 3.9 and 3.10 below show the reflectivity spectrum and Raman Gain Flattening when 10 cm PMF is used. The second plotted curve in Fig 3.9 shows a flattened Raman Gain with fluctuation about ± 0.5 dB with about 29 nm bandwidth from 1539 nm to 1568 nm. The average gain obtained with this 29 nm bandwidth is about 13.5 dB, which is about 3 dB dropped from the original peak gain.

Fig. 3.9 The Reflectivity spectrum of single section 10 cm Hi-Bi Fiber Loop Mirror Filter.

Fig. 3.10 Flattened Raman gain profile by using single section 10 cm Hi-Bi Fiber Loop Mirror. Dashed line represents the original Raman gain profile, whereas solid line represents the flattened Raman gain.

From those experiment results, the optimum result of Raman gain flattening is obtained when 5 cm length of PMF is used. Nevertheless this result shows poor amplification efficiency as the gain is suppressed quite significantly from its original obtainable peak gain. This corresponds to poor gain efficiency and requires high pump power level to produce moderate level of gain. In the next section, we would present further work on this gain flattening by using two sections of Hi-Bi fiber inside the fiber loop mirror. We

want to observe the overall filter spectrum if we combine two different interferometers, i.e. different length of Hi-Bi fibers, inside the fiber loop mirror. Experimentally, this would further create more complexity in designing the fiber loop mirror. The increase in the number of polarization controllers would also induce more measurement time and perhaps affect the overall stability of the optical filter. Nevertheless, we'd like to see whether this technique could give us better Raman gain flatness.

3.3.3 Two Sections of High Birefringence Fiber Loop Mirror

In our second set of experiments, two High Birefringence Fiber sections are employed in order to possibly improve the flatness of the gain, as shown in Fig. 3.11. The lengths of two Hi-Bi fiber sections are 8.5 cm and 5 cm, respectively. The insertion loss of the filter is about 3.5 dB, which is mainly due to splices, connectors and PC.

Fig. 3.11 Experimental setup of flattened Raman gain by using two sections Hi-Bi Fiber Loop Mirror.

Fig 3.12 and Fig. 3.13 show the measured reflectivity spectrum and flattened On-Off Raman gain. We obtain flattened gain from 1530 nm up to 1568 nm (38 nm bandwidth) with gain fluctuation of ± 0.5 dB. The average flattened gain is about 12.5 dB, which is 4

dB suppressed from the peak gain. By using this method, we could get a relatively broad flattened gain (38 nm) while still maintaining low gain suppression (4 dB). As compared to the result produced by single section 5 cm Hi-Bi section, this result produces lower gain suppression but slightly less gain bandwidth. Obviously, one can always modify the component of Hi-Bi FLM, i.e. the number of Hi-Bi fiber and lengths, to achieve result based on the system requirement.

Fig. 3.12 The Reflectivity spectrum of double section 5 cm and 8.5 cm Hi-Bi Fiber Loop Mirror.

Fig. 3.13 Flattened Raman gain profile by using double section 5 cm and 8.5 cm Hi-Bi Fiber Loop Mirror. Dashed line represents the original Raman gain profile, whereas solid line represents the flattened Raman gain.

3.4 Summary

Raman gain flattening by using high-birefringence fiber loop mirror is presented in this chapter. Section 3.2 presents the Sagnac interferometer using the birefringence property of a fiber. This becomes the foundation of the optical filter design based on interferometric method. The fiber birefringence beat length is the key parameter in determining the operation of interferometer. We have demonstrated a dynamic method to flatten Raman gain by using high birefringence fiber loop mirror in section 3.3. We use both single and double section Hi-Bi fiber loop mirror with various lengths of Hi-Bi fiber. The best result we obtain when we use single section Hi-Bi FLM is 43 nm flat gain bandwidth with ± 0.5 dB gain ripple. The average flattened On-Off Raman gain is about 11.3 dB, which corresponds to 5 dB gain suppression from its original peak gain level. When we use two sections of Hi-Bi FLM, we obtain about 38 nm flat gain bandwidth with 4 dB gain suppression. This shows the trade-off between flattened gain bandwidth and amplifier efficiency to sufficiently cover the amplification of each communication channel in WDM system. Optimization is required for different transmission systems to achieve the system requirement.

In addition to the use of optical filter for gain flattening process, another possible method to flatten Raman gain is the use of multi-wavelength Raman pump. Each of the pumps contributes certain amplification amount to different carrier signal and the summation of all the amplification from different pump can achieve relatively flat Raman gain within certain optical signal bandwidth. Despite of the higher cost imposed by using multiple Raman pump, this method could give us better gain efficiency due to no-gain suppression, as introduced by the use of optical filter. However, careful attention still needs to be given to maintain gain efficiency and low additional noise generation. We will explain and analyze this method in more details in the next chapter.

CHAPTER 4

Time Division Multiplexed Raman Amplifier

4.1 Introduction

In addition to the use of optical filter for Raman gain flattening, as elaborated in previous chapter, another more commonly used method is using multi-wavelength pump. In comparison with the use of optical filter, this method gives us advantages such as: i) the amplified does not experience losses introduced by the filtering process and also ii) giving us more flexibility and opportunity to design broader bandwidth amplification with better gain flatness. However, the use of multi-wavelength pump would surely introduce more cost in the system design, especially in the design of long-haul transmission whereby multi-amplifier span is involved. We have presented a few research works on this area, both experimentally and theoretically in chapter 3 [48-62]. These works mainly focused on how to design and choose appropriate pump wavelength configuration and its corresponding pump powers, which would result in broad and flat Raman gain.

Despite of the cost-effectiveness problem, some other technical problem accompanying the use of multi-wavelength Raman pump is strong and harmful interaction among the pumps by means of the Raman effect itself. This could be in a form of power transfer among pumps, from shorter wavelength to longer wavelength as the pump wavelengths travel together simultaneously [63]. This induces a change of distribution of relative powers among the pumps. In addition, this interaction could also cause severe nonlinear

effect between two high intensities pump beams, such as the four wave mixing [64]. This effect is especially important when zero-dispersion wavelength lies within the Raman pump bands. Four-wave mixing effect generates noises on pump and/or signal bands, which ultimately degrade the amplifier noise figure. We will discuss this detrimental effect in more details in the next section.

One way to solve this detrimental effect is to temporally separate Raman pump in a form of train of pulses, called Time Division Multiplexed (TDM) Raman pump scheme [81]. In this pumping scheme, each pump source is modulated out of phase with respect to other ones so as to lower or avoid pump-to-pump interactions. In this chapter, we are going to investigate in details the necessary operating conditions to optimize the performance of this new pumping scheme. We also propose the use of Gaussian pulse modulation as a better solution to the existing square ones. As typical amplifier, we focus our analysis on both gain and noise performance, which covers amplification to the C-band WDM signal. Based on this, one may further analyze the amplifier performance covering wider bandwidth in the real fiber data transmission.

4.2 Pump-To-Pump Interaction Effects

When pump beams with different wavelengths travels co-propagating simultaneously, nonlinear interactions between pump fields occur, such as cross-phase modulation, four-wave mixing and Raman Effect. In this section, we present some analysis on this effect before we touch on the design of TDM multi-wavelength Raman pumping scheme.

4.2.1 Pump Power Transfer due to Raman Effect

Stimulated Raman scattering between pump fields causes power transfer between pumps from shorter wavelength to longer wavelength. The equation governing the pump-signal interaction under Raman amplification, which includes the pump-to-pump interaction, can be presented as [63]:

$$\frac{dP_j(z)}{dz} = \pm \alpha_p P_j(z) - \sum_i \frac{\nu_{pj}}{\nu_{pi}} g_{Rij} P_j(z) P_i(z) + \sum_k g_{Rik} P_j(z) P_k(z) \quad (4.2.1)$$

$$\frac{dS(z)}{dz} = -\alpha_s S(z) + \sum_j g_R P_j(z) S(z) \quad (4.2.2)$$

where $P_j(z)$ denotes the power evolution of pump beam at wavelength λ_j and $S(z)$ denotes the signal power evolution. Both the second and third terms in the right hand of (4.2.1) refer to the pump power transfer due to SRS. The former refers to pump depletion suffered by pump at λ_j due to pump at λ_i (longer wavelength), whereas the latter refers to amplification to pump at λ_j by pump at λ_k (shorter wavelength). In the coupled equation above, we ignore the generation of noises, such as spontaneous emission noise and Rayleigh backscattered noise. In order to illustrate the impact of this pump-to-pump interaction, we simulated Raman amplification by using multi-wavelength pumps and plot the Raman gain obtained within C-band in Fig. 4.1.

Flat On-Off Raman gains are produced by two sets of pump wavelengths: (A). $\lambda_p = 1420$ nm, 1444 nm, 1477 nm, and 1490 nm; (B). $\lambda_p = 1421$ nm, 1442 nm, 1453 nm, and 1479 nm. Peak Raman gain coefficient g_R equals to $0.56 \text{ W}^{-1}\text{km}^{-1}$, and fiber attenuation $\alpha_p = 0.22 \text{ dB/km}$ which corresponds to fiber effective length $L_{eff} \approx 19.745 \text{ km}$. Gain ripple

changes from 1.6 dB to 6 dB in (A) and 4.5 dB in (B) due to pump-to-pump power transfer. Closer pump wavelength separation imposes less pump-to-pump power transfer.

Fig. 4.1 Pump-to-pump interaction effect on gain ripple Raman amplifier on two different pump wavelength configuration (A). $\lambda_p = 1420$ nm, 1444 nm, 1477 nm, and 1490 nm; (B). $\lambda_p = 1421$ nm, 1442 nm, 1453 nm, and 1479 nm. Dashed lines represent the Raman gain without pump-to-pump interaction, whereas dotted lines represent the Raman gain with pump-to-pump interaction.

An investigation on this pump-to-pump interaction in 100 nm bandwidth Raman amplifier, from 1520 nm to 1620 nm, by using 8 pump wavelengths was reported by H. Kidorf *et al* [63]. Initially, the pump wavelengths were evenly spaced from 1420 nm to 1516 nm with each pump power ranging from 120-130 mW. This design suffered from excessive gain at longer signal wavelength and gain ripple of 10.5 dB due to pump-to-pump interaction. Therefore, modification to the pump spectral density is required and gain ripple as low as 1.1 dB was thus obtained.

4.2.2 Pump-to-Pump Four Wave Mixing

In addition to pump power transfer due to SRS, nonlinear interaction such as Four-Wave Mixing (FWM) may create detrimental effect to the amplifier performance. FWM refers to the generation of frequency ω_1 by mixing three waves of frequencies $\omega_2, \omega_3, \omega_4$ which states the conservation of energy. Conservation of momentum (phase matching) is also necessary for the most efficient generation of the frequency ω_1 , which requires propagation constants to be $k_1 + k_2 = k_3 + k_4$, where k_j denotes the propagation constant in fiber associated with frequencies $\omega_j (j=1,...,4)$. In the case of multimode fibers, the propagation constants of the higher-order modes are smaller than those of the low order modes. By appropriately selecting fiber modes of the launched lights, phase matching can be obtained and to produce four wave mixing. In single mode fiber, strong four-wave mixing of 514.5 nm argon laser light was reported by K. O. Hill *et al.* [82]. Fiber nonlinearities mix the frequency components to produce new frequencies.

Basically, similar to the concept of nonlinear polarization defined in chapter 2, third order nonlinear polarization for difference frequency generation can be written as:

$$P_{NL}(\omega_1, z) = \sum_{m,n,o} \int_{-\infty}^{\infty} d\omega_2 \int_{-\infty}^{\infty} d\omega_3 \int_{-\infty}^{\infty} d\omega_4 \chi_{lmno}(-\omega_1, -\omega_2, \omega_3, \omega_4) \delta(\omega_1 + \omega_2 - \omega_3 - \omega_4) \times \tilde{E}_m(-\omega_2, z) \tilde{E}_n(-\omega_3, z) \tilde{E}_o(-\omega_4, z) \quad (4.2.3)$$

Assuming that the electric susceptibility χ is independent of frequency, nonlinear polarization can be simplified as:

$$P_{NL}(\omega_1, z) = \chi \int_{-\infty}^{\infty} d\omega_3 \int_{-\infty}^{\infty} d\omega_4 \tilde{E}(-\omega_2, z) \tilde{E}(\omega_3, z) \tilde{E}(\omega_4, z) \quad (4.2.4)$$

For the monochromatic field:

$$\tilde{E}(\omega_j, z) = \frac{1}{2} \tilde{E}_j(z) \delta(\omega_j - \omega) + \frac{1}{2} \tilde{E}_j^*(z) \delta(\omega_j + \omega) \quad (4.2.5)$$

The monochromatic nonlinear polarization for frequency ω_1 is presented as:

$$P_{NL}(\omega_1, z) = \frac{1}{2} A_1(z) \delta(\omega_1 - \omega) + \frac{1}{2} A_1^*(z) \delta(\omega_1 + \omega) \quad (4.2.6)$$

By substituting (4.2.5) and (4.2.6) into (4.2.4), we obtain:

$$A_1(z) = \frac{1}{4} \chi \tilde{E}_2^*(z) \tilde{E}_3(z) E_4(z) \quad (4.2.7)$$

Substituting (4.2.5), (4.2.6) and (4.2.7) into the inhomogeneous wave equation

$$\frac{\partial^2}{\partial z^2} \tilde{E}(z, t) - \frac{n^2}{c^2} \frac{\partial^2}{\partial t^2} \tilde{E}(z, t) - \frac{\alpha n}{c} \frac{\partial}{\partial t} \tilde{E}(z, t) = \frac{4\pi}{c^2} \frac{\partial^2}{\partial t^2} P_{NL}(z, t) \quad (4.2.8)$$

results in first order differential equation for the monochromatic plane-wave amplitude at frequency ω_1 below:

$$\frac{\partial}{\partial z} \tilde{E}_1(z) = -\frac{1}{2} \alpha \tilde{E}_1(z) + i \frac{2\pi\omega_1}{n_1 c} (D\chi_{1111}) \times \tilde{E}_2^*(z) \tilde{E}_3(z) \tilde{E}_4(z) \exp(ik_1 z) \quad (4.2.9)$$

Substituting the propagation constant k_j and the preservation of momentum $\Delta k = k_1 + k_2 - k_3 - k_4$ into the wave equation, we obtain the optical power at frequency ω_1 as:

$$P_1 = \frac{256\pi^4 \omega_1^2}{n_1 n_2 n_3 n_4 c^4} (D\chi_{1111})^2 L_{eff}^2 \eta \exp(-\alpha_p L) \frac{P_2 P_3 P_4}{A_{eff}^2} \quad (4.2.10)$$

where $L_{eff} = [1 - \exp(-\alpha_p L)] / \alpha$, and A_{eff} denotes effective cross area similar as for the stimulated Raman scattering as defined in chapter 2. Factor D represents the degeneracy factor, whereas η represents dependence of FWM efficiency on the phase mismatching $\Delta\beta$ which is defined as:

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left[1 + \frac{4e^{-\alpha L} \sin^2(\Delta\beta L / 2)}{\{1 - \exp(-\alpha L)\}^2} \right] \quad (4.2.11)$$

Pump-to-pump FWM impairments are classified into two categories, depending on the location of the generated FWM field [83]. The worst impairment occurs when FWM product falls at the signal band and directly contributes to noises at signal band through Rayleigh backscattering process, which then degrades amplifier noise figure. Second impairment is when the FWM product falls outside the signal band. This new frequency component induces change in the gain spectrum and possibly involves in power transfer process between pump, which ultimately also degrades the amplifier gain ripple by a few decibels.

Major factor determining the penalty induced by pump-to-pump FWM is the relative between pump wavelengths and location of zero-dispersion wavelength (ZDW). Hence, the impairment can be reduced by moving the pump wavelengths or the ZDW. Moving pump wavelengths are changing the gain shape; therefore, controlling the location of ZDW can help to reduce FWM impairment. A 10 dB penalty to noise figure can be induced by just a 2 nm change in zero-dispersion wavelength. Intuitively, wide pumps should be more sensitive to the location of ZDW. It was concluded that the NF penalty increases with pump width, at constant offset with respect to ZDW. Even though the spectral power density decreases, which mean pump power spreads out, new non-degenerate mixing occurs, involving two pump photons of the same pump but at different wavelengths and adding to the classical degenerate mixing of two pump photons at the same wavelength. Ultimately, the penalty region broadens with the pump width.

Increasing the number of Raman pumps increases the probability of pump-to-pump FWM. In addition to that, non-uniform zero-dispersion wavelength profiles due to multiple shorter spans increase the probability of impairment due to the wide distribution of zero-dispersion wavelength. FWM is a high gain process when good phase matching is achieved and therefore, does not require long lengths of fiber to occur. Significant amount of FWM impairment is still observed even when there is one short “*harmful*” fiber segment [83]. Harmful refers to a condition where the location of zero-dispersion wavelength allows the FWM be possible. Simulation results show that, in the multiple short spans, even when the probability of picking harmful fiber is as small as 3.3%, the probability of inserting one of these harmful fibers can be as high as 23%. It implies that every 5 short span, we could possibly have 1 harmful fiber span which generates FWM impairment and the effect is significant, even though it’s a very short length of fiber.

4.3 Time Division Multiplexed Raman Pump Scheme

Fundamental problems that occur due to nonlinear interaction between multi-wavelength pump beams, either through Raman Effect or Four-Wave Mixing, could be harmful to the transmission system. This could be reduced or eliminated by temporally separating the multi-wavelength pump beams in the form of pump pulses. Nevertheless, it is important to note that pump modulation induces another noise generation to the signal from the transfer of relative intensity noise (RIN), as discussed in chapter 2, section 2.3.2.3. Counter-propagating Raman pump becomes the solution to limit this noise transfer, especially at relatively low pulse repetition rate. Therefore, Time Division Multiplexed (TDM) Raman pumping scheme is formed through train of pump pulses propagating in backward direction. The signal light experiences gain when it overlaps with the pump pulses as shown in Fig. 4.2.

Two possible mechanisms to generate the Raman pump pulses are as follows: 1). A tunable laser is periodically scanned by using electronic driven pulse to produce flat gain Raman amplifier, 2). A number of fixed wavelength Raman lasers are multiplexed together and temporally separated by using electronic driven pulse or simply fiber delay line. Each method introduces different pro- and cons- and therefore will be applied according to the performance requirement and component availability. The first method introduces simplicity and hence cost efficiency, whilst resolution is limited by the bandwidth of scanning drive electronics. However, the flat gain bandwidth is limited by the range of the tunable laser and also some other forms of nonlinearity are introduced by the rapid frequency scanning. On the other hand, the second method is a more costly solution as a number of pump lasers are required. Nevertheless, simpler algorithm is required to adjust the pump powers to maintain the flat Raman gain, unlike the first method, which requires temporal weighting function to attain a flat Raman gain.

Fig. 4.2 Raman Pump pulses propagating in backward direction.

4.3.1 Single Wavelength Time Division Multiplexed Raman Pump

Consider Raman pump pulses propagate in counter-propagation direction with pulse repetition rate f and duty cycle ρ . As mentioned above, pump pulses are generated either through either amplified tunable laser or multi pump lasers multiplexed to produce flat Raman gain. These two options will create significant difference in the case of multi-wavelength Raman pump, which will be explained in the next section. At first, we consider single wavelength Raman pump propagating with group velocities V_p and signal light propagating with group velocity V_s .

The interaction between counter-propagating pump and signal is simply governed by:

$$\frac{dP(z)}{dz} = \alpha_p P(z) + \frac{\nu_p}{\nu_s} g_R P(z) S(z) \quad (4.3.1)$$

$$\frac{dS(z)}{dz} = -\alpha_s S(z) + g_R P(z) S(z) \quad (4.3.2)$$

where $P(z)$ and $S(z)$ are pump and signal power evolution respectively, α_p and α_s are fiber loss at pump and signal wavelengths respectively, ν_p and ν_s are pump and signal optical frequencies and g_R denotes Raman gain coefficient ($W^{-1} km^{-1}$). The first term on the right hand of the equation represents the fiber attenuation, whereas the second term represents the power transfer through stimulated Raman scattering which amplifies the signal light and depletes the pump. We assume that no intra-band stimulated Raman scattering and no spontaneous Raman emission involved in our model.

Within a small fiber segment, (4.3.1) and (4.3.2) can be solved as:

$$P(z + \Delta z) = P(z) \exp \left\{ \left(\alpha_p + \frac{\nu_p}{\nu_s} g_R S(z + \Delta z) \right) \Delta z \right\} \quad (4.3.3)$$

$$S(z + \Delta z) = S(z) \exp \{ (-\alpha_s + g_R P(z + \Delta z)) \Delta z \} \quad (4.3.4)$$

where Δz denotes the interaction length between pump and signal.

Net Raman gain can thus be obtained through the ratio of signal power at distance L and the launched signal power:

$$G_{R-net} = \frac{S(L)}{S(0)} \quad (4.3.5)$$

The total number of interaction fiber segment experienced by signal light and the interaction length determine the total amplification. Total number of pump-signal interaction is given by the summation of total initial pump pulses in transmission at $t = 0$ and pump pulses generated within the duration of signal propagation from $z = 0$ to $z = L$. Initial number of pump pulses exist in the transmission is given by:

$$N_0 = f \frac{L}{V_p} \quad (4.3.6)$$

Total propagation time of signal light within distance of L km is simply represented by:

$$T_{prop} = \frac{L}{V_s}$$

Therefore the total number of pump pulses interacting with each signal pulse is

$$N = N_0 + N_{prop} = f \frac{L}{V_p} + f T_{prop} \approx f L \left[\frac{1}{V_p} + \frac{1}{V_s} \right] \quad (4.3.7)$$

Interaction length between pump and signal pulses is given by $\Delta z = V_s T_A$, where T_A represents the interaction period, which is given by:

$$T_A = \frac{V_s T_s + V_p T_p}{V_s + V_p} \approx \frac{V_p}{V_s + V_p} \frac{\rho}{f} \quad (4.3.8)$$

Equation (4.3.8) above is taken by assuming that signal pulse period is much smaller than pump pulse, i.e. much higher repetition rate as compared to the pump repetition rates.

Interaction length can therefore be defined as:

$$\Delta z \approx \frac{V_s V_p}{V_s + V_p} \frac{\rho}{f} \quad (4.3.9)$$

Equations (4.3.3) and (4.3.4) divide the fiber into N segments at which each Raman interaction occurs. The segment length L_N can thus be approximated as:

$$L_N = \frac{L}{N} = \frac{V_s V_p}{f(V_s + V_p)} \quad (4.3.10)$$

Assuming that pump depletion is negligible under small-signal approximation, pump power distribution $P(z)$ is in a form of linear exponential decay function:

$$P_i(z) = P_L \exp[-\alpha_p(L - (i-1)L_N)]_{i=1}^N \quad (4.3.11)$$

where P_L denotes the launched pump power at $z = L$.

From (4.3.5) to (4.3.11), the On-Off Raman gain can be defined as:

$$G_{OO} = \exp \left[g_R \frac{V_s V_p}{V_s + V_p} \frac{\rho}{f} \sum_i^N P_i(z) \right] \quad (4.3.12)$$

Define
$$\xi = \frac{V_s V_p}{V_s + V_p} \frac{1}{f} \sum_i^N \exp[-\alpha_p(L - (i-1)L_N)] \quad (4.3.13)$$

This then modifies the On-Off Raman gain as:

$$G_{OO} = \exp[g_R \rho P_L \xi]$$

We obtain the group velocities from the approximated linear group delay and dispersion profile, as given by [84]:

$$\tau(\lambda) = \tau_0 + S_0 \lambda_0^2 \left(\frac{\lambda_0 - \lambda}{\lambda} + \ln \frac{\lambda}{\lambda_0} \right) \quad (4.3.14)$$

$$D(\lambda) = S_0 \left(\frac{\lambda_0}{\lambda} \right)^2 (\lambda - \lambda_0) \quad (4.3.15)$$

where $\tau(\lambda)$ and $D(\lambda)$ denote the group delay per unit length and dispersion as a function of wavelength, whereas τ_0, S_0 are the group delay and dispersion slope at zero dispersion wavelength λ_0 . Another expression of group delay and dispersion profile based on Taylor expansion can be written as:

$$\tau(\lambda) = \tau_0 + \frac{S_0}{2} (\lambda - \lambda_0)^2 - \frac{C_0}{6} (\lambda - \lambda_0)^3 \quad (4.3.16)$$

$$D(\lambda) = S_0 (\lambda - \lambda_0) - \frac{C_0}{2} (\lambda - \lambda_0)^2 \quad (4.3.17)$$

where C_0 is the dispersion curvature $C(\lambda) = -\frac{dD}{d\lambda}$ at λ_0 . The group velocity is thus defined as $V(\lambda) = \tau(\lambda)^{-1}$. Chromatic dispersion measurement results can be more accurately described in dispersion curve fitting by using two parameters: zero dispersion wavelength and dispersion slope. However, including the dispersion curvature C_0 may increase the closeness fit of the dispersion curve. Fig. 4.3 below describes the difference in dispersion plot based on (4.3.16) and (4.3.17), when zero-dispersion wavelength $\lambda_0 = 1400$ nm, $S_0 = 0.086$ ps/nm²km and $C_0 = 250 \times 10^{-6}$ ps/nm³km.

Fig. 4.3 Fiber dispersion profiles with 1400nm zero dispersion wavelength.

From the curve, we can see the difference gets more significance at wavelengths further away from zero-dispersion wavelength. By changing the dispersion curvature allows us to tune this dispersion curve, not only for those around zero-dispersion wavelength, thus could give more accurate dispersion curve fitting. We will observe the impact of group velocities of pump and signal to the TDM Raman amplifier in more details later.

We plot the factor ξ with respect to pulse repetition rate f in Fig. 4.4. Pump and signal wavelengths are set to be $\lambda_p = 1450$ nm and $\lambda_s = 1550$ nm respectively with fiber attenuation $\alpha = 0.22$ dB/km. Pump and signal group velocities are obtained through linear dispersion profile.

Fig. 4.4 Plot of ξ vs. pump pulse repetition rate.

When pulse repetition rate is sufficiently high, i.e. $f > 200 \text{ kHz}$ and $L \gg L_{eff}$, $\xi \approx L_{eff} \approx 1/\alpha_p$

When transmission length is much longer than L_{eff} and repetition rate is sufficiently high, factor ξ approaches a constant value, which can be approximated as $\xi \approx L_{eff}$.

This thus results in the expected On-Off Raman gain $G_{OO} \approx \exp\left[\frac{\rho P_L g_R}{\alpha_p}\right]$ (4.3.18)

The term ρP_L denotes the average pump power, which determines the average Raman gain. Our model agrees well with the notion that, given a sufficiently fast pump repetition rate, it is the average pump power that determines the average Raman gain [85-86]. This thus confirms the validity of our derived model to analyze the Time Division Multiplexed pumping scheme, in a simpler way yet accurate, as long as Raman amplifier is working in linear amplification region.

In multi-wavelength TDM pump scheme, On-Off Raman gain in (4.3.12) can be expanded as:

$$G_{OO} = \exp \left[\sum_{k=1}^M \left(g_{R(k)} \frac{V_s V_{p(k)}}{V_s + V_{p(k)}} \frac{\rho_{eff}}{f_{eff}} \sum_i^N P_{(k)i}(z) \right) \right] \quad (4.3.19)$$

where M refers to the number of pump wavelengths. Modification to the pump power distribution in (4.3.11) is required according to which method of generating multi-wavelength Time-Division Multiplexed pump is employed. Greater details on this will be presented in section (4.3.2).

4.3.1.1 Temporal Gain Fluctuation in TDM Raman Scheme

Modulated pump causes temporal gain fluctuation to the signal, which will affect the receiving signal process at the receiver. In order to quantify the temporal gain by using our model, we need to temporally adjust the pump power distribution in (4.3.11), as illustrated in Fig. 4.5.

Fig. 4.5 Temporal pump power distribution.

As TDM pumping scheme involving modulation of pump pulses and multiplexing the pump pulses in time domain, we consider both spatial and temporal distribution of the pump pulses and calculate the output signal to noise ratio and output signal power, at $z =$

L within certain time-range. This can be done by solving the generalized coupled equation of (4.3.1) and (4.3.2), which include both spatial and temporal term, by using some available numerical methods, such as Finite Difference method [87]. This method could give accurate results, even if some nonlinear effects are involved in the coupled equations. However, due to its iterative nature, this method will generate much more complex calculation and simulation time, especially if i) a large number of fiber segments are required, or ii) high order nonlinearity is involved. In our case, the problem we have is having a large number of fiber segments, e.g. due to long fiber length and high pulse repetition rate, and also multi-coordinate transformation due to multiple pump wavelengths. This will unfortunately require complex and long simulation process. When very high repetition rate is involved, i.e. in tens of MHz or higher, this will involve very complex matrices and requires huge amount of computer memory for simulation. Therefore, instead of using the above-mentioned method, we used an approximation method, i.e. we simulated the pump, signal and noise power distribution from $z = 0$ to $z = L$ at different instantaneous time. This can be done by inserting time-varying pump power distribution $P_p(z, t)$, representing Fig. 4.5 above, as described by:

$$P_i(z, t) = P_L(t) \exp\left[-\alpha_p (L - (i-1)L_N)\right]_{i=1}^N \quad (4.3.20)$$

From the temporal pump power distribution (4.3.20), we simulated and plotted the temporal gain fluctuation, as shown in Fig. 4.6, for various pulse repetition rates. Fig. 4.6(A) describes the temporal gain variation under 50 kHz pulse repetition rate and 50% pulse duty cycle. It shows that as the On-Off gain increases, the temporal gain variation increases correspondingly, i.e. 10 dB and 15 dB On-Off Raman gain result in 0.5 dB and 0.74 dB gain variation, respectively. Furthermore, Fig. 4.6(B) shows the effect of pulse duty cycles to the temporal gain variations, which can be seen more clearly when pulse repetition rate is as low as 2.5 kHz.

(A) Pulse repetition rate = 50 kHz

(B) Pulse repetition rate = 2.5 kHz

Fig. 4.6 Temporal gain variation at single wavelength TDM Raman pump.

Temporal gain fluctuation directly affects the process of receiving information bits at the receiver. For example, in digital lightwave system with RZ modulation format and Intensity-Modulation Direct-Detection (IMDD) receiver, its performance is determined by the Q factor, which is defined as:

$$Q = \left(\frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \right) \quad (4.3.21)$$

where μ_1 and μ_0 are the mean power levels of the “ones” and “zeros”, whilst σ_1 and σ_0 are the corresponding standard deviations due to noise and interferences. Bit Error Ratio (BER) is directly related to the Q factor in (4.3.21) as:

$$BER(Q) = \frac{1}{2} \left[1 - \operatorname{erf} \left(\frac{Q}{\sqrt{2}} \right) \right]$$

where:

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\alpha^2} d\alpha$$

From the estimation of Q factor, it is clear that the decision level is set between μ_1 and μ_0 . Amplifier gain affects μ_1 , while μ_0 remains constant. Therefore, max-min gain fluctuation directly affects the receiver decision level, i.e. receiver sensitivity level. Higher gain

fluctuation imposes bigger receiver sensitivity penalty. On the other hand, noise fluctuation, i.e. Forward ASE (co-propagating with signal) does not have any significant effect on the information receiving process. Nevertheless, it is still important to keep the average noise level as low as possible in order to have a better BER. Pulse repetition rate higher than 10 kHz is required to achieve a receiver sensitivity penalty less than 0.5 dB. When the pulse repetition rate is increased up to 50 kHz, the receiver sensitivity penalty can be reduced up to 0.2 dB. This will give us a total of 2 dB accumulated sensitivity penalty, when 10 amplifier spans are used [86]. Further investigation needs to be carried on to characterize the system penalty induced by this pumping scheme, especially when this pumping scheme is employed for various optical data transmission formats.

4.3.1.2 Noise Properties of Single-wavelength TDM Raman Scheme

Some possible noise sources in Time-Division Multiplexed Raman scheme are amplified spontaneous emission (ASE) noise and multiple path interference (MPI) noise due to Rayleigh backscattering. As pump and signal propagate in opposite direction and the pulse repetition rate is much higher than the corner frequency, the RIN-transfer from pump to signal is assumed to be negligible. ASE noises that directly affect signals are counter-propagating ASE (in the direction of signal propagation, i.e. Forward ASE) and Rayleigh backscattered co-propagating ASE, named Rayleigh backscattered Backward ASE. In this context, we define Forward and Backward directions as according to the direction of signal propagation. As in (2.4.13) and (2.4.14), ASE noise in TDM Raman scheme is governed by:

$$\frac{dP_{ASE-F}}{dz} = [g_R P_p(z) - \alpha_A] P_{ASE-F} + 2h\nu B_0 g_R P_p(z) + \kappa_{Ray} P_A^+ \quad (4.3.22)$$

$$\frac{dP_{ASE-B}}{dz} = -[g_R P_p(z) + \alpha_A] P_{ASE-B} - 2h\nu B_0 g_R P_p(z) \quad (4.3.23)$$

where P_{ASE-F} and P_{ASE-B} are Forward and Backward ASE.

In continuous wave pump Raman amplifier, co-propagating ASE noise experiences dramatic enhancement when ASE and pump propagating with similar or almost similar group velocity, especially at high pump RIN level. This effect becomes significant at high Raman On-Off gain, i.e. 20 dB Raman On-Off gain produces 8 dB noise overshoots; whereas 25 dB On-Off gain produces 17 dB ASE noise overshoots, as shown in Fig. 2.5. This similar effect will even be more severe at TDM Raman scheme, especially at low pulse duty cycle. Lower duty cycle imposes higher peak pump power in order to produce the same level of On-Off Raman gain. Higher peak pump power produces higher instantaneous gain to co-propagating ASE (Backward ASE), which ultimately increases the Forward ASE through Rayleigh backscattering.

We simulated both Forward and Backward ASE within signal wavelengths 1525 nm – 1565 nm, generated by square pump pulses with various pulse duty cycles, as shown in Fig. 4.7. We used non-zero dispersion shifted fiber with fiber attenuation coefficient $\alpha = 0.22$ dB/km, zero-dispersion slope $S_0 = 0.086$ ps/nm²-km and dispersion curvature $C_0 = 250 \times 10^{-6}$ ps/nm³-km. We set Raman pump wavelength $\lambda_p = 1450$ nm modulated with pulse repetition rate of 500 kHz and average pump power equals to 200 mW to generate average 10 dB On-Off gain. Assuming no gain-enhancement due to group-velocity matching condition, i.e. $\lambda_0 = 1400$ nm. Pump pulses were assumed to be RIN-free and having pulse duty cycles of 50% and 25%. Strong Backward ASE enhancement

is induced by lower duty cycle which then enhances the Forward ASE by up to 4 dB, which corresponds to 1 dB difference in the amplifier noise figure, as shown in Fig. 4.8.

Fig. 4.7 Forward and Backward ASE noise of TDM Raman pump scheme (RIN-free).

Fig. 4.8 Effective noise figure in TDM Raman pump under RIN-free pump condition for various pulse duty cycles.

Noisy pump will further enhance the ASE noise as shown in Fig. 4.9. Pump RIN is set to be -110 dB/Hz with 25 GHz noise bandwidth. At this pump RIN level, only at 25% pulse

duty cycle or lower; there is significant noise figure degradation, which is up to 15 dB, as shown in Fig. 4.10.

Fig. 4.9 Forward and Backward ASE noise of TDM Raman pump scheme with -110 dB/Hz pump RIN.

Fig. 4.10 Effective noise figure in TDM Raman pump with -110 dB/Hz pump RIN for various pulse duty cycles.

A detailed characterization of the Forward ASE with respect to gain levels, RIN level and pulse duty cycle are presented in Fig. 4.11 till Fig. 4.14. Fig. 4.11 shows the contour

of noise figure at various pulse duty cycles and On-Off gains under RIN-free pump condition. From Fig. 4.11, if we increase the Raman gain level, from 10 dB to 15 dB, in order to maintain the effective noise figure equals to -8 dB, which corresponds to 14 dB real noise figure (if total fiber loss equals to 22 dB), the pump pulse duty cycle must be increased from around 35% up to 45%. The increment in the pulse duty cycle when gain is increased corresponds to maintaining peak pump power almost constant, such that the ratio of signal amplification and amplified ASE is kept constant. In addition to that, there is certain level of On-Off gain, i.e. 9.5 dB, where the increase in the pulse duty cycle, which corresponds to change in peak pump power, would not significantly change the effective noise figure. From this we can conclude that when the amplifier is producing gain within a range of 10-15 dB On-Off gain, pulse duty cycle greater than 45% is a safe operating region if we want to maintain an effective noise figure as low as -8 dB.

Fig. 4.11 The contour of effective Noise Figure (NF) at $\lambda_s = 1550$ nm for square pulse TDM Raman pump (RIN-free) at various pulse duty cycles.

Fig. 4.12 The contour of RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for square pulse TDM Raman pump with 25% pulse duty cycle.

Fig. 4.13 The contour of RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for square pulse TDM Raman pump with 50% pulse duty cycle.

Fig. 4.14 The contour of RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for square pulse TDM Raman pump with 60% pulse duty cycle.

Fig. 4.15 The contour of RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for square pulse TDM Raman pump with 80% pulse duty cycle.

Fig. 4.12 till Fig. 4.14 show the noise figure contours with respect to various pump RIN levels at 25%, 50%, 60% and 80% pump pulse duty cycle. Fig. 4.12 shows that when pulse duty cycle is 25%, the amplifier introduces significant amount of noise, such that the effective noise figure is very poor, as compared to other figures. At typical gain level of around 12 dB and pump RIN of about -120 dB/Hz, the effective noise figure is very poor, i.e. bigger than 0 dB. From Fig. 4.13, we can see that when we operate the amplifier up to 15 dB On-Off gain, as long as the pump RIN is less than -110 dB/Hz, the effective noise figure is less than 0 dB. At zero effective noise figure, the noise generation during the amplification process is not so significant as compared to the signal amplification, and the degradation of signal to noise ratio in distributed Raman amplifier is mainly due to the total fiber loss. Higher pulse duty cycle will further ensure low degradation of signal to noise ratio, especially if we operate the amplifier in the high On-Off gain levels, as shown in Fig. 4.14 and 4.15.

In addition, group velocity matching condition further enhances the instantaneous gain in backward direction, which in turn enhances the noise level. This can occur when zero-dispersion wavelength is located between pump and ASE wavelengths, i.e. $\lambda_0 = 1500$ nm, as shown in Fig. 4.16. At relatively low pump RIN, Forward ASE noise can be enhanced by up to 20 dB (25% duty cycle) and 10 dB (50% duty cycle). ASE noises generated by 50% duty cycle are shown by the dotted lines, whereas 25% duty cycle-noises are shown by dashed lines. With pump RIN equals to -120 dB/Hz and 25% pulse duty cycle, the peak Forward ASE enhancement can be up to 30 dB, which degrades the noise figure severely, i.e. up to 20 dB.

Fig. 4.16 Forward and Backward ASE noise in TDM Raman pump under group-velocity matching condition with -120 dB/Hz pump RIN.

Fig. 4.17 Effective noise figure in TDM Raman pump under group-velocity matching condition with -120 dB/Hz pump RIN.

Therefore, avoidance of group velocity matching, lower pump RIN level and lower instantaneous co-propagating Raman gain help to reduce ASE enhancement. This can be achieved by having zero-dispersion wavelength outside the pump-signal band and increasing the pulse duty cycle. However, another possible solution is to increase pulse

repetition rate in order to provide sufficient walk-off between pump and co-propagating ASE pulses [88]. This will average the co-propagating ASE noise level, which then ultimately reduce the Forward ASE enhancement. When pulse repetition rate is increased to 8 MHz, 10 MHz and 15 MHz, we see significant reduction in Backward ASE enhancement, as shown in Fig. 4.18. The plotted Backward ASE is produced under similar condition as in Fig. 4.6, when pulse duty cycle equals to 25%.

Fig. 4.18 Reduction of Backward ASE enhancement due to high pulse repetition rates.

Another source of noise in TDM Raman scheme is double Rayleigh backscattering (DRS) noise. As in (2.3.16) – (2.3.18), DRS noise in TDM Raman scheme is governed by:

$$\frac{dP_{SRB}}{dz} = -[g_R P_p(z) - \alpha_s] P_{SRB} - \kappa_{Ray} P_s \quad (4.3.24)$$

$$\frac{dP_{DRS}}{dz} = [g_R P_p(z) - \alpha_s] P_{DRS} + \kappa_{Ray} P_{SRB} \quad (4.3.25)$$

Similar to co-propagating ASE, single Rayleigh backscattering noise experiences significant enhancement as it co-propagates with the pump pulses, especially at low pulse duty cycle. This ultimately increases the DRS noise. Using similar conditions as in Fig. 4.6, we plot the signal to DRS noise ratio (S/DRS) in TDM Raman scheme in Fig. 4.19 below. Signal power is set to be 0 dBm, with Rayleigh scattering coefficient $\kappa_{Ray} = 100 \times 10^{-6} \text{ km}^{-1}$.

Fig. 4.19 Double Rayleigh backscattering (DRS) noise of TDM Raman pump scheme (RIN-free).

Lower duty cycle imposes higher instantaneous gain in backward direction which enhances the single Rayleigh backscattering (SRB) noise significantly. More than 10 dB degradation in S/DRS ratio is shown between 50% and 25% duty cycle. In addition, noisy pump also degrades this ratio further as shown in Fig. 4.20. Similar to ASE noise, DRS noise enhancement can be reduced by setting higher pulse repetition rate, as shown in Fig. 4.21.

Fig. 4.20 Double Rayleigh Backscattering (DRS) noise of TDM Raman pump scheme with pump RIN equals to -110 dB/Hz).

Fig. 4.21 Reduction of DRS noise enhancement due to high pulse repetition rates (pump RIN equals to -110 dB/Hz).

4.3.2 Multi-wavelength Time Division Multiplexed Raman Scheme

Multi-wavelength TDM Raman pump is arranged by temporally separating pump pulses with different wavelengths. At sufficiently high repetition rate, signals propagating in backward direction will be able to interact with all the pump wavelengths forming flat Raman gain. When multi-wavelength pump is generated through periodically scanned

tunable laser, gain flatness is produced by adjusting the pump weighting function. This weighting function is formed by the number of multiple-time slots occupied by each pump wavelength with uniform pump power level as demonstrated by P. J. Winzer *et al.* [86].

We focus on employing the second method, which uses a number of pump sources forming alternating temporal pump sequence, as shown in Fig. 4.22. The weighting function is simply formed by combination of various pump power levels to generate flat Raman gain. This method introduces simplicity in design and less impact from other nonlinear effects as compared to the previous method.

Fig. 4.22 Multi-wavelength Alternating Raman Pump pulses propagating in backward direction.

4.3.2.1 Gain Properties of Multi-wavelength TDM Raman Scheme

On-Off Raman gain in multi-wavelength TDM Raman pump can be obtained from

$$(4.3.19): \quad G_{OO} = \exp \left[\sum_{k=1}^M \left(g_{R(k)} \frac{V_s V_{p(k)}}{V_s + V_{p(k)}} \frac{\rho}{f_{eff}} \sum_i^{N_{tot}} P_{(k)i}(z) \right) \right] \quad (4.3.26)$$

where M is the number of pump wavelengths and f_{eff} is the effective pulse repetition rate experienced by each pump wavelength, defined as $f_{eff} = 1/T_{eff}$. Similarly, effective pulse duty cycle of each pump wavelength ρ_{eff} is defined as $\rho_{eff} = T_p/T_{eff}$. The factor T_{eff} is defined as: $T_{eff} = MT$. Overall, the combined pulse pumping is having pulse period T and pulse repetition rate f . We simulated the multi-wavelength TDM Raman pumping to produce a flat Raman gain profile, as shown in Fig. 4.23. We used 100 km Non-Zero Dispersion Shifted Fiber (NZDF) with fiber attenuation coefficient $\alpha_p = 0.22$ dB/km, zero-dispersion wavelength = 1400 nm with zero-dispersion slope $S_0 = 0.086$ ps/nm²-km and peak Raman gain coefficient $g_R = 0.598$ W⁻¹km⁻¹. We proposed to use 4 pump wavelengths to flatten the Raman gain. This would then cause each pump wavelength having effective pulse repetition rate f_{eff} and ρ_{eff} equals to $1/4$ of the original pulse repetition rate and duty cycle. Also, each pump wavelength contributes amplification within $1/4$ of the original L_{eff} . This implies that the contribution of each pump wavelengths will be lower, as the effective amplification length is divided among the four-pump wavelengths, considering we use uniform pulse repetition rate and duty cycle for all the pump wavelengths. We used two different pump wavelength combinations to generate 12 dB average On-Off Raman gain. In order to produce a flat Raman gain within our desired bandwidth, we adjusted the pump power level for each pump wavelength combination. We used this pump wavelength combination only as an illustration in generating multi-wavelength pump flattening Raman gain. One can always employ different number and configuration of pump wavelengths to flatten Raman gain, based on the performance specifications required. Raman pumps were assumed to be RIN-free and square modulated with 500 kHz pulse repetition rate and 50% duty cycle. This corresponds to 0.125 effective pulse duty cycle of each pump wavelength. Average pump power of each

pump source is ranging from 0.4 W till 1.7 W. We used 0.95 W, 0.93 W, 0.91 W and 0.86 W peak pump powers for pump configuration (A), whereas for pump configuration (B), we used 0.97 W, 1.69 W, 0.95 W, and 0.8 W. Both pump wavelength configuration resulted in similar flat bandwidth and gain ripple. The difference among the two pump configurations is the distribution of gain contribution from each of the pump source to the overall gain.

Fig. 4.23 Flat Raman On-Off gain in 1525 – 1560 nm wavelength range with pump wavelengths: (A) 1421 nm, 1442 nm, 1453 nm, and 1479 nm (dashed lines); (B) 1420 nm, 1444 nm, 1477 nm, and 1490 nm (dotted lines).

When pump wavelengths are wider spread, i.e. pump configuration in (B), one or two pump sources will dominate (i.e. higher power) over the others in order to maintain similar flat gain within similar signals band. Peak pump power as high as 1.69 W is required by the pump source with wavelength $\lambda_p = 1444$ nm in (B). Closer pump wavelength separation makes almost-uniform pump power levels possible. Higher peak pump power produces higher instantaneous gain, which could be detrimental to the amplifier performance, i.e. degradation of the noise performance. In addition, it could also be harmful to the gain property of the amplifier, which will be discussed shortly.

Alternating multi-wavelength TDM Raman pump imposes an upper limit to the pulse repetition rate. Higher repetition rate corresponds to shorter pulse period, which makes two neighboring pulses possibly interact with each other after certain transmission length due to the group-velocity difference between two pulses. The upper limit of pulse repetition rate can be defined as:

$$f_{\max} \leq \frac{(1 - \rho)}{L_C \left| \frac{1}{V_{p1}} - \frac{1}{V_{p2}} \right|} \quad (4.3.27)$$

where V_{p1} and V_{p2} are the group velocities of two neighboring pump pulses and L_C denotes the location where two neighboring pump pulses start to collide and after which interact with each other. Obviously, when two neighboring pump pulses having wider wavelength separation, group velocity difference between the two pulses gets bigger, the maximum pulse repetition rate $f_{\max}$ becomes lower, unless zero-dispersion wavelength is located in between the two pump wavelengths. Table 1 shows the various maximum repetition rates for two pump wavelength combinations used in Fig. 4.23 for various length of L_C . In this table, we set the zero-dispersion wavelength $\lambda_0 = 1400$ nm (outside the pumps band) and 50% pulse duty cycle. When more than two pump wavelengths are employed, we measure $f_{\max}$ based on the worst condition, which is when two neighboring pump pulses are having the biggest group-velocity difference, i.e. when pump pulses with $\lambda_p = 1421$ nm and 1479 nm are adjacent. It is clearly shown that when pump wavelength separations are smaller, the biggest group velocity difference is smaller, which then increases $f_{\max}$.

Table 3 Maximum pulse repetition rates for two pump wavelength configurations at various length of collision.

Length L_c	$\lambda_p = 1421\text{ nm}, 1442\text{ nm}, 1453\text{ nm},$ and 1479 nm	$\lambda_p = 1420\text{ nm}, 1444\text{ nm}, 1477\text{ nm},$ and 1490 nm
100 km	$f_{\max} = 36.8\text{ MHz}$	$f_{\max} = 30.0\text{ MHz}$
50 km	$f_{\max} = 73.5\text{ MHz}$	$f_{\max} = 60.3\text{ MHz}$
40 km	$f_{\max} = 92.0\text{ MHz}$	$f_{\max} = 75.4\text{ MHz}$
30 km	$f_{\max} = 122.5\text{ MHz}$	$f_{\max} = 100.5\text{ MHz}$

Fig. 4.24 Maximum pulse repetition rates with respect to zero dispersion wavelengths for pump wavelength combinations (A) 1421 nm and 1479 nm; (B) 1420 nm and 1490 nm.

Fig. 4.25 Maximum pulse repetition rate with respect to pulse duty cycle for 1421 nm and 1479 nm pump wavelengths with respect to zero dispersion wavelengths (a) 1450 nm, (b) 1445 nm, (c) 1400 nm and (d) 1500 nm respectively.

Figure 4.24 shows that under group velocity matching condition, i.e. when zero-dispersion wavelength is located in the mid of two pump wavelengths, f_{max} is dramatically increased, i.e. when pump wavelengths are (A) $\lambda_p = 1421$ nm, 1442 nm, 1453 nm, 1479 nm, and $\lambda_0 = 1450$ nm, f_{max} can be higher than 10 GHz. Moreover, under pump wavelength combination (B), when zero-dispersion wavelength λ_0 is around 1452 nm, the maximum pulse repetition rate f_{max} can be as high as 100 GHz or more. Under this condition, slight change of pulse duty cycle will significantly change the allowable f_{max} as shown in Fig. 4.25.

When pulse repetition rate is set beyond f_{max} , pump-to-pump interaction may occur. The effect of pump-to-pump interaction, i.e. pump-to-pump power transfer, depends on where the interaction starts to occur. If interaction occurs when the pump powers are not much depleted by fiber loss yet, the effect of pump power transfer could be severe. We show the impact of the power transfer in pump-to-pump interaction due to Raman effect in Fig. 4.26. To simulate this condition, we did mapping of pump pulses evolution in spatial and time domain for each pump wavelength. We introduced time delay from one pump wavelength to another to temporally alternate the pump pulses. Subsequently, we inserted each pump power distribution into (4.3.26) and calculate the overall On-Off Raman gain. We also included the factor of pump-to-pump power transfer due to Raman effect within the pump power spatial distribution. One can always include the possibility of Four-Wave Mixing generation into the pump pulses evolution; so long the parametric coefficient and fiber dispersion profile is known. In our work, we focused on the effect of pump-to-pump power transfer when pumps interact. The alternating position of the various pump wavelengths can be randomly assigned. In this work, as we need to observe the impact of pump-to-pump power transfer, we designed the alternating position

in such that we would have two adjacent pump pulses with the longest pump wavelength separation. This gives us the worst scenario, which is, when these two pump pulses start to interact to each other, based on the Raman gain profile of fiber we used, we would expect strongest pump-pump power transfer due to Raman effect. For different pump wavelength configuration, one needs to determine which pump-to-pump interaction shows the strongest Raman interaction to represent the worst scenario, which actually depends on the Raman gain coefficient and pump power configuration. Fig. 4.26(A) shows that pulse repetition rate as high as 92 MHz does not have any significant effect on the flatness of the Raman gain as compared to the one in Fig. 4.26(B). Raman gain ripple degradation in Fig. 4.26(A) is about ± 1.9 dB and whereas in Fig 4.26(B) is about ± 2.6 dB. This is because the location of collision (interaction) in the former is further away from the latter, such that smaller Raman pump powers due to fiber attenuation are involved in the power transfer process. Moreover, pulse repetition rate as high as 122.5 MHz causes gain ripple degradation up to ± 3 dB in Fig. 4.26(A) and ± 5.5 dB in Fig. 4.26(B).

Fig. 4.26 Flat Raman gain is affected by pump-to-pump interaction for 50% duty cycle and pulse repetition rates are 73.5 MHz (line with circles), 92 MHz (line with stars) and 122.5 MHz (line with squares) respectively. Pump wavelength combinations are (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

Furthermore, when pulse duty cycle is smaller, this pump scheme is more sensitive to the pump-to-pump interaction effect, as higher peak pump powers are involved in the pump power transfer, as shown in Fig. 4.27. In this figure, pump wavelengths are $\lambda_p = 1421$ nm, 1442 nm, 1453 nm, and 1479 nm with 25% pulse duty cycle, while the remaining conditions are similar as in Fig. 4.26. In order to compare the effect of duty cycle in the pump interaction process, we use the same length of collisions as in Fig. 4.26, as shown in Table 4. When pump interaction starts at distance of 50 km, the gain ripple degradation in Fig. 4.27 can be as high as ± 1.75 dB, unlike in Fig. 4.26, which is about ± 1.5 dB. The nearer the location of collision from its launched point, the more severe the pump interaction effect is.

Table 4 Maximum pulse repetition rates for two pulse duty cycles at various length of collision.

Length L_C	Duty cycle = 50%	Duty cycle = 25%
100 km	$f_{\max} = 36.8$ MHz	$f_{\max} = 55.1$ MHz
50 km	$f_{\max} = 73.5$ MHz	$f_{\max} = 110.3$ MHz
40 km	$f_{\max} = 92.0$ MHz	$f_{\max} = 137.9$ MHz
30 km	$f_{\max} = 122.5$ MHz	$f_{\max} = 183.9$ MHz

Fig. 4.27 Flat Raman gain is affected by pump-to-pump interaction for 25% duty cycle and pulse repetition rates are 110.3 MHz (line with circles), 137.9 MHz (line with stars) and 183.9 MHz (line with squares) respectively.

This severe gain flatness degradation defeats the purpose of designing TDM Raman pump scheme. In addition to that, additional noises generated during the pump interaction process could impose severe degradation in overall signal to noise ratio. This limitation should be seriously taken into consideration in designing this new pump scheme.

4.3.2.2 Noise Properties of Multi-wavelength TDM Raman Scheme

Similar to the ASE noise generation in single wavelength TDM Raman amplifier, a proper design is required to reduce ASE enhancement due to modulated pump, level of relative intensity noise (RIN) of the pump and high instantaneous gain enhancement due to group velocity matching condition. Two possible solutions to reduce the ASE enhancement are to provide sufficient walk-off between pump pulses and ASE and/or to reduce the instantaneous gain in backward direction by increasing the pulse duty cycle. In order to illustrate the ASE noise generation in multi-wavelength TDM pump, we plot the Forward ASE noise generated by two pump wavelength configurations as shown in Fig. 4.28 and Fig. 4.29. We used similar pump power levels and 50% pulse duty cycle used in Fig. 4.23.

Fig. 4.28 Forward ASE generated by multi-wavelength TDM Raman amplifier with RIN-free pump wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

Fig. 4.29 Forward ASE generated by multi-wavelength TDM Raman amplifier with pump wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm. Pump RIN equals to -120 dB/Hz.

Wider pump wavelength separation as shown in pump configuration (B) causes one pump wavelength to dominate over the others, i.e. having much bigger peak power. This increases both backward instantaneous ASE generation and backward gain, which then

enhance the Forward ASE severely. That is why, shorter pump wavelengths separation with almost uniform pump power levels helps to reduce the ASE enhancement.

In single wavelength TDM pump, less pump-RIN can be tolerated when zero- dispersion wavelength is located between pump and ASE wavelengths. This is due to the sharp increase in Raman instantaneous gain in backward direction due to group-velocity matching condition. In multi-wavelength TDM pump, the tolerance to the pump intensity noise is even lower. This is because higher peak pump power for each pump wavelength is required to achieve the same level of peak flat On-Off gain as in single wavelength pump. This increases the sensitivity of RIN pump level to the Backward ASE even when zero-dispersion wavelength is not located in the mid of pump-noise wavelengths. Fig. 4.29 shows the impact of pump RIN to the ASE enhancement for both pump wavelength combination, as compared to Fig. 4.28. Pump combination (B) shows more sensitivity to the level of pump RIN, due to its high peak pump power at 1444 nm, which generates about 10 dB ASE enhancement at around 1545 nm, under -120 dB/Hz pump RIN.. On the other hand, there is no significant enhancement occurs to the Forward ASE generated by pump combination (A) between RIN-free and -120 dB/Hz RIN level.

Moreover, Fig. 4.30 shows sensitivity of ASE enhancement to the pump RIN level for pump wavelength combination (A). Pump RIN is set equal to -120, -118, -116, -114, -112, -110, -108, -105 dB/Hz.. When pump RIN increases from -120 dB/Hz to -116 dB/Hz, the ASE noise enhancement is increased by maximum 5 dB, however when pump RIN equals to -114 dB/Hz, the ASE experiences dramatic enhancement up to 10 dB. Beyond -114 dB/Hz pump RIN level, the ASE enhancement is very poor and causes much degradation to the effective noise figure, which is bigger than 0 dB effective noise

figure, as shown in Fig. 4.31. In addition to the overall enhancement of the Forward ASE levels, the pump RIN also causes enhancement to the gain ripple, which then affects the ASE ripple as well. From the figure, we see that at -110 dB/Hz RIN level, the ASE ripple experiences degradation as high as 15 dB, as compared to ASE ripple at lower level RIN (-120 dB/Hz). Correspondingly, Fig. 4.31 shows the effective noise figures (NF) at various pump RIN levels. Pump RIN as high as -110 dB/Hz produces as high as 25 dB effective NF. From both figures, we observe a dramatic increase in the sensitivity of ASE enhancement to the pump RIN level, when compared to the results obtained in single wavelength TDM pumping scheme [88].

Fig. 4.30 Forward ASE generated from multi-wavelength pump with pump RIN equals to -120, -118, -116, -114, -112, -110, -108, -105 dB/Hz.

Fig. 4.31 Effective Noise Figures of multi-wavelength TDM Raman amplifier due to different pump RIN levels.

At high repetition rates, when sufficient walk-off between pump and ASE pulses is reached, we could see the reduction of the ASE enhancement as shown in Fig. 4.32. Pump is modulated with 25% duty cycle and assumed to be RIN-free, while the remaining conditions are similar to previous figures. It is clearly shown that as the repetition rate increases, Backward ASE starts to average and total Forward ASE is reduced until it reaches the constant lowest value. Nevertheless, it is important to note that at such high pulse repetition rate, pump-to-pump interaction starts to occur. This is shown when pulse repetition rate is set higher than 109 MHz, the ASE noise at longer wavelength experiences higher gain.

Fig. 4.32 Forward ASE from RIN-free high repetition rates Raman pump pulses with 25% pump pulse duty cycle.

Therefore, in order to optimize both gain and noise performance of TDM Raman scheme, we conclude that bigger pulse duty cycle is a better solution to maintain relatively low noise level and at the same time to avoid any pump-to-pump interaction effect. We show various levels of Forward ASE produced by similar pump combination as above with several bigger pulse duty cycles in Fig. 4.33. Peak pump powers are modified accordingly to produce similar flat 12 dB Raman On-Off gain.

A 50% duty cycle produces -52 dBm maximum Forward ASE, which corresponds to -2.5 dB effective noise figure, whereas 60% duty cycle produces lower maximum Forward ASE of about -58 dBm corresponding to -6.1 dB noise figure. Furthermore, at 80% duty cycle, maximum Forward ASE generated is about -60 dBm corresponding to -6.7 dB noise figure. In conclusion, bigger pulse duty cycle can significantly help in reducing the ASE enhancement without the need to have very high pulse repetition rate.

Fig. 4.33 Forward ASE generated by multi-wavelength RIN-free pumps with greater duty cycles.

Finally, the maximum pulse repetition rate needs to be adjusted accordingly based on the level of duty cycle and pump wavelength combinations. Maximum pulse repetition rate at 60% duty cycle is about 29 MHz, whereas 80% duty cycle sets the maximum pulse repetition rate as low as 14.5 MHz. Please note that all values in Fig. 4.33 were taken under RIN-free condition. Under noisy pump condition, pump RIN as high as -110 dB/Hz at this gain level may increase the ASE level up to 20-30 dB. Therefore, controlling the pump noise level is also an important factor to be taken into consideration when designing TDM Raman scheme.

Based on the similar conditions above, we can also observe the noise contribution from double Rayleigh backscattering (DRS) in multi-wavelength TDM Raman pump scheme. Using (4.3.24) and (4.3.24), we plot the S/DRS ratio with respect to signal wavelengths with initial signal power equals to 0 dBm and Raman On-Off gain is about 10 dB. Pump pulses are assumed to be RIN-free with 1 MHz pulse repetition rate for both pump

wavelength configurations. Pulse duty cycles are set to be 50% and 40% in Fig. 4.34 and Fig. 4.35, respectively.

Fig. 4.34 S/DRS ratios in multi-wavelength TDM Raman amplifier with 50% pulse duty cycle RIN-free pump sources with wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm; and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

Fig. 4.34 shows that shorter pump wavelength separation with almost uniform peak pump powers also produces much better S/DRS due to the avoidance of gain enhancement experienced by SRB noise. Pump wavelength configuration in Fig. 4.34(B) degrades the S/DRS up to 27 dB compared to the one in Fig. 4.34(A). This is due to huge peak pump power level of the 1444 nm pump source that dominates the instantaneous gain enhancement in backward direction to the SRB noise.

Fig. 4.35 S/DRS ratios in multi-wavelength TDM Raman amplifier with 40% pulse duty cycle RIN-free pump sources with wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

It is also shown that bigger pulse duty cycle improves S/DRS significantly, i.e. pump wavelength configuration in Fig. 4.34(A) with 50% pulse duty cycle improves the S/DRS up to 32 dB compared to the one in Fig. 4.35(A) with 40% pulse duty cycle. The S/DRS shown in Fig. 4.35 for pump combination (B) shows negative dB values for some signal wavelength, which means the DRS noise generation is much more than the signal amplification. This causes a very noisy signal, and practically it is no longer possible to detect such a signal. We can only predict theoretically the level of S/DRS ratio under this excessive noise environment and this estimation is important for us to determine the necessary operating condition. If we use pump combination (B), we need to employ bigger pulse duty cycle in order to ensure the lowest S/DRS ratio is still sufficiently high to produce good bit error rate (BER).

Fig. 4.36 S/DRS ratios in multi-wavelength TDM Raman amplifier with 25% (dotted line with circles), 30% (dotted line with squares), 40% (dashed-dotted line), 50% (dashed line), 60% (dotted line), and 80% (solid line) pulse duty cycle RIN-free pump sources with wavelength combinations: 1421 nm, 1442 nm, 1453 nm, 1479 nm.

Fig. 4.37 S/DRS ratios in multi-wavelength TDM Raman amplifier with 50% pulse duty cycle with various pump RIN levels with pump wavelength combinations: 1421 nm, 1442 nm, 1453 nm, 1479 nm.

Fig. 4.36 shows direct comparison of S/DRS values between different pulse duty cycles, when pump combination (A) is employed. When pulse duty cycle is 25% or lower, there is excessive DRS noise generation till the noise dominates the signals, i.e. negative S/DRS ratio. Theoretically, we still can estimate this noise generation and its corresponding S/DRS value, however in real situation; this condition is no longer practical. Therefore, when we want to setup this pumping scheme in distributed Raman amplification, this estimation could give us guideline about which operating condition we should work on. When pulse duty cycle is set 50% or higher (as required by the ASE noise improvement), the S/DRS ratio will be around 30 dB, which is sufficiently high to produce good BER for the WDM signal transmission. All the results reported from Fig. 4.34 to 4.36 are under RIN-free pump condition. Fig. 4.37 shows the impact of pump RIN levels to the S/DRS ratio when pulse duty cycle is 50%. Degradation to the S/DRS ratio can be up to 7 dB and 22 dB when pump RIN equals to -120 dB/Hz and -110 dB/Hz, respectively. Therefore, it is important to include the further enhancement of DRS noise due to pump RIN level. Adjusting the pulse duty cycle based on the RIN levels of the pump is important to optimize the S/DRS. In conclusion, when noisy pump is used, pulse duty cycle bigger than 50% would give us better amplifier noise performance, for both ASE and DRS noise.

4.4 Gaussian Pulse Time Division Multiplexed Raman Pump

We propose to use Gaussian pump pulses in TDM Raman pump scheme in addition to the existing square pulse modulation. We define the Gaussian profile based on this following scheme:

Fig. 4.38 Gaussian Raman pump pulses propagating in backward direction.

In time domain, the amplitude of the Gaussian pulse is given by:

$$f(t) = Ae^{(-t/\sigma)^2} \quad (4.4.1)$$

where A and σ are the maximum amplitude and the pulse half-duration at the $1/e$ points respectively, with Full Width Half Maximum T_{FWHM} defined as:

$$T_{FWHM} = 2\sqrt{\ln(2)}\sigma \quad (4.4.2)$$

$$\text{We define the active period of the pulse as: } T_p = 2\sqrt{2}T_{FWHM} \quad (4.4.3)$$

$$\text{As shown in Fig. 4.38, we define the pulse duty cycle as: } \rho = T_p/T \quad (4.4.4)$$

The active periods T_{p1} and T_{p2} in Fig. 4.38 illustrate the Gaussian pulses with 50% and 100% duty cycles, respectively, corresponding to the same Gaussian areas.

From (4.4.2), (4.4.3) and (4.4.4), we can get the value of σ as:

$$\sigma = \frac{\rho T}{4\sqrt{2\ln(2)}} \quad (4.4.5)$$

From (4.4.5), by knowing the pulse duty cycle and pulse repetition rate, we can get the Gaussian pulse as defined in (4.4.1). From the definition of pulse active period in (4.4.3), a 100% pulse duty cycle will not cause pulse overlapping between two neighboring pulses. This is to ensure minimum interaction between two neighboring pulses. However, as a consequence, in order to generate similar gain level with the same duty cycle level, as compared to square pulse, the Gaussian peak pulse power will be higher than the power of active square pulse, i.e. approximately 2.6 times. We will see this effect in more details in subsequent sections.

4.4.1 Temporal gain fluctuation in Gaussian pulse Time Division Multiplexed Raman Amplifier

Similar to the square pulse TDM, Gaussian pulse TDM Raman pump scheme also introduces temporal gain fluctuation, as shown in Fig. 4.39. At 50 kHz pulse repetition rate, Gaussian pump pulses introduce 0.45 dB more gain variation than the square pulse ones, as can be compared with Fig. 4.6(A). This therefore increases the minimum pulse repetition rate when we design the TDM Raman scheme so to achieve insignificant temporal gain variation.

Fig. 4.39 Temporal gain variation at single wavelength TDM Gaussian Raman pump.

Fig. 4.40 shows the comparison of max-min gain variation with respect to pulse repetition between square pulse and Gaussian pulse modulation. Temporal gain fluctuation introduced by Gaussian pulse is higher at the low repetition rate region. Beyond 200 kHz repetition rate, temporal gain fluctuation effects of both pulse modulations are insignificant.

Fig. 4.40 Maximum-minimum gain variation due to temporal gain variation TDM Raman pump.

4.4.2 Noise properties of Gaussian pulse TDM single wavelength Raman pump

By using similar approach as in previous section, in this section we characterize the proper operating condition for Gaussian pulse TDM to optimize the amplifier performance. Under pump RIN-free condition, Gaussian pump pulses produce a very high ASE enhancement up to 57 dB (from -57 dBm in square pulses, as shown in Fig. 4.7) at 25% duty cycle and 10 dB at 50% duty cycle. At these pulse duty cycles, there is significant enhancement in the peak power of the Gaussian pulse in order to produce similar gain level, i.e. 10 dB On-Off gain.

Fig. 4.41 Forward and Backward ASE noise of Gaussian pulse RIN-free TDM Raman pump.

The dependence of ASE enhancement to the pulse duty cycle is presented in more details in the contour plot in Fig. 4.41. From the definition of pulse duty cycle we have in (4.4.4), we have less possibility of pulse-to-pulse interaction; however this increases the amount of peak pump power, as compared with square pulse, with similar pulse duty cycle level to achieve similar gain. The higher peak pump power significantly increases the Backward ASE generation and amplification, which ultimately increases the total

Forward ASE. This thus degrades the effective noise figure of the amplifier, e.g. to produce less than 0 dB effective noise figure, a 15 dB On-Off Raman gain requires pulse duty cycle to be at least 75%, as shown in Fig. 4.42 below.

Fig. 4.42 Effective Noise Figure (NF) at $\lambda_s = 1550$ nm for Gaussian pulse RIN-free TDM Raman pump at various pulse duty cycles.

Furthermore, the dependence of ASE enhancement level to pump RIN is also presented in more details in the contour plots in Fig. 4.43 to Fig. 4.45. From Fig. 4.43, it's clearly shown that at 12 dB On-Off gain level produced by 100% duty cycle Gaussian pulse, -110 dB/Hz pump RIN produces noise figure less than 0 dB; however, when gain level is raised up to 15 dB, the noise figure is degraded up to around 10 dB. Lower duty cycle, as shown in Fig. 4.44 and Fig. 4.45, increases the sensitivity of amplifier effective noise figures to the pump noise level, e.g. Fig. 4.45 shows that by using 60% pulse duty cycle, On-Off Raman gain higher than 12 dB produces positive effective noise figure regardless the pump RIN level. Moreover, the amplifier will produce a very poor noise figure when

the On-Off gain is set higher than 14 dB, as shown by the green, yellow and red region of the ASE contour in Fig. 4.45.

Fig. 4.43 RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for Gaussian pulse TDM Raman pump with 100% duty cycle.

Fig. 4.44 RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for Gaussian pulse TDM Raman pump with 80% duty cycle.

Fig. 4.45 RIN-induced effective Noise Figure (NF) at $\lambda_s = 1550$ nm for Gaussian pulse TDM Raman pump with 60% duty cycle.

The double Rayleigh backscattering (DRS) noise at this TDM pump scheme is characterized by Fig. 4.46 and Fig. 4.47. Again, some negative S/DRS values shown in both figures do not show a realistic figure, as the noise is significantly dominating the signals. We can only obtain this figure theoretically but not in practical situation. However, this figure gives us an estimate on what is the appropriated operating condition when we use Gaussian pulse in this TDM pumping scheme. From Fig. 4.45, we see that pulse duty cycle greater than 50% is necessary to keep this noise level low. Moreover, Fig. 4.47 shows that -110 dB/Hz pump RIN further triggers the DRS noise generation, which then degrades the S/DRS even more severely. Under 50% pulse duty cycle, the S/DRS ratio is degraded up to 25 dB, as compared with the RIN-free case. This obviously shows a very poor and noisy amplifier. Thus, pulse duty cycle bigger than 50% is required to overcome this problem. We will summarize the necessary operating condition in the next section, when multi-wavelength Gaussian pulse TDM Raman pumping is employed to generate flat Raman gain.

Fig. 4.46 Double Rayleigh Backscattering noise of Gaussian pulse RIN-free TDM Raman pump scheme.

Fig. 4.47 Double Rayleigh Backscattering noise of Gaussian pulse TDM Raman pump scheme (Pump RIN = -110 dB/Hz).

4.4.3 Multi-wavelength Gaussian pulse TDM Raman pump

Based on similar pump configuration in section 4.3.2, we analyze the impact of high peak pump power of Gaussian pump pulses in multi-wavelength TDM Raman pump scheme. Using similar approach as the square pump pulses TDM scheme, we obtain the Forward ASE generated by both pump wavelength combinations under both RIN-free and noisy pump pulses with pulse repetition rate of 500 kHz and 100% pulse duty cycle, as shown in Fig. 4.48 and 4.49, respectively. Under RIN-free pump, pump combination (B) causes much ASE enhancement, especially around 1545 nm signal wavelength, which is about 40 dB higher than pump combination (A). By introducing -120 RIN pump to the system, the pump combination (A) experiences about 5 dB noise enhancement, whereas pump combination (B) is further degraded by about 10 dB, as shown in Fig. 4.49. Again, this design shows more sensitivity to both pump wavelength configuration and pump RIN levels, as compared to the square pulse. More uniform peak pump power distribution among different pump wavelengths, such that no domination of single pump wavelength over others, would help to prevent a dramatic ASE enhancement.

Fig. 4.48 Forward ASE generated by multi-wavelength TDM Gaussian pump pulses with 100% pulse duty cycle and RIN-free pump sources with wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

Fig. 4.49 Forward ASE generated by multi-wavelength TDM Gaussian pump pulses with 100% pulse duty cycle and -120 dB/Hz RIN pump with wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

Furthermore, Fig. 4.50 shows us the impact of pump RIN levels, when only pump wavelength combination (A) is employed. When compared with the square pulse modulation, as shown in Fig. 4.30, Gaussian pulse TDM pumping with -115 dB/Hz causes about 10 dB ASE noise enhancement (on average), whereas square pulse causes slightly lower ASE enhancement, i.e. about 7-8 dB. Furthermore, higher pump RIN causes more severe effect, e.g. -110 dB/Hz RIN causes 30 dB and 50 dB ASE enhancement in square pulse and Gaussian pulse TDM, respectively. From this we draw the necessary operating condition for different kind of pulse modulation used in this TDM pumping scheme, which will optimize both gain and noise performance.

Fig. 4.50 Forward ASE generated by multi-wavelength TDM Gaussian pump pulses with 100% pulse duty cycle and various pump RIN levels, with pump wavelength combinations: 1421 nm, 1442 nm, 1453 nm, 1479 nm.

Fig. 4.51 Effective Noise Figures of multi-wavelength TDM Raman amplifier due to different pump RIN levels with 100% pulse duty cycle and pump wavelength combinations 1421 nm, 1442 nm, 1453 nm, 1479 nm.

The major difference between this Gaussian pulse and square pulse is when we use Gaussian pulse, we only need to define the pulse duty cycle properly, by defining the active pulse period T_p , such that very minimum amount of pulse power interacting with neighboring pulses. At that point, we define this duty cycle as the 100% duty cycle. By

doing this, not much adjustment to the pulse duty cycle needs to be done, unless the fiber has high dispersion values, which cause high group-velocity differences among pump pulses. In Fig. 4.52, we plot the Forward ASE generated when we vary the Gaussian pulse duty cycles under RIN-free pump. As compared to the square pump pulse, a 100% Gaussian pulse results causes similar ASE noise levels as the 50% square pulse. A 90% pulse duty cycle causes 5 dB enhancements in the ASE noise levels. Further reduction in pulse duty cycle will cause significant ASE enhancement. In fact, based on our design of Gaussian pulse, pulse duty cycle not lower than 90% is sufficiently good to prevent pump overlapping.

Fig. 4.52 Forward ASE generated by multi-wavelength TDM Gaussian pump pulses with various pulse duty cycles and RIN-free pump with wavelength combinations: 1421 nm, 1442 nm, 1453 nm, 1479 nm.

Finally, we also analyze the noise contributed from double Rayleigh backscattering process in multi-wavelength Gaussian pump TDM Raman amplifier. Fig. 4.53 shows the DRS noise performance under two pump wavelength configurations that generate a flat Raman gain.

Fig. 4.53 Double Rayleigh Backscattering noise of Gaussian pulse multi-wavelength TDM Raman pump scheme (RIN-free) 100% duty cycle with pump wavelength combinations: (A). 1421 nm, 1442 nm, 1453 nm, 1479 nm, and (B) 1420 nm, 1444 nm, 1477 nm, 1490 nm.

From this figure, it is clearly shown that wider pump wavelength separation with one pump wavelength dominating the gain contribution severely degrades the S/DRS ratio under this Gaussian pump pulse scheme.

Fig. 4.54 Double Rayleigh Backscattering noise of Gaussian pulse multi-wavelength TDM Raman pump scheme (RIN-free, various duty cycles).

Fig. 4.55 Double Rayleigh Backscattering noise of Gaussian pulse multi-wavelength TDM Raman pump scheme (various RIN, duty cycles = 100%).

The S/DRS in Fig. 4.53 is obtained under RIN-free pump with 100% duty cycle. When we vary the duty cycle levels, we observe that duty cycle lower than 90% shows considerable amount degradation to the S/DRS ratio, as shown in Fig. 4.54. However, when pulse duty cycle is further reduced to 80% and lower, significant degradation to the S/DRS occurs. In addition to that, we also show that pump RIN greater than -120 dB/Hz may significantly degrade the S/DRS ratio, i.e. lower than 20 dB, as shown in Fig. 4.55. Therefore, in order to optimize the Raman amplifier performance by using Gaussian pulse TDM Raman pump scheme, we need to set pulse duty cycle greater than 90% and control the pump RIN level not to be greater than -120 dB/Hz. A moderate level pulse repetition rate is sufficient, i.e. greater than 200 kHz, to avoid the temporal gain fluctuation due to pump modulation.

Comparison of both ASE and DRS noises generated by both square and Gaussian pulses are tabulated in Table 5 and 6 below. These tables give us estimation on the amplifier

noise performance under certain operating condition, from which we can use when designing this TDM Raman pumping scheme. From the tables, we observe that we use square pulse modulation, pulse duty cycle greater than 60% would give us better noise performance, i.e. ASE ripple, average ASE levels and S/DRS ratio, and also greater tolerance to the pump RIN levels. In Gaussian pulse TDM scheme, due to its design and definition of pulse duty cycle, the noise generation is more sensitive to the pulse duty cycles and pump RIN levels. Under 100% pulse duty cycle, -120 dB/Hz pump RIN could induce positive effective noise figure. As compared to square pulse scheme, 100% Gaussian pulse produces almost noise performance as the 50% square pulse. From this, we can see that square pulse modulation has more possibility to further improve the noise performance, i.e. by further increasing the pulse duty cycle. Further improvement can also be done to the Gaussian pulse modulation by slightly increasing the period of the active pulse T_p in (4.4.3), which then slightly reduces the peak Gaussian pulse and ultimately reduce both ASE and DRS noise enhancement.

Table 5 Noise properties of the Square pulse TDM Raman pumping

Pulse duty cycles	Pump RIN levels (dB/Hz)	Forward ASE ripple (dB)	Average Forward ASE (dBm)	Effective Noise Figure (dB)	S/DRS (dB)
50%	-120	± 2.5	-53	-10 to -5	25-35
50%	-114	± 6	-46	-7.5 to 2.5	22-32
60%	RIN free	± 2	-56	-	35-40
80%	RIN free	± 1	-57.5	-	40-45

Table 6 Noise properties of the Gaussian pulse TDM Raman pumping

Pulse duty cycles	Pump RIN levels (dB/Hz)	Forward ASE ripple (dB)	Average Forward ASE (dBm)	Effective Noise Figure (dB)	S/DRS (dB)
100%	-120	± 4	-45	-8 to 2	20-25
100%	-115	± 6	-50	-5 to 8	10-25
90%	RIN free	± 5	-48	-	20-30

4.5 Summary

In this chapter, we report multi-wavelength Raman pump in the form of Time-Division Multiplexed Pump to generate flat Raman gain for DWDM communication. By using this scheme, we will optimize both gain and noise performance as there is no pump power transfer and four-wave mixing noise induced by pump-to-pump interaction effect. In the widely known single-wavelength pump modulation, pulse repetition rate has a minimum value so as to avoid temporal gain fluctuation. In multi-wavelength TDM Raman pump, we conclude two necessary conditions to optimize its performance: 1). Pulse repetition rate also has maximum value, beyond which pump-to-pump interaction becomes severe, 2). Bigger pulse duty cycle is necessary to improve the signal to noise ratio of the amplifier. We present complete characterization of both amplifier gain and noise performance by taking into account some important factors, such as fiber properties (attenuation, gain coefficient, Rayleigh backscattering coefficient and dispersion), pump power, wavelength combination and RIN level. We also conclude that shorter pump wavelength separation with almost uniform pump power reduces both ASE and DRS enhancement. In addition to square pulse modulation, we introduce Gaussian pulse as an alternative modulation format for this application.

When we use square pump pulse modulation, pulse duty cycle bigger than 50% is necessary to ensure the optical signal to noise ratio better than 20 dB under -110 dB/Hz pump RIN level. Under this condition, a ratio of signal-DRS noise can be up to 30 dB. Moreover, when we use Gaussian pump pulse modulation, based on our defined pulse duty cycle, it is required to have pulse duty cycle bigger than 90% to ensure both optimized ASE and DRS noise performance. Less pump RIN can be tolerated under this pulse modulation, e.g. RIN = -115 dB/Hz or less produces about -5 to 8 dB effective

noise figure. However, the sensitivity of DRS to pump RIN level requires pump RIN less than or equal to -120 dB/Hz to produce S/DRS bigger than 20 dB. Clearly, Gaussian pulse imposes more stringent requirement as compared with square pulse. On the other hand, Gaussian pulse modulation provides better protection to avoid the pump-to-pump interaction, especially at high gain level. Both modulation techniques can be employed in Time Division Multiplexing Raman pump scheme with proper operating condition to optimize its performance.

CHAPTER 5

Identification of Nonlinear Raman Kernels in DWDM Communication

5.1 Introduction

The increase in system capacity can be achieved by having both larger number of channels and higher data rates. In long haul transmission, longer transmission span helps reducing the cost as fewer components are used, thus providing more economic incentives. This corresponds to the need of higher channel powers to sustain fiber attenuation, which increases the effect of fiber nonlinearities. Fiber nonlinearities ultimately determine the fundamental transmission limits, thus requiring more detailed investigation. Basically, nonlinear effects are classified into two major types: scattering and Kerr effect. Scattering process, particularly Raman scattering, has been described in previous chapters; whereas Kerr effect refers to the intensity dependent refractive index, which in turn gives rise to the intensity dependent phase shift of the optical field. This leads to some nonlinear phenomena, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM).

In this chapter, we propose a method to identify the interaction between various channels in DWDM communication due to nonlinear effect, particularly Raman scattering effect. We approximate the fiber nonlinearity by using linearization method, in a form of Volterra series. By using this series, we classify the fiber nonlinearity components into third order, fifth order or even higher order. It was proven that the linearization for weakly nonlinear system in fiber transmission by using this series shows quite good

accuracy as compared to the well-known split-step Fourier method [90]. By using the cross-correlation method and mean square error algorithm, we can obtain the series of identification formula to determine the third order or even higher order kernels representing the Raman scattering effect. We report the identification of Raman kernels in WDM transmission for On-Off Keying modulation format.

5.2 Nonlinear Effects in Optical Fiber Transmission

5.2.1 Kerr Effect

Refractive index of the silica increases as the intensity increases as:

$$n = n_0 + n_2 I \quad (5.2.1)$$

where n_0 is the linear refractive index at low power and I is the intensity of the optical field, defined as $I = P/A_{eff}$, where P denotes the optical power and A_{eff} denotes the effective cross area. The propagation of optical pulses in single mode fiber subject to linear dispersion and nonlinearities are governed by nonlinear Schrödinger equation

(NLSE) [91]:

$$\frac{\partial u}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial t^2} + \frac{\alpha}{2} u = i \gamma |u|^2 u \quad (5.2.2)$$

where u is the normalized pulse amplitude that $|u|^2$ represents the optical power; β_2 and α denote the group velocity dispersion and fiber loss, respectively. The fiber nonlinear coefficient γ is defined as $\gamma = \frac{n_2 \omega_0}{c A_{eff}}$, where ω_0 is the optical carrier frequency.

The NLSE above is commonly solved numerically by using Split-Step Fourier Method (SSFM) proposed by Tappert (1993) [92].

Self-phase modulation (SPM) is the change of optical phase of an optical field by its own intensity. The phase shift after propagation over distance L is given by:

$$\Delta\Phi_{SPM} = \gamma P L_{eff} \quad (5.2.3)$$

where L_{eff} denotes the effective length with the fiber loss being taken into account. This phase shift induces a varying instantaneous frequency across the pulse, which is defined as:

$$\partial\omega(t) = -\frac{d\Phi_{SPM}}{dt} = -\gamma \frac{dP}{dt} L_{eff} \quad (5.2.4)$$

The time dependence of $\partial\omega$ is referred to as frequency chirping. The chirp induced by SPM increases as pulse propagate, thus new frequency components are continuously generated as pulse propagates, which then broaden the spectrum. In addition, as the bit rate increases, the rate of change of power with respect to time increases thus increasing the frequency chirp due to SPM. However, chromatic dispersion causes pulse broadening such that the rate of change of power reduces. Therefore, two key parameters are defined to measure the significance of SPM: 1) dispersion length $L_D = T_0^2 / |\beta_2|$ and 2) nonlinear length $L_{NL} = 1/\gamma P_0$, when $L_{NL} < L_D$, SPM will be significant.

In WDM transmission, the interaction between lights at different frequency components leads to phase modulation of the channels and thus generates modulation sidebands at new frequencies, named Four-Wave Mixing (FWM). This phenomenon has been explained in details in the previous section. Moreover, coupling among optical fields through fiber nonlinearity also induces cross phase modulation (XPM) without involving energy transfer between them. In XPM, the phase of one optical field is modulated by the intensity fluctuations of other optical fields with different frequencies [93].

The origin of XPM can be seen from nonlinear polarization induced by two frequency electric fields:

$$P_{NL}(z, t) = \frac{1}{2} \hat{x} [P_{NL}(\omega_1) \exp(-i\omega_1 t) + P_{NL}(\omega_2) \exp(-i\omega_2 t) + P_{NL}(2\omega_1 - \omega_2) \exp[-i(2\omega_1 - \omega_2)t] + P_{NL}(2\omega_2 - \omega_1) \exp[-i(2\omega_2 - \omega_1)t] + c.c] \quad (5.2.5)$$

$$\text{where: } P_{NL}(\omega_1) = \chi_{eff} (|E_1|^2 + 2|E_2|^2) E_1 \quad (5.2.6)$$

$$P_{NL}(\omega_2) = \chi_{eff} (|E_2|^2 + 2|E_1|^2) E_2 \quad (5.2.7)$$

$$P_{NL}(2\omega_1 - \omega_2) = \chi_{eff} E_1^2 E_2^* \quad (5.2.8)$$

$$P_{NL}(2\omega_2 - \omega_1) = \chi_{eff} E_2^2 E_1^* \quad (5.2.9)$$

with $\chi_{eff} = (3\epsilon_0 / 4) \chi_{xxxx}^{(3)}$ is the effective nonlinear parameter.

The first two terms in (5.2.5) correspond to nonlinear phenomena due to intensity dependent refractive index whereas the subsequent two terms correspond to Four-Wave Mixing where new frequency component is generated. The nonlinear polarization factors in (5.2.6) and (5.2.7) are responsible for self-phase modulation and cross-phase modulation. The first term is responsible for SPM, whereas the second ones refer to XPM. It clearly shows that XPM is twice as effective as SPM for the same intensity. The phase shift induced XPM over a distance Δz is defined as:

$$\Delta\Phi_{XPM} = 2\gamma P_p \Delta z \quad (5.2.10)$$

where P_p is the power of interfering optical pulse.

5.2.2 Identification of Nonlinear System

A system can be defined in a mathematical representation by which system excitation is mapped into system response. It is an assemblage of interacting things, i.e. independent source of parameter known as input and input-dependent variation of parameter known as output, which is symbolically represented by:

$$y = \tilde{T}[x] \quad (5.2.11)$$

where y, x, T denote input, output and system operator respectively.

When sufficient information concerning the system is available, a set of equations that accurately represents the system can be derived. Otherwise the system may be represented as a black box where the relationship between input and output is not so derivable. Two major aspects of system theory are analysis and synthesis. In analysis, the operator $\tilde{T}$ of a given system is determined. This is called *system-identification*. In synthesis, a system with a given operator is constructed from a given set of elemental systems. The constructed system and the expression of the constructed system operator in terms of the elemental system operators are called a model of the given system.

Generally, the model of a system can be classified into either *implicit* or *explicit*. An implicit model is the one in which the system response is expressed as an implicit operation on the system input, e.g. *differential-equation system*, whereas an explicit model is the one in which the system response is expressed as an explicit operation on the system input, e.g. *convolution-integral system*. The significance of each model above depends on the specific question being asked and specific understanding of the system being sought, e.g. study of system oscillation is best achieved by using implicit model,

whereas study of spectrum of the system response is best achieved by using explicit model.

Volterra series is one of the explicit models that are being used intensively in system model especially when there is not sufficient information concerning the system available, i.e. black box system approach. This was originally proposed by Vito Volterra in the 1880s as a generalization of Taylor series expansion of a function. It was further developed in 1910 by Frechet, who was studying continuous functional. He showed that “any continuous functional can be represented by a series of functionals of integer order whose convergence is uniform in all compact sets of continuous functionals”, as

$$\begin{aligned}
 F(x) = & k_0 + \int_a^b k_1(\tau)x(\tau)d\tau + \int_a^b \int_a^b k_2(\tau_1, \tau_2)x(\tau_1)x(\tau_2)d\tau_1d\tau_2 \\
 & + \int_a^b \int_a^b \int_a^b k_3(\tau_1, \tau_2, \tau_3)x(\tau_1)x(\tau_2)x(\tau_3)d\tau_1d\tau_2d\tau_3 + \dots
 \end{aligned} \tag{5.2.12}$$

In the analysis of nonlinear system, Wiener (1930) showed that by means of a Gram-Schmidt type orthogonalization process, the input-output relationship for a white Gaussian input process is expressed by orthogonal series (Wiener series):

$$y(t) = \sum_{n=0}^{\infty} [G_n(k_n, x(t))] \tag{5.2.13}$$

where $\overline{[G_n(k_n, x(t))][G_m(k_m, x(t))]} = 0$ for $m \neq n$; k_n is the n^{th} degree kernel in the n^{th} degree functional G_n , where the first three terms are defined as:

$$\begin{aligned}
 G_1\{k_1, x(t)\} &= \int_{-\infty}^{\infty} k_1(\tau)x(t-\tau)d\tau \\
 G_2\{k_2, x(t)\} &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_2(\tau_1, \tau_2)x(t-\tau_1)x(t-\tau_2)d\tau_1d\tau_2 - A \int_{-\infty}^{\infty} k_2(\tau_1, \tau_2)d\tau_1
 \end{aligned}$$

$$G_3\{k_3, x(t)\} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 \\ - 3A \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) d\tau_1 d\tau_2$$

Volterra series expansion can be used in the analysis of weakly nonlinear systems which procedure requires the algebraic determination of Volterra nonlinear transfer function. The complexity of the expansion depends on the level of the nonlinearity of the system, which ultimately determines the complexity of kernel coefficient determination. However, this model is useful in the case where spectrum information of the system is required, as mentioned above. By proper identification of nonlinear kernel, we obtain the spectrum information of the nonlinearity, which ultimately enables us to design corresponding nonlinear compensator/equalizer of the system. Therefore, the main objective of this work is to implement this series expansion into fiber nonlinearity, particularly stimulated Raman scattering and to identify the component of Raman nonlinearity kernel for various types of data transmission.

5.3 Volterra Series Properties

A time invariant nonlinear system with input $x(t)$ and output $y(t)$ can be expressed by this relation:

$$y(t) = h_0 + \int_{-\infty}^{\infty} h_1(\tau) x(t - \tau) d\tau + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) x(t - \tau_1) x(t - \tau_2) d\tau_1 d\tau_2 + \\ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_3(\tau_1, \tau_2, \tau_3) x(t - \tau_1) x(t - \tau_2) x(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 + \dots \\ \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} h_n(\tau_1, \tau_2, \dots, \tau_n) x(t - \tau_1) x(t - \tau_2) \dots x(t - \tau_n) d\tau_1 d\tau_2 \dots d\tau_n + \dots \quad (5.3.1)$$

Another way of expressing (5.3.1) is

$$y(t) = H_0 + H_1[x(t)] + H_2[x(t)] + H_3[x(t)] + \dots + H_n[x(t)] + \dots \quad (5.3.2)$$

$$\text{which } H_n[x(t)] = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} h_n(\tau_1, \tau_2, \dots, \tau_n) x(t - \tau_1) x(t - \tau_2) \dots x(t - \tau_n) d\tau_1 d\tau_2 \dots d\tau_n$$

5.3.1 First Order Volterra Series System

Consider a linear and time-invariant (LTI) system, whose system response is

$$y(t) = \int_{-\infty}^{\infty} h(\tau) x(t - \tau) d\tau \quad (5.3.3)$$

Due to the commutative property of convolution, (5.3.3) can also be expressed as:

$$y(t) = \int_{-\infty}^{\infty} h(t - \tau) x(\tau) d\tau \quad (5.3.4)$$

which can be divided into two parts: (a) $\int_{-\infty}^t h(t - \tau) x(\tau) d\tau$ and (b) $\int_t^{\infty} h(t - \tau) x(\tau) d\tau$.

As the system response is not a function of the future of the input, part (b) above must be zero, which corresponds to $h(t - \tau) = 0$ for $\tau > t$. Thus, $h(\sigma) = 0$ for $\sigma < 0$. This is the necessary and sufficient condition for an LTI system to be *causal*.

A system is said to be *stable* if every bounded input gives rise to bounded output. By

$$\text{Volterra series, a stable LTI system is if and only if: } \int_{-\infty}^{\infty} |h_1(\tau)| d\tau < \infty \quad (5.3.5)$$

The condition (5.3.5) is both necessary and sufficient to ensure a stable LTI system.

We can define the characteristic function of a system, i.e. $y(t) = cx(t)$, in which c is constant, from the first order kernel when input phasor $x(t) = e^{j\omega t}$ is applied, which

produces

$$y(t) = \int_{-\infty}^{\infty} h(\tau) e^{j\omega(t-\tau)} d\tau \quad (5.3.6)$$

$$y(t) = H_1(j\omega)x(t) \quad (5.3.7)$$

From (5.3.6), we observe that $|H_1(j\omega)| \leq \int_{-\infty}^{\infty} |h_1(\tau)| d\tau$, which means the stability condition

of LTI system ensures the transfer function $H_1(j\omega)$ and therefore if the input is bounded,

i.e. $|x(t)| = |e^{j\omega t}| = 1$, the output will also be bounded, i.e. $|y(t)| = |H_1(j\omega)|$.

Generally the characteristic function of a stable LTI is described by gain and phase shift

as a function of ω . When a stable LTI system has an input for which $\int_{-\infty}^{\infty} |x(t)| dt < \infty$, the

Fourier transform pair $X(j\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt$ has the system response

$$Y(j\omega) = \int_{-\infty}^{\infty} y(t) e^{-j\omega t} dt = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_1(\tau) x(t-\tau) e^{-j\omega t} d\tau dt \quad (5.3.8)$$

By introducing variable $\sigma = t - \tau$, we obtain $Y(j\omega) = H_1(j\omega)X(j\omega)$ (5.3.9)

5.3.2 Second and Higher Order Volterra Series System

The p^{th} order Volterra operator is an extension of the 1^{st} order Volterra operation. Based on (5.2.11), the response of the homogeneous second order operator is

$$y(t) = \tilde{T}_2[x(t)] = \tilde{T}_2 \left[\sum_{n=1}^N c_n x_n(t) \right] \quad (5.3.10)$$

which is translated into system response with Volterra operator as $y(t) = H_2[x(t)] \Rightarrow$

$$y(t) = H_2[x_1(t) + x_2(t)] = H_2[x_1(t)] + 2H_2\{x_1(t), x_2(t)\} + H_2[x_2(t)] \quad (5.3.11)$$

$$\text{where } H_2[x_n(t)] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) x_n(t - \tau_1) x_n(t - \tau_2) d\tau_1 d\tau_2 \quad (5.3.12)$$

$$\text{and } H_2\{x_1(t), x_2(t)\} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) x_1(t - \tau_1) x_2(t - \tau_2) d\tau_1 d\tau_2$$

Rearrange (5.3.11), we obtain the basic relation of the *bilinear* Volterra operator in terms of the second order Volterra operator as:

$$g(t) \approx 2H_2\{x_1(t), x_2(t)\} = y(t) - H_2[x_1(t)] - H_2[x_2(t)] \quad (5.3.13)$$

This relationship enables us to measure the second order kernel by getting the response of unit impulse input $x_1(t) = u_0(t - T_1)$ and $x_2(t) = u_0(t - T_2)$. The kernel $h_2(\tau_1, \tau_2)$ is obtained as half the value of $g(t)$ along a 45° in the $(\tau_1 - \tau_2)$ plane.

Based on causality principle, second order Volterra operator is causal if and only if $h_2(\tau_1, \tau_2) = 0$ for $\tau_1 < 0$ and/or $\tau_2 < 0$ so that $h_2(\tau_1, \tau_2)$ can be non-zero only in the first quadrant of the $(\tau_1 - \tau_2)$ plane. The condition stipulated above is necessary but not sufficient to ensure that the second-order system is causal. For non-causal system, the output is at rest at $t < T$ if the input $x_1(t) = 0$ for $t < T$. Based on (5.3.5), we can intuitively set a condition for a stable second order system as:

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |h_2(\tau_1, \tau_2)| d\tau_1 d\tau_2 < \infty \quad (5.3.14)$$

This is a sufficient but not necessary condition for a stable second order system, i.e. there exist kernels of stable second order Volterra operators H_2 that do not exactly satisfy (5.3.14). Similar to the first order Volterra system, the response function of the second-order Volterra system can be determined when the stability condition is fulfilled, i.e. integral with respect to τ_1 and τ_2 converge.

The two-dimensional Fourier transform of (5.3.14) is obtained by:

$$H_2(j\omega_1, j\omega_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) e^{-j\omega_1 \tau_1} e^{-j\omega_2 \tau_2} d\tau_1 d\tau_2 \quad (5.3.15)$$

The homogeneous response function of the system from (5.3.10) can be expressed as:

$$y_{(2)}(t_1, t_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) x(t_1 - \tau_1) x(t_2 - \tau_2) d\tau_1 d\tau_2 \quad (5.3.16)$$

and its transform is given by

$$Y_{(2)}(j\omega_1, j\omega_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y_{(2)}(t_1, t_2) e^{-j(\omega_1 t_1 + \omega_2 t_2)} dt_1 dt_2 \quad (5.3.17)$$

which ultimately shows the input-output relation as:

$$Y_{(2)}(j\omega_1, j\omega_2) = H_2(j\omega_1, j\omega_2) X(j\omega_1) X(j\omega_2) \quad (5.3.18)$$

Equation (5.3.18) shows that the response function of the system is expressed as the multiplication of kernel transform and all the input transform of the system. The kernel function represents the interaction between inputs with different frequency ω_1 and ω_2 .

Let $t_1 = t_2 = t$, the output function can be expressed as:

$$y(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} Y_{(2)}(j\omega) e^{j\omega t} d\omega = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Y_{(2)}(j\omega_1, j\omega_2) e^{j(\omega_1 + \omega_2)t} d\omega_1 d\omega_2 \quad (5.3.19)$$

Thus

$$Y(j\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} Y_{(2)}(j\omega_1, j\omega - j\omega_1) d\omega_1 \quad (5.3.20)$$

where $\omega = \omega_1 + \omega_2$.

The kernel transform plays an important role in the synthesis of the system. For a given n th order kernel function, the n^{th} order operator can be synthesized by using a finite number of multiplier. However, this property will not be much used in this work.

By using similar approach as above, we could obtain the expression, causality and stability necessary and sufficient and finally the kernel transform. The homogeneous response function of the p^{th} order Volterra system is expressed as:

$$y_{(p)}(t_1, \dots, t_p) = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} h_p(\tau_1, \dots, \tau_p) x(t_1 - \tau_1) \dots x(t_p - \tau_p) d\tau_1 \dots d\tau_p \quad (5.3.21)$$

for which the kernel transform is

$$Y_{(p)}(\omega_1, \dots, \omega_p) = H_p(\omega_1, \dots, \omega_p) X_1(\omega_1) \dots X_p(\omega_p) \quad (5.3.22)$$

$$\text{and } Y_{(p)}(j\omega) = \frac{1}{(2\pi)^{p-1}} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} Y_{(p)}(j\omega - j\omega_1, j\omega_1 - j\omega_2, \dots, j\omega_{p-1}) d\omega_1 \dots d\omega_{p-1} \quad (5.3.23)$$

5.3.3 Response Characteristics of Stationary Systems

Volterra functional $H_n[x(t)]$ is a time function that is dependent on the input $x(t)$, therefore an orthogonal set of functions from the Volterra functional is formed based on specific input, relative to which the members of the set are to be orthogonal. Based on this fact, the considerations taken in choosing an appropriated input are that its use will result in the characterization of the unknown nonlinear system in a physically meaningful manner and also its use must be practical both theoretically and experimentally.

There are several types of input signals generating output with special features that characterize the system. When the input is composed by *impulse* functions $x(t) = \delta_0(t)$, the system response traces out the kernel, i.e. $y(t) = h(t)$ for $t > 0$. Similarly, for p^{th} order homogeneous system as in (5.3.21), the input $x(t) = \delta_0(t)$ yields the response $h_p(\tau_1, \dots, \tau_p)$.

When the input is a single frequency *sinusoidal* function with frequency ω $x(t) = 2A \cos(\omega t), t \geq 0$, the output of a linear time-invariant system can be expressed as:

$$y(t) = A \int_{-\infty}^{\infty} h(\tau) e^{j\omega(t-\tau)} d\tau + A \int_{-\infty}^{\infty} h(\tau) e^{-j\omega(t-\tau)} d\tau \quad (5.3.24)$$

with its steady state response, i.e. $t \rightarrow \infty$ is

$$y_{ss}(t) = AH(j\omega)e^{j\omega t} + AH(-j\omega)e^{-j\omega t} \quad (5.3.25)$$

The output function in (5.3.25) can be simplified in short form as:

$$y_{ss}(t) = 2A|H(j\omega)|\cos[\omega t + \angle H(j\omega)] \quad (5.3.26)$$

This shows that the output of sinusoidal input signal is also sinusoidal with frequency ω , amplitude and phase as a function of the kernel function $H(j\omega)$.

When the inputs composed by more than one frequency component are present in the system with Volterra order greater than one, the output response will be more complicated by the nonlinear interaction. Consider M-tone input $x(t)$ given by

$$x(t) = \sum_{k=1}^K |A_k| \cos(\omega_k t) = \sum_{k=1}^K \left[\frac{A_k}{2} \exp(j\omega_k t) + \frac{A_k^*}{2} \exp(-j\omega_k t) \right] \quad t \geq 0 \quad (5.3.27)$$

Denote $A_{(-k)} = A_k^*$ and $\omega_{-k} = -\omega_k$, (5.3.27) can be rewritten as:

$$x(t) = \sum_{\substack{k=-K \\ k \neq 0}}^K \frac{A_k}{2} \exp(j\omega_k t) \quad (5.3.28)$$

which gives steady state response contains frequency range

$$\omega_{out} = \sum_{\substack{k=-K \\ k \neq 0}}^K m_k \omega_k = \sum_{k=1}^K (m_k \omega_k + m_{-k} \omega_{-k}) = \sum_{k=1}^K (m_k - m_{-k}) \omega_k \quad (5.3.29)$$

where m_k are nonnegative integers; $k = \pm 1, \pm 2, \dots, \pm M$; and $\sum_{k=-K}^K m_k = p$.

The steady state response function of p^{th} order homogeneous system is given by

$$y_{(p)}(t) = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} h_{(p)}(\tau_1, \dots, \tau_p) \prod_{i=1}^p x(t - \tau_i) d\tau_i \quad (5.3.30)$$

From (5.3.28) and (5.3.30), the frequency component of the response function of p^{th} order nonlinear homogeneous system is shown by:

$$y_{(p)\omega_{out}}(t) = n! \left[\prod_{\substack{k=-K \\ k \neq 0}}^K \frac{(A_k/2)^{m_k}}{m_k!} \right] H_{(p)}\{m_{-1}[j\omega_{-1}], \dots, m_{-1}[j\omega_{-1}], m_1[j\omega_1], \dots, m_{-k}[j\omega_{-k}]\} \exp(j\omega_{out}t) \quad (5.3.31)$$

Consider two frequencies ($K = 2$) input signal with ω_1 and ω_2 , according to (5.3.31) the response at ω_1 is given as:

$$y_{\omega_1}(t) = \left[\frac{1}{2} A_1 H_1(j\omega_1) + \frac{3}{8} |A_1|^2 A_1 H_3(-j\omega_1, j\omega_1, j\omega_1) + \frac{3}{4} |A_2|^2 A_1 H_3(-j\omega_2, j\omega_2, j\omega_1) \right] \exp(j\omega_1 t) \\ + \left[\frac{1}{2} A_1^* H_1(-j\omega_1) + \frac{3}{8} |A_1|^2 A_1^* H_3(-j\omega_1, j\omega_1, -j\omega_1) + \frac{3}{4} |A_2|^2 A_1^* H_3(-j\omega_2, j\omega_2, -j\omega_1) \right] \exp(-j\omega_1 t)$$

All the types of input signal above are deterministic signal where the behavior can be determined by certain mathematical expression, rule or table. To characterize the unknown nonlinear system, the response function must be taken based on several sampled signals, which are generated by *random* (or *stochastic*) process. Random signal behavior can only be analyzed by statistics and probability, and due to the randomness nature, average values are usually studied.

Suppose the input of the system as in (5.3.3) is a sample function of a real stochastic process with mean value $E[x(t)]$ defined as:

$$E[x(t)] = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t) dt \quad (5.3.32)$$

and autocorrelation $R_{xx}(t_1, t_2)$ as:

$$R_{xx}(t_1, t_2) = E[x(t_1)x(t_2)] \quad (5.3.33)$$

The average output response of an LTI system is given by:

$$E[y(t)] = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T \int_{-\infty}^{\infty} h(\tau) x(t - \tau) d\tau dt = E[x(t - \tau)] \int_{-\infty}^{\infty} h(\tau) d\tau \quad (5.3.34)$$

Furthermore, the cross-correlation between output-input can be obtained from

$$y(t_1)x(t_2) = \int_{-\infty}^{\infty} h_1(\tau)x(t_1 - \tau)x(t_2)d\tau \Rightarrow R_{yx}(t_1, t_2) = \int_{-\infty}^{\infty} h_1(\tau)R_{xx}(t_1 - \tau, t_2)d\tau \quad (5.3.35)$$

Similarly, the output autocorrelation can be obtained from:

$$\begin{aligned} y(t_1)y(t_2) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_1(\tau_1)h_1(\tau_2)x(t_1 - \tau_1)x(t_2 - \tau_2)d\tau_1d\tau_2 \Rightarrow \\ R_{yy}(t_1, t_2) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_1(\tau_1)h_1(\tau_2)R_{xx}(t_1 - \tau_1, t_2 - \tau_2)d\tau_1d\tau_2 \end{aligned} \quad (5.3.36)$$

The autocorrelation function is usually expressed as the difference ($t_1 - t_2 = \sigma$), thus it can be written as $R(\sigma)$. By using this method, we can thus obtain the kernel component $h(\tau)$.

5.3.4 Discrete-Time Volterra Series

Nonlinear system can also be expressed as discrete time system. Consider a discrete-system representation as

$$y(k) = \sum_{i_1=0}^{\infty} \dots \sum_{i_n=0}^{\infty} h(i_1, \dots, i_n)x(k - i_1) \dots x(k - i_n), k = 0, 1, 2, \dots \quad (5.3.37)$$

It shows that when the input and output $x(k)$ and $y(k)$ are zeros for $k < 0$ and the kernel $h(i_1, \dots, i_n)$ is zero for any one of $(i_1, \dots, i_n)$ is zero; the system is *stationary*, *causal* and *degree-n homogeneous*.

Based on (5.3.37), the output is basically the impulse response of the input

$$\text{when } h(i_1, \dots, i_n) = \begin{cases} 1, i_1 = \dots = i_n = 0 \\ 0, \text{otherwise} \end{cases}.$$

The output $y(k)$ in (5.3.37) can also be represented as

$$y(k) = \sum_{i_1=0}^k \dots \sum_{i_n=0}^k h(k, i_1, \dots, i_n) x(i_1) \dots x(i_n), k = 0, 1, 2, \dots \quad (5.3.38)$$

Based on stationary principle, where $h(t, i_1, \dots, i_n) = h(0, i_1 - t, \dots, i_n - t)$ the kernel $h(i_1, \dots, i_n)$ can be represented as $g(0, -i_1, \dots, -i_n)$, which yields a representation:

$$y(k) = \sum_{i_1=0}^k \dots \sum_{i_n=0}^k h(k - i_1, \dots, k - i_n) x(i_1) \dots x(i_n), k = 0, 1, 2, \dots \quad (5.3.39)$$

We employ this property, i.e. discrete time Volterra series, in our numerical calculation for identification of Raman kernels, which will be presented in more details in the next section.

5.3.5 Analysis of Single Mode Fiber Transmission by Volterra Series Transfer

The generalized nonlinear Schrödinger (NLS) wave equation is commonly used to describe the slowly varying complex envelope of the optical field in the fiber. It was derived from Maxwell's equations both in time domain [94] and frequency domain [95]. Some methods have been used to solve the NLS equation and explain the linear and nonlinear phenomena in optical fiber. Those methods are classified into two major methods [96]: Finite Difference Methods and Finite Fourier Transform or Pseudo-spectral Methods. The first group of method consists of explicit method, such as classical explicit method and implicit method, such as Crank-Nicolson implicit method. The latter group of methods consists of Split Step Fourier Method and Pseudo-Spectral Method.

The Split Step Fourier Method (SSFM) is well known and most accurate in solving the nonlinear Schrödinger equation. Yao *et al.* [94] analyzed the effect of fiber nonlinearity and dispersion on a fiber optical CDMA communication system. Using the new approach on defining the pulse propagation and solving it using SSFM, the limitation of peak pulse power and pulse width in CDMA fiber system was evaluated. Marcuse [97] presented the approximated analytical expression for the root mean square (RMS) pulse width, which is propagating in nonlinear and dispersive fibers. The results were then compared with the result from computer simulation using SSFM. Stern *et al.* [98] analyzed the limit imposed to the transmission by higher order dispersion and self-phase modulation by modifying the nonlinear Schrödinger equation and solving it using SSFM.

All methods used in previous works are numerical methods and recursive in nature. This may impose difficulty when optimization of the system involving many parameters is required. Therefore, the availability of an analytical transfer function model of NLS equation allows optimized design of optical fiber transmission involving dispersion, fiber nonlinearities and ASE noise simultaneously. Kumar *et al.* presented the analytical form of NLS equation by using Volterra Series Transfer Function (VSTF) [90]. It was reported that third order approximation to the VSTF compares favorably with the SSFM in accuracy for power levels used in current optical communication system. Higher order VSTF increases the accuracy, especially at higher power levels, at the cost of increased computational time. Detailed analytical expression is presented in Appendix C.

5.4 Identification of Raman Kernels by Using Volterra Series Transfer Function

In this section, we present a method to identify the nonlinear kernel from any real time transmission system, particularly due to stimulated Raman scattering. Basic problem in system identification is the determination of the optimum n^{th} order physical model of a given time-invariant system. It is optimum when the output of the n^{th} order system $y_n(t)$ and its real output $y(t)$ shows the smallest error. This corresponds to the determination of Volterra kernels which gives smallest mean square modeling error, i.e. mean square algorithm.

Several studies have been done prior to this work to identify the nonlinear kernel by using cross-correlation technique. It was postulated that the Kernel response of the nonlinear system is dependent on the type of input signal. Continuous-time linear and nonlinear system identification based on the impulse response is widely discussed, even though it shows limited potential for application.

Assuming a stationary linear system is given by $y(t) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)d\tau$, with the input being assumed as real, stationary zero-mean Gaussian white noise with intensity A. By cross-correlating the output $y(t)$ and time-delayed-input $x(t-T_1)$ as shown in Fig. 5.1,

we obtain:

$$y(t)x(t-T_1) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)x(t-T_1)d\tau, T_1 \geq 0$$

Fig. 5.1 Cross-correlation technique

After averaging the cross-correlated product, we obtain:

$$\overline{y(t)x(t-T_1)} = \int_{-\infty}^{\infty} h_1(\tau) \overline{x(t-\tau)x(t-T_1)} d\tau = \int_{-\infty}^{\infty} h_1(\tau) A \delta_0(\tau-T_1) d\tau$$

$$\overline{y(t)x(t-T_1)} = Ah_1(T_1)$$

This then gives us:
$$h_1(T_1) = \frac{1}{A} \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T y(t)x(t-T_1) dt \quad (5.4.1)$$

By using similar method, we could obtain higher degree kernel components, e.g. 2nd order kernel can be described as:

$$h_2(T_1, T_2) = \frac{1}{2A^2} \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T y(t)x(t-T_1)x(t-T_2) dt; T_1 \neq T_2 \quad (5.4.2)$$

The nonlinear Schrödinger equation (NLS) for monochromatic light propagating in single mode fiber can be described in time domain as:

$$\frac{\partial A(z,t)}{\partial z} = \sum_{k=2}^{\infty} \frac{(-i)^{k+1} \beta_0^{(k)}}{k!} \frac{\partial^k A(z,t)}{\partial t^k} - \Gamma(\omega_0) A(z,t)$$

$$- \left(i + \frac{1}{\omega_0} \frac{\partial}{\partial t} \right) Q_{Kerr} A(z,t) |A(z,t)|^2$$

$$- \left(i + \frac{1}{\omega_0} \frac{\partial}{\partial t} \right) Q_{Raman} A(z,t) FT^{-1} \left[S_R FT \left(|A(z,t)|^2 \right) \right]$$

and in frequency domain as:

$$\begin{aligned} \frac{\partial A(z, \Omega)}{\partial z} = & \left[i \sum_{k=2}^{\infty} \frac{\beta_0^{(k)} \Omega^k}{k!} - \Gamma(\omega_0) \right] A(z, \Omega) \\ & - \left(i + \frac{\Omega}{\omega_0} \right) \mathcal{Q}_{Kerr} \iint A(\Omega - (\Omega_1 - \Omega_2), z) A(\Omega_1, z) A(\Omega_2, z) d\Omega_1 d\Omega_2 \\ & - \left(i + \frac{\Omega}{\omega_0} \right) \mathcal{Q}_{Raman} \iint A(\Omega - (\Omega_1 - \Omega_2), z) S_R(\Omega_1 - \Omega_2) A(\Omega_1, z) A(\Omega_2, z) d\Omega_1 d\Omega_2 \end{aligned} \quad (5.4.4)$$

Both equation above can be described by the Volterra series in both time and frequency domain. The time-domain Volterra series expression representing the nonlinear Schrödinger equation involving Kerr and Raman Effect can be described as:

$$\begin{aligned} A(z, t) = & \int_{-\infty}^{\infty} h_1(z, \tau) A(t - \tau) d\tau + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_3(z, \tau_1, \tau_2, \tau_3) A(t - \tau_1) A(t - \tau_2) A^*(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 + \\ & \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_5(z, \tau_1, \tau_2, \dots, \tau_n) A(t - \tau_1) A(t - \tau_2) A^*(t - \tau_3) A(t - \tau_2) A^*(t - \tau_3) d\tau_1 d\tau_2 d\tau_3 d\tau_4 d\tau_5 + \dots \end{aligned} \quad (5.4.5)$$

The terms $h_3(z, \tau_1, \tau_2, \tau_3)$ and $h_5(z, \tau_1, \tau_2, \dots, \tau_5)$ represent the third order and fifth order nonlinear kernels. Under weak nonlinear system, fifth order nonlinear kernel is sufficient to represent the system with very small error. By comparing (5.4.3) with (5.4.5), we could define different nonlinear kernels. Consider two input signals $A_s(z, t)$ and $A_p(z, t)$ with centre frequencies ω_s and ω_p . The propagation and interaction between these two signals can be generally represented by (5.4.5) and different kernels can be defined as in Table 5. From the table, we see that the inter-channel Raman effect experienced by $A_s(z, t)$ due to $A_p(z, t)$ is shown in row two, whereas the Raman effect experienced by $A_p(z, t)$ due to $A_s(z, t)$ is shown in row 5. Furthermore, pump-mediated Raman crosstalk can be represented by fifth order kernels. In this work, we focus on identifying third order Raman kernels due to inter-channel interaction. Further work needs to be done to

include the fifth-order or perhaps higher order Raman kernels to completely describe the whole type of Raman crosstalk.

Table 7 Various nonlinear components in two-signal analyses

Term	Centre Frequency	Nonlinear Effect
$A_s A_s A_s^*$	ω_s	SPM & Intra-pulse Raman effect
$A_s A_p A_p^*$	ω_s	XPM & Inter-pulse Raman effect
$A_s A_s A_p^*$	$2\omega_s - \omega_p$	Four-Wave Mixing
$A_p A_p A_s^*$	$2\omega_p - \omega_s$	Four-Wave Mixing
$A_p A_s A_s^*$	ω_p	XPM & Inter-pulse Raman effect
$A_p A_p A_p^*$	ω_p	SPM & Intra-pulse Raman effect

The knowledge of Volterra kernels of a nonlinear system will help us: 1) to compensate the nonlinearity, so that high power amplifier can operate as near its saturation region as possible, 2) to estimate the inter-modulation distortion induced in the nonlinear system. Many nonlinearity compensation techniques in digital transmission have been proposed, such as p-order inverse [99], fixed-point approach [100], both of which have been using Volterra model of nonlinear system to be compensated.

As the application of Volterra series in single mode fiber transmission shows good accuracy as compared to the existing split-step Fourier method, we would like to employ this series into identification of nonlinear kernel, particularly due to Raman scattering. In linear amplification region, the crosstalk between WDM channels due to stimulated Raman scattering can be estimated by identifying the Raman kernels for various transmission formats. In addition, we could use the knowledge of Raman kernels to identify the linear-nonlinear transition amplification region. In this work, we focus on identifying the Raman induced crosstalk for DWDM transmission.

Consider dual channel transmission system as illustrated in Fig. 5.2 below.

Fig. 5.2 Dual-channel Raman amplified transmission.

The coupled equations governing the signal power evolution are given by [101]:

$$\frac{\partial S_i(z,t)}{\partial z} + \frac{1}{V_i^s} \frac{\partial S_i(z,t)}{\partial t} = -\alpha_i^s S_i(z,t) + [\pm g_{im}^{ss} S_m(z,t)] S_i(z,t) \quad (5.4.6)$$

$$\frac{\partial S_m(z,t)}{\partial z} + \frac{1}{V_m^s} \frac{\partial S_m(z,t)}{\partial t} = -\alpha_m^s S_m(z,t) + [\mp g_{mi}^{ss} S_i(z,t)] S_m(z,t) \quad (5.4.7)$$

where $S_i(z,t)$ and $S_m(z,t)$ denote the signal power evolution at wavelengths λ_{s_i} and λ_{s_m} , V is the group velocities of the signals, α and g denote the fiber attenuation and Raman gain coefficient respectively. The 2nd term in (5.4.6) and (5.4.7) represents the inter-channel crosstalk induced by stimulated Raman scattering. The amount of crosstalk is commonly measured in SIR (Signal-Interference Ratio), which is defined as [101]:

$$SIR(dB) = 10 \log_{10} \frac{S(L)}{I(L)} \quad (5.4.8)$$

where interference $I(L)$ is defined as: $I(L) = S(L)|_{S_{other}(0)>0} - S(L)|_{S_{other}(0)=0}$

We simulated the inter-channel crosstalk based on the schematic in Fig. 5.2 and coupled equations (5.4.6) and (5.4.7) using split step Fourier method (SSFM). The input signal was modulated with On-Off Keying Non-Return to Zero (OOK-NRZ) at 10Gbps bits rate with 60 nm wavelength separation. We used pseudorandom binary sequence (PRBS) up to (2^7-1) to generate the input bit stream. In our simulation, we only considered the inter-channel crosstalk due to inter-pulse Raman scattering only, i.e. self-phase modulation,

cross-phase modulation and intra-pulse Raman scattering were assumed to be negligible. We plotted the SIR with respect to input signal power levels when two signal wavelengths are present simultaneously at the transmission, as shown in Fig. 5.3. We used band-pass filter based on the 5th-order Bessel function in our Multiplexer (MUX) and De-Multiplexer (DEMUX). We used fiber length $L = 100\text{km}$ with constant fiber attenuation $\alpha = 0.22\text{ dB/km}$, effective cross-area $A_{\text{eff}} = 50\text{ }\mu\text{m}^2$ and peak Raman gain coefficient $g_R = 5.568\text{mW}^{-1}$. Generally, as the input signal level increases, the SIR decreases. A 30 dB SIR or higher is required to produce good SNR performance in WDM system [102] and therefore, based on the fiber characteristics, we could set an upper limit of the input signal power.

Fig. 5.3 SIR vs. input signal power at dual channel fiber transmission using OOK modulation format.

Benedetto *et al.* proposed the band-pass Volterra series of which the input and output are represented by complex amplitudes [103], which are approximated to be:

$$\begin{aligned} \hat{y}(t) = & \sum_{\tau_1=0}^N h_1(t)x(t-\tau_1) + \sum_{\tau_1=0}^N \sum_{\tau_2=0}^N \sum_{\tau_3=0}^N h_3(\tau_1, \tau_2, \tau_3)x(t-\tau_1)x(t-\tau_2)x^*(t-\tau_3) \\ & + \sum_{\tau_1=0}^N \sum_{\tau_2=0}^N \sum_{\tau_3=0}^N \sum_{\tau_4=0}^N \sum_{\tau_5=0}^N h_5(\tau_1, \tau_2, \tau_3, \tau_4, \tau_5)x(t-\tau_1)x(t-\tau_2)x(t-\tau_3)x^*(t-\tau_4)x^*(t-\tau_5) + \varepsilon_n \end{aligned} \quad (5.4.9)$$

where $h_1(i)$, $h_3(i, j, k)$, and $h_5(i, j, k, l, m)$ are known as “low-pass equivalent kernels”, ε_n is the modeling error and N is the memory length. Based on the properties of Gaussian random profile, C –H Cheng *et al.* had derived the 3rd and 5th order kernel estimation for general nonlinear system [104]. The proposed algorithm was under both uniformly i.i.d rectangular M-QAM input and uniformly i.i.d M-PSK input. The kernels were estimated by using Mean Square Error (MSE) approach, which is described as:

$$MSE = \overline{(y(t) - \hat{y}(t))(y(t) - \hat{y}(t))^*} \quad (5.4.10)$$

To derive a Volterra model, by minimizing the mean square error, a set of “normal equations” are derived through differentiating the MSE with respect to each Volterra kernel, which latter of which can be classified into different types according to the permutation of their argument, i.e. time-delay function within the memory length,

$$\text{which is expressed as:} \quad \frac{\partial MSE}{\partial h} = 0 \quad (5.4.11)$$

By using similar algorithm, we derive the kernel estimation in an On-Off Keying modulation format, which will be used particularly to identify the Raman kernels.

In two-channel transmission with wavelengths λ_s and λ_p where the nonlinear system is approximated to be up to 3rd order kernel only, the total output can be approximated as:

$$\begin{aligned}
\hat{y}(t) = & h_{1s}(\tau_1)x_s(t-\tau_1) + h_{1p}(\tau_1)x_p(t-\tau_1) \\
& + h_{3ss}(\tau_1, \tau_2, \tau_3)x_s(t-\tau_1)x_s(t-\tau_2)x_s^*(t-\tau_3) \\
& + h_{3sp}(\tau_1, \tau_2, \tau_3)x_s(t-\tau_1)x_p(t-\tau_2)x_p^*(t-\tau_3) \\
& + h_{3pp}(\tau_1, \tau_2, \tau_3)x_p(t-\tau_1)x_p(t-\tau_2)x_p^*(t-\tau_3) \\
& + h_{3ps}(\tau_1, \tau_2, \tau_3)x_p(t-\tau_1)x_s(t-\tau_2)x_s^*(t-\tau_3)
\end{aligned} \tag{5.4.12}$$

At centre wavelength λ_s , the output can be summarized as:

$$\begin{aligned}
\hat{y}_s(t) = & h_{1s}(\tau_1)x_s(t-\tau_1) + \\
& h_{3ss}(\tau_1, \tau_2, \tau_3)x_s(t-\tau_1)x_s(t-\tau_2)x_s^*(t-\tau_3) + h_{3sp}(\tau_1, \tau_2, \tau_3)x_s(t-\tau_1)x_p(t-\tau_2)x_p^*(t-\tau_3)
\end{aligned}$$

First term in the right hand is the linear kernel, which represents both attenuation and dispersion effect; the 2nd term represents the self-phase modulation (SPM) effect; whereas the 3rd term could represent both the cross-phase modulation and Raman effects.

To analyze the Raman crosstalk, we focus on the estimation of nonlinear kernel $h_{3sp}(\tau_1, \tau_2, \tau_3)$, which is done by applying (5.4.11) with respect to $h_{3sp}(\tau_1, \tau_2, \tau_3)$.

$$\begin{aligned}
\frac{\partial \text{MSE}}{\partial h_{3sp}(\tau_i, \tau_j, \tau_l)} = & \\
& - \overline{y_s^*(t) h_{3sp}(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{1s}^*(\tau_i) x_s^*(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{1s}^*(\tau_j) x_s^*(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ss}^*(\tau_i, \tau_j, \tau_l) x_s^*(t-\tau_i) x_s^*(t-\tau_j) x_s(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ss}^*(\tau_i, \tau_j, \tau_l) x_s^*(t-\tau_i) x_s^*(t-\tau_j) x_s(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ss}^*(\tau_j, \tau_j, \tau_j) x_s^*(t-\tau_j) x_s^*(t-\tau_j) x_s(t-\tau_j)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ss}^*(\tau_j, \tau_k, \tau_k) x_s^*(t-\tau_j) x_s^*(t-\tau_k) x_s(t-\tau_k)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ss}^*(\tau_j, \tau_k, \tau_l) x_s^*(t-\tau_j) x_s^*(t-\tau_k) x_s(t-\tau_l)} \\
& + \overline{(\tau_i, \tau_j, \tau_l) x_s(t-\tau_i) x_p(t-\tau_j) x_p^*(t-\tau_l) h_{3ps}^*(\tau_i, \tau_j, \tau_l) x_s^*(t-\tau_i) x_p^*(t-\tau_l) x_p(t-\tau_l)} = 0
\end{aligned} \tag{5.4.13}$$

Equation (5.4.13) shows an example of MSE differentiation with respect to $h_{3sp}(\tau_1, \tau_2, \tau_3)$ when $\tau_1 = \tau_2 = \tau_3 = \tau_i$. We derive the properties of input signal using OOK modulation format using i.i.d input bit stream with equal probability as follows:

$$\begin{aligned} 1) \overline{X_n X_k} &= \overline{X_n} \times \overline{X_k} & 2) \overline{X_n^m} &= \frac{1}{2^m} |X|_{Bit1}^2, m \geq 2 \\ 3) \overline{\prod_{m=2}^N X_m} &= \frac{1}{2^m} |X|_{Bit1}^2 & 4) \overline{X_n X_n^*} &= 0.5 * |X|_{Bit1}^2, m \geq 1 \end{aligned}$$

Therefore, based on On-Off Keying system input, we could characterize this following statistic average value of the input as:

$$\begin{aligned} \overline{x(t)x^*(t)} &= \mu_2 \\ \overline{x(t)x^*(t)x(t)x^*(t)} &= \mu_4 \\ \overline{x(t)x^*(t)x(t)x^*(t)x(t)x^*(t)} &= \mu_6 \end{aligned} \tag{5.4.14}$$

Thus, by using (5.4.14), equation (5.4.13) can be modified as:

$$\begin{aligned} & -y_s^* x_s(t - \tau_i) x_p(t - \tau_i) x_p^*(t - \tau_i) \\ & + \mu_{2si} \mu_{2pi} h_{1s}^*(t - \tau_i) + 0.5 \mu_{2sij} \mu_{2pi} h_{1s}^*(t - \tau_j) \\ & + \mu_{4si} \mu_{2pi} h_{3ss}^*(\tau_i, \tau_i, \tau_i) \\ & + \sum_{i \neq j} \mu_{2si} \mu_{2pi} \mu_{2sj} h_{3ss}^*(\tau_i, \tau_j, \tau_j) \\ & + \sum_{i \neq j} 0.5 \mu_{2s} \mu_{2pi} \mu_{2sj} h_{3ss}^*(\tau_j, \tau_j, \tau_j) \\ & + \sum_{i \neq j \neq k} 0.25 \mu_{2s} \mu_{2pi} \mu_{2sk} h_{3ss}^*(\tau_j, \tau_k, \tau_k) \\ & + \sum_{i \neq j \neq k \neq l} 0.125 \mu_{2sij} \mu_{2pi} \mu_{2skl} h_{3ss}^*(\tau_j, \tau_k, \tau_l) \\ & + \mu_{2si} \mu_{4pi} h_{3ps}^*(\tau_i, \tau_i, \tau_i) = 0 \end{aligned} \tag{5.4.15}$$

Chapter 5

Identification of Raman Kernels in DWDM

Assuming that the contribution of $0.5\mu_{2s}\mu_{2p}$ to first order kernel and $0.25\mu_{2s}\mu_{2p}\mu_{2s}$ or lower to third order kernel are small and considered negligible, then (5.4.15) can be simplified as:

$$\begin{aligned}
& -y_s^* x_s(t-\tau_i) x_p(t-\tau_i) x_p^*(t-\tau_i) \\
& + \mu_{2si} \mu_{2pi} h_{1s}^*(t-\tau_i) \\
& + \mu_{4si} \mu_{2pi} h_{3ss}^*(\tau_i, \tau_i, \tau_i) \\
& + \sum_{i \neq j} \mu_{2si} \mu_{2pi} \mu_{2sj} h_{3ss}^*(\tau_i, \tau_j, \tau_j) \\
& + \sum_{i \neq j} 0.5 \mu_{2s} \mu_{2pi} \mu_{2sj} h_{3ss}^*(\tau_j, \tau_j, \tau_j) \\
& + \mu_{2si} \mu_{4pi} h_{3ps}^*(\tau_i, \tau_i, \tau_i) = 0
\end{aligned} \tag{5.4.16}$$

Let

$$\begin{aligned}
& \frac{\partial MSE}{\partial h_{1s}(\tau_i)} = \\
& -y_s^* x_s(t-\tau_i) \\
& + \mu_{2si} h_{1s}^*(\tau_i) \\
& + \mu_{4si} h_{3ss}^*(\tau_i, \tau_i, \tau_i) \\
& + \sum_{i \neq j} \mu_{2si} \mu_{2sj} h_{3ss}^*(\tau_i, \tau_j, \tau_j) \\
& + \sum_{i \neq j} 0.5 \mu_{2s} \mu_{2sj} h_{3ss}^*(\tau_j, \tau_j, \tau_j) \\
& + \sum_{i \neq j \neq k} 0.5 \mu_{2s} \mu_{2sk} h_{3ss}^*(\tau_j, \tau_k, \tau_k) \\
& + \sum_{i \neq j \neq k \neq l} 0.25 \mu_{2s} \mu_{2s} h_{3ss}^*(\tau_j, \tau_k, \tau_l) \\
& + \mu_{2si} \mu_{2pi} h_{3ps}^*(\tau_i, \tau_i, \tau_i) = 0
\end{aligned}$$

which can be approximated as:

$$\begin{aligned}
& -y_s^* x_s(t - \tau_i) \\
& + \mu_{2si} h_{1s}^*(\tau_i) \\
& + \mu_{4si} h_{3ss}^*(\tau_i, \tau_i, \tau_i) \\
& + \sum_{i \neq j} \mu_{2si} \mu_{2sj} h_{3ss}^*(\tau_i, \tau_j, \tau_j) \\
& + \sum_{i \neq j} 0.5 \mu_{2s} \mu_{2sj} h_{3ss}^*(\tau_j, \tau_j, \tau_j) \\
& + \mu_{2si} \mu_{2pi} h_{3ps}^*(\tau_i, \tau_i, \tau_i) = 0
\end{aligned} \tag{5.4.17}$$

By using formulation: (5.4.15) – (5.4.17) * μ_{2pi} , we obtain:

$$h_{3sp}(\tau_i, \tau_i, \tau_i) = \frac{y_s x_s^*(t - \tau_i) x_p^*(t - \tau_i) x_p(t - \tau_i) - y_s x_s^*(t - \tau_i) \mu_{2pi}}{\mu_{2si} \mu_{4pi} - \mu_{2si} \mu_{2pi}^2} \tag{5.4.18}$$

By using similar approach and derivation technique as (5.4.8), we obtain all the third order Kernels as a function of combination of the time delays. All the third order Kernels can be classified into 3 main groups, which is tabulated in Table 6.

Table 8 Third order Raman kernels estimation

$h_{3sp}(\tau_i, \tau_i, \tau_i)$	$\frac{y_s x_s^*(t - \tau_i) x_p^*(t - \tau_i) x_p(t - \tau_i) - y_s x_s^*(t - \tau_i) \mu_{2pi}}{\mu_{2si} \mu_{4pi} - \mu_{2si} \mu_{2pi}^2}$
$h_{3sp}(\tau_i, \tau_k, \tau_k)$	$\frac{y_s x_s^*(t - \tau_i) x_p^*(t - \tau_k) x_p(t - \tau_k) - y_s x_s^*(t - \tau_i) \mu_{2pk}}{\mu_{2si} \mu_{4pk} - \mu_{2si} \mu_{2pk}^2}$
$h_{3sp}(\tau_i, \tau_j, \tau_k)$	$\frac{y_s x_s^*(t - \tau_i) x_p^*(t - \tau_j) x_p(t - \tau_k)}{\mu_{2si} \mu_{2pi} \mu_{2pk}}$

Based on the third order kernels formulation in table 6, we can obtain the third order Raman kernels in On-Off Keying modulation format by using numerical experiment, as shown in schematic in Fig. 5.3. The schematic comprises two major parts, the fiber data transmission part and the signal processing part. The first part comprises the data transmission using On-Off modulation format of two channels with 60 nm difference in the centre wavelengths. After multiplexed, the data streams are propagating through standard single mode fiber, with certain length of transmission. At the end of transmission, after de-multiplexing process, we recover the signals. The second major

part of the schematic is the signal processing, in which we take both input signal (before multiplexer) and output signals (after de-multiplexer) and correlate the two signals based on formula in table 6. We apply various time delays to the input signals in order to get the Raman kernels based on the time delay function. The step of the time delay we used was defined based on the sampling rate of the signal pulse itself. We sampled the signal 8 times the signal bit rate, which means for 10 Gb/s data, which corresponds to 100 ps pulse width, we used time delay of 12.5 ps. We swept the time delays within a time window of two signal periods in order to get the Raman kernels. After getting the Raman kernels, we used (5.4.9) to get the Raman kernels between two channels by inputting the two channels input signals. By applying this method, we could directly measure and identify various Raman crosstalks experimentally from the real data fiber transmission. This method offers a simpler way of measuring and identifying Raman crosstalk, even though it has a drawback of longer measurement time. By using time-delay line and control the time delay from 0 till $4T_s$, where T_s denotes the bit or symbol periods, we could get the three kernels and directly measure the amount of crosstalk. Measurement of Raman crosstalk induced by signals with different modulation format may need adjustment in the time window T_s according on the symbol period.

Fig. 5.4 The schematic of Raman kernel estimation process

Fig. 5.5 – 5.7 show various results of Signal to Interference Ratio (SIR) taken in dual channel fiber transmission using On-Off Keying Non-Return to Zero (OOK-NRZ) modulation format. We use similar configuration as in Fig. 5.2 and take 3 input power levels for characterization. We take into account both fiber attenuation and channel-crosstalk due to stimulated Raman scattering. We assume that the dispersion effect and some other nonlinear effects are negligible, especially at the low power region. From the graphs, we observe a small discrepancy between results from SSFM and Volterra Series Transfer Function. Due to weak nonlinear effect, no difference shown between 100 km and 50 km fiber segment, as can be seen from Fig. 5.5 and Fig. 5.6. The maximum discrepancy can be up to 1.2 dB SIR. The sensitivity and accuracy of SIR in this weak nonlinear effect can be further improved by applying longer memory length, i.e. bigger number of PRBS bits. Unlike, other nonlinear effects, such as SPM/XPM-GVD, crosstalk due to SRS shows great dependency on the word length of the pseudorandom binary sequence. As the bit rate increases or the utilizing bandwidth becomes wider, the walk-off between the target channel and the other WDM channels in the Raman gain bandwidth is large; the number of independent pulses in the other WDM channels that overlap with the target pulse during fiber propagation becomes large. In this case, if the word length is not sufficiently long, as compared to the number of independent overlapped pulses, the same bit pattern appears periodically during the transmission and thus the transmission data is not considered sufficiently random. A bit rate as high as 10 Gb/s may require the word length at least (2^9-1) [104]. Fig. 5.7 shows SIR levels under no-fiber attenuation. Under this condition, we could expect that nonlinear effect due to Raman scattering shows stronger effect, however, due to small power level, no significant difference in SIR as compared to Fig. 5.6. Again, we prove that very small

discrepancy is obtained when we use Volterra Series Transfer Function as compared to the Split Step Fourier Method.

Fig. 5.5 SIR ratio for dual channel On-Off Keying transmission with 100 km length transmission and fiber attenuation = 0.22 dB/km.

Fig. 5.6 SIR ratio for dual channel On-Off Keying transmission with 50 km length transmission and fiber attenuation = 0.22 dB/km.

Fig. 5.7 SIR ratio for dual channel On-Off Keying transmission with 50 km length transmission and zero fiber attenuation.

Further works can be done to employ this Volterra-based identification method in determining the Raman kernels at any fiber transmission with different input modulation formats. Based on similar approach as we propose here, one can use this methodology to accurately determine Raman kernels in QPSK or QAM input modulation format. Other modulation format requires modification in the kernel approximation. Also, one can use several available modified Volterra series to improve and shorten the data collection and data calculation process.

5.5 Summary

We have investigated a method of identifying Raman kernels based on Volterra Series Transfer Function. We derive the Raman kernels when input signal is using On-Off Keying Non-Return to Zero modulation format. Based on cross-correlation method and by using mean-square algorithm with some approximations, we have derived the third order kernels due to stimulated Raman scattering in fiber transmission. We thus employ this method in calculating the signal-to-interference ratio (SIR) in dual-channel transmission and compare its accuracy with the existing Split-Step Fourier Method (SSFM). Our results show good agreement with the ones from SSFM. By increasing the memory length of the nonlinear system, we could expect an improvement in accuracy. Unfortunately, this will significantly increase the data collection and computation time. However, some modified Volterra series would be able to help solving this problem. Based on our findings, one can always employ this method to identify any nonlinear interactions, especially those induced by stimulated Raman scattering in any fiber transmission system.

CHAPTER 6

Conclusions and Future Recommendations

6.1 Conclusions

Fiber Raman amplifiers have become one of the key technologies supporting the DWDM communication due to its broad bandwidth, i.e. over 100 nm bandwidth. They have been widely deployed in long haul fiber optic transmission system, making them one of the most commercialized nonlinear effect-based optical devices for communication. Distributed Raman amplifier provides improved noise figure and reduces nonlinear penalty of fiber systems, thus allowing for longer transmission span, higher bit rates and close channel spacing. These ultimately increase the total capacity and improve the cost-efficiency.

Fiber Raman amplifier is originated from a nonlinear phenomena, Raman scattering, which involves the molecular transition energy level and producing Stokes and anti-Stokes components. Stimulated Raman scattering refers to the generation of Stokes components due to the presence of stimulating photons at longer wavelength. A pump photon is converted into a second signal photon that is an exact replica of the first, and the remaining energy produces optical phonon. The initial signal photon is therefore amplified. One important parameter defined in this process is the Raman gain coefficient at the Raman resonance frequency, where coherence is automatically generated due to phase matching condition. We have presented a detailed characterization of fiber Raman amplifier for the continuous wave Raman pump by considering some important factors such as fiber properties (length, dispersion, attenuation, cross-sectional area, Raman gain

coefficient, Rayleigh backscattering coefficient and polarization dependent factor) as well as Raman pump properties (line-width, relative-intensity noise). Optical signal to noise ratio and amplifier effective noise figure become important parameters that determine the performance of fiber Raman amplifier.

Fundamental issues related to gain performance of Raman amplifier are non-uniformity of Raman gain coefficient with respect to wavelength and poor Raman gain efficiency. We have proposed new methods and investigated both gain and noise performance of Raman amplifier. We demonstrated a dynamic method to flatten Raman gain by using high birefringence fiber loop mirror. We used both single and double sections Hi-Bi fiber loop mirror with various lengths of Hi-Bi fiber. Gain flatness performance was measured in terms of flat gain bandwidth and gain ripple. In addition to that, the amplifier gain efficiency was also taken into account in designing the gain flattening filter, i.e. making the gain suppression as small as possible. The result we obtained when we use single section Hi-Bi FLM was 43 nm flat gain bandwidth with ± 0.5 dB gain ripple. The average flattened On-Off Raman gain was about 11.3 dB, which correspond to 5 dB gain suppression from its original peak gain level. When we used two sections of Hi-Bi FLM, we obtained about 38 nm flat gain bandwidth with 4 dB gain suppression. This showed the trade-off between flattened gain bandwidth and amplifier efficiency to sufficiently cover the amplification of each communication channel in DWDM system.

Multi-wavelength Raman pump is another method to produce flat Raman gain covering all communication channels in DWDM transmission. Both noise and gain performance in multi-wavelength Raman pump can be improved by using special pump scheme, called Time-Division Multiplexed Raman pump scheme. By temporally separating the multi-

Chapter 6**Conclusions and Recommendations**

wavelength pump beams, we could improve both the gain efficiency, i.e. no pump-to-pump power transfer, and the noise performance, i.e. no four-wave mixing induced noise. In the widely known single-wavelength pump modulation, pulse repetition rate has a minimum value so as to avoid temporal gain fluctuation. In multi-wavelength TDM Raman pump, we analyzed two necessary conditions to optimize its performance and found that 1). Pulse repetition rate also has a maximum value, beyond which pump-to-pump interaction becomes severe, 2). Greater pulse duty cycle is necessary to improve the signal to noise ratio of the amplifier. Moreover, we investigated some fundamental issues related to the noise performance by investigating several sources of noise such as amplified spontaneous emission, Rayleigh backscattering noise, and noise due to Four-Wave Mixing effect. Both gain and noise performance in multi-wavelength Raman pump can be improved by using special pump scheme, called Time-Division Multiplexed Raman pump scheme. We aimed to set certain operating conditions to optimize its performance. We also proposed different pump modulation format, i.e. Gaussian pulse, as an alternative solution in addition to the existing square pulse modulation. We presented complete characterization of both amplifier gain and noise performance in multi-wavelength Alternating TDM Raman pump scheme. Some important factors taken into account were fiber properties (attenuation, gain coefficient, Rayleigh backscattering coefficient and dispersion), pump power, wavelength combination and RIN level. We also concluded that shorter pump wavelength separation with almost uniform pump power reduces both ASE and DRS enhancement. In addition to square pulse modulation, we introduced Gaussian pulse as an alternative modulation format for this application. Our investigation concluded that Gaussian pulse imposes more stringent requirement as compared to the square pulse. On the other hand, Gaussian pulse modulation provides better protection to avoid the pump-to-pump interaction, especially at high level of pulse

duty cycle. However, both modulation techniques can be employed in Time Division Multiplexing Raman pump scheme by properly adjusting its operating condition so as to optimize its performance.

Finally, we conducted investigation on other source of noise, Raman crosstalk. We proposed a method based on Volterra series transfer function to identify the crosstalk between DWDM channels induced by Raman scattering. We derived the Raman kernels when input signal is using On-Off Keying modulation format. We derived the third order kernels due to stimulated Raman scattering in fiber transmission based on cross-correlation method and by using mean-square algorithm with some approximation. We calculated signal-to-interference ratio (SIR) in dual-channel transmission and compared its accuracy with the existing split-step Fourier method (SSFM). Our results showed good agreement with the simulation results from SSFM. By increasing the memory length of the input of the nonlinear system, we could have an improvement in accuracy. Unfortunately, this will significantly increase the data collection and computation time. However, some modified Volterra series would be able to help solving this problem. Based on our findings, one can always employ this method to identify any nonlinear interaction, especially induced by stimulated Raman scattering.

6.2 Recommendations for Future Research

We recommend three major points for near future research development. Further research and application development of the new Raman pump scheme, i.e. TDM Raman pump, will benefit the research and development in DWDM communication. One may want to investigate the other method of designing multi-wavelength modulation pump by using tunable pump source. We can also combine this new distributed Raman amplification scheme with existing discrete Raman amplifier acting as post- and pre-amplifier of the data transmission. Furthermore, one can also investigate Raman amplification in different fiber designs, particularly the photonic crystal fibers.

6.2.1 Further Development and Application of Time-Division Multiplexed Raman Amplifier

6.2.1.1 Multi-wavelength TDM Raman scheme using Tunable Pump Source

Multi-wavelength Time Division Multiplexed Raman pump scheme can also be produced by wavelength-sweeping the tunable laser. The pump beam produced by tunable laser source is modulated and transmitted in counter-propagating direction. A modulation period is further divided into a number of time slots which are occupied by pump pulses. The weighting function of pump wavelengths are determined by the number of time slots allocated to each pump wavelength. Therefore more accurate control to the pump pulse modulation is necessary to ensure flat gain Raman amplifier. By using this scheme, we can set uniform pump power for all the pump pulses. By setting relatively low peak pump power, we could thus obtain lower noise enhancement. One can investigate this method of designing TDM Raman amplifier and characterize its performance thoroughly.

6.2.1.2 Hybrid of Discrete Amplifier-TDM Raman Amplifier for DWDM Transmission

We know that distributed Raman amplifier provides improvement to the optical signal to noise ratio. However, it has been well proven that Hybrid EDFA-Raman amplifier produces better gain and noise improvement to the transmission system [117]. One can possibly design a Hybrid optical amplifier based on EDFA and distributed TDM Raman amplifier to then evaluate its performance in various transmission systems. In addition, discrete optical amplifier can also be obtained from the recently-investigated discrete Raman amplifier technologies, such as the double-pass discrete Raman amplifier using dispersion compensating fiber (DCF) [112] or even photonic crystal fibers (PCF) based discrete Raman amplifier.

6.2.2 Raman Amplification by using Photonics Crystal Fiber

Photonic crystal fibers (PCF) have attracted increased interest over the past few years as they provide extra degree of freedom in manipulating the optical properties of light, such as dispersion, nonlinearity and birefringence of optical fibers. Typically, these fibers incorporate a number of air holes that run along the length of the fiber and have a variety of different shape, size and distribution. Light in PCF can be guided either by total internal reflection at the silica-air interface or through band gap effect by periodically spaced air holes [113], [114].

Holey Fiber (HF) has progressed rapidly in recent years leading to the development of novel devices. Due to large refractive index contrast and special cladding features on the scale of the wavelength of the light, this fiber offers tight modal confinement. This induces much higher effective nonlinearity per unit length, i.e. 10-100 times higher than

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the ordinary silica fiber. This attractive feature may lead to the design of high gain efficiency discrete Raman amplifier by using holey fiber [115]. By using this special fiber, gain efficiency can be enhanced up to 6 dB/W for a very short amplification length, i.e. 75m for a signal wavelength of 1635 nm.

Further investigation can be carried out to produce and improve the Raman amplifier by using photonic crystal fibers [114-115]. Multipump Flattened Gain Raman amplifiers based on Photonic Crystal Fibers has been reported by [116]. Also, Raman amplification characteristics at 850 nm in a silica-based Photonic Crystal Fiber were reported recently [117]. Generally, there are wide possible designs of PCF to optimize the induced Raman effect. High gain efficiency and gain bandwidth are two major factors to be taken into consideration. In addition, one can design discrete Raman Amplifier based on this special fiber for post- and pre-amplifier in the WDM transmission. It could also be in a form of hybrid-distributed Raman amplifier in optical fiber transmission. Last but not least, high nonlinearity in this special fiber can be very useful in the application and design of optical switching and wavelength converter, particularly using the Raman effect.

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2. Andrew A. B. Tio, K. F. Lim and P. Shum, "Propagation of Soliton in Optical Fiber Amplifier," *Journal of The Institution of Engineers, Singapore*, vol. 44, no. 3, pp. 27-37, 2004 (Invited Paper). (Chapter 2)
3. Andrew A. B. Tio and P. Shum, "Gain properties of multi-wavelength Time Division Multiplexed Raman amplifier," *Optics Express*, vol.14, no. 12, pp. 5061-5066, 2006. (Chapter 4)
4. Andrew A. B. Tio and P. Shum, "Study of Noise Properties of Raman Amplifier using Time-Division Multiplexed Pumping Scheme," *IEEE Journal of Lightwave Technology* (submitted). (Chapter 4)
5. Andrew A. B. Tio and P. Shum, "Flat Raman Gain Using Time Division Multiplexed Pumping Scheme – Design and Guidelines," *Journal of Optical Society of America B* (submitted). (Chapter 4)
6. Andrew A. B. Tio, L. N. Binh, and P. Shum, "Identification of Raman nonlinear Kernels by using Volterra Series Transfer Function," *Optics Communication* (submitted). (Chapter 5)
7. Andrew A. B. Tio and P. Shum, "Propagation of Optical Soliton in a Fiber Raman Amplifier", *Proceeding of Asia Pacific Optical and Wireless Communications (APOC)*, 2003. (Chapter 2)
8. Andrew A. B. Tio, P. Shum, and Y. D. Gong, "Raman Gain Flattening by Using a High Birefringence Fiber Loop Mirror", *Proceeding of 2nd International Conference on Optical Communications and Networks (ICO CN)*, 2003. (Chapter 3)

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 10. Andrew A. B. Tio, P. Shum, M. S. Kao, "Multi-wavelength pulsed pump Raman amplifier", *Proceeding of Australian Conference on Optical Fiber Technology (ACOFT)*, 2005 (Chapter 4).

APPENDIX A

Raman Gain Coefficient In The Presence of Dispersion

In forward stimulated Raman scattering, we obtain the growth rate of the Stokes modes

from [1] as:

$$G_n = G_n^{(0)} + G_n^{(1)} + G_n^{(2)} + \dots \quad (\text{A1})$$

Only the odd order eigenvalue will contribute to the growth rate of the Stokes mode.

The first order eigenvalue gives the first order growth rate of the Stokes as:

$$G_n^{(1)} = \frac{g_0}{2} \quad (\text{A2})$$

The third order growth rate of Stokes mode is given by:

$$G_n^{(3)} = (g_0 |B|^2 / 4) q^2 \quad (\text{A3})$$

where: $q = \frac{G_C}{\left(\frac{1}{V_s} - \frac{1}{V_p} \right) \Delta \omega}$

$$G_C = \frac{g_0}{2} |B|^2 \text{ with } |B|^2 \text{ is pump power and } \Delta \omega \text{ is the pump laser bandwidth.}$$

Therefore, Raman gain coefficient in the presence of dispersion can be defined as:

$$g_{RR} = g_R \left(1 + \frac{1}{2} \left[\frac{g_R P(z,t)}{\left| \frac{1}{V_p} - \frac{1}{V_s} \right| \Delta \omega} \right]^2 \right) \quad (\text{A4})$$

where $G_R = \frac{g_0}{2A_{eff}}$

When dispersion is large, the second term in (A4) vanishes, left only the average Raman gain coefficient g_R .

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APPENDIX B

Pump-Mediated Raman Crosstalk In Co-Propagating Raman Amplifier

Assuming the solution (2.3.19) – (2.3.21) are:

$$P_{s1}(z) = U.e^{(-\alpha z)} \quad (B1)$$

$$P_{s2}(z) = V.e^{(-\alpha z)} \quad (B2)$$

$$P_p(z) = W.e^{(-\alpha z)} \quad (B3)$$

Taking the derivatives of (B1) – (B3), we obtain:

$$\frac{dP_{s1}(z)}{dz} = \frac{dU}{dz} e^{(-\alpha z)} + (-\alpha)P_{s1}(z) \quad (B4)$$

$$\frac{dP_{s2}(z)}{dz} = \frac{dV}{dz} e^{(-\alpha z)} + (-\alpha)P_{s2}(z) \quad (B5)$$

$$\frac{dP_p(z)}{dz} = \frac{dW}{dz} e^{(-\alpha z)} + (-\alpha)P_p(z) \quad (B6)$$

From (B4) – (B6) and (2.3.19) – (2.3.21), we obtain:

$$\frac{dU}{dz} e^{(-\alpha z)} = g_{R1} P_p(z) P_{s1}(z) \quad (B7)$$

$$\frac{dV}{dz} e^{(-\alpha z)} = g_{R2} P_p(z) P_{s2}(z) \quad (B8)$$

$$\frac{dW}{dz} e^{(-\alpha z)} = -\frac{\nu_p}{\nu_{s1}} g_{R1} P_p(z) P_{s1}(z) - \frac{\nu_p}{\nu_{s2}} g_{R2} P_p(z) P_{s2}(z) \quad (B9)$$

Inserting (B7) and (B8) to (B9), we obtain:

$$\frac{dW}{dz} e^{(-\alpha z)} + \frac{\nu_p}{\nu_{s1}} \frac{dU}{dz} e^{(-\alpha z)} + \frac{\nu_p}{\nu_{s2}} \frac{dV}{dz} e^{(-\alpha z)} = 0 \quad (B10)$$

Solution to (B10) is:
$$W + \frac{v_p}{v_{s1}} U + \frac{v_p}{v_{s2}} V = C_0 \quad (\text{B11})$$

Where:
$$C_0 = P_{p0} + \frac{v_p}{v_{s1}} P_{s10} + \frac{v_p}{v_{s2}} P_{s20}$$

Substituting (B11) into (B4) and (B5), we obtain the solutions as:

$$P_{s1}(z) = P_{s10}(t - z/V_{s1}) \frac{1 + \frac{v_p}{v_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} + \frac{v_p}{v_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}}}{1 + \frac{v_p}{v_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R1} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right) + \frac{v_p}{v_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R2} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right)} \times \exp\left(\frac{g_{R1} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right) \exp(-\alpha z) \quad (\text{B12})$$

$$P_{s2}(z) = P_{s20}(t - z/V_{s2}) \frac{1 + \frac{v_p}{v_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} + \frac{v_p}{v_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}}}{1 + \frac{v_p}{v_{s1}} \frac{P_{s10}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R1} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right) + \frac{v_p}{v_{s2}} \frac{P_{s20}(t - z/V_{s1})}{P_{p0}} \exp\left(\frac{g_{R2} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right)} \times \exp\left(\frac{g_{R2} P_{p0}}{\alpha} (1 - e^{-\alpha z})\right) \exp(-\alpha z) \quad (\text{B13})$$

APPENDIX C

VOLTERRA SERIES TRANSFER FUNCTION OF SINGLE MODE

FIBERS

The nonlinear Schrodinger equation (NLS) expressed in frequency domain is as follow:

$$\begin{aligned} \frac{\partial A(\omega, z)}{\partial z} = & -\alpha(\omega)A(\omega, z) - j\Delta(\omega)A(\omega, z) \\ & + j\left(1 + \frac{\omega}{\omega_0}\right)a_0 \iint A(\omega_1, z)A^*(\omega_2, z)A(\omega - \omega_1 + \omega_2, z)d\omega_1 d\omega_2 \\ & + j\left(1 + \frac{\omega}{\omega_0}\right)Q_R \iint S_R(\omega_1 - \omega_2)A(\omega_1, z)A^*(\omega_2, z)A(\omega - \omega_1 + \omega_2, z)d\omega_1 d\omega_2 \end{aligned} \quad (C.1)$$

Where: $A(\omega, z)$: Fourier transform of the complex envelope $A(t, z)$

$\alpha(\omega)$: Fiber attenuation as a function of frequency ω

$\Delta(\omega)$: Linear dispersion in fiber

$Q_R = \frac{\omega_0}{cA_{eff}}G_R$: Raman constant

G_R : Raman gain coefficient

ω_0 : Optical central frequency

A_{eff} : Effective cross-area, and

$S_R(\omega_1 - \omega_2)$: Raman gain spectrum

Output-input relationship in frequency domain based on VSTF is defined as:

$$Y(\omega) = \sum_{n=1}^{\infty} \int \dots \int H_n(\omega_1, \dots, \omega_{n-1}, \omega - \omega_1 - \dots - \omega_{n-1}) X(\omega_1) \dots X(\omega_{n-1}) X(\omega - \omega_1 - \dots - \omega_{n-1}) d\omega_1 \dots d\omega_{n-1}$$

Retaining only up to fifth order kernels in VSTF and seeking the approximation to NLS

above, the output input relationship is then defined as:

$$A(\omega, z) = H_1(\omega, z)A(\omega) \quad (C.2)$$

$$\begin{aligned} & + \iint H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) A(\omega_1) A^*(\omega_2) A(\omega - \omega_1 + \omega_2) d\omega_1 d\omega_2 \\ & + \iiint H_3(\omega_1, \omega_2, \omega_3, \omega_4, \omega - \omega_1 + \omega_2 - \omega_3 + \omega_4) \\ & \times A(\omega_1) A^*(\omega_2) A(\omega_3) A^*(\omega_4) A(\omega - \omega_1 + \omega_2 - \omega_3 + \omega_4) d\omega_1 d\omega_2 d\omega_3 d\omega_4 \end{aligned}$$

By substituting (C.2) into (C.1), first-, third-, and fifth- order Kernels are given by:

$$\frac{\partial H_1(\omega, z)}{\partial z} = G_1(\omega) H_1(\omega, z) \quad (C.3)$$

$$\frac{\partial H_3(\omega_1, \omega_2, \omega_3, z)}{\partial z} = G_1(\omega_1 - \omega_2 + \omega_3) H_3(\omega_1, \omega_2, \omega_3, z) \quad (C.4)$$

$$+ G_3(\omega_1, \omega_2, \omega_3) H_1(\omega_1, z) H_1^*(\omega_2, z) H_1(\omega_3, z)$$

$$\frac{\partial H_5(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, z)}{\partial z} = \quad (C.5)$$

$$G_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5) H_3(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, z)$$

$$+ G_3(\omega_1, \omega_2, \omega_3 - \omega_4 + \omega_5) H_1(\omega_1, z) H_1^*(\omega_2, z) H_3(\omega_3, \omega_4, \omega_5, z)$$

$$+ G_3(\omega_1, \omega_2 - \omega_3 + \omega_4, \omega_5) H_1(\omega_1, z) H_3^*(\omega_2, \omega_3, \omega_4, z) H_1(\omega_5, z)$$

$$+ G_3(\omega_1 - \omega_2 + \omega_3, \omega_4, \omega_5) H_3(\omega_1, \omega_2, \omega_3, z) H_1^*(\omega_4, z) H_1(\omega_5, z)$$

where: $G_1(\omega) = -\alpha(\omega) + j\Delta(\omega)$

$$G_3(\omega_1, \omega_2, \omega_3) = j \left(1 + \frac{\omega_1 - \omega_2 + \omega_3}{\omega_0} \right) [a_0 + Q_R S_R(\omega_1 - \omega_2)]$$

Equations (C.3), (C.4), and (C.5) can be solved as:

$$H_1(\omega, z) = \exp(G_1(\omega)z)$$

$$H_3(\omega_1, \omega_2, \omega_3, z) = G_3(\omega_1, \omega_2, \omega_3) \frac{\exp[(G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3))z] - \exp[G_1(\omega_1 - \omega_2 + \omega_3)z]}{G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3) - G_1(\omega_1 - \omega_2 + \omega_3)}$$

$$\begin{aligned}
 & H_5(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5 z) = \\
 & H_5'(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, z) \\
 & - \frac{G_3(\omega_1, \omega_2, \omega_3 - \omega_4 + \omega_5)G_3(\omega_3, \omega_4, \omega_5)}{G_1(\omega_3) + G_1^*(\omega_4) + G_1(\omega_5) - G_1(\omega_3 - \omega_4 + \omega_5)} \\
 & \times \frac{H_1(\omega_1, z)H_1^*(\omega_2, z)H_1(\omega_3 - \omega_4 + \omega_5, z) - H_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5, z)}{G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3 - \omega_4 + \omega_5) - G_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5)} \\
 & - \frac{G_3(\omega_1, \omega_2 - \omega_3 + \omega_4, \omega_5)G_3^*(\omega_2, \omega_3, \omega_4)}{G_1^*(\omega_2) + G_1(\omega_3) + G_1^*(\omega_4) - G_1^*(\omega_2 - \omega_3 + \omega_4)} \\
 & \times \frac{H_1(\omega_1, z)H_1^*(\omega_2 - \omega_3 + \omega_4, z)H_1(\omega_5, z) - H_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5, z)}{G_1(\omega_1) + G_1^*(\omega_2 - \omega_3 + \omega_4) + G_1(\omega_5) - G_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5)} \\
 & - \frac{G_3(\omega_1 - \omega_2 + \omega_3, \omega_4, \omega_5)G_3(\omega_1, \omega_2, \omega_3)}{G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3) - G_1(\omega_1 - \omega_2 + \omega_3)} \\
 & \times \frac{H_1(\omega_1 - \omega_2 + \omega_3, z)H_1^*(\omega_4, z)H_1(\omega_5, z) - H_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5, z)}{G_1(\omega_1 - \omega_2 + \omega_3) + G_1^*(\omega_4) + G_1(\omega_5) - G_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5)}
 \end{aligned}$$

where:

$$\begin{aligned}
 & H_5'(\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, z) = \\
 & \frac{H_1(\omega_1, z)H_1^*(\omega_2, z)H_1(\omega_3, z)H_1^*(\omega_4, z)H_1(\omega_5, z) - H_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5, z)}{G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3) + G_1^*(\omega_4) + G_1(\omega_5) - G_1(\omega_1 - \omega_2 + \omega_3 - \omega_4 + \omega_5)} \\
 & \times \left[\begin{aligned} & \frac{G_3(\omega_1, \omega_2, \omega_3 - \omega_4 + \omega_5)G_3(\omega_3, \omega_4, \omega_5)}{G_1(\omega_3) + G_1^*(\omega_4) + G_1(\omega_5) - G_1(\omega_3 - \omega_4 + \omega_5)} \\ & + \frac{G_3(\omega_1, \omega_2 - \omega_3 + \omega_4, \omega_5)G_3^*(\omega_2, \omega_3, \omega_4)}{G_1^*(\omega_2) + G_1(\omega_3) + G_1^*(\omega_4) - G_1^*(\omega_2 - \omega_3 + \omega_4)} \\ & + \frac{G_3(\omega_1 - \omega_2 + \omega_3, \omega_4, \omega_5)G_3(\omega_1, \omega_2, \omega_3)}{G_1(\omega_1) + G_1^*(\omega_2) + G_1(\omega_3) - G_1(\omega_1 - \omega_2 + \omega_3)} \end{aligned} \right]
 \end{aligned}$$