Development of high performance fiber Raman amplification systems for optical fiber communications

Tang, Ming

2005

Tang, M. (2005). Development of high performance fiber raman amplification systems for optical fiber communications. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/3352>

<https://doi.org/10.32657/10356/3352>

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Development of High Performance Fiber Raman Amplification Systems for Optical Fiber Communications

Tang Ming

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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Tang Ming
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ACKNOWLEDGEMENT

This thesis would not have been successful without the generous help from many people who have had a hand in shaping my intellectual and personal growth. Here, I would like to express my deepest appreciation to my supervisor, Assoc/Prof. Shum Ping, for his consistent guidance and encouragement throughout the whole period of my PhD study. I always feel inspired by his enthusiasm, dedication to excellence, and careful attention to details. I feel very proud to be given this opportunity to study under him. I would also like to express my sincere gratitude to Assoc/Prof. Hooshang Ghafouri-Shiraz from the University of Birmingham, UK, for his continuous encouragement and strong support during my first year PhD study.

I want to express my special thanks to Dr. Gong Yandong for his kind guidance, great help and fruitful discussion on my research works. I wish to thank Dr. Dong Hui for his instruction in fundamental theory and assistance in experiments. I am grateful to Dr. Dong Xinyong, Mr. Yan Min, Mr. Li Yi, and Ms Zhang Jing for useful discussions. I would also like to thank Mr. Liu Duan, Ms Shao Xuguang, Ms Tang Wenli and Ms Yu Xia for their assistance during the thesis writing. Their insight, expertise and wealth of knowledge were invaluable to me.

Many thanks go to all staffs and students in Network Technology Research Centre (NTRC) for providing a very friendly and entertaining working environment.

Finally, my deepest appreciation goes to my beloved family, especially to my parents. Their understanding, encouragement and loving support throughout all my years of study have made this work both possible and meaningful.

SUMMARY

Fiber Raman amplification (FRA) has been studied intensively since 1990s owing to its potential applications in fiber optic communication systems. Compared with the lumped erbium-doped fiber amplifier (EDFA), the distributed Raman amplification (DRA) takes the advantages that: 1) amplification can be provided at any frequency by simply changing the pump wavelength; 2) any existing transmission line can be upgraded directly to DRA by simply adding pumps accordingly; 3) the Raman gain distributed over tens of kilometers of transmission fiber provides in a superior end-of-system optical signal-to-noise-ratio (OSNR).

This thesis documents the investigations of high performance Raman amplification. For the ultra-broadband Raman amplification, a semi-analytical method based on the equivalent fiber attenuation coefficient has been proposed to enlarge the iteration step size and save the computing time. Furthermore, a nonlinear shooting method and a multistep integration algorithm based on the Newton-Raphson formula are proposed to efficiently solve the two-point boundary condition problem when counterpumping scheme is deployed. The novel modeling and simulation algorithms reduce the exhaustive computing time and maintain fast convergence.

In order to optimize the transmission performances of Raman amplification systems, an optimization process based on the Q-factor analysis is conducted to find out optimal operation conditions of the co-pumping percentage and total Raman gain in the bidirectional-pumped long-haul multispans fiber link by considering noise performances and nonlinear penalties. The deviation of the optimal operation condition as a function of pump relative intensity noise (RIN) is investigated to guide the practical pump requirement for optimal Raman amplification.

A cost-effective discrete Raman amplifier (DCRA) is proposed and implemented in a double-pass configuration with the dispersion compensation fibers (DCFs). Theoretical analysis and experimental results validate the significantly enhanced gain-pumping efficiency in double-pass DCRA. The MPI noise is proved to be the dominating source of noise impairments in the double-pass system. Also, the double-pass structure of DCRA initiates the enhanced Brillouin scattering phenomena with the distributed Raman gain and the reflector-induced feedback. We analyze the dynamics of SBS and the threshold of comb generation by adjusting the pump and input signal conditions. An all-optical automatic feedback gain-clamping scheme is proposed to suppress the SBS generation and control the amplifier transient effects. With 3-km DCFs, the gain-clamped double-pass DCRA provides a flat Raman net gain of more than 14 dB with large input power variations and only 0.17 dB gain ripple over 30-dB input signal dynamic range when pump power is fixed at 410 mW.

Furthermore, the Raman amplification has been implemented to assist the four-wave mixing (FWM) all-optical wavelength conversion. We propose and demonstrate a highly efficient Raman-assisted FWM wavelength conversion scheme in the highly nonlinear fibers (HNLFs) based on our proposed double-pass system. The mutual influence of FWM on Raman scattering contributes to the efficient wavelength conversion. Wavelength conversion with efficiency larger than 0 dB over 50 nm bandwidth (1530 nm – 1580 nm) is realized. The converted wave with conversion efficiency greater than -3 dB can be adjusted arbitrarily for a wavelength range of 15 nm. In addition, we propose and investigate a group-velocity matched fiber Raman wavelength converter with birefringent fiber. With numerical simulations, the power and temporal evolutions of the converted wave and pump wave for 10 Gb/s and 20 Gb/s systems are analyzed and discussed under phase-matching conditions.

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LIST OF ABBREVIATIONS

AB	Adams-Bashforth
AM	Adams-Moulton
ASE	Amplified spontaneous emission
BER	Bit error rate
CFBG	Chirp-FBG
CW	Continuous-wave
DCF	Dispersion-compensating fiber
DCM	Dispersion-compensating module
DCRA	Discrete-Raman-amplifier
DFG	Difference frequency generator
DRA	Distributed Raman amplification
DRBS	Double Rayleigh backscattering
DSF	Dispersion shifted fiber
DWDM	Dense-wavelength-division multiplexing
EDFA	Erbium-doped fiber amplifier
FBG	Fiber Bragg grating
FEC	Forward error correction
FEM	Finite-element method
FHD	Flame hydrolysis deposition
FRA	Fiber Raman amplifier
FWM	Four-wave mixing
GC	Gain-clamping
GVD	Group velocity dispersion
GVM	Group-velocity matching
HF	Holey fiber
HNLF	Highly nonlinear fiber
IXPM	Intrachannel cross-phase modulation
IVP	Initial-value-problem
LD	Laser diode
MAN	Metro-area network
MF	Microstructured fiber
MPI	Multi-path-interference
MZI	Mach-Zehnder interferometer

NF	Noise figure
NLSE	Nonlinear Schrödinger equation
NOLM	Nonlinear optical loop mirror
NRZ	Nonreturn-to-zero
NZDF	Nonzero dispersion fiber
OC	Optical circulator
ODE	Ordinary differential equation
OSNR	Optical signal-to-noise ratio
PCF	Photonic crystal fiber
PD	Photodetector
PDG	Polarization-dependant gain
PLC	Planar lightwave circuit
PRBS	Pseudonym-random-binary-sequence
RZ	Return-to-zero
SBS	Stimulated Brillouin scattering
SMF	Single-mode fiber
SNR	Signal-to-noise ratio
SOA	Semiconductor optical amplifier
SOP	State of polarization
SPM	Self-phase modulation
SRS	Stimulated Raman scattering
SSMF	Standard single-mode fiber
TDFA	Tellurium-doped fiber amplifier
TLS	Tunable laser source
WDM	Wavelength-division multiplexing
WDMs	Wavelength-division-multiplexers
XGM	Cross-gain modulation
XPM	Cross-phase modulation
ZDW	Zero-dispersion wavelength

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1 Introduction

1.1 BACKGROUND AND MOTIVATIONS

1.1.1 Emerging Development In Optical Communications

The development of optical fiber technology has been a critical milestone in the global telecommunications and information technology revolution. The ability to communicate worldwide on demand would not have been possible without the development of low-loss silica fibers as broadband medium for transporting voice, video, and data traffic [1-4]. During the last few years, there has been an increasing data-driven bandwidth demand for high-capacity fiber-optic transmission systems ranging from short to ultra-long distances. This has led to a rapid development of new hardware components and transmission technologies [5]. To utilize the available bandwidth, numerous channels at different wavelengths have been multiplexed on the same fiber. The technology of combining a number of wavelengths onto the same fiber is known as *wavelength-division multiplexing* (WDM) [4]. Currently, dense-WDM (DWDM) system is becoming the vital networking technology with the developments in optical components in terms of capacity, flexibility, reliability and scalability [6]. A wide range of technologies have attributed to these advances, such as specially designed fibers, optical amplifiers, tunable laser sources and filters, and

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optical switching devices, together with sophisticated forward error correction (FEC) codes and distributed algorithms/software for flexible network configuration [3, 6-12].

In WDM systems, multiple optical carriers at different wavelengths are modulated by using independent external electrical signal bit sequences and are then multiplexed into a single fiber for transmission. The optical signal at the receiver side is demultiplexed into separate channels in the optical domain and detected by photodetectors (PDs). WDM has the potential for exploiting the large bandwidth offered by optical fibers. For example, hundreds of 10-Gb/s channels can be transmitted over the same fiber with the channel spacing less than 100 GHz. Figure 1.1 shows the available low-loss transmission windows of optical fibers. Although the early lightwave transmission systems operate in the first wavelength window near 1310 nm, typical WDM systems are developed near 1550 nm where fiber losses reach the minimum value with the introduction of dispersion shifted fibers (DSFs) and erbium-doped fiber amplifiers (EDFAs) [4, 5].

Figure 1. 1: Low loss transmission windows of silica fibers in the wavelength regions near 1.3 and 1.55- μ m. The inset shows the WDM technique schematically.

The latest generation of fiber-optic communication systems is concerned with extending the size of wavelength window. The conventional wavelength window,

known as C-band, covers the wavelength range 1530-1565 nm. It is being extended on both long- (1565-1625 nm) and short-wavelength (1480-1530 nm) sides, resulting in the L- and S-bands, respectively (as illustrated in Fig. 1.1) [6-8].

1. 1. 2 Nonlinear Effects in Optical Transmission Systems

When you dial a number on your phone or press the “send” button for your email, you actually initiate a series of light pulses on an optical fiber, and the quality of the established communication link depends on both the strength and the shape of these pulses when they reach the receiving end. As technology advances, the pulses get shorter and shorter and the length of optical link becomes longer and longer. Deployed telecommunication systems are capable of sending very short optical pulses of less than 100 ps over several hundred kilometers without conversion to an electronic form. Unfortunately, these achievements also lead to new impairments to the transmission quality, which arise from new and subtler physical phenomena. Actually, all these attempts to fully utilize the capabilities of silica fibers will ultimately be limited by nonlinear interactions between the information carrier lightwaves and the transmission medium [12, 13]. These optical nonlinearities can lead to interference, distortion, and excess attenuation of the optical signals, resulting in system performance variations or degradations.

Nonlinearities arise since the glass has varied refractive index when exposed to light, which causes optical pulses to alter themselves or each other. There are two categories of nonlinear effects. The first category encompasses the nonlinear inelastic scattering process. These are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The second category of nonlinear effects known as Kerr effects arises from intensity-dependent variations in the refractive index of silica fibers. This

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produces effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [14]. While stimulated scatterings are responsible for intensity dependent gain or loss [14, 15], the nonlinear refractive index is responsible for intensity dependent phase shift of the optical signal [16, 17]. The study of nonlinear fiber optics is introduced with the availability of low-loss silica fibers (only 0.2 dB/km in the 1.55- μm wavelength region since 1979). Although SRS and SBS processes in optical fibers were studied as early as 1972 [15-18], the revolution in the field of optical fiber communications since 1980s stimulated the study of other nonlinear phenomena such as optically induced birefringence, parametric FWM and SPM [19, 20]. Optical soliton, a result of interplay between the dispersive and nonlinear effects, has been observed and explored, which leads to a number of advances in the generation and control of ultrashort optical pulses during the 1980s [21-25]. In the 1990s, the advent of rare-earth elements doped fiber amplifiers has led to a considerable attention in the analysis of fiber nonlinearities of multichannel WDM lightwave systems [26, 27]. Clearly, the field of nonlinear fiber optics is expected to grow prosperously during the twenty-first century. Lots of important advances have been developed from the fundamental as well as the technological point of view to promote the development of photonic-based technologies for information management.

1. 1. 3 All-Optical Raman Amplification

In this thesis, we focus on the Raman effect that based on the SRS. SRS is an interaction between light waves and vibrational modes of silica molecules [13, 15]. In a quantum mechanical picture shown in Fig. 1. 2. (a), if a photon with energy $h\nu_1$ (h is the Plank's constant) is impinged on a molecule with a vibrational frequency ν_m ,

Introduction

some energy can be transferred from the original photon to the molecule in the form of kinetic energy through the inelastic scattering process. In this interaction, a new photon with lower frequency ν_2 is generated with energy $h\nu_2$. The change in optical frequency is just the molecular-vibrational frequency. The generated new photon is called a Stokes photon. Quanta of these mechanical oscillations, known as optical phonons, have frequencies that are specific to the material and are strongly damped. The opposite process, known as anti-Stokes scattering, where energy is transferred from the molecules to the photons, may also be possible but occurs rarely because it requires the presence of a phonon with right energy and momentum. In this process (shown in Fig. 1. 2. (b)), the scattered photon has a higher frequency than the launched photon.

Figure 1. 2: Schematic of Raman scattering

Because the optical signal wave that is injected into the fiber is the source of the interacting photon, it is often called the pump wave, which provides power gain for the Raman scattering process. The probability of a Raman scattering event is proportional to the number of photons in the pump wave and the frequency spectrum of the Raman process is a function of material properties. In crystalline materials, the Raman scattered light has a narrow bandwidth centered about a specific frequency

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that is offset from the frequency of the launched light. For silica fiber, currently the main constituents of practical optical fibers, the Raman spectrum is relatively broad, in excess of 20 THz. As shown in the early experiments [15, 16], the most significant feature of the Raman gain in silica fibers is that its spectrum extends over a large frequency range (up to 40 THz) with a peak located near the frequency shift of 13 THz. This behavior is due to the noncrystalline nature of silica glass. In amorphous materials such as fused silica, molecular vibrational frequencies spread out into bands that overlap and create a continuum.

The process by which a single photon scatters, generates an optical phonon, and attains a new frequency is referred as spontaneous Raman scattering. The Raman process may also be stimulated. If a probe beam at the frequency ν_2 is coincident with the pump at the frequency ν_1 at the fiber input, it will be amplified because of the Raman gain, as long as the frequency difference $\Delta\nu = \nu_1 - \nu_2$ lies within the bandwidth of the Raman gain spectrum. The detailed analysis of stimulated Raman gain will be given in Chapter 2. Since SRS may be used to amplify communication signals in a broadband, it is of great interest in optical communication systems.

Early experiments on optical data transmission using Raman amplification were carried out by Aoki *et al.* [28], and Mollenauer *et al.* utilized a fiber Raman amplifier to carry out optical soliton transmission [19]. Although it was even before EDFAs that Raman amplifiers were demonstrated in experiments using large-scale solid-state lasers, they were not actually deployed in the real systems due to the lack of low-loss fibers and appropriate pump sources. However, over the last several years, there was a tremendous rebirth of the interest in Raman amplification in optical fibers. Practical, efficient, high-power diode pump sources [29, 30] have diminished the disadvantage

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of the relatively low efficiency of the Raman process compared to the erbium amplification process. As pump laser diodes (LDs) became mature and powerful due to the demand of high capacity, the feasibility of Raman amplifiers has increased accordingly. 14XX-nm pump LD has achieved more than 300 mW at commercial level [31]. There has also been an alternative approach for achieving Watt-class 14XX-nm output based on the cascaded Raman fiber laser technology [32].

Figure 1. 3: Wavelength window for different optical fiber amplifiers

Raman amplifiers do own several very attractive advantages over EDFAs. One very important feature of Raman amplifiers is their capability to provide gain at any signal wavelength by adjusting the pump wavelengths, as opposed to optical amplifiers based on rare-earth ions (shown in Fig. 1. 3). The nonresonant gain is available over the entire transmission region of the fiber ranging from approximately 0.3 to 2 μm [33]. This feature makes the Raman amplifier particularly attractive for future lightwave systems, where there is a strong desire to continually increase the number of signal wavelengths by extending the bandwidth in DWDM systems. Multiple

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Raman pumps can be used to increase the amplification bandwidth, and the pump distribution determines the gain flatness [34].

Besides the ability of providing gain at any wavelength, the Raman amplifier offers improved noise performance. Since the amplification occurs over a significant segment of the transmission fiber itself, the signal does not drop as much as it would in a conventional system based on lumped amplification. Thus, the signal-to-noise ratio (SNR) in this distributed amplifier is improved over lumped amplification [35].

Finally, the Raman amplifier is very simple. Raman gain exists in all silica-based optical fibers, which provides a cost-effective means of upgrading from the terminal ends. All that needed to turn the transmission fiber into an amplifier is to launch pump light simultaneously with the signal light.

Overall, Raman amplifiers provide a convenient platform for long-haul (typically ~300 to ~800 km) and ultralong-haul (typically above 800 km) amplifier needs. Raman amplifiers are broadband and wavelength agnostic. For high channel count systems, as will be deployed in the next few years, Raman amplification efficiency actually exceeds 1480-nm pumped C-band EDFAs [36]. Consequently, Raman amplifiers will be widely deployed in fiber-based optical telecommunication systems in the next decades [36-38]. This motivates the investigation of this thesis in developing new devices and design methods to reduce cost and achieve stable, excellent amplified transmission performances.

1. 1. 4 All-Optical Signal Processing Based on Raman Effects

In future optical communication networks, each local network would have an appropriate carrier wavelength depending on the demand for the network (e.g., $\lambda =$

1.3, 1.5- μm , or visible wavelength for plastic fibers). Wavelength conversion has been suggested as a method of enhancing routing options and network performances like reconfigurability, nonblocking capability and wavelength reuse [39].

In recent years, many promising techniques have been proposed to achieve the wavelength conversion through all-optical signal processing. There are methods including cross-gain modulation (XGM) [40], XPM in semiconductor optical amplifiers (SOAs) [41], FWM in SOAs [42], and FWM or XPM in DSF [43, 44]. Some devices have been developed for the all-optical wavelength conversion, such as the nonlinear optical loop mirrors (NOLMs) [45] and SOAs based on the XPM induced on the output beam by the input light. However, due to the relatively slow carrier recovery time of SOAs (1~2 ns), the signal speed is limited and the output signals are always nonreturn-to-zero (NRZ)-like pulses, which is not suitable for return-to-zero (RZ)-based links [46]. On the other hand, the scheme using the NOLMs requires the dispersion-shifted fibers for compensating the walk-off effect in NOLM. Thus the system become more complicated and the wavelength conversion range is limited near the zero-dispersion region. Moreover, difference frequency generators (DFGs) using quasi-phase-matched *LiNbO3* utilize a secondary nonlinear effect [47]. Which results in relatively slow conversion efficiency. Thus, these schemes are far away from the requirements for ideal wavelength converters.

Wavelength conversion by SRS in fibers is known to be efficient in obtaining a large frequency shift because of the broadband Raman gain spectrum. At the same time, the use of parametric FWM for wavelength conversion attracts considerable attention because of its potential applications in WDM lightwave systems. The data sequence carried by the signal can be transferred to the idler wave at a new frequency through

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the parametric FWM. Due to the instantaneous dynamics and phase-matching conditions, FWM transfers the signal data to the idler wave with perfect fidelity and even better signal quality by reducing the intensity noise. Thus, various schemes based on the Raman-assisted FWM or Raman-resonant FWM have been proposed [48-52]. The key issue is that the lower frequency parametric Stokes wave generated by FWM will also experience gain through subsequent Raman amplification when the frequency shift falls within the Raman gain band [52]. Furthermore, Recent studies show that distributed Raman amplification (DRA) in optical digital regenerative devices can eliminate timing jitter significantly [53]. Thus we can expect that Raman-FWM interaction will achieve a very promising wavelength conversion technique, which results in high conversion speed, good SNR, voluntary modulation format, high conversion efficiency, and ultra-broad conversion range based on the Raman effects.

1.2 OBJECTIVES

The main objective of this thesis is to investigate new devices and design methods for Raman amplified long-haul or ultra long-haul WDM transmission systems to reduce cost and improve the amplified transmission performance. In order to utilize the broad Raman gain spectrum and provide the flattened gain performance within a wide range, novel modeling method and simulation algorithms for the multi-wavelength pumping Raman amplifier are to be developed to reduce the exhaustive computing time and maintain fast convergence. Also, for the Raman amplified long-haul fiber link, we need to optimize the operation conditions according to the gain and noise performances to ensure best transmission quality. For the relatively poor pumping efficiency of Raman amplifiers, new structure/configuration should be implemented in a discrete Raman system to enhance the gain efficiency by using high Raman gain

coefficient fiber. The optical gain and dispersion compensation in the same fiber will be achieved simultaneously. At the same time, all-optical feedback will be developed in this discrete Raman amplifier to suppress the amplification transient effect and provide automatic gain control. What's more, new schemes of Raman-assisted parametric FWM wavelength conversion will be developed utilizing our high-efficiency Raman amplifier.

1.3 OUTLINE OF THE THESIS

After the introduction of Chapter 1, Chapter 2 presents the principle of Raman effects and the Raman amplification for WDM systems. Fundamentals of SRS are illustrated and a theoretical model based on small-signal approximation is derived to analyze the properties of distributed Raman amplification. Gain and noise characteristics are discussed to highlight the advantages and limitations of Raman amplification compared with EDFA. Three pumping schemes are described and compared in terms of the optical signal-to-noise ratio (OSNR) performances. We demonstrate the constraints of real-world Raman amplifier and introduce some novel pumping techniques. Finally, full temporal model of Raman amplification is developed based on the nonlinear Schrödinger equation (NLSE) to include the walk-off effects and other nonlinear impairments.

The novel numerical simulation algorithms for the ultrabroad band multi-pumps fiber Raman amplifier (FRA) are presented in Chapter 3. An equivalent fiber attenuation coefficient is introduced to enlarge the iteration step size and save the computing time. Further, a nonlinear shooting method and a multistep integration algorithm based on the Newton-Raphson formula are proposed to approximate the signal power propagation precisely in backward-pumped multichannel wideband Raman amplifier.

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Both signal and pumps' evolutions have been numerically simulated and compared with initial conditions to prove the validity of our algorithm. With the very fast convergence, these methods are quite useful to analyze the real system performance when it is upgraded to backward- or bidirectional-pumped DRA.

In Chapter 4, we investigate the signal transmission quality of bidirectionally pumped all-Raman amplification system. We conduct the optimization process of bidirectionally pumped system based on the Q-analysis using OSNR parameters to find out optimal operation conditions of Raman amplified fiber transmission system. By implementing partial copumping Raman gain, improved noise performance due to low amplified spontaneous emission (ASE) and multi-path-interference (MPI) noise accumulation is achieved compromises impairments due to nonlinearity enhancement and the relative intensity noise (RIN) transfer. The explicitly optimized Raman pumping conditions for multispans long-haul transmission systems are obtained.

We then demonstrate an intensive theoretical and experimental investigation in Chapter 5 on the dispersion-compensating Raman amplification module configured in double-pass geometry. Dispersion-compensating fiber (DCF) is used as the gain medium. An analytical model is developed to study the gain/pump efficiency improvement and the noise performance in a novel double-pass discrete-Raman-amplifier (DCRA) system. We demonstrate that the gain and pump efficiency can be improved significantly by using the double-pass configuration and the pump light reflector. The MPI noise due to the Rayleigh scattering and the external reflection are analyzed in order to balance the high gain efficiency and the enhanced MPI noise in the double-pass DCRA. Furthermore, we investigate the nonlinear penalty in the DCRA system and simulate a 10-Gb/s nonreturn-to-zero (NRZ) signal transmission in

a 4×100 km fiber system. The signal quality and bit-error-rate are examined and the optimization is implemented with reference to the input signal level and Raman gain.

Chapter 6 demonstrates characteristics of Brillouin-shifted Stokes light in double-pass fiber Raman amplifiers considering signal and Raman pump conditions experimentally. The dynamics of Brillouin scattering and the cascaded Brillouin Stokes comb are observed and analyzed. The multiwavelength Brillouin scatterings consume the pump power significantly and make the Raman amplifier unstable. We then propose an all-optical gain-clamping technique in the double-pass system to achieve the uniform gain and noise performance for large signal variations and mitigate the detrimental Brillouin scattering of Raman amplified signal.

In Chapter 7, the feasibility of our proposed group-velocity matched fiber Raman wavelength converter using extended birefringent fiber is demonstrated, where the high power pumping laser diodes are used to achieve sufficient conventional Raman-resonant FWM conversion. The power intensity and temporal properties of the converted wave have been investigated using numerical simulations. Furthermore, a simpler but more efficient Raman-assisted parametric FWM wavelength conversion using distributed Raman gain in 1 km of highly nonlinear fibers (HNLFs) is implemented based on our proposed double-pass Raman amplifier. Theoretical analysis and experimental results realize tunable wavelength conversion capability with efficiency larger than 0 dB over 50 nm signal bandwidth (1530 nm ~ 1580 nm).

Chapter 8 summarizes the main achievements and draws the conclusions of the thesis. Discussions and recommendations of possible future works are presented.

1.4 ORIGINAL CONTRIBUTIONS

The original contributions of this thesis are as follows:

- Design of an ultrabroad band multi-pumping FRA with our proposed numerical modeling method using the equivalent attenuation coefficient (Chapter 3).
- Proposal and demonstration of the nonlinear shooting algorithm and multistep integration method to calculate the multi-pump FRA performances with counterpumping schemes (Chapter 3).
- Optimization of bidirectional pumping Raman amplifiers for multispan long-haul transmission link based on Q-analysis considering the copumping percentage, total Raman gain and the RIN transfer induced penalty (Chapter 4).
- Design and demonstration of a novel double-pass dispersion-compensated discrete Raman amplifier using DCF. Significant gain/pump efficiency enhancement is achieved. Optimum gain distribution of amplifier has been found to make the discrete Raman amplifiers competitive with the performance of new types of EDFAs (Chapter 5).
- Proposal and implementation of a discrete fiber Raman amplifier configured in double-pass scheme together with FBG-based all-optical feedback to provide automatic gain control. The gain-clamping technique eliminates the Raman-reflection-enhanced Brillouin scattering and provides a stable and efficient Raman-amplified module for the dispersion-managed fiber transmission line (Chapter 6).

- Theoretical investigation of the novel wavelength conversion scheme based on the group-velocity matched fiber Raman-resonant FWM. A highly efficient tunable wavelength converter based on the FWM-Raman interaction in HNLFs is developed in the double-pass Raman amplifier with efficiency larger than 0 dB over 50 nm signal bandwidth (Chapter 7).

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2 Principle of Fiber Raman Amplification

2.1 INTRODUCTION

During the last few years, there has been a unique explosion in growth of the optical telecommunications industry driven by technology and massive increases in data-traffic bandwidth demand [1-5]. To provide sufficient cost-efficient network capacity for future bandwidth demand, higher bit-rate and higher channel density systems are being rapidly developed. Especially, discoveries in novel optical fiber amplifier devices enable the evolution of the optical network infrastructure [1, 5]. Cost-effective, terrestrial transmission systems require amplifier spacing of at least 80 km and at least five to six spans between electrical regeneration [6, 7]. The amplifier brought to the market will tend to be those that can be mass manufactured at low cost while providing acceptable – hopefully outstanding – performance for the customer. Among the various competing candidates for next generation fiber amplifiers, fiber Raman amplifiers (FRAs) offer the necessary low-noise performance thus is promising for economical systems [8-10].

This chapter explores the principle of Raman amplification in optical fiber communication systems. A literature review of existing works is demonstrated in Section 2.2. Section 2.3 introduces amplification by stimulated Raman scattering.

Fundamentals of Raman amplifiers are reviewed. The Raman gain properties are investigated by deriving the small-signal approximated analytical model. Also, we measure the Raman gain coefficients of different optical fibers in this section. Section 2. 4 discusses noise performance from ASE and MPI sources. Other sources of noise that are particularly relevant are also introduced in this section. Some novel Raman pumping schemes that are developed recently are described in Section 2. 5. Moreover, ultrafast SRS occurring for pulses of 100-ps width or less is discussed in Section 2. 6, in which the group-velocity dispersion (GVD), SPM and XPM effects are taken into account. Finally, the conclusions are given in section 2. 7.

2. 2 LITERATURE REVIEW

The Raman gain arises from the transfer of power from one optical beam to another that is downshifted in frequency by the energy of an optical phonon [11]. Research on Raman amplification in optical fibers started as early as 1970s [12-15]. The benefits by using Raman amplification in the fiber transmission system were already being investigated since mid-1980s [16, 17]. However, the low efficiency (roughly 0.06 dB of gain per mW of pump power in Raman amplifier is obtainable as compared to several dB per mW of pump power in EDFA) of Raman gain combined with the lack of the high power pump light source at that time restricts the Raman amplifier research during the commercialization of EDFAs in early 1990s [18, 19].

The application of Raman amplification in optical fibers has spurred renewed interests in the mid-1990s with the development of suitable high-power pumps (either LDs or fiber lasers) [20-28]. Researchers and engineers worldwide have demonstrated some of the advantages that Raman amplifiers have over EDFAs, particularly when the transmission fiber itself is turned into Raman amplifier for extending the capabilities

Chapter 2

of lightwave communication systems [29]. Various transmission experiments have demonstrated the exponential increase in the capacity-distance product with Raman amplifications since 1994 [30-41]. Hansen *et al.* showed that a 2.5 Gb/s system could be upgraded to 10 Gb/s directly by only adding Raman amplification [30]. Nissov *et al.* demonstrated a 7200-km WDM transmission using only Raman amplifiers [31]. By implementing the experimental comparison of all-Raman and Raman/EDFA hybrid amplifications using 40 Gb/s-based transmissions over 400 km TW-RS fiber, Zhu *et al.* showed that the system based only on Raman amplifiers has superior noise performances [32]. They also demonstrated a 16×40 GB/s transmission over 500 km by using dispersion-managed fiber based Raman amplification [33]. In order to employ the wide bandwidth of Raman spectrum, multi-pumping scheme is proposed to create ultra-wideband Raman amplifiers by multiple-LD or cascaded Raman fiber lasers. Emori *et al.* has proposed a Raman amplifier pumped with the so-called WDM pumping technique, in which 12-wavelength channel high power LDs are used to generate 100 nm bandwidth flat Raman gain [34].

Since distributed Raman amplification improves the system OSNR, the increased power budget in system design can be used to extend the fiber span distance between amplifiers and enhance spectral efficiency. J. Bromage *et al.* investigated the bidirectional Raman pumping scheme and conducted the experiments using 200-km spans of nonzero dispersion fiber (NZDF), where 40×10 Gb/s signal is transmitted over 2400 km with error-free performance [35]. Similarly, 2.56 Tb/s (64×42.7 Gb/s) WDM transmission over 6000 km using all-Raman amplified inverse double-hybrid spans has been achieved recently [36]. Also, Leng *et al.* reported a transmission experiment of 1.6 Tb/s (160×10.7 Gb/s) over 4000 km of NZDF at 25-GHz channel spacing using 100-km amplified fiber spans [37]. Mizuochi *et al.* have shown that

unrepeated bidirectional transmission system of 43-Gb/s is feasible by using band-separated Raman amplification [38]. The Raman amplification has been proved to be able to reduce the effects of SPM and XPM in multi-span systems [39] as well as to suppress the four-wave mixing even in the zero-dispersion region of DSFs [40]. Moreover, Raman amplifiers operate nearly as well as those in lab, even though the deployed fiber cables with many connectors cause reflections [41]. In a word, together with a number of technologies such as dispersion management, higher modulation rates, fiber engineering, forward-error correction, and advanced modulation formats, Raman amplifiers is now an accepted technique for enhancing performance in transoceanic and terrestrial optical telecommunication systems.

Besides the experimental demonstration, researchers have conducted extensive investigation on the modeling and analysis of Raman amplification in fiber communication systems. Aoki *et al.* and Takachio *et al.* have analyzed Raman amplifier under small signal regime for single signal channel [46, 47]. Kidorf *et al.* proposed a general multi-wavelength model to simulate the multi-pumped wideband Raman amplifiers [48] and hence many numerical methods (average power analysis, multistep method, genetic algorithm, etc) have been proposed to solve the complex nonlinear system considering the strong pump-to-pump interaction [49-51]. A detailed numerical comparison between distributed Raman amplification and discrete EDFA in a point-to-point 40×40 Gb/s WDM systems has been demonstrated with different modulation formats [52]. Moreover, various novel pumping techniques, which will be illustrated in Section 2. 5, have been proposed for the past few years to improve the Raman amplified system performance. Although many efforts have been done to help Raman amplifiers practical and acceptable, a number of challenges exist and prevent their wide adoption. The relatively poor pumping efficiency, the exhaustive time-

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consuming numerical simulation for broadband Raman amplification, the additional new noise sources incorporated in FRA (presented in section 2. 4. 3 and 2. 4. 4), and the nonlinear penalty are the major problems and design issues for the implementation of Raman amplification, which will be addressed in this thesis.

2. 3 FUNDAMENTALS OF RAMAN AMPLIFIERS

2. 3. 1 Raman Scattering Induced Optical Amplification

Raman scattering was first observed and discovered by Raman in 1928 and because of that he received the Nobel Prize in Physics in 1930 [42]. When an optical field is incident on a molecule, the bound electrons oscillate at the optical frequency. This induced nonlinear polarization produces optical radiation at the same frequency, with a phase-shift that leads to the change of medium's refractive index. Simultaneously, the finite response time due to Kerr effect results in energy loss of incident photon and excites the molecule vibration or phonon. For silica, the response time is on the order of 10 femtosecond (fs). Even though the response is extremely fast, the delay of nonlinear polarization with respect to the electric field of incident optical field causes the molecule structure itself oscillate at the frequencies of various molecule vibrations, which is known as the vibration modes. Therefore, the induced oscillating modes cause absorption of incident wave and gain to Stokes shifted wave. In quantum mechanical description, optical photons are inelastically scattered by the quantized molecular vibrations called optical phonons. The scattered light that are shifted to lower frequencies are called Stokes lights and those shift to higher frequencies are called anti-Stokes light. According to the Fig. 1. 2, the Stokes shift corresponds to the energy level of phonon, which is approximately 13.2 THz for silica-based optical fibers [43]. Since the anti-Stokes scattering rarely occurs in Raman amplifiers, the

signal wavelength is always longer than pump wavelength by the equivalent amount of frequency shift. When a signal photon at an appropriate frequency shift from pump is injected into a fiber, the pump and signal light are coherently coupled by the Raman scattering process. A pump photon is converted into the second signal photon that is an exact replica of the first one. Thus the initial signal is therefore be amplified by this stimulated Raman scattering (SRS).

Figure 2. 1: Schematic of the general Raman amplifier configuration. Both copumping (CO) and counterpumping (CT) are illustrated.

Note that the SRS due to the optical phonons is distinct from another inelastic scattering caused by acoustic phonons, which is known as the stimulated Brillouin scattering [44, 45]. Because the optical phonon has almost uniform dispersion relation versus wave number, the momentum conservation is guaranteed for arbitrary relative directions between pump and signal waves. Therefore, Raman amplifiers can be implemented in both co- and counter-pumping schemes. Figure 2. 1 illustrates the general pumping scheme of Raman amplifiers.

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2.3.2 Amplification of a Signal by a Single-Frequency Pump

To start a quantitative analysis for stimulated Raman scattering, the coupled ordinary differential equations (ODEs) are usually examined [46]. To simplify the model, we ignore other nonlinear processes and assume the SRS is under continuous-wave (CW) or quasi-CW conditions. We also neglect higher order Stokes waves. This is valid in the small signal amplification scheme. Thus the coupled equations that describe photon number transfer from the pump to the Stokes waves of a given mode or per unit frequency interval can be written as [11, 46]:

$$\frac{dN_p^\pm(z)}{dz} = \mp \alpha_p N_p(z) \mp C_r N_p(z) \cdot [N_s(z) + 1] \quad (2.1)$$

$$\frac{dN_s(z)}{dz} = -\alpha_s N_s(z) + C_r N_p(z) \cdot [N_s(z) + 1] \quad (2.2)$$

where N_p is the pump photon number and N_s is the Stokes photon number. Here, and throughout this chapter, subscripts p and s refer to the pump and Stokes signal, respectively. α_s and α_p represent signal and pump light transmission loss in fibers, and C_r is the Raman gain coefficient. The negative (positive) sign refers to the forward (backward) propagation direction. It is assumed that the signal propagates in the $+z$ direction and the pump can be copropagate or counterpropagate with the signal. In the above equations, the first terms represent linear absorption in optical fibers and the second terms express nonlinear interactions due to Raman effects. Integer 1 in equation (2.1) accounts for the spontaneous emission. Note that these steady-state equations can be applied to amplification of a modulated signal light whose pulse width is larger than one-picosecond (ps).

Raman gain properties can be derived analytically from equations (2. 1) and (2. 2) with the assumption that pump depletion due to Raman interaction may be neglected. That is, the second term on the right hand side of equation (2. 1) is omitted, which is valid in small signal-input and average gain regime. Thus the solution for pump photon number under negligible pump depletion is:

$$N_p^+(z) = N_{pf}(z) = N_{pf}(0) \exp(-\alpha_p z), \text{ (for forward pumping)} \quad (2. 3)$$

$$N_p^-(z) = N_{pb}(z) = N_{pb}(L) \exp[-\alpha_p (L - z)], \text{ (for backward pumping)} \quad (2. 4)$$

where $N_{pf}(0)$ and $N_{pb}(L)$ is the photon number of the pump input at both fiber ends. L is the fiber length. Thus the solution of equation (2. 2) can be derived as:

$$N_s(L) = N_{signal}(L) + N_{noise}(L) \quad (2. 5)$$

where

$$N_{signal}(L) = N_s(0) \exp(-\alpha_s L + \int_0^L C_r N_p(\eta) d\eta) \quad (2. 6)$$

$$N_{noise}(L) = \int_0^L C_r N_p(\xi) \exp[\alpha_s(\xi - L) + \int_\eta^L C_r N_p(\eta) d\eta] d\xi \quad (2. 7)$$

In formula 2. 5, the first term N_{signal} represents the fiber output signal photon number after amplification and the second term N_{noise} represents the spontaneous Raman scattering induced ASE per unit frequency interval, which exists even if the input signal $N_s(0)$ is zero. Substituting equations (2. 3), (2. 4) into (2. 6), we get

$$N_{signal}(L) = N_s(0) \exp(-\alpha_s L) \exp[C_r (N_{pf}(0) + N_{pb}(L)) L_{eff}] \quad (2. 8)$$

where L_{eff} is the effective fiber length, within which most of the Raman gain occurs:

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \quad (2. 9)$$

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Here, both copumping and counterpumping are taken into account. In equation (2. 8), the term $\exp(-\alpha_s L)$ represents fiber transmission loss of signal, whereas the term $\exp[C_r(N_{pf}(0) + N_{pb}(L))L_{eff}]$ represents the amplification factor in fiber. Therefore, under negligible pump depletion, the Raman amplification factor in linear unit can be found as:

$$G = \exp(C_r L_{eff} N_p) \quad (2. 10)$$

where $N_p = N_{pf}(0) + N_{pb}(L)$ accounts for the total pump power injected at both fiber ends. We then introduce the following relationship [47]:

$$C_r N_p = C_R P_p \quad (2. 11)$$

where P_p is the total pump power. $C_R = \frac{g_R}{KA_{eff}^R}$ is the effective Raman gain coefficient with unit of $(W \cdot km)^{-1}$ and g_R is the Raman gain coefficient. Here the numerical factor K accounts for polarization scrambling between the pump and signal since the Raman gain is polarization dependent. For complete polarization scrambling as in conventional single mode fibers, K is equal to 2. Therefore, we can write equation (2. 10) in terms of light power rather than photon number:

$$G = \exp(C_R L_{eff} P_p) \quad (2. 12)$$

where P_p is the total pump power. Actually, the Raman amplification factor G is often called the on-off Raman gain, which is defined as the increase in signal power at the amplifier ($P_s(L)$) output when the pumps are turned on. That is, in the small signal limit, the on-off gain is:

$$G_{ON-OFF} = \frac{P_s(L) \text{ with pumps ON}}{P_s(L) \text{ with pumps OFF}} = \exp[C_R L_{eff} (P_{pf} + P_{pb})] \quad (2.13)$$

Similarly, the net gain for the small signal of Raman amplifier is:

$$G_{net} = \frac{P_s(L)}{P_s(0)} = \exp[-\alpha_s L + C_R L_{eff} (P_{pf} + P_{pb})] \quad (2.14)$$

These equations can be used to estimate the pump power requirement for a given fiber span and background loss. Note that all the gain formula is in linear unit.

2.3.3 Fiber Effective Area of Raman Amplification

The expression of effective Raman gain coefficient C_R imply that the effective area A_{eff}^R play an important role. From the definition of C_R , much stronger Raman process inside fibers can be obtained with smaller effective core area.

In the conventional single-mode optical fibers, the increment of stimulated Raman scattered signal intensity is proportional to the product of the pump and signal intensities and the gain coefficient g_R , as shown below:

$$\frac{dI_s}{dz} = \frac{g_R}{K} I_p I_s \quad (2.15)$$

where I_s and I_p are the intensities of the Stokes-shifted and pump waves, respectively. In order to generate stimulated emission, the spatial and temporal overlap between pump and Stokes waves is necessary. In circular single-mode fibers, the power P is found by integrating the intensity over the cross-section of the fiber:

$$P = \int_0^{2\pi} \int_0^\infty I(r, \theta) \cdot r dr d\theta \quad (2.16)$$

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By integrating equation (2. 15) over the cross-section of the fiber, the power evolution of Raman scattered light is given by:

$$\frac{dP_S(z)}{dz} = P_P(z)P_S(z) \frac{\int_0^\infty \frac{g_R}{K} I_S I_P \cdot r dr}{2\pi \int_0^\infty I_S \cdot r dr \int_0^\infty I_P \cdot r dr} = P_P(z)P_S(z)C_R \quad (2. 17)$$

Since the g_R is assumed uniform along the radius, a new parameter A_{eff}^R that describes the spatial overlap between the signal and pump modes can be given as:

$$C_R = \frac{\int_0^\infty \frac{g_R}{K} I_S I_P \cdot r dr}{2\pi \int_0^\infty I_S \cdot r dr \int_0^\infty I_P \cdot r dr} = \frac{g_R}{KA_{eff}^R} \quad (2. 18)$$

$$A_{eff}^R = \frac{2\pi \int_0^\infty I_S \cdot r dr \int_0^\infty I_P \cdot r dr}{\int_0^\infty I_S I_P \cdot r dr} \quad (2. 19)$$

where the Raman effective core area A_{eff}^R is similar to the effective area of SPM and XPM [11]. The value of the Raman effective area usually presents values between those of pump mode and signal mode. This parameter provides an insight into the Raman interaction that is the Raman effects depends not only on the small fiber core area but also on the spectral separation between the pump and signal wavelength. A fiber with small A_{eff}^R for a given pump source can provide a large Raman gain. Normally, the equation (2. 19) can be replaced by a simple but useful expression $A_{eff}^R \cong \pi\omega_{eff}^2$ to estimate the effective area, where ω_{eff} is the effective core radius [48].

Figure 2. 2: Raman gain dependence on the fiber length and pump loss. Input pump power is 1.0 W and core-diameter is 10 μm .

Figure 2. 3: Raman gain dependence on the fiber core-diameter. Fiber length 200 km.

Figure 2. 2 and 2. 3 show the calculated Raman gain as a function of fiber length and core-diameter, respectively, for several different fiber losses. We assume the value of g_R is $6.7 \times 10^{-14} \text{ m/W}$ and pump input power is 1.0 W. From Fig. 2. 2 we can observe that Raman gain becomes larger as the fiber length increases up to approximate 50 km

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and reaches a constant value after that. This is because the interaction length or the effective fiber length L_{eff} becomes $1/\alpha_p$ when $L \rightarrow \infty$. Therefore, in order to obtain larger Raman gain at a fixed pumping level, it is effective to use lower loss fibers. From Fig. 2. 3, we also observe that the Raman gain can be quadratically increased by reducing the core-diameter.

2. 3. 4 Measurement of Raman Gain Coefficients

For design of real Raman amplifiers, we need to measure the Raman gain coefficients for various optical fibers. We do not have to directly measure the effective area and the Raman gain coefficient separately. Instead, We can measure the effective Raman gain coefficient $C_R = \frac{g_R}{KA_{eff}}$ calculated from equation (2. 12). In order to eliminate the polarization dependent gain in Raman amplification, we use the backward pumping scheme so that the polarization-scrambling factor K is equal to 2. The measurement system is shown in Fig. 2. 4:

Figure 2. 4: Raman gain coefficient measurement system setup. OSA: optical spectrum analyzer, TLS: tunable laser source, WDM: wavelength division multiplexer.

Here, the 1455 nm Raman fiber laser is used as the pump laser source, a tunable laser source (TLS) provides the input signal and the OSA scans wavelength range from 1520 to 1600 nm to measure the ON-OFF Raman gain of the corresponding signal

wavelength. The pump driven current is fixed at 1.6 A (corresponds to 700 mW pump light power) when it is turned on. Since the total insertion loss of isolator and WDM is about 1.5 dB, 0.56 W pump laser power can be obtained for Raman amplification. In order to measure the small signal Raman gain using the analytical model described in 2. 2. 2 and eliminate Brillouin scattering induced power transfer, the input signal power is fixed at -20 dBm for the entire wavelength range.

	DCF	HNLF	SSMF	DSF
Loss @ 1550 nm (dB/km)	0.49	0.7	0.22	0.21
Loss @ 1450 nm (dB/km)	0.69	0.85	0.25	0.25
Length (km)	3	1	50	18.875

Table 2. 1: Parameters of four types of fibers under measured.

Four types of fibers in our lab, dispersion compensating fiber (DCF), high nonlinear fiber (HNLF), standard single mode fiber (SSMF), and dispersion-shifted fiber (DSF), are tested for the measurements. The attenuation coefficients at pump and signal wavelengths for these fibers are listed in Table. 2. 1. The lengths of fibers under test are also shown in the Table.

With these parameters, we can compare the ON-OFF amplified signal spectrum and calculate the effective Raman gain coefficient by using equation (2. 9), (2. 12), and (2. 13). The measured effective Raman gain coefficient C_R is shown in Fig. 2. 5 as a function of signal wavelength respect to the 1455 nm pump light. Also, the Raman gain coefficient versus the frequency shift is shown in Fig. 2. 6. The Raman gain coefficient spectra exhibit a pattern resembled in triangular shape. We can obtain that

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the maximum Raman gain occur at 13.086 THz, 13.34 THz, 13.073 THz, and 13 THz for DCF, DSF, HNLF, and SSMF, respectively. The corresponding maximum values are $3.2 \times 10^{-3} W^{-1} m^{-1}$, $0.56 \times 10^{-3} W^{-1} m^{-1}$, $5.9 \times 10^{-3} W^{-1} m^{-1}$, $0.34 \times 10^{-3} W^{-1} m^{-1}$, respectively.

The measured Raman gain coefficients depend on both the effective area and the doping concentration of germania. The peak values are approximately inversely proportional to the effective area of the signal mode. Actually, at 1550 nm, the effective areas are $15 \mu m^2$, $10 \mu m^2$, $55 \mu m^2$, and $80 \mu m^2$ for DCF, HNLF, DSF, and SMF, respectively. The large Raman gain coefficient of HNLF is due to the small effective area and higher GeO_2 doping concentration. In addition, the maximum value of effective Raman gain coefficient depends on the specific pump wavelength used in amplifier. In general, the maximum value of C_R increases as the pump wavelength decreases [53].

Figure 2. 5: Effective Raman gain coefficients for different signal wavelength with respect to the 1455 nm pump.

Figure 2. 6: Effective Raman gain coefficient versus frequency shift with respect to 1455 nm pump wavelength.

Based on the different Raman gain features of optical fibers, various Raman amplification schemes can be developed. Because Raman effect does not require special dopants or structures in fibers to provide gain, any fiber can be used to achieve Raman amplification at any place in a lightwave system (Although the pump power will be different according to the gain and loss properties). In general, there are two classes of Raman amplifiers. One is the distributed Raman amplifier because the gain is distributed along the transmission fiber itself [30, 54]. Normally, to compensate the 100 km fiber span loss (22 dB for SSMF), total pump power of 860.4 mW is needed according to equation (2. 13). Another class is called discrete Raman amplifier because the signal gain occurs within relatively shorter fiber segments in the transmission system, such as the dispersion-compensating module (DCM) based on

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DCF. The DCF module can be pumped by Raman pump to offset the fiber loss of DCM, provide net gain, or open new wavelength windows for transmission [52, 53]. For instance, 260.7 mW pump power is needed to provide a small-signal net gain of 10 dB in 5 km short length DCF although higher signal and pump losses are experienced.

2.3.5 Gain Performances of Raman Amplifiers

In this subsection, we will analyze the signal gain properties of Raman amplifier in different pumping schemes. When a FRA is copumped and the pump depletion can be neglected, the signal power evolution in the transmission fiber can be written as:

$$P_{sig}(z) = P_{sig}(0) \cdot \exp\left[-\alpha_s z + \frac{K}{L_{eff}} \ln(G_{CO}) \cdot \frac{1 - e^{-\alpha_p z}}{\alpha_p}\right] \quad (2.19)$$

where G_{CO} is the forward Raman ON-OFF gain from copumping and is defined by equation (2.13). Similarly, when a FRA is counterpumped, the signal power is:

$$P_{sig}(z) = P_{sig}(0) \cdot \exp\left[-\alpha_s z + \frac{K}{L_{eff}} \ln(G_{CT}) \cdot \frac{e^{-\alpha_p(L-z)} - e^{-\alpha_p L}}{\alpha_p}\right] \quad (2.20)$$

where G_{CT} is the backward Raman ON-OFF gain from counterpumping. Therefore, when bidirectional pumping scheme is used, the signal power evolution is:

$$P_{sig}(z) = P_{sig}(0) \cdot \exp\left\{-\alpha_s z + \frac{K}{L_{eff}} \left[\ln(G_{CO}) \cdot \frac{1 - e^{-\alpha_p z}}{\alpha_p} + \ln(G_{CT}) \cdot \frac{e^{-\alpha_p(L-z)} - e^{-\alpha_p L}}{\alpha_p}\right]\right\} \quad (2.21)$$

Figure 2. 7 shows the normalized signal power distribution along the Raman amplified fiber span. For a constant fiber output power, the fiber input power can be reduced as the Raman gain increases. We assume that forward pumping and backward pumping each offered the Raman gain of 10 dB. Thus when bidirectional pumping is used, the total Raman gain is 20 dB. The Raman amplification is applied to a 100 km SSMF fiber span. The signal light (1550 nm) and pump light (1450 nm) loss are 0.22 dB/km and 0.3 dB/km, respectively.

Figure 2. 7: Normalized signal power distribution in fiber longitudinal direction for each pumping scheme in FRAs. Fiber span length is 100 km.

From Fig. 2. 7, we can observe that the average signal power distribution with counterpumping is smaller than that with copumping although the required input power is the same for both pumping schemes. With copumping scheme, the signal experiences Raman gain first followed by attenuation along the fiber span. Since the signal experiences gain before loss, the OSNR can be improved but the higher signal

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power will accumulate more nonlinearities. On the other hand, the signal attenuates first and being amplified near the output fiber end with counterpumping scheme. As a result, when the bidirectional pumping with 20 dB Raman gain is used, the signal power is flatted along the entire fiber length and the required input power is reduced significantly. Therefore, it is expected that the fiber nonlinear effects can be strongly mitigated by DRA with bidirectional pumping.

Then, we can define the equivalent fiber loss using the following equation:

$$\alpha_{eq} = -\frac{dP_s}{P_s \cdot dz} \quad (2.22)$$

By using equation (2.13) and (2.21), the equivalent fiber loss can be derived as:

$$\alpha_{eq} = \alpha_s - \frac{K}{L_{eff}} [\ln(G_{CO}) \cdot e^{-\alpha_p z} + \ln(G_{CT}) \cdot e^{-\alpha_p(L-z)}] \quad (2.23)$$

where the bidirectional pumping is used. Figure 2.8 shows the calculated equivalent fiber loss when Raman gain is applied in the passive fiber span. A negative loss is equivalent to gain in signal power increases along the direction of transmission. In the case of copumping, signal power increases near the input end. In the case of counterpumping, equivalent fiber loss at the fiber input is the same as that without Raman gain and it becomes negative near the fiber output end. That is, the signal is amplified at both fiber ends when bidirectional pumping is used.

Figure 2. 8: Fiber equivalent loss of signal for each pumping scheme. In bidirectional case, total Raman gain is 20 dB.

Now, an important and interesting problem is how accurate the analytical model is and what's the limitation of the small signal assumption-based analysis. For this reason, we compare the signal power evolution calculated using numerical simulation and analytical model. For the coupled ODEs 2. 1 and 2. 2, when we consider the pump depletion effect, the equations can be solved as an initial value problem using 4-th order Runge – Kutta integration method.

Figure 2. 9 compares the amplified signal evolution versus fiber length between numerical simulations (dash-dot line) and analytical calculations (solid line) (equation (2. 19)). Forward pumping scheme is used to provide 23 dB ON-OFF Raman gain on a 100 km SSMF fiber span. That is the required pump power is 935 mW and it is used as the pump initial value for numerical simulations. Different signal input power level (-20 dBm, -10 dBm, -5 dBm and 0 dBm, respectively) is considered to alter the pump

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depletion level. We can observe that when the input signal is quite low (-20 dBm), numerical and analytical results are almost the same and the difference between two methods is negligible. When input signal power becomes larger and the transmission distance becomes longer, the discrepancy of two results methods also increases. When the input signal is 0 dBm, the numerical value of output signal power is almost 2 dB lower than the analytical one. However, the power evolution of signal is almost the same in most of the fiber length.

Figure 2. 9: Comparison between numerical simulation and analytical calculation – Signal power distribution versus fiber length with different signal input level. 23 dB Raman ON-OFF gain is assumed. Solid line: analytical results; Dash-dot line: numerical results.

Figure 2. 10: Comparison between numerical simulation and analytical calculation – Output signal power after a fiber span versus ON-OFF gain with different signal input level (from lower to upper, -20, -10, -5, and 0 dBm, respectively). Fiber length is 100 km. Solid line: analytical results; Dash-dot line: numerical results.

In Fig. 2. 10, we plot the output signal power after a 100 km fiber span as a function of Raman ON-OFF gain defined in equation (2. 13) (equivalently the pump power). Both numerical and analytical results are shown for comparison. The analytical results of amplified signal power show a linear relation with Raman gain in dB. However, the output signal power saturates when the Raman gain is greater than 20 dB and input signal power is larger than -5 dBm. Because of this saturation, the difference between two methods is almost 2 dBm when the input signal power is 0 dBm with Raman gain at 24 dB. These imply that our small-signal approximation model can be used to analyze the gain performances of Raman amplifiers accurately when the input signal power is lower than 0 dBm and applied ON-Off gain is less than 25 dB. The analytical

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model can also be used to predict the amplifier behavior qualitatively although gain saturation may occur under pump depletion conditions.

2.4 NOISE PROPERTIES OF RAMAN AMPLIFIERS

In addition to producing gain, Raman amplifiers also accumulate noise [57]. Understanding the properties of noise accumulation is crucial for optical transmission system since the OSNR may be deteriorated by the poor noise performance. We consider the noise feature of Raman amplifiers in this section.

2.4.1 Noise From Spontaneous Raman Scattering

One of the most important sources of noise is the amplified spontaneous noise (ASE) that is unavoidable in all optical amplifier providing optical gain [7, 58]. In Raman amplifiers, the ASE is induced by the spontaneous Raman scattering – the integer 1 in the equation (2. 2). The photon number of ASE per unit frequency interval with bidirectional pumping in each polarization state N_{noise} can be derived as:

$$N_{noise}(L) = \int_0^L C_r [N_{pf}(z) + N_{pb}(z)] \cdot \exp[\alpha_s(z-L)] + \int_y^L C_r [N_{pf}(z) + N_{pb}(z)] dy dz \quad (2. 24)$$

Using equation (2. 3) and (2. 4),

$$N_{noise}(L) = \int_0^L C_r \{ N_{pf}(0) \exp(-\alpha_p z) + N_{pb}(L) \exp(-\alpha_p(L-z)) \} \cdot \exp[\alpha_s(z-L) + \int_y^L \frac{C_r}{\alpha_p} [N_{pf}(0) \cdot (\exp(-\alpha_p z) - \exp(-\alpha_p L)) + N_{pb}(L) \cdot (1 - \exp(-\alpha_p(L-z)))] dy \} dz \quad (2. 25)$$

Using the expressions in previous equations, the output ASE noise power with bidirectional pumping within a bandwidth of optical filter B_s can be written as:

$$\begin{aligned}
P_{ASE}(L) = & h\nu_s B_s \int_0^L \left(\frac{K \ln(G_{CO})}{L_{eff}} \cdot \exp(-\alpha_p z) \right. \\
& + \frac{K \ln(G_{CT})}{L_{eff}} \cdot \exp[-\alpha_p (L-z)] \cdot \exp\{\alpha_s (z-L)\} \\
& + \frac{K \ln(G_{CO})}{\alpha_p L_{eff}} \cdot [\exp(-\alpha_p z) - \exp(-\alpha_p L)] \\
& \left. + \frac{K \ln(G_{CT})}{\alpha_p L_{eff}} \cdot [1 - \exp(-\alpha_p (L-z))] \right) dz
\end{aligned} \tag{2.26}$$

where h is the Planck's constant and ν_s is the signal frequency. The noise power with only copumping can be obtained by setting $G_{CO} = 1$ (0 dB) and that with only counterpumping can be obtained by setting $G_{CT} = 1$. Note that for an accurate modeling of the spontaneous Raman scattering, one needs to replace the integer 1 in equation (2.2) by $1 + \eta(T)$ where $\eta(T) = 1 / [\exp(\frac{h\Delta\nu}{k_B T}) - 1]$ is the temperature dependent phonon occupancy factor [59, 60]. k_B is Boltzmann's constant, T is the fiber absolute temperature in Kelvins, and $\Delta\nu$ is the frequency separation between pump and signal. Although it is a small correction factor at the peak Raman gain, it needs to be taken into account particularly for broadband Raman amplifiers where $\Delta\nu$ may be small when short wavelength signal channels are near the long wavelength pump channels [9, 34, 61]. We will consider this factor in Chapter 3 in which the multi-pumping broadband Raman amplifiers are intensively studied by numerical simulations.

On the other hand, the ASE noise power from a lumped EDFA in each polarization state is given by [18]:

$$P_{ASE-EDFA} = h\nu_s n_{sp} (G_{EDFA} - 1) B_s \tag{2.27}$$

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where n_{sp} is the inversion parameter. Figure 2. 11 shows the ASE noise power of FRA and EDFA versus ON-OFF gain. It shows that ASE noise power with counterpumping is 10 dB larger than that with copumping. That is the copumping scheme is more advantageous than the counterpumping from the viewpoint of minimizing ASE noise. Even if the counterpumping is used, FRA noise power is 7 dB less than that of a lumped EDFA. Therefore, optical ASE noise can be reduced significantly by using the distributed Raman amplifiers to replace the EDFAs.

Figure 2. 11: ASE noise power versus ON-OFF gain of co- and counterpumping FRA.

For comparison, the noise power caused by an EDFA is also plotted.

When the ASE light power accumulates along the fiber span, the signal light will interfere with copolarized ASE light that is propagating in the same direction. The interference will produce intensity fluctuations called “signal-spontaneous noise”. That is the reason we calculate the ASE light power in each state of polarization.

When the signal and ASE light is detected by a square-law detector, beat noises within the detector electrical bandwidth generate electrical current fluctuations. As a result, the digital signal bit sequences may be misinterpreted by the fluctuations. In order to analyze the noise impairments, the parameter OSNR_{ASE} is introduced and defined as the ratio of the optical signal power to the power of the ASE in a given reference bandwidth. Usually, ASE power in all polarizations is included.

2. 4. 2 Noise Figure of Raman Amplifiers

A convenient parameter to describe the noise performance is the so-called Noise figure (NF), which represents how much the signal's signal-to-noise ratio (SNR) degrades from the input to the output of an amplifier [34]. It is adapted to both optical and microwave amplifiers [62] and is defined as:

$$NF = \frac{SNR_{in}}{SNR_{out}} \quad (2. 28)$$

Note that the SNR_{in} and SNR_{out} are the input and output electrical SNR measured with an ideal Photodetector (quantum efficiency is 100%), and assuming the input signal is shot-noise limited [63].

When the signal-spontaneous beat noise dominates the optical amplifier noise characteristics (it is true when the noise power is much less than signal power), the total NF in linear units can be approximated as [34, 64]:

$$NF \cong \frac{1}{G_{net}} \left(\frac{2P_{ASE}(L)}{h\nu_s B_s} + 1 \right) \quad (2. 29)$$

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The first term corresponds to noise from signal-spontaneous beating and the $1/G_{net}$ represents the shot noise. Since the ASE light is randomly polarized, we multiply $P_{ASE}(L)$ by 2 to consider the polarization scrambling effect in Raman amplifiers.

If several optical amplifiers are cascaded in chain, the overall NF is given as [65]:

$$NF_{overall} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots \quad (2.30)$$

2.4.3 Multiple-Path Interference Noise

Besides the noise from ASE power, noise from multiple-path interference (MPI) occurs when signal light reaches the receiver by more than one optical paths. A small portion of signal light can be delayed either by multiple reflection or Rayleigh scattering [66-75]. The straightforward signal light will interfere with the delayed light at the receiver site. The interference will convert the phase noise to intensity noise [66, 67].

In Raman-amplified system, multiple-reflection sites can be induced by faulty connectors or splices in fibers [67]. The reflection-delayed signal will be amplified twice when it passes through the reflection sites. The original low level of reflected light will be enhanced significantly in high Raman gain region. Even the discrete reflections within a fiber span can be eliminated by careful design, there are still distributed reflections from Rayleigh scattering, which is the major concern of the MPI noise in Raman amplified systems [68-70].

As opposed to Raman scattering (nonlinear process), Rayleigh scattering is an elastic process (linear process), and therefore the scattered light has the same frequency as the incoming light [70-72]. Typically, Rayleigh scattering is proportional with λ^{-4} . It

is largely due to the variations in fiber's refractive index, which is caused by submicron inhomogeneities frozen into the glass when it solidified. When the signal propagates inside a fiber span, a portion of Rayleigh scattered light can be recaptured in the fiber. Half of the light copropagates in the forward direction and half in the backward direction. The backward propagating light recaptured by a fiber due to Rayleigh scattering of signal power P_s in length dz is $rP_s dz$ where r is the Rayleigh backscattering coefficient and it depends on the fiber composition and design structure [7]. The Rayleigh backscatter coefficient can be easily determined by measuring the light reflected from a segment of fiber of known loss:

$$\frac{P_R(z=0)}{P_{in}} = \frac{r}{2\alpha_s} [1 - \exp(-\alpha_s L)] \quad (2.31)$$

where $P_R(z=0)$ is the backscattered light power measured at the fiber input end and P_{in} is the input signal power. If the fiber length is very long ($L \rightarrow \infty$), the ratio is approximately $r/(2\alpha_s)$. Typical values of r for transmission fibers lie between 0.6 and $1 \times 10^{-4} \text{ km}^{-1}$ for SSMF and DSF. Due to the impurity and imperfection of fiber micro-structure, a signal may undergo two, or any even number Rayleigh backscattering and contribute to the system noise in the form of double-Rayleigh backscattering (DRB) incoherent MPI. This source of MPI sets a fundamental limit on the maximum distributed Raman gain along fiber span and it also limits the designed gain in discrete Raman amplifiers. The applied Raman gain cannot be too high otherwise the MPI will dominate the noise performance.

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Figure 2. 12: Schematic of small-signal model for DRB-induced MPI noise accumulation.

The DRB-induced MPI noise accumulation can be analytically modeled under the undepleted pump assumption by means of the co- and counterpumping net gain formula. Figure 2. 12 illustrates how the Rayleigh backscattered light flow in a fiber span with length L . We set the ξ and $z \in (0, L)$ as the coordinates between which DRB takes place. The first backscattering occurs at the z point and the reflected light power is $rP_{in}G(0, z)$, where $G(0, z)$ is the net gain from 0 to z and P_{in} is the signal input power. The backscattered light transmits backward and is amplified by the Raman net gain $G(z, \xi)$ until it is backscattered again at point ξ . The DRB light at this point is $r^2P_{in}G(0, z)G(z, \xi)$ and it will transmit through the remaining fiber length and be amplified accordingly. Finally, the output DRB light at $z = L$ is $r^2P_{in}G(0, z)G(z, \xi)G(\xi, L)$. Note that the net gain $G(z, \xi)$ is equal to $G(0, z)/G(0, \xi)$. The whole DRB power can be obtained by integrating ξ from 0 to z . Thus by integrating z from 0 to L , the total DRB light power at the output end can be given as:

$$P_{DRB}(L) = r^2 P_{sig}(0) G(0, L) \int_0^L \frac{1}{G^2(0, z)} \int_z^L G^2(0, \xi) d\xi dz \quad (2. 32)$$

where G is the net gain defined in equation (2. 14).

Figure 2. 13: DRB and ASE noise light power versus Raman ON-OFF gains under 3 pumping schemes for 100 km DSF fiber span.

Equation (2. 32) can be solved by numerical quadrature by considering different pumping schemes. We calculate the DRB noise power after a 100 km fiber span under copumping, counterpumping, and bidirectional pumping schemes. For bidirectional pumping, the powers of forward pump and backward pump are assumed the same. The input signal power is -10 dBm. Both SSMF and DSF (or NZDSF) are considered as the distributed Raman gain medium. The results for DSF span as a function of Raman ON-OFF gain are shown in Fig. 2. 13. The measured value of r is $1.03 \times 10^{-4} \text{ km}^{-1}$. For comparison, we also plot the ASE noise power (the resolution bandwidth is 0.1 nm) in each scheme. From Fig. 2. 13, we can see that the DRB noise power has no difference under copumping or counterpumping scheme if the net gain is the same,

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which is consistent with previous report [73]. However, bidirectional pumping scheme is able to suppress the DRB noise accumulation since the Raman gain is distributed symmetrically along the fiber. The DRB light amplified by the full Raman gain at both ends must have also double-passed the net loss of fiber in the center [73-77]. Therefore, bidirectional pumping is quite effective to reduce the DRB noise.

Figure 2. 14: DRB and ASE noise light power versus Raman ON-OFF gains under 3 pumping schemes for 100 km SSMF fiber span.

The results for SSMF span as a function of Raman ON-OFF gain are shown in Fig. 2. 14. The measured value of r is $0.6 \times 10^{-4} \text{ km}^{-1}$. Similar features of DRB noise power are obtained except the light power is less than that in DSF span due to the low Rayleigh backscattering coefficient. From the two figures, we can observe that the DRB-MPI noise power increases dB-for-dB with the net gain of the amplifier and eventually overwhelms the ASE noise power. The dominating MPI noises in high Raman gain regime actually limit the maximum tolerant gain for the optimal OSNR.

We can also characterize DRB-induced MPI in terms of the amplifier's NF. Since the interference only occurs between signal and the MPI light that is copolarized with the signal, care needs to be taken to define the polarization properties of the MPI light. In the case of DRB-induced MPI, the fiber birefringence causes the DRB-light to be depolarized. However, the DRB is not randomly polarized, but as a degree of polarization 5/9, copolarized with the signal [75, 76]. That is, $P_{MPI} = (5/9)P_{DRB}$. Also, this analysis should consider the spectral features of MPI, which typically has the same spectrum as the signal, a reference bandwidth is not needed. Thus, the relative impact of beat noise from the signal beating with either ASE or MPI light depends on the details of optical and electrical filtering inside the receiver. If we assume that the signal spectra and all filters are Gaussian, an analytical form can be obtained from equation (2. 29) in the limits of large optical filter bandwidth [75]:

$$\begin{aligned}
 NF_{total} &= NF_{sig-spon} + NF_{shot} + NF_{MPI} \\
 &= \frac{2P_{ASE}(L)}{h\nu_s B_s G_{net}} + \frac{1}{G_{net}} + \frac{(5/9)P_{DRB}}{h\nu_s G_{net} \sqrt{B_e^2 + B_o^2}/2}
 \end{aligned} \tag{2. 33}$$

where B_e is the equivalent square bandwidth of the electrical filter and B_o is the equivalent square bandwidth of the optical signal.

2. 4. 4 Other Sources of Noise in Raman Amplifiers

Besides the main noise sources from ASE and MPI, some of the other sources should be taken into consideration when designing Raman amplifiers.

A. Interchannel Four-Wave Mixing

Another potential noise is the four-wave mixing (FWM) between multi-channels within the broadband Raman amplifier [78-80]. FWM is a third-order nonlinear

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interaction among four photons. Two photons at one or two frequencies (ν_1, ν_2) are annihilated and new photons at different frequencies are created (ν_3, ν_4). This process is strictly energy conserved such that the frequencies of generated photons obey $\nu_1 + \nu_2 = \nu_3 + \nu_4$. Also the momentum conservation is required to achieve an efficient process. This phase matching condition requires that the propagation constant of four waves satisfy $\beta_1 + \beta_2 = \beta_3 + \beta_4$. Therefore, the FWM process depends on the dispersion properties of transmitted fibers [78].

Since multi-wavelength pump light is used in the broadband Raman amplifiers, the FWM between pump channels may occur if the zero dispersion wavelength (ZDW) of the fiber lies within the pump channels or is near the longest wavelength of pump light [79]. Problems arise if the FWM generated light wavelength overlaps in the signal band. This new light can interfere with the original signal channels and produce beating noise. Even though the Raman amplifier is counterpumped, the light generated by FWM may be strong enough so that its Rayleigh backscattered portion can be above the Raman ASE noise floor.

FWM process is also possible to occur between the pump and signal light if the copumping scheme is used and the ZDW is located between the pump and signal wavelength [80]. A signal and pump photon are annihilated to produce a photon at a different pump wavelength and a new photon in the signal band. This FWM light will exhibit a spectrum that is similar with the mode structure of the pump.

Both FWM processes highly depend on the dispersion map of the transmission fiber and they primarily occur in the broadband amplifiers made from NZDF with a ZDW at 1500 nm. The OSNR of signal channels may be significantly degraded if the pump

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and signal wavelengths are not carefully chosen. Actually, the FWM process can be eliminated by using appropriate types of transmission fibers such as SSMF (ZDW is 1310 nm) or TrueWave REACH fiber (ZDW is 1400 nm). The poor phase matching properties of these fibers ensure that no FWM will occur.

B. Polarization-Dependent Gain

Raman gain is polarization dependent. The peak coupling strength between a pump and signal is approximately an order of magnitude stronger if they are copolarized than orthogonally polarized [12, 13]. The polarization-dependent gain (PDG) in FRAs can lead to transmission impairments. Obviously, random amplitude fluctuations due to PDG can occur if the relative polarization states of pumps and signals vary randomly. However, the amount of PDG produced in real Raman amplifiers is not as large as is seen in small bulk samples. Because the interaction lengths of Raman amplification are typically more than a few tens of kilometers, the correlation between the states of polarization (SOP) of signal and pump is lost during interactions [81]. Therefore, even if the pump were polarized, the polarization dependence of Raman gain should be diminished. This is particularly the case in counterpumping scheme. Even if the Raman amplifier is copumped using a shorter fiber length in discrete type, the pump light can be depolarized by simple techniques [8]. The high power LD can be depolarized by polarization-multiplexing the same wavelength output from two independent pump LDs [20, 34]. Also, Raman fiber lasers with large spectral linewidth can be depolarized using fiber Lyot depolarizers [82, 83]. With this measures, PDG impairments in Raman amplifiers can be eliminated successfully.

C. Pump-Signal Crosstalk

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One particularly important source of noise in Raman amplifiers is the coupling of amplitude noise from the pump to the signal through the Raman scattering [84-87]. The reason is that SRS is a nonresonant process with the extremely fast response time over subpicosecond scales. Unlike EDFAs, Raman amplifiers do not have a long upper-state lifetime to buffer the gain fluctuation from pump power. Therefore, pump intensity fluctuations may be transferred to signals as noise. However, in Raman amplifiers, pump and signals interact over time scales that are quite longer because they propagate along many kilometers of fiber. The long interacting time produces an averaging effect that limits the transfer bandwidth of pump noise. This noise transfer can be described in the frequency domain as a transfer of relative intensity noise (RIN) from a pump to a signal, using a transfer function $H(f)$ [84]:

$$RIN_s(f) = H(f)RIN_p(f) \quad (2.34)$$

where the RIN is defined as the noise power spectral density at that frequency divided by the square of the average optical power [63]. The transfer function $H(f)$ depends on the pumping configuration, the pump and signal wavelengths, and the applied Raman gain.

The copumping and counterpumping schemes are different from the mechanisms of RIN transfer suppression. In the case of counterpumping, the counter-propagating pump uses the transit time through the effective length of the Raman amplifier to average fluctuations in the pump power. The averaging effect greatly reduces the impact of pump fluctuations above a few kilohertz. For copumping case, the pump and signal pass through each other inside the fiber by the chromatic dispersion induced walk-off effect [84, 85]. Thus the averaging just reduces RIN transfer at much higher frequencies. Low loss, high dispersion fibers such as DCFs may be

appropriate for copumping. In general, we need stable pumps for copumping because it has a broader RIN transfer bandwidth than counterpumping. Approximately, copumps with RIN less than -120 dB/Hz are required for negligible noise penalties, whereas RIN level as high as -90 dB/Hz can be used for counterpumped amplifiers [84]. In order to employ the copumping scheme for its advantage of low ASE noise, one must consider the noise impairments induced by RIN transfer to achieve optimal noise performances.

2.5 VARIOUS RAMAN PUMPING TECHNIQUES

In order to improve the Raman amplified system performance, many novel pumping schemes have been proposed and extensively studied by researchers recently [86-95]. Some of them are briefly introduced here to provide an overview of existing techniques.

2.5.1 Multiwavelength-Pumping Broadband Amplifiers

Since the bandwidth of Raman amplification is extremely broad and the amplified spectrum can be shaped arbitrarily by simply adding pump, the broadband Raman fiber amplifier can be achieved by combining multiple pump wavelengths to make a flat gain spectrum. Using this pumping method, amplifiers with gain bandwidth more than 100nm covering C- plus L-band has been demonstrated with gain ripple less than 0.5 dB [34]. When designing such broadband amplifiers, a series of coupled ordinary differential equations should be used to model strong Raman interactions between pumps and signals. The intensive numerical study of the multiwavelength pumped Raman amplifiers is investigated in Chapter 3.

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2. 5. 2 Higher-Order Raman Pumping

Classically, the pump and signals are separated by a single Raman Stokes shift thus it is referred to as first-order Raman amplification. In order to further improve the OSNR, higher-order pumping is proposed to use the main pump separated from signal by two or higher order Stokes shifts [86-90]. The main pump amplifies a lower power first-order pump, which then amplifies the signal. Higher order pumping schemes can be implemented either in bidirectional or counter-propagating configurations [88]. In the bidirectional second-order pumping scheme, the first order pump is counter-propagating with the signal while the second-order pump is launched at the beginning of the fiber span. The first-order pump can be amplified by the second-order pump at the beginning of the span to provide the Raman gain for the signal at both fiber ends. If all the pumps counter-propagate with the signal, the first-order pump is Raman amplified by the higher order pumps propagating in the same direction, pushing the gain region for signals further into the span. Thus the signal power can be maintained relatively consistent to lower the noise figure of amplifier.

A number of experiments have shown the benefits of higher-order pumping techniques [88-90]. While the impacts of DRB-induced MPI noise and RIN transfer in distributed higher-order Raman pumping scheme have been investigated [89]. A third-order pump system based on this mechanism has been experimentally demonstrated with a broader and flatter gain profile than in conventional first-order schemes and with an equivalent NF improvement up to 2.8 dB [89]. Although the ASE-noise and gain flattening can be improved by using higher-order Raman pumping, the MPI noise and the nonlinear impairments are also increased [90]. At the same time, the multiwavelength high power Raman fiber laser source must be used to provide watts

of depolarized power at any wavelength from 1200 to 1500 nm (covering several Stokes shifts). All these factors should be considered to implement the higher-order pumping scheme in real Raman amplified systems.

2. 5. 3 Time-Dependent Raman Pumping

In conventional Raman systems, the Raman pump lasers operate in continuous-wave (CW) condition at fixed predetermined wavelengths. Due to pump-to-pump Raman interactions, the shorter wavelength pumps transfer a significant amount of energy to the longer wavelength pumps. Thus much higher power is needed at the shortest wavelengths and the noise figure is worse at the short wavelength signal channels. Furthermore, strong FWM between pumps can produce strong undesired lines in the signal band. In order to avoid the pump-pump Raman interactions and FWM, a new pumping scheme has been recently proposed and experimentally demonstrated in which the pump powers and/or wavelengths are time-division multiplexed (TDM) in the counterpumped Raman amplifiers [91-95]. Thus the entire pump wavelength will never simultaneously present at the same location within the fiber. Such a pump source can be obtained by switching among a set of wavelengths using a single tunable laser, or by switching between lots of fixed wavelength pump lasers [92, 93].

Since the pump light is deeply modulated in time domain, the TDM pumping scheme can be only used for counterpumped amplifiers [84, 94]. In addition, the repetition rate of the pump modulation must be high enough to suppress the significant temporal gain variation of signal [93-95]. Although the TDM pumping technique is able to eliminate the nonlinear interactions between pumps and to provide the dynamic wavelength and power reconfiguration functions, the additional cost/complexity and the temporal gain ripple prevent this scheme from being widely used in real systems.

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2.6 ULTRAFAST SRS

The coupled equations (2. 1) and (2. 2) can be used to describe the SRS in CW case or quasi-CW regime for pump pulses' widths > 1 ns. However, for ultrashort pulses of widths below 100 ps, SRS is then limited by the group-velocity mismatch and other nonlinear effects such as SPM and XPM. Thus the CW theory of SRS needs to be modified when ultrashort optical pulses are involved [11]. This is always the case for optical fibers since most modern optical telecommunication systems are operated at 10 Gb/s or beyond. The pulse width of signal is less than 100 ps or even shorter. In this case, each pulse acts as a Raman pump and generates Stokes pulse once the SRS threshold is reached. Since the broad gain spectrum measured in Fig. 2. 6 implies the response time of SRS is below 100 fs, we can considerably simplify the analysis by assuming the response is instantaneously. The assumption is always valid except for ultrashort pulses (width ~ 10 fs). The mutual interaction between the copolarized Raman pump and Stokes pulses is governed by two simplified coupled amplitude equations in which the effects of Raman gain, pump depletion, SPM, XPM, and GVD are included [14]:

$$\begin{aligned} \frac{\partial A_p}{\partial z} + \frac{1}{v_{gp}} \frac{\partial A_p}{\partial t} + \frac{i}{2} \beta_{2p} \frac{\partial^2 A_p}{\partial t^2} + \frac{\alpha_p}{2} A_p \\ = i\gamma_p [|A_p|^2 + (2 - f_R) |A_s|^2] A_p - \frac{g_p}{2} |A_s|^2 A_p \end{aligned} \quad (2. 35)$$

$$\begin{aligned} \frac{\partial A_s}{\partial z} + \frac{1}{v_{gs}} \frac{\partial A_s}{\partial t} + \frac{i}{2} \beta_{2s} \frac{\partial^2 A_s}{\partial t^2} + \frac{\alpha_s}{2} A_s \\ = i\gamma_s [|A_s|^2 + (2 - f_R) |A_p|^2] A_s + \frac{g_s}{2} |A_p|^2 A_s \end{aligned} \quad (2. 36)$$

here p and s represent pump and Stokes wave, respectively. v_g is the group velocity, β_2 is the GVD coefficient, and $\gamma = \omega n_2 / c A_{eff}$ is the nonlinear coefficient

where ω is the center frequency of pump or Stokes wave, n_2 is the nonlinear index coefficient. $f_R \cong 0.18$ is the fractional contribution of Raman effect. The effective gain coefficient g_s and g_p are related to the peak value of Raman gain coefficient g_R by:

$$g_s = g_R / A_{eff}, \quad g_p = (\omega_p / \omega_s) g_s \quad (2.37)$$

Equation (2.35) and (2.36) can be used to analyze the SRS effect when ps pulses propagate through optical fibers. Due to the dispersion property, the group-velocity mismatch limits the SRS process to certain duration, during which the pump and Stokes pulses overlap temporally. A new length scale, known as the walk-off length, can be defined as:

$$L_w = T_0 / |v_{gp}^{-1} - v_{gs}^{-1}| \quad (2.38)$$

where T_0 is the duration of the pump pulses. For pulses width ≥ 1 ns, the GVD effects are negligible. Note that these equations are not valid for femtosecond pump pulses whose spectral width already exceeds the Raman Stokes shift. The generalized propagation equation should be used in that case [11].

2.7 CONCLUSIONS

Due to the rapid development of optical fiber communication, and for the preparation of next generation terabit telecommunication, the cost-efficient, flexible Raman fiber amplifier has a promising application potential in fiber-based communication network. In this chapter, we investigate the principle of fiber Raman amplifiers

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according to the gain and noise performances. After reviewing the origin of SRS and recent research achievements in Raman amplification, we derive an analytical model for the CW Raman amplifier under small-signal assumption. Based on the theoretical model, we calculate the parameters associated with the Raman gain performances under copumping, counterpumping and bidirectional pumping schemes using our measured effective Raman gain coefficient. The major noise sources from ASE and DRB-induced MPI are also analyzed using this model to discuss the benefits and limitations of real Raman amplification. Raman amplification can reduce the ASE accumulation compared with the lumped EDFA significantly. Given the same amount of Raman gain, the forward pumping scheme is advantageous for a better ASE noise suppression while the bidirectional pumping can be used to reduce the MPI noise. By considering other noise source such as FWM, RIN transfer and PDG, backward pumping is more preferred due to its average effect. The MPI noise actually limits the maximal Raman gain that can be applied in the fiber system. The DRB noise power eventually exceeds the ASE noise power after a certain Raman gain value (dependent on the pumping scheme and fiber type) and dominates the noise performance of Raman amplifiers. However, the optimal choice of pumping scheme depends on the specific fiber span parameters and the pump laser properties.

We also discussed the limitations of the analytical model considering the pump depletion. The comparison between the numerical simulation and theoretical calculation reveals the valid (signal power less than 0 dBm and Raman ON-OFF gain less than 25 dB) regime in which our small-signal approximation is accurate. Finally, we extend the Raman scattering theory into ultrashort pulse regime to consider the SRS effect between modulated high-repetition rate signals in ultrahigh speed telecommunication systems including GVD, SPM and XPM.

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3 Broadband Multi-Pump Fiber Raman Amplifiers

3.1 INTRODUCTION

As described in Chapter 2, the most interesting features of fiber Raman amplification are the broadband Raman gain spectrum and the gain dependence only on the pump and signal wavelength [1-4]. Thus we can expect that it is possible for wideband optical fiber amplifiers to exploit more of the available fiber bandwidth hence increase the capacity of DWDM systems by using multi-pump Raman amplifiers. In principle, the spectral flexibility of Raman amplification allows the gain spectrum to be shaped by combining multiple pump wavelengths to make a polychromatic pump spectrum. There have been many studies searching for the appropriate modeling and simulation methods that give the flattened gain [5-27]. Using this broadband pumping approach, amplifiers with gain bandwidths over 100 nm have been demonstrated [5, 28].

When designing such broadband fiber Raman amplifiers (FRAs), one must consider the strong Raman interaction between the pumps [5, 13]. The short wavelength pumps amplify the longer wavelength pumps so that more power is typically needed at the shortest pump wavelengths [2, 5]. This interaction between the pumps also affects the

noise properties of broadband amplifiers. Because of the large number of channels employed in the wideband range, the corresponding inverse highly nonlinear system cannot be solved effectively and the pump depletion cannot be neglected. Therefore the intensive numerical simulation is needed instead of analytical solutions [5-20].

In this chapter, an efficient numerical method is presented by using the equivalent attenuation concept to solve the multi-pump FRA design problem. The configuration of multi-pump is demonstrated in Section 3. 2. Theoretical modeling and the proposed algorithm are presented in Section 3. 3. To optimize the iteration process in the numerical simulation, a nonlinear shooting algorithm is proposed and utilized in Section 3. 4 for the purpose of designing a counterpumped FRA efficiently.

3. 2 MULTI-PUMPING SCHEME FOR RAMAN AMPLIFIERS

The maturity of 14XX-nm pump LDs for EDFA readily let us realize practical broadband Raman amplifiers for WDM purposes. The multi-wavelength pumping scheme (“WDM” pumping) has been proposed to achieve a sufficient wideband and flat gain spectrum in Raman amplifiers [2-4]. The idea of “WDM” pumping is to prepare a set of pumps operating at different wavelengths combined through WDM couplers into a single fiber to realize a composite Raman gain. The composite Raman gain created by multiple pumps of different wavelengths can be so designed as to be arbitrarily broad and flat.

For stable and efficient WDM pumping, pump lasers ought to have narrow and stable lasing spectra. Koyanagi *et al.* have achieved a very high power from fiber Bragg grating (FBG) stabilized pump LDs [29]. Tanaka *et al.* developed integrated

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imbalance Mach-Zehnder interferometers (MZIs) on a planar lightwave circuit (PLC) based on flame hydrolysis deposition (FHD) method [30]. Fig. 3. 1 shows the schematic diagram of WDM pumping. 8-channel pump LDs have been coupled together by using PLC-MZI type optical WDM combiner with only 1.2 dB average insertion loss [29, 30]. The largest pump source yet constructed with this technology utilized twenty-four pump diodes at twelve wavelengths, producing 2 W of output power and generate a very flat, 100 nm – wide Raman gain spectrum [28]. Other different WDM coupler types, such as dielectric thin-film filter type, fused fiber coupler type, can also be designed and realize Raman amplifiers with various gain shapes.

Figure 3. 1: schematic diagram of WDM pumping

An alternative pump source, known as the cascaded Raman fiber laser, relies on Raman amplification itself [31-41]. The device is depicted schematically in Fig. 3. 2. Intense pump light is injected into the Raman laser at a wavelength easily generated by an ytterbium-doped, cladding pumped fiber laser. The initial pump wavelength emitted from the ytterbium laser is typically near 1100 nm. The presence of the intense pump light in the length of small core germanosilicate fiber generates Raman gain at 1155 nm. A low-loss resonator is created at that wavelength with FBGs. When

light begins lasing in the 1155 nm resonator, it serves to pump another fiber laser at 1218 nm. This light pumps another laser at 1288 nm and so forth, until light of the desired wavelength is created. As shown in Fig. 3. 2, the desired 1455 nm light is coupled out of the cavity with an output grating whose reflectivity is substantially less than 100%. Since the wavelength of the initial pump light and the intermediate lasers may be substantially tuned without significantly degradation in the conversion efficiency, any wavelength between 1100 nm and 1650 nm may be generated. A slope efficiency for conversion from 1100 nm to 1455 nm of 55% has been demonstrated [34].

Figure 3. 2: Schematic illustration of a cascaded Raman fiber laser.

Similar devices to those shown in Fig. 3. 2 have been created using fused fiber couplers and rings to create the lasing cavities [37-39]. Also, by using phosphosilicate fiber, Raman frequency shifts of ~ 40 THz can be efficiently achieved [31, 35]. Moreover, 10 W Raman fiber laser at 1248 nm using phosphosilicate fibers has been developed [35]. Recently, this technology has been extended to simultaneously produce three power-stabilized output wavelengths using tunable FBGs [34, 38]. A reliable dynamic control mechanism has been built in the Raman fiber laser to achieve dynamic gain flattening for the Raman amplification.

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3.3 DESIGN OF MULTI-PUMPING RAMAN AMPLIFIERS

3.3.1 Power Analysis Model

Although the architecture of Raman amplifiers is very simplistic, many factors must be considered in the proper design. The analysis of the multi-wavelength pumping FRA is based on a rate equation model that includes amplified spontaneous emission (ASE), spontaneous Raman emission and its temperature dependence, stimulated Raman amplification, and back capturing of Rayleigh scattering. These effects are all included in the following set of coupled steady state equations [5]:

$$\begin{aligned}
 \frac{dP^{\pm}(z, \nu)}{dz} = & \mp \alpha(\nu) P^{\pm}(z, \nu) \pm r(\nu) P^{\mp}(z, \nu) \\
 & \pm \sum_{\zeta > \nu} \{ C_R(\nu - \zeta) \cdot [P^{\pm}(z, \zeta) + P^{\mp}(z, \zeta)] \\
 & \cdot P^{\pm}(z, \nu) + 2h\nu \cdot C_R(\nu - \zeta) [P^{\pm}(z, \zeta) + P^{\mp}(z, \zeta)] \\
 & [1 + \frac{1}{e^{h(\zeta - \nu)/k_B T} - 1}] d\nu \} \mp \sum_{\zeta < \nu} \{ C_R(\nu - \zeta) \cdot [P^{\pm}(z, \zeta) + P^{\mp}(z, \zeta)] \\
 & P^{\pm}(z, \nu) + 4h\zeta \cdot C_R(\nu - \zeta) \cdot P^{\pm}(z, \nu) [1 + \frac{1}{e^{h(\zeta - \nu)/k_B T} - 1}] d\zeta \}
 \end{aligned} \tag{3.1}$$

In the above, the + and – symbols denote the direction of propagations, α is the fiber loss, r is the Rayleigh backscattering coefficient, $C_R(\nu - \zeta)$ is the effective Raman gain coefficient between frequency components ν and ζ . h is the Planck's constant, k_B is the Boltzmann's constant, and T is the absolute temperature of the fiber. $P^{\pm}(z, \nu)$ denotes the light power as a function of distance z for a specific frequency ν (may be signal or pump) with forward (+) or backward (-) direction. In this equation, we include highly nonlinear pump-to-pump, pump-to-signal, signal-to-signal Raman interactions and pump depletions due to Raman energy transfer. equation (3. 1) will

be extended into a series of coupled equations when we consider the multi-wavelength pumps and the correspondingly multiplexed signal channels.

To design the composite Raman gain, loss and gain terms are important. We have found that the frequency dependence of effective area A_{eff} plays an important role for accurate modeling, especially when the pump band is quite wide [2]. We have measured the effective Raman gain coefficient spectrum $C_R(\nu - \zeta)$ for different types of fibers in Chapter 2 using 1455 nm Raman pump. The measured value will be used in our following simulations.

3.3.2 Novel Power Analysis Simulation Model

For thorough analysis and designs, one needs to numerically solve equation (3. 1). Simulation methods for Raman amplifiers that have been demonstrated so far have been using direct integration of coupled differential equations (4-th order Runge-Kutta method), and demanding exhaustive computational times to achieve well-behaved predictions. As Raman amplifiers use much longer fiber length and even wider bandwidth than EDFA in addition to multiple pumps, the increase in the required computation efforts makes this task to be an even more time-consuming and non-practical problem.

Here, we introduce a new simplified method to solve those problems. The above highly nonlinear-coupled equations can be simplified as follows:

$$\frac{dP^\pm(z, \nu)}{dz} = \pm \alpha_{eq} P^\pm(z, \nu) + nsp(z, \nu) \quad (3. 2)$$

Where the key to our approach is to define the α_{eq} as the equivalent fiber loss using the following equations:

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$$\begin{aligned}
\alpha_{eq} = & \mp \alpha(v) + \sum_{\zeta > v} C_R(v - \zeta) \cdot [P^\pm(z, \zeta) + P^\mp(z, \zeta)] \\
& - \sum_{\zeta < v} C_R(v - \zeta) \cdot [P^\pm(z, \zeta) + P^\mp(z, \zeta)] \\
& - \sum_{\zeta < v} C_R(v - \zeta) \cdot 4h\zeta d\zeta \left[1 + \frac{1}{e^{h(\zeta - v)/kT} - 1} \right]
\end{aligned} \tag{3.3}$$

The $nsp(z, v)$ is the noise factor which includes the Rayleigh scattering terms and the spontaneous emission factors:

$$\begin{aligned}
nsp(z, v) = & r(v)P^\mp(z, v) + 2hv\Delta v \cdot \sum_{\zeta > v} C_R(v - \zeta) \\
& \cdot [P^\pm(z, \zeta) + P^\mp(z, \zeta)] \left[1 + \frac{1}{e^{h(\zeta - v)/kT} - 1} \right]
\end{aligned} \tag{3.4}$$

Assuming we divide the transmission fiber of FRA into a series of elemental sections with the equal step size Δz . Thus the α_{eq} can be considered constant within each step $[z_0, z_0 + \Delta z]$, and the noise power is negligible compared with the signal power (which is always the case in the practical regime), then

$$P^\pm(z, v) = P^\pm(z_0, v) \exp(\pm \alpha_{eq} \cdot z) \tag{3.5}$$

denotes the first-order variation. Substitute it into equation (3.1) we have

$$\frac{dP^\pm(z, v)}{dz} = g_{eq} \cdot P^\pm(z, v) + \Delta N(z, v) \tag{3.6}$$

where

$$\begin{aligned}
g_{eq} = & \mp \alpha(v) \pm \sum_{\zeta > v} C_R(v - \zeta) \cdot [P^+(0, \zeta) \exp(\alpha_{eq} z) \\
& + P^-(0, \zeta) \exp(-\alpha_{eq} z)] \mp \sum_{\zeta < v} \{ C_R(v - \zeta) \\
& \cdot [P^+(0, \zeta) \exp(\alpha_{eq} z) + P^-(0, \zeta) \exp(-\alpha_{eq} z)] \\
& + 4h\zeta \cdot C_R(v - \zeta) \cdot \left[1 + \frac{1}{e^{h(\zeta - v)/kT} - 1} \right] d\zeta \}
\end{aligned} \tag{3.7}$$

$$\begin{aligned} \Delta N(z, \nu) = & \pm \sum_{\zeta > \nu} \left\{ 2\hbar\nu \cdot C_R(\nu - \zeta) \cdot [P^+(0, \zeta) \exp(\alpha_{eq} z) \right. \\ & + P^-(0, \zeta) \exp(-\alpha_{eq} z)] \cdot \left[1 + \frac{1}{e^{h(\zeta - \nu)/kT} - 1} d\nu \right\} \\ & \pm r(\nu) P^\mp(0, \nu) \exp(\mp \alpha z) \end{aligned} \quad (3.8)$$

These variables are simple exponential functions of z , so that equation (3.6) can be solved analytically within Δz and leads to a good numerical accuracy even with an extended iteration step size.

Equation (3.6) can be solved analytically as:

$$P_{sig}^\pm(z_0 + \Delta z, \nu) = P^\pm(z_0, \nu) \cdot \exp(G_s(\Delta z, \nu)) \quad (3.9)$$

$$\begin{aligned} P_N(z, \nu) = & \exp(G_s) \left\{ \pm \sum_{\zeta > \nu} 2\hbar\nu \Delta\nu \cdot C_R(\nu - \zeta) \cdot [P^+(0, \zeta) \right. \\ & \cdot \frac{\exp((\alpha_{eq} + G_n)\Delta z) - 1}{\alpha_{eq} + G_n} + P^-(0, \zeta) \frac{\exp((G_n - \alpha_{eq})\Delta z) - 1}{G_n - \alpha_{eq}}] \\ & \cdot \left[1 + \frac{1}{e^{h(\zeta - \nu)/kT} - 1} \right] \pm r(\nu) P^\mp(0, \nu) \frac{\exp((G_n \mp \alpha_{eq})\Delta z) - 1}{G_n \mp \alpha_{eq}} \left. \right\} \end{aligned} \quad (3.10)$$

where

$$\begin{aligned} G_s = & \mp \alpha(\nu) \Delta z \pm \sum_{\zeta > \nu} C_R(\nu - \zeta) \cdot [P^+(0, \zeta) \frac{\exp(\alpha_{eq} \Delta z) - 1}{\alpha_{eq}} + \\ & P^-(0, \zeta) \frac{1 - \exp(-\alpha_{eq} \Delta z)}{\alpha_{eq}}] \mp \sum_{\zeta < \nu} \{ C_R(\nu - \zeta) \\ & \cdot [P^+(0, \zeta) \frac{\exp(\alpha_{eq} \Delta z) - 1}{\alpha_{eq}} + P^-(0, \zeta) \frac{1 - \exp(-\alpha_{eq} \Delta z)}{\alpha_{eq}}] \\ & + 4\hbar\zeta \Delta\zeta \cdot C_R(\nu - \zeta) \cdot \left[1 + \frac{1}{e^{h(\zeta - \nu)/kT} - 1} \right] \Delta z \} \end{aligned} \quad (3.11)$$

$$G_n = -G_s / \Delta z \quad (3.12)$$

Here G_s is the net gain within $[z_0, z_0 + \Delta z]$ for either pump or signal channels. The equation (3.9) and (3.10) represent the signals and noise power in each elemental

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amplifier sections, and then these formulas are used for our simulation. Note that we assume that the Rayleigh backscattering light does not grow significantly in case of moderate pump power level, which is always the case for the system of interest. Actually, the MPI due to the double Rayleigh backscattering (DRB) of the signal can be evaluated separately and does not affect the gain profile.

3.3.3 ON-OFF Gains and Effective Noise Figure

The distributed Raman gain takes place during the signal propagation in the fiber. It is equivalent to place a string of line amplifiers in the transmission fiber. The simplest criterion to describe the amplifier noise performance is its noise figure (NF). The NF is originally defined as the ratio of input SNR and output SNR. According to our previous discussion in Chapter 2, the effective NF in this model is defined as:

$$NF = \frac{1}{G_{ON-OFF}} \left(\frac{P_N}{h\nu\Delta\nu} + 1 \right) \quad (3.13)$$

where the G_{ON-OFF} is the ON-OFF gain defined in Chapter 2.

3.4 SIMULATION RESULTS AND DISCUSSIONS

Our novel model is suitable for forward-, backward-, or bidirectional-pumping scheme. Since this type of equation system is a typical two-point boundary value problem, only the initial power value of the forward propagating waves at the fiber input end and the initial value of backward propagating waves at the fiber output end are known. It is solved by using an iterative method to guess the missing values of backward propagating waves at the fiber input end at each run time of our algorithm.

3. 4. 1 Validity of Simulation Model

As is well known for iterative method, the simulation results, speed and accuracy strongly depend on the step size. Using our semi-analytical method, we can achieve high accuracy at a high speed with an enlarged step size. In this case, we consider the forward-pumping FRA first. The transmission medium is 40 km conventional SSMF. Fiber parameters include $A_{eff} = 80 \mu m^2$, $r = -40$ dB/km, $\alpha_p = 0.25$ dB/km and $\alpha_s = 0.2$ dB/km, where the subscript P and S denote the pump and signal light. Eight pumps working at $\lambda_p = 1425, 1432.5, 1440, 1450, 1461, 1472, 1489, 1508$ nm and $P_p = 250, 210, 210, 165, 130, 69, 68, 68$ mW are used [5]. Total input signal power of 50 mW is evenly distributed over 101 signal channels, starting from 1530 nm and with a channel spacing of 0.8 nm.

Figure 3. 3 shows the Raman net gain and the effective NF with forward pumping at different step size. We can see that the results at step size 10 m are very close to those at step size 1000m. The differences in net gain and NF are less than 0. 3 dB. Thus we can enlarge the step size from 10 m to 1000m without loss of accuracy so that the computation speed can be enhanced significantly.

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Figure 3. 3: Net gain (a) and effective NF (b) spectrum of 101-channel Raman amplifier system (simulated at different step size), $T = 300$ K.

3. 4. 2 Gains and NF at Different Cases

For the application of our novel simulation model, a multi-wavelength pumped FRA is simulated using the similar parameters as reported in previous experiments [28] for a backward pumping case. As mentioned in Chapter 2, pump RIN strongly affects the WDM signals to be amplified if forward pumping is applied. When the Raman pump wave has slight random power fluctuations in time, individual bits might be amplified differently and amplitude fluctuations or jitter will occur. Traditionally, in order to minimize the amount of pump-to-signal crosstalk and polarization-dependant gain (PDG), FRA is always operated in the counterpumping configuration. Power fluctuations of the Raman pump will be averaged such that each individual signal bit will see several milliseconds of the Raman pump wave if counterpumping is deployed.

In this simulation, the transmission medium is 25 km of SSMF and the fiber parameters are the same as above. The amplifier is designed with the twelve backward

pump sources (1405, 1413, 1420, 1427.5, 1435, 1442, 1450, 1458, 1465, 1480, 1495, and 1510 nm) and 101 input signal channels, starting from 1530 nm and with a channel spacing of 0.8 nm. Figure 3. 4 shows the net gain and NF spectrum of the simulation results at different input signal power levels. The experimental results (small signal gain) from Ref. [28] are also plotted for comparison. Considering the loss variation in real fibers, the simulation and experimental results match very well, which also prove the validity of our numerical model. For both input signal power, we achieve less than ± 0.5 dB variation over 100 channels with proper pump power arrangements. In both cases, the NF is worse in shorter-wavelength signal channels. It is clear that shorter-wavelength channels near pump bands experience more noise accumulation compared to longer-wavelength channels.

Figure 3. 4: Net gain and NF spectrum of the 101-channel Raman amplifier system at different input signal power levels (at -3 dBm/ch and at -8 dBm/ch), $T = 300$ K.

Experimental results from Ref. [28] are plotted for comparison.

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Figure 3. 5: Evolution of (a) pump channels, (b) signal channel powers in the fiber span with the designed multi-wavelength FRA. The system is the same as that in Fig. 3. 4 (backward pumping). $T = 300$ k.

The evolution of the signal and pump waves along the fiber span in our designed multi-wavelength FRA is shown in Fig. 3. 5. For comparison, the evolution of the signal and pump waves with forward pumping scheme is shown in Fig. 3. 6. For both pumping configurations, Raman amplification also affects the pumps themselves. The longer wavelength pumps absorb energy from the short wavelength pumps, which are

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directly responsible for signal amplification. In the backward-pumping scheme, the shortest wavelength pumps contribute more gain at the end of the transmission fiber. As a result, the highest gain is achieved in the second half of the fiber, but the high gain accompanies the large noise.

Figure 3. 6: Evolution of (a) pump channel, (b) signal channel powers in the fiber span with forward-pumping FRA. $T = 300\text{ K}$

The forward-pumping case exhibits the highest gain in the first half of the fiber, where the pump and signal powers are the highest. The signal power reaches a maximum

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value near the first quarter of the fiber and leads to higher nonlinear effects. Furthermore, in the backward-pumping case, the shorter wavelength signal channels have deeper power distribution along the fiber because they experience more loss due to signal-to-signal Raman scattering and they experience their gain later in the span because shorter wavelength pump channels decay much faster (due to Raman pump-to-pump interactions). It is a serious problem because the power decay of shorter wavelength signals in the middle of the fiber span results in the decrease of signal's OSNR at the receiver side.

3.4.3 Temperature Stability

Figure 3. 7: Temperature dependence on Raman gain (a) and NF (b). The Raman system is the same as that in Fig. 3. 3.

The temperature dependence of Raman scattering should be included in any modeling of Raman amplifiers if an accurate prediction of noise performance is required at temperatures above zero Kelvin. Actually, our model developed in this section is perfectly capable of accurately treating the temperature dependence of Raman amplifiers. Figure 3. 7 shows the temperature dependence on Raman gain and NF in the broadband Raman amplifier. The temperatures are chosen as 300 Kelvin and 400 Kelvin. We can see that there is nearly no differences in Raman gain at different temperature, that is, the signal gain is independent of temperature. The variation of effective NF due to the temperature change is less than 0.5 dB. The temperature stability of Raman gain is magnificent. The noise variation in Fig. 3. 7 can be attributed to the temperature dependence of the spontaneous emission. In a real field Raman amplifier installed to provide significant gain in conventional WDM signal bands, only a few tenths of one dB variations of NF occur when the temperature varies from $-25\text{ }^{\circ}\text{C}$ to $75\text{ }^{\circ}\text{C}$ [42].

3.5 NONLINEAR SHOOTING METHOD

Conventionally, multi-pumping FRA is always operated in the counterpumping (backward-pumping) configuration to minimize the amount of pump-to-signal crosstalk, PDG, and the RIN transfer from pump to signal. However, with the availability of low-noise pump lasers (relative intensity noise $< -145\text{ dB/Hz}$) nowadays and the requirement of enhancing the OSNR, copumping and bidirectional pumping of a Raman amplifier is now becoming feasible [43]. Intensive studies have been focused on the gain and noise performance via numerical simulation such as the average power analysis [5], [6], [7] and our proposed semi-analytical algorithm in

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above sections. Unfortunately, for the ultrabroad bandwidth Raman amplifier with multiple pumps, although the exhaustive computing time to achieve well-behaved results can be decreased significantly with our simulation method, only the initial forward propagating light power at the input end and the initial backward light power at the output end are known as two-point boundary conditions in backward- or bidirectionally-pumped FRA (as shown in Fig. 3. 8). Thus multiple iterations are required to simulate the propagation of lightwaves in the Raman amplifier correctly. This makes the simulation cost additional exhaustive computing time and there is no efficient way yet presented towards the iteration in an explicit formula up to our knowledge.

Figure 3. 8: Two-point boundary conditions for the counterpumped Raman amplifiers. Integration is conducted from $z = 0$ to L .

Figure 3. 9: Shooting method for the two-point boundary problem.

The two-point boundary condition problem can be solved using the so-called shooting method. As shown in Fig. 3. 9, the evolution of pump power P depends on the initial value and follows the relationship given by the differential equation (3. 1). Since the pump power at the output end is known, we can compare the calculated value with the boundary condition. The discrepancies can be used to correct the initial guessed value to start the next new iteration. Thus the key problem is to explore an efficient method using the discrepancies to achieve the accurate simulation results within the least number of iterations.

In this section, we present a novel and accurate numerical method for counterpumped Raman amplifiers based on the nonlinear shooting method and multistep predictor-corrector integration algorithm. Basically we guess the backward pumps' power at the input end and derive a Newton-Raphson method to iteratively solve the problem. The integration is implemented by the multistep procedure. With the very fast convergence, this method is quite useful to analyze the real system performance when it is upgraded to backward-pumped DRA.

3. 5. 1 Formulation for Simulation

In order to simplify the analysis, we modify the previous equation (3. 1) and consider wave propagation in the counterpumped DRA with multiple signal and pump channels as the following system of nonlinear coupled equations, taking into account pump-to-pump, pump-to-signal and signal-to-signal stimulated Raman scattering (SRS) [5, 11, 12]:

$$\pm \frac{dP_k}{dz} = -\alpha_k P_k + \sum_{j=1}^{n+m} g_{jk} P_j P_k, \quad (3. 14)$$

$$k = 1, 2, \dots, n + m$$

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Here the subscript $k=1,2,\dots,n$ represent pump wavelengths and the subscript $k=n+1,\dots,n+m$ represent signal wavelengths. Note that the frequency $\nu_i > \nu_j$ for $i < j$. P_k and α_k describe the light power and attenuation coefficient for the k -th wave. z is the distance from the fiber input and $g_{jk} = \text{sgn}(\nu_j - \nu_k) \cdot C_R(\Delta\nu)$ where $C_R(\Delta\nu)$ is the effective Raman gain coefficient between signal and pump with a frequency interval $\Delta\nu$. We don't consider the temperature dependence because of the magnificent temperature stability of Raman amplifier. Because the Rayleigh backscattering and ASE will not affect the gain profile, they are not included in equation (3. 14) and can be treated separately following the analysis in Chapter 2.

For the average power analysis and our semi-analytical method, only one of the previous mesh points are used to predict the information of the next step, it is then a one-step method. Since all the previous approximation solution is available at the current step and the multistep method can increase the accuracy and stability, we will employ the multistep method to simulate the power evolution and further enhance the calculation efficiency.

We can rewrite equation (3. 14) as $dP_k/dz = G(z, \nu_k)P_k = F(z, P_k)$ for $0 \leq z \leq L$

where the $G(z, \nu_k) = -\alpha_k + \sum_{j=1}^{n+m} g_{jk}P_j$. According to [44], equation (3. 14) can be solved as:

$$P^\pm(z_{j+1}, \nu) = P^\pm(z_j, \nu) \exp[G(z_j, \nu)\Delta z] \quad (3. 15)$$

where Δz is the step size at each elemental section. As the multistep method, we can use the so-called open formula of explicit four-step Adams-Bashforth (AB) method to represent equation (3. 15) as [45]:

$$\begin{aligned}
P^\pm(z_{j+1}, v) = P^\pm(z_j, v) \exp\{[55 \cdot G(z_j, v) \\
- 59 \cdot G(z_{j-1}, v) + 37 \cdot G(z_{j-2}, v) \\
- 9 \cdot G(z_{j-3}, v)] \cdot \Delta z / 24\}
\end{aligned} \quad (3.16)$$

Our 4-step AB method estimates the solution of point z_{j+1} from the previous points of z_j , z_{j-1} , z_{j-2} and z_{j-3} . But for maintaining the accuracy and stability, after the 4-step AB prediction, we always need to correct the estimation in the corrector's step applying the closed-type formula. In this case, we use the implicit 3-step Adams-Moulton (AM) method to correct the value [44, 45]:

$$\begin{aligned}
P^\pm(z_{j+1}, v) = P^\pm(z_j, v) \exp\{[9 \cdot G(z_{j+1}, v) \\
+ 19 \cdot G(z_j, v) - 5 \cdot G(z_{j-1}, v) \\
+ G(z_{j-2}, v)] \cdot \Delta z / 24\}
\end{aligned} \quad (3.17)$$

Thus the multistep method can be described as a predictor-corrector method and can guarantee 4-th order accuracy. In order to get the start values at z_1 , z_2 and z_3 , one can use our proposed semi-analytical method to find the solutions at those points.

Based on this multistep integration method, we can propose an accurate nonlinear shooting algorithm to solve the 2-point boundary value problem of the counterpumped FRA. Assuming that the original backward pumps' condition is $P_k(L, v_k) = Y_k$ with $k = 1, 2, \dots, n$, where the input signal power is known and Y is a multi-dimensional scalar containing pumping power. We implement the simulation by choosing the initial values of pumps as $P_k(0, v_k) = X_k$ to ensure that $\lim_{N \rightarrow \infty} P_k(L, v_k, X_k^N) = P_k(L, v_k) = Y_k$, N is the iteration number. The system is to determine the parameter X_k in the initial-value-problem (IVP) so that $f(X_k) = P_k(L, v_k) - Y_k = 0$. For the simultaneous nonlinear differential equation (3.

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14), we use the discrepancies in the final pump value to construct a set of new differential equations as:

$$f_k(X_1, \dots, X_n) = P_k(L, X_1, \dots, X_n) - Y_k; \quad k=1, 2, \dots, n \quad (3.18)$$

Assuming that $\bar{X}_k = X_k + \Delta X_k$, $k=1, 2, \dots, n$ satisfy the specified final boundary conditions, we can expand equation (3.18) into Taylor's series about the guessed solution X_k as

$$f_k(\bar{X}_1, \dots, \bar{X}_n) = f_k(X_1, \dots, X_n) + \sum_{j=1}^n \frac{\partial f_k}{\partial X_j} \Delta X_j = 0 \quad k=1, 2, \dots, n \quad (3.19)$$

Where the partial derivatives are evaluated $z = L$. From equation (3.18) and (3.19), the solutions of equation (3.19), which give the corrections to be made to the guessed values to start the next iteration, can be expressed by the Newton-Raphson method [45] as:

$$\Delta \underline{X} = -[J(\underline{X}, L)]^{-1} \underline{f}(\underline{X}) \quad (3.20)$$

where the corrections $\Delta \underline{X} = \{\Delta X_1, \dots, \Delta X_n\}^T$ is a column vector, and

$$\underline{f}(\underline{X}) = \begin{Bmatrix} f_1(X_1, \dots, X_n) \\ \vdots \\ f_n(X_1, \dots, X_n) \end{Bmatrix} \quad (3.21)$$

$$[J(\underline{X}, L)] = \begin{pmatrix} \frac{\partial f_1}{\partial X_1} & \dots & \frac{\partial f_1}{\partial X_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial X_1} & \dots & \frac{\partial f_n}{\partial X_n} \end{pmatrix}_{z=L} \quad (3.22)$$

Noting that the derivatives $\frac{\partial f_k}{\partial X_j} = \frac{\partial P_k}{\partial X_j}$ in equation (3.19), which in turn can be found

by differentiating equation (3.14) as

$$\frac{\partial}{\partial X_j} \left(\frac{dP_K}{dz} \right) = \frac{d}{dz} \left(\frac{\partial P_K}{\partial X_j} \right) = \sum_{i=1}^{n+m} \frac{\partial F_K}{\partial P_i} \frac{\partial P_i}{\partial X_j}; \quad (3.23)$$

$$K = 1, \dots, n+m; j = 1, \dots, n$$

By defining the sensitivity functions $Q_{Kj} = \frac{\partial P_K}{\partial X_j}$; $K = 1, \dots, n+m$; $j = 1, \dots, n$, since the pump-to-pump interactions take the strongest and the most important role, we can neglect the factor of signals and the equation (3.23) can be expressed as a set of $n \times n$ ordinary differential equations (ODEs):

$$\frac{dQ_{Kj}}{dz} = \sum_{i=1}^n \frac{\partial F_K}{\partial P_i} Q_{Ki}; \quad (3.24)$$

$$K = 1, \dots, n; j = 1, \dots, n$$

The initial conditions can be found from the initial guessed value as $Q_{Kj}(0) = 1$ if $k = j$ or $Q_{Kj}(0) = 0$ if $k \neq j$. Thus, the differential equations (3.24) will be solved as IVP as well as the couple equation (3.14) of counterpumped Raman amplifier. After integrating these equations, the values of $P_K(L, X_1, \dots, X_n)$ and $\left. \frac{\partial P_K}{\partial X_j} \right|_{z=L}$ can be used to determine $\Delta \underline{X}$ according to equation (3.20). Finally the corrected guessed initial values to start the next iteration are $\underline{X}_{new} = \underline{X}_{old} + \Delta \underline{X}$. With the new initial values, the entire procedure is to be repeated until the calculated final boundary values shoot their aims (satisfy the convergence criterion).

3.5.2 Applications of Shooting Method

In order to prove the validity of our method, we firstly consider a system of single 1455 nm pump and a single signal channel of 1555 nm with backward pumping configuration. The DRA has a length of 50 km SSMF, $\alpha = 0.2$ or 0.25 dB/km for signal and pump. The Raman gain coefficient comes from our measurements. The

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pump power is set to be 21.6 dBm to make a transparent propagation with the signal input of -8 dBm. Figure 3. 10 shows the numerical results with iterations. With the guessed initial pump value at input end, the first iteration gives a bad curve with relative error of 24.6% (compare the calculated output pump power with the exact one). After correction, the 2-nd iteration converges rapidly with the accuracy of $7e-4$ and the 3-rd iteration achieves the accuracy of $2e-6$. That is, the Newton formula based shooting algorithms own a very fast second-order convergence rate although we need to integrate the additional sensitivity equation (3. 23). The inset of Fig. 3. 10 illustrates the convergence rate of final boundary value's relative error.

Figure 3. 10: The pump and signal power evolution and their convergence rate with 3 iterations. Signal is -8 dBm at 1555 nm and the pump is 21.6 dBm at 1455 nm.

Next, we use our shooting method to simulate multi-pump wideband DRA. The 8 pumps are 1410, 1420, 1425, 1430, 1440, 1457, 1475 and 1505 nm and the 101 signal channels from 1520 to 1600 nm with 100 GHz separations are input with -8 dBm/ch. The aim pump powers are set as 17, 16.5, 16.3, 16, 16.3, 16, 16, 17 dBm respectively.

By using the previous parameters, we run the iteration process to predict the gain performance precisely. Since good guessed values are helpful to maintain the stability of shooting algorithm, we simulate the pump propagations from $z = L$ to $z = 0$ assuming the signals are off to get the initial values of pumps. Figure 3. 11 shows the numerical results of power evolution after 4-th iteration for both pump and signal light. The strong pump-to-pump and pump-to-signal interactions are clearly shown.

Figure 3. 11: Power evolutions of 8-backward-propagating pump and 101 signal channels at 4-th iteration.

The graph in Fig. 3. 12 is the net gains of all signal channels at the fiber output end; note that we don't optimize the pump power allocation in this simulation so that the gain ripple is a little bit larger. Also, the convergence rates of relative error of 8-pump's final boundary values at different iteration are plotted in Fig. 3. 13. Although the complex nonlinear effects among pumps and signals make the system convergent slower than the example above, it can be seen that with just 4 iterations using Newton-based shooting method, we can achieve very high accuracy calculations

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(relative error is less than 10^{-3} for 8 pumps after 4-th iteration, which is good enough in practice).

Figure 3.12: The net gain of signal channels after 4-th iteration.

Figure 3.13: Convergence of relative error of 8-pump with 4 iterations.

In summary, the nonlinear shooting method based on the Newton-Raphson formula and the multistep predictor-corrector integration algorithm can simulate the gain

performance of two-point boundary condition counterpumped wideband Raman amplifier with high accuracy and fast/stable convergence rate.

3.6 CONCLUSIONS

This chapter presented the multi-pumping FRA, which employs several pump lasers at appropriate wavelengths and power allocation. The multi-pumping FRA can achieve the ultra-broad band signal amplifications. We proposed a novel simulation model for the design of the wideband FRA with the introduction of the equivalent attenuation coefficient α_{eq} . The signal and pump power evolutions become the simple exponential functions of transmission line within each iteration step. The semi-analytical method can enlarge the step size significantly without loss of accuracy. This technique has been successfully used in designing a 100-channel wideband Raman amplifier with 0.5 dB gain ripple.

In order to solve the two-point boundary condition problem in the counterpumped Raman amplifier effectively, we developed an efficient nonlinear shooting method based on the Newton-Raphson formula and the multistep predictor-corrector integration algorithm. This algorithm can be used to simulate the gain performance of the two-point boundary condition counterpumped wideband Raman amplifier with high accuracy. The iteration process can be conducted with quite fast/stable convergence rate (with just 4 iterations, we can get $10^{-3} \sim 10^{-4}$ accuracy in a very complicated system of 8 pump- and 101 signal-channels). Although we need to solve the additional sensitivity ODEs to get the iteration corrections, the shooting method owns the excellent convergence feature and the multistep algorithm can drastically increase the computational efficiency, which are quite attractive in real applications

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where counterpumping or bidirectional pumping Raman scheme is used to upgrade the capacity of optical fiber link. This method should also be useful in the design problem of L-band EDFAs where counterpumping scheme may be involved.

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4 Optimization of Bidirectionally Pumped Fiber Raman Amplifiers

4.1 INTRODUCTION

The distributed Raman amplification has been accepted as a promising amplification scheme for fiber-optic transmission systems. Compared with the lumped EDFA, the distributed fiber Raman amplifier (FRA) achieves flexible amplification at any frequency by multi-pumping and results in superior end-of-system OSNR [1-4]. The existing transmission line can be upgraded directly to FRA by simply adding pump lasers. We have investigated the wideband multipumped FRA in Chapter 3 to solve the multi-channel system under copumping or counterpumping condition. Although the proposed method is very essential for analyzing the bi-directionally pumped Raman amplifiers with high accuracy and high speed, it is necessary to balance the co- and counter-pumping percentage to obtain an optimized system performance, which is the focus of this Chapter.

As demonstrated in Chapter 2, copumping of Raman amplifier is more advantageous than counterpumping from the perspective of minimizing signal-ASE beat noise [5].

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The improved noise figure (NF) is obtained in copumping. Also, the multi-path interference (MPI) noise due to the double-Rayleigh backscattering (DRB) can be suppressed in the bidirectional pumping FRA if a larger fraction of the gain comes from the copumping [6]. However, the counterpumping scheme, where the Raman pump and the signal propagate in opposite directions, has received most of the attention in conventional systems. FRA is always operated in the counterpumping configuration to minimize the amount of polarization-dependent gain (PDG) and the relative intensity noise (RIN) transfer from pump to signal. Performance degradations due to PDG and RIN transfer may occur in copumping system. Also, signal distortions from fiber Kerr nonlinearities increase when large amounts of copumping gain are used due to the relatively higher signal power distribution [7]. However, with the availability of low-noise pump lasers (relative intensity noise < -145 dB/Hz) nowadays and the requirement of enhancing the OSNR, copumping and bidirectional pumping of Raman amplifier become feasible. The deployment of Raman co-gain is a key technique in the nearest experimental demonstrations of ultralong-haul, super-dense wideband WDM transmissions [8-13]. Actually, as indicated in Fig. 2. 7, if the output signal power is the same, the required input signal power can be reduced significantly by using Raman co-gain. The signal power is distributed uniformly along the fiber span and the Kerr nonlinearity can be minimized.

In order to take advantages of copumping, researchers have calculated the optimal amounts of co-gain in bidirectional pumping scheme by calculating the overall NF caused by ASE and MPI [7]. But till now, there is no study about the impact of RIN transfer on the optimal design of bidirectional pumped Raman amplifiers. The power fluctuations of copropagating pumps will deteriorate the signal quality thus affect the optimal combination of copumping and counterpumping. This is particularly

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important when the high power fiber lasers are employed as the pump sources, which typically has much higher intensity noise. Meanwhile, there is no theoretical or numerical investigation on the signal quality factor (Q-factor) for multispan long-haul transmission systems although lots of experiments have been performed [4, 8-12]. In this chapter, we investigate the benefits and impact of copumping scheme on the Raman amplified system compared with the counterpumped system. Furthermore, we conduct the optimization of bidirectional pumping system based on the Q-analysis using OSNR parameters. The benefits from low ASE and MPI noise accumulation, impairments due to nonlinearity enhancement caused by signal amplification and the RIN transfer penalty are taken into account. We assume the pump is totally depolarized so that the PDG can be neglected. Also, we don't consider the pump-pump, pump-signal four-wave mixing (FWM) since these phenomena can be suppressed by expanding pumps spectral width and proper design of fiber dispersion map [14].

4.2 DESIGN OF BIDIRECTIONALLY-PUMPED SYSTEM

4.2.1 ASE and DRB-Induced MPI Noise

In this section, we investigate the ASE and MPI induced noise performance in the bidirectionally pumped Raman amplifiers. According to the small-signal model developed in Chapter 2, for the bidirectionally pumped FRA, by neglecting the pump depletion, the signal power at fiber distance z is given by:

$$P_{sig}(z) = P_{sig}(0) \cdot G(0, z) \quad (4.1)$$

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where $G(0, z) = A(0, z)G_R(0, z)$ is the net gain from distance 0 to z , $A(0, z) = \exp(-\alpha_s z)$ is the passive fiber loss at the signal wavelength and the ON-OFF gain G_R in linear unit is given by:

$$G_R(0, z) = \exp\left\{\frac{C_R}{\alpha_p}[P_{pf} \cdot (1 - \exp(-\alpha_p z)) + P_{pb} \cdot (\exp[-\alpha_p(L - z)] - \exp(-\alpha_p L))]\right\} \quad (4.2)$$

where α_s and α_p are the fiber loss at signal and pump wavelength λ_s and λ_p , L is the total fiber span length. P_{pf} is the copumping power at the input fiber end. P_{pb} is the counterpumping power at the fiber output end. C_R is the effective Raman gain coefficient as defined in Chapter 2. We assume that the pump and signal are separated by one Stokes shift (13.2 THz in silica fiber) such that maximum Raman gain coefficient is obtained. Using these expressions and assuming ASE light is totally polarization scrambled, the ASE light power along the fiber span in each state of polarization with bidirectional pumping can be derived as:

$$P_{ASE}(z) = h\nu_s B_s \int_0^z C_R \cdot \{P_{pf}(0) \exp(-\alpha_p \xi) + P_{pb}(L) \exp[-\alpha_p(L - \xi)]\} G(\xi, z) d\xi \quad (4.3)$$

where $h\nu_s$ is the energy of a single photon at signal wavelength and B_s is the resolution bandwidth of the ASE light. The $OSNR_{ASE}$ can be defined as $P_{sig}(L)/[2 \cdot P_{ASE}(L)]$. Here we use the standard definition of the ratio of signal power to the ASE power in all polarizations in a 0.1 nm (B_s) resolution bandwidth around the signal wavelength.

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At the same time, the MPI noise can be accumulated by the double-Rayleigh scattering of transmitted signal light. Under the undepleted pump approximation, the total DRB signal power along the fiber length z can be given as:

$$P_{DRB}(z) = r^2 P_{sig}(0) G(0, z) \int_0^z \frac{1}{G^2(0, \xi)} \int_{\xi}^z G^2(0, \eta) d\eta d\xi \quad (4.4)$$

Where r is the Rayleigh backscattering coefficient. It is worth noting that DRB is not randomly polarized, but has a degree of polarization 5/9, copolarized with the signal [7]. As discussed in Chapter 2, only the copolarized MPI noise will interfere with the signal light to generate intensity noise. Thus the $OSNR_{MPI}$ is defined as the ratio of signal power ($P_{sig}(L)$) to MPI power ($P_{MPI}(L) = (5/9)P_{DRB}(L)$).

4.2.2 Rayleigh-Backscattered Counterpropagating ASE Noise

Besides the MPI noise, another significant effect of the Rayleigh scattering is that the initially backward-propagating ASE relative to the signal light may backscatter, adding to the ASE noise in the system. Denoting forward- and backward-propagating ASE power relative to the signal as P_{ASE+} and P_{ASE-} , we can calculate the Rayleigh reflected portion of P_{ASE-} at the end of the fiber:

$$P_{ASE-}^{RB}(L) = rG(0, L) \int_0^L \frac{P_{ASE-}(z)}{G(0, z)} dz \quad (4.5)$$

The Rayleigh backscattered backward-propagating ASE light P_{ASE-}^{RB} has the same features as the co-propagating ASE light. $P_{ASE-}(z)$ is the backward-propagating ASE noise power in each state of polarization and can be derived by inverse-symmetry:

$$P_{ASE-}(z) = h\nu_s B_s \int_0^{L-z} C_R \cdot \{P_{Pf}(0) \exp[-\alpha_p(z-\xi)] + P_{pb}(L) \exp(-\alpha_p \xi)\} G^-(0, L-\xi) d\xi \quad (4.6)$$

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where $G^-(z_1, z_2) = A^-(z_1, z_2)G_R^-(z_1, z_2)$ is the net gain experienced by the counter-propagating ASE. $A^-(z_1, z_2) = \exp[-\alpha_s(z_2 - z_1)]$ is the passive transmission loss and the ON-OFF Raman gain $G_R^-(z_1, z_2)$ experienced by backward-propagating P_{ASE^-} is derived as:

$$G_R^-(z_1, z_2) = \exp\left\{\frac{C_R}{\alpha_p} [P_{pf} \cdot (\exp(-\alpha_p z_1) - \exp(-\alpha_p z_2)) + P_{pb} \cdot (\exp[-\alpha_p(L - z_2)] - \exp[-\alpha_p(L - z_1)])]\right\} \quad (4.7)$$

The backward-propagating ASE noise power distribution is an image of the forward-propagating ASE light. Thus the copumping gain relative to the signal for P_{ASE^-} is a counterpumping and vice versa.

Figure 4. 1: Forward-propagating and backward-propagating ASE noise power distribution along 100 km SSMF fiber span. The Raman ON-OFF gain is 23 dB. The pumping scheme relative to the signal direction is (from upper to lower): copumping, counterpumping, and bidirectional pumping, respectively.

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Figure 4. 1 shows the comparison between the forward-propagating (solid line) and backward-propagating (dashed line) ASE noise light distribution along 100 km SSMF span with 23 dB ON-OFF Raman gain in three pumping schemes. Note that co-gain and counter-gain are equal in this bidirectional-pumping scheme and the resolution bandwidth is 0.1 nm. As expected, the distributions of backward-propagating ASE noise power P_{ASE^-} follow the same behavior as the forward-propagating ASE. P_{ASE^-} accumulates slowly when the counterpumping (copumping relative to P_{ASE^-}) is used and becomes higher when the copumping scheme (counterpumping relative to P_{ASE^-}) is used. When the symmetrical bidirectional pumping is used, forward-propagating and backward-propagating ASE noise power distributions are exactly symmetric about the central point of the fiber span.

In order to explore the impact of Rayleigh backscattered (RB) backward-propagating ASE noise light, we calculate the reflected ASE power $P_{ASE^-}^{RB}$ and compare it with the DRB-induced MPI noise and copropagating ASE noise power. The 3 types of noise powers are shown in Fig. 4. 2 versus Raman ON-OFF gain in a 100 km SSMF span. The input signal power is assumed at -10 dBm. The same comparison for 100 km NDSF span is shown in Fig. 4. 3 since it has larger RB coefficient.

From the two figures, we can observe that DRB-induced MPI noise (solid lines) exceeds the copropagating ASE noise (dashed lines) at high Raman gain region. Since the forward ASE in copumping scheme is much less than that in counterpumping scheme and MPI noise is the same in copumping and counterpumping, the MPI noise dominates the noise performance in copumping Raman amplifiers at medium Raman gains. For instance, in SSMF span, $P_{MPI}^P > P_{ASE^+}$ when the Raman gain is larger than

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15 dB in copumping scheme and the same phenomenon occurs when Raman gain exceeds 25 dB in counterpumping scheme. Since the bidirectional pumping is able to suppress the MPI noise due to the uniform gain distribution, $P_{MPI}^P > P_{ASE}^+$ only occurs when Raman gain is larger than 30 dB. The same features can be observed in the results of NDSF span but the MPI noise grows faster due to the higher Rayleigh backscattering coefficient.

Figure 4. 2: Comparison of DRB-signal MPI noise, copropagating ASE noise and the Rayleigh-backscattered counter-propagating ASE noise versus Raman ON-OFF gain in 100 km SSMF span. 3 pumping schemes are considered.

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Figure 4. 3: Comparison of DRB-signal MPI noise, copropagating ASE noise and the Rayleigh-backscattered counter-propagating ASE noise versus Raman ON-OFF gain in 100 km NDSF span. 3 pumping schemes are considered.

However, the situations are different for the RB-induced reflected counter-propagating ASE noise (dash-dot lines). P_{ASE}^{RB} is the highest in counterpumping configuration while the RB-induced noises in copumping and bidirectional pumping schemes are at similar levels. The reason is that the RB-reflected backward-propagating ASE P_{ASE}^{RB} is equivalently counterpumped by the counter-gain of Raman pumps in counterpumping configuration. The ASE noise power is always higher in the counterpumping case. Although the noise power of P_{ASE}^{RB} is still lower than the

copropagating ASE noise even the Raman gain is 30 dB, it is evident that P_{ASE-}^{RB} can be higher than the P_{ASE+} if the Raman gain is larger than 35 dB, especially for copumping systems. We can see from Fig. 4. 2 and 4. 3 that the reflected total power of P_{ASE-}^{RB} is proportional to G_R^2 in linear units (P_{ASE-}^{RB} increases from -80 dBm to -60 dBm when ON-OFF gain increases from 15 dB to 25 dB as shown in Fig. 4. 3). Thus we must add the noise power P_{ASE-}^{RB} into the calculation of $OSNR_{ASE}$ at this high gain regime, which is possible when extremely long fiber span (such as 200 km SSMF) is implemented [15].

In our work, we just consider the multispans system with 100 km per-span and the applied Raman ON-OFF gain will not greater than 25 dB. Thus it is reasonable to neglect the impact of the Rayleigh-backscattered backward-propagating ASE noise in our optimization process.

4. 2. 3 Fiber Nonlinearity Mitigation

In the typical high-capacity digital communication systems, the optical signal power launched into a fiber span is adjusted to minimize the bit-error rate (BER) at receiver side. The BER will be deteriorated not only at lower launched signal power due to worse OSNR, but also at higher launched signal power due to the nonlinear impairments. These nonlinear impairments come from the Kerr effects in optical fibers and lead to the pulse distortions arising from SPM, XPM or intrachannel XPM (IXPM). Thus we should consider the nonlinear impairments when we optimize the OSNR performances.

As the lowest order approximation, the signal distortions from Kerr nonlinearities were assumed equal if they have the same integrated nonlinear phase or path-average

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signal power [6]. The integrated nonlinear phase of a signal power distribution over a fiber span of length L is given by $\phi(L) = \int_0^L \gamma \cdot P_{sig}(z) dz$ where γ is the nonlinear coefficient of silica-fiber. We calculate the ratio of the signal cumulative nonlinear phase in a Raman amplified system relative to the passive fiber span at a fixed input signal power:

$$R_{NL} = \frac{\int_0^L \gamma P_{sig}(0) G(0, z) dz}{\int_0^L \gamma P_{sig}(0) A(0, z) dz} = \frac{\alpha_s}{1 - \exp(-\alpha_s L)} \int_0^L G(0, z) dz \quad (4.8)$$

$$= \frac{\alpha_s L}{1 - \exp(-\alpha_s L)} \frac{\langle P_{sig}(z) \rangle}{P_{sig}(0)}$$

R_{NL} represents the nonlinearity enhancement in Raman amplified fiber span and is determined by the path average signal power $\langle P_{sig}(z) \rangle$.

Figure 4. 4: Nonlinearity enhancement R_{NL} (in dB) versus Raman ON-OFF gain in 100 km NDSF span.

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Figure 4. 4 displays the nonlinearity enhancement of R_{NL} as a function of Raman ON-OFF gain in a 100 km NDSF span for various percentage of copumping. Note that we define that the copumping percentage is the ratio of copump-power to total pump-power at a given Raman gain. As expected in Chapter 2, the rapid increase of relative nonlinearity R_{NL} with increasing of copumping percentage is due to higher signal power distribution that is forward amplified at the beginning of fiber span. To ensure constant nonlinearity when the passive fiber becomes the distributed FRA, the launched signal power should be reduced from $P_{\max}$ to $P_{\max} / R_{NL}$ where $P_{\max}$ is the maximum allowable signal input power to a passive fiber span. The significantly severe nonlinear impairments due to forward gain suggest that the pure copumping scheme could not be used in Raman amplification systems and bidirectional pumping is more attracted. However, the improved noise figure of systems utilizing copumping Raman amplification also permits the use of lower launch signal power to reduce the nonlinear impairments (as illustrated in Fig. 2. 7). This tradeoff between improved noise performances and nonlinear impairments need to be considered carefully when we optimize the bidirectional pumping fiber Raman amplification systems.

4.3 OPTIMIZATION OF BIDIRECTIONALLY PUMPED FRA

4.3.1 OSNR_{ASE} and OSNR_{MPI} in Single Span

We have defined OSNR_{ASE} and OSNR_{MPI} to characterize the relative impact of ASE and MPI noise on the receiver performances. Based on our previous investigation, both OSNR_{ASE} and OSNR_{MPI} depend not only on the pumping schemes (the gain amount and pumping direction), but also on the launch signal conditions. Here, we

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study the two OSNR impairments due to ASE and MPI noise by considering the nonlinearity enhancement.

Figure 4. 5: Contour map of R_{NL} (in dB) as a function of Raman ON-OFF gain and copumping percentage in 100 km NDSF span.

Figure 4. 5 is a contour map of the nonlinearity enhancement of R_{NL} as a function of Raman gain and copumping contribution. This map provides us the reduction factor of input signal power at each combination of Raman gain and pumping scheme. Using this map, we calculate the $OSNR_{ASE}$ as a function of ON-OFF Raman gain and copumping percentage in a 100 km NDSF fiber. The reference input power P_{max} is set as -3 dBm. The results are plotted in Fig. 4. 6 as a contour map. Without considering R_{NL} (upper graph), we can observe that the $OSNR_{ASE}$ increases with increasing Raman gain at a certain copumping percentage. However, with the introduction of nonlinearity enhancement (lower graph), $OSNR_{ASE}$ decreases with increasing Raman ON-OFF gain when the copumping percentage is high and remains almost the same when the copumping percentage is relatively low (less than 20%). At the same time,

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in order to ensure constant Kerr nonlinearity, the average OSNR_{ASE} is reduced due to reduced signal input power.

Figure 4. 6: Contour map of OSNR_{ASE} versus Raman ON-OFF gain and copumping percentage in 100 km NDSF span with (lower figure) and without (upper figure) considering R_{NL} .

Figure 4. 7: Contour map of OSNR_{MPI} versus Raman ON-OFF gain and copumping percentage in 100 km DSF span.

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Figure 4. 7 is the contour map of OSNR_{MPI} versus Raman gain and copumping percentage in the same single fiber span. Since the ratio of optical signal power to DRB-induced MPI noise is independent on the input signal power, OSNR_{MPI} will not be affected by Kerr nonlinearity. Actually, from Fig. 4. 7, we can observe that OSNR_{MPI} depends only on the pumping configuration (copumping percentage). The best OSNR_{MPI} is always obtained when copumping percentage is 50%, which is consistent with previous results in Chapter 2. And it decreases with increasing ON-OFF gain.

4. 3. 2 OSNR_{ASE} and OSNR_{MPI} in Long-Haul System

Figure 4. 8: Typical optical transmission system made up of N concatenated spans of fiber and amplifiers.

Our aim is to optimize the long-haul or ultralong-haul multispan fiber transmission system with bidirectional pumping Raman amplification and obtain the optimal signal quality. A typical long-haul fiber system is shown in Fig. 4. 8. Here, L_t is the total length between two terminals and L is the length of each single span. To investigate total OSNR of the link, an often-sited equation describing the OSNR degradation (in dB) is given by:

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$$OSNR_{ASE}^{link} (in \text{ dB}) = P_{s-input} + 58 \text{ dBm} - NF_{ASE} - 10 \log_{10}(N_{span}) \quad (4.9)$$

where OSNR is defined in 0.1 nm resolution bandwidth, $P_{s-input}$ is the input signal power (in dBm) for a channel launched into each fiber span. NF_{ASE} is the total noise figure and N_{span} is the total number of spans in this link. This formula assumes the input signal power is equally distributed in each span and the total NF accounting for any loss and distributed amplification is identical for any span. Note that here NF_{ASE} only considers signal-spontaneous ASE beat noise and shot noise. The 58 dBm represents $-10 \log_{10}(h\nu_s B_s)$. Since the total noise figure including ASE and MPI described in equation (2.33) can be written as:

$$NF_{total} = \frac{P_{s-input}}{h\nu_s B_s \cdot OSNR_{ASE}} + \frac{1}{G_{net}} + \frac{P_{s-input}}{h\nu_s G_{net} \sqrt{B_e^2 + B_o^2/2} \cdot OSNR_{MPI}} \quad (4.10)$$

The degradation of MPI induced OSNR can be given similarly to equation (4.9):

$$OSNR_{MPI}^{link} (in \text{ dB}) = P_{s-input} + 60 \text{ dBm} - NF_{MPI} - 10 \log_{10}(N_{span}) \quad (4.11)$$

where NF_{MPI} just considers the signal-DRB interference beat noise and shot noise. We can see that the overall $OSNR_{MPI}^{link}$ depends not only on the NF_{MPI} in each span but also on the launched signal power. Since DRB-light of signal cannot be filtered out because its wavelength is the same as the signal. Therefore, from beginning it transmits along concatenated span and accumulates to the MPI noise. Hence, the choice of input signal power is important to determine the $OSNR_{MPI}^{link}$. The 60 dBm represents $-10 \log_{10}(h\nu_s G_{net} \sqrt{B_e^2 + B_o^2/2})$ and B_e and B_o are set as 20 GHz and 10 GHz, respectively.

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Figure 4. 9: Output OSNR induced by ASE (upper) and MPI (lower) for 24×100 km multispan fiber transmission link versus Raman ON-OFF gain in each span and copumping percentage.

Using equation (4. 9) and (4. 11), we can calculate the output $OSNR_{ASE}^{link}$ and $OSNR_{MPI}^{link}$ for a given multispan long-haul system. Here, we assume all the losses are compensated by the bidirectional pumping distributed Raman gain. The ASE- and MPI-induced NF for each span can be calculated versus Raman ON-OFF gain and copumping percentage ratio using the contour data of $OSNR_{ASE}$ (Fig. 4. 6) and $OSNR_{MPI}$ (Fig. 4. 7). The input signal power in each span is reduced by the factor R_{NL} to ensure a constant nonlinear penalty and the reference input power is -3 dBm. We plot the output $OSNR_{ASE}^{link}$ and $OSNR_{MPI}^{link}$ for a 24×100 km multispan fiber transmission link in Fig. 4. 9. Parameters of NDSF are used for the calculations. After 2400 km transmission, the best $OSNR_{ASE}^{link}$ is obtained when 40% copumping and 24 dB ON-

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OFF Raman gain are used. At the same time, the combination of 18 dB ON-OFF Raman gain and 35% copumping provides the maximum $OSNR_{MPI}^{link}$. Note that the transparency ON-OFF gain (net gain is 0 dB) is about 22 dB.

4.3.3 Optimization with Q-factor Analysis

To fully evaluate the impact of noises from ASE and MPI on lightwave communication systems, we need to translate the above results into BER penalties or equivalently, Q-factors. Actually, with the $OSNR_{ASE}$ and $OSNR_{MPI}$, we can study the signal transmission quality using Q-factor analysis. The penalty from pump RIN transfer can be also considered. The Q-factor in linear units can be written as $(\langle I_1 \rangle - \langle I_0 \rangle) / (\sigma_1 + \sigma_0)$, where $\langle I_1 \rangle$ is the mean current on “1” bits, $\langle I_0 \rangle$ is the mean current on the “0” bits, σ_1 and σ_0 are their standard deviations. We assume the beat noise dominates and the spontaneous-spontaneous beat noise can be suppressed by optical filtering. The noise on the “0” bits can be neglected and the Q-factor in the absence of pump-to-signal RIN is given as [15-17]:

$$Q_s = \langle I_1 \rangle / \sigma_1 \quad (4.12)$$

For constant average received signal power, we assume that the RIN on the signal can be treated as a Gaussian random variable and the noise source of RIN is uncorrelated with the noise sources of σ_1 . Thus the degraded Q value is:

$$Q_R = \langle I_1 \rangle / \sqrt{\sigma_1^2 + \sigma_R^2} \quad (4.13)$$

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where σ_R is the standard deviation of the noise from the RIN on the signal. By integrating the RIN on the signal across the receiver bandwidth between frequencies f_1 and f_2 , we can find that [15]:

$$\sigma_R^2 = \langle I_1 \rangle^2 \int_{f_1}^{f_2} RIN_s(f) df \quad (4.14)$$

The Q penalty is given by:

$$Q_S / Q_R = \sqrt{1 + \sigma_R^2 / \sigma_1^2} = \sqrt{1 + Q_S^2 \int_{f_1}^{f_2} RIN_s(f) df} \quad (4.15)$$

Since Q factor expressed in dB is equal to $20 \log_{10}(Q)$, the penalty measured in dB is therefore:

$$\Delta Q_{dB} = Q_{S_dB} - Q_{R_dB} = 10 \log_{10} (1 + Q_S^2 \int_{f_1}^{f_2} RIN_s(f) df) \quad (4.16)$$

The baseline Q-factor is dominated by MPI and ASE noises. For a constant received signal power, the variance of the signal-ASE beat noise (σ_{ASE}^2) is inversely proportional to $OSNR_{ASE}$. Similarly the variance of MPI beat noise (σ_{MPI}^2) scales inversely with $OSNR_{MPI}$ [16]. Since these sources of noise are uncorrelated, the sum of standard deviation is proportional to the square root of ($\sigma_{ASE}^2 + \sigma_{MPI}^2$). Therefore, we can present the Q-factor as a function of the two OSNR in following equation:

$$Q_S = \frac{1}{\sqrt{\frac{1}{OSNR_{ASE}} + \frac{\epsilon}{OSNR_{MPI}}}} \quad (4.17)$$

where ϵ is a weighting factor dependent on the transmission format. All the parameters are in linear units. Thus the bidirectional pumping system performance

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can be estimated by Q-factor using the above equations. The real system Q value can be calculated as $Q_{R_dB} = Q_{S_dB} - \Delta Q_{dB}$ where the impact of pump RIN transfer can be included.

Figure 4. 10: Q-factor (in dB) distribution versus Raman gain and copumping percentage for 24×100 km multispan system. RIN-transfer is neglected. NRZ and RZ format are considered.

Equation (4. 17) is applied to a 10 Gb/s data stream transmitted in a 24×100 km multispan fiber system. The ε factor is experimentally verified as 1. 89 for nonreturn-to-zero (NRZ) data format. For return-to-zero (RZ) data format, ε is 1.65 [17]. As shown in Fig. 4. 10, we calculate the Q-factor distribution versus Raman ON-OFF gain and copumping percentage for the 24-span fiber transmission system. The contour data of OSNR-map in Fig. 4. 9 is used. The RIN-transfer penalty is not

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considered in this figure. We can observe that (pointed out by gray square) for NRZ format, the optimal Q value is 21.5 dB when 40% copumping and 19.5 dB ON-OFF gain (a slightly negative net gain) are used. For RZ data format, the optimal Q value is 22 dB with 40% copumping and 22 dB ON-OFF gain (transparent gain). Actually, these results match very well with the reported optimization process and experimental results [7, 11] without considering the RIN transfer induced penalties. The slightly higher Q-factor in RZ system is due to the relatively smaller weighting factor ε , which means that RZ is more tolerant to MPI than NRZ. Since the signal bandwidth increases in RZ coding, the MPI-beat noise beyond the receiver's electrical bandwidth can be eliminated hence the impact of MPI is reduced in RZ system. As a result, the optimal ON-OFF gain is also larger in RZ system. However, ASE noise dominates the signal quality in both cases due to the medium Raman gain and the small input signal power reduced by the nonlinear enhancement R_{NL} . Using the value of R_{NL} in Fig. 4. 5, the input signal power corresponding to the optimal Q value is -9 dBm for NRZ and -10 dBm for RZ, respectively.

4. 3. 4 Q-Penalty Due to Pump-RIN Transfer

In the previous subsection, we neglect RIN transfer penalty. Here, we study the impact of RIN transfer on the optimal choice of bidirectional pumping Raman amplification system. As described in equation (4. 16), the Q-penalty caused by the RIN transfer can be obtained by integrating the RIN spectra at signal channel across the receiver electrical bandwidth. We follow the analysis of RIN transfer in Ref. [15] and present the integration for copumping scheme as:

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$$\int_{f_1}^{f_2} RIN_s(f) df = RIN_p \cdot [\ln(G_{CO})]^2 \cdot \frac{\tan^{-1}\left(\frac{2\pi D \cdot \Delta\lambda}{\alpha_p} \cdot f_2\right) - \tan^{-1}\left(\frac{2\pi D \cdot \Delta\lambda}{\alpha_p} \cdot f_1\right)}{2\pi D \cdot \Delta\lambda \cdot \alpha_p \cdot L_{eff}^2} \quad (4.18)$$

and for counterpumping:

$$\int_{f_1}^{f_2} RIN_s(f) df = RIN_p [\ln(G_{CO})]^2 \cdot \frac{\tan^{-1}\left(\frac{4\pi}{\alpha_p V_s} \cdot f_2\right) - \tan^{-1}\left(\frac{4\pi}{\alpha_p V_s} \cdot f_1\right)}{4\pi \cdot \alpha_p \cdot L_{eff}^2 / V_s} \quad (4.19)$$

where RIN_p is the RIN spectrum on pump light. $\Delta\lambda$ is the wavelength difference between pump and signal, D is the chromatic dispersion at signal wavelength, and α_p is the attenuation at pump wavelength. Since the signal is one Stokes shift away from pump to obtain the largest Raman gain, $\Delta\lambda$ is 100 nm at 1550 nm band. The dispersion parameter of NDSF at 1550 nm is 10 ps-nm⁻¹km⁻¹ (TrueWave REACH fiber). G_{CO} is the co-gain in bidirectional pumping system. V_s in equation (4.19) is the group velocity at signal wavelength.

Figure 4.11: Estimated Q penalty versus pump RIN at co- (solid) and counterpumping (dash-dot) schemes.

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By choosing the receiver bandwidth from 10 KHz to 20 GHz, we calculate the Q-penalty due to RIN transfer for a co- or counterpumping 100 km Raman amplified span and plot the results in Fig. 4. 11. The gain is 10 dB for each case and baseline Q value is 10. From Fig. 4. 11, it can be seen that the counterpumping scheme is significantly more tolerant of pump RIN than the copumping. With NDSF, the counterpumping amplifier may have a pump with a RIN up to -60 dB/Hz (50 dB more tolerance than copump) without suffering a 0.1 dB Q penalty. For this reason, we neglect the RIN transfer penalty due to counter-propagating pumps.

Figure 4. 12: Q-factor (in dB) distribution versus Raman gain and copumping percentage for 24×100 km multispan system when copumping has the RIN of -120 dB/Hz. NRZ and RZ format are considered.

By considering copump's RIN transfer induced Q-penalty, we calculate ΔQ_{dB} as a function of copumping percentage and Raman ON-OFF gain using equation (4. 16) and (4. 18). The RIN on pump is assumed as -120 dB/Hz. It should be noted that RIN

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transfer would accumulate linearly as the number of spans increases. The total Q-penalty should be $\Delta Q_{dB} \times N_{span}$ (in dB). The calculated results are shown in Fig. 4. 12 for NRZ and RZ modulation format. The optimal Q factor for NRZ shifts to 21 dB with 35% copumping and 19 dB ON-OFF gain. For RZ format, the optimal Q-value is 21.4 dB with 35% copumping and 20 dB ON-OFF gain. That is, both copumping percentage and total Raman ON-OFF gain are reduced to suppress the RIN transfer induced penalty.

Figure 4. 13: Optimal Q-factor and corresponding copumping percentage and Raman gain versus pump RIN for NRZ and RZ data format. The same multispan system as in

Fig. 4. 12 is assumed.

Following the same procedure, we search the optimal Q-factor by tuning the RIN intensity on pump to investigate the impact of RIN transfer on the optimal operation conditions of bidirectional pumping system. Figure 4. 13 shows the optimal Q-factor and corresponding copumping percentage and ON-OFF Raman gain versus pump RIN. The left column is for NRZ format while the right column is for RZ. It can be

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seen that the maximally optimal Q-factor begins to decrease at the pump RIN of -125 dB/Hz. The allowable copumping percentage and Raman ON-OFF gain are also reduced. For both data format, zero percent of copumping gain can be used when the pump RIN is larger than -100 dB/Hz. The maximal gain from pure counterpumping is about 15 dB. These results suggest that pump lasers with RIN larger than -100 dB/Hz should not be used for copumping Raman amplified multispan system made of NDSF. From Fig. 4. 13, it is clear that, for negligible Q-penalties, the pump RIN should be no larger than -120 dB/Hz. Obviously, the recently commercially available high power, narrowband semiconductor pumps with RIN as low as -145 dB/Hz [18] are quite suitable for the copumping scheme without Q-penalty.

4. 4 CONCLUSIONS

In this chapter, we conducted the optimal design of bidirectional pumping Raman amplified fiber transmission system. Based on the analytical model derived in Chapter 2, we obtained the explicit expressions for OSNR_{ASE} and OSNR_{MPI} under small-signal approximation. Also, the Rayleigh-backscattered backward-propagating ASE noise is taken into account in different fiber spans. We compared the evolutions of copropagating ASE, DRB-induced MPI and RB- backward-propagating ASE noise versus ON-OFF Raman gain for different pumping schemes. MPI noise will dominate the noise performance at high Raman gain regime (around 20 dB). The RB- backward-propagating ASE noise power will exceed the copropagating ASE if the ON-OFF Raman gain is above 35 dB and lead to deterioration of OSNR_{ASE} . We calculated the nonlinearity enhancement in Raman amplified fiber system compared with passive fiber span. The significant nonlinearity enhancement caused by

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copumping counteracts its advantage of low noise thus the bidirectional pumping is expected to provide better performance with the tradeoff between NF and nonlinearity.

We then investigated the OSNR as a function of copumping percentage and Raman ON-OFF gain while keeping a constant nonlinear impairment. Both OSNRs induced by ASE and MPI are calculated for single and multispans fiber transmission line. With the Q-analysis model, we can obtain the Q-factor distribution for NRZ and RZ data format versus copumping percentage and Raman ON-OFF gain by using the $OSNR_{ASE}$ and $OSNR_{MPI}$. In addition, the impact of pump RIN transfer on the transmission quality is incorporated in the Q-analysis. The optimal operation of bidirectional Raman pumped long-haul multispans fiber system (24×100 km NDSF) is investigated considering the copumping percentage, total Raman gain and pump RIN intensity. Without RIN caused Q-penalty, the best Q-factor is 21.5 dB with 40% copumping and 19.5 dB Raman gain for NRZ. The optimal Q-factor is 22 dB with 40% copumping and 22 dB Raman gain for RZ system. However, the optimal choices of pumping conditions can be affected by the pump RIN transfer induced Q-penalty. Our calculation has proved that Q-penalty caused by RIN transfer deteriorates the system performance. We need to reduce the corresponding copumping percentage and Raman gain to suppress the RIN penalty. For instance, the optimal Q factor is 21 dB with 35% copumping and 19 dB ON-OFF gain for NRZ. For RZ format, the optimal Q-value is 21.4 dB with 35% copumping and 20 dB ON-OFF gain. Furthermore, by adjusting the pump RIN intensity, we analyzed the optimal operation conditions as a function of pump RIN. All the maximal Q-factor, copumping percentage and total Raman gain decrease with increasing RIN intensity. When pump RIN is larger than – 100 dB/Hz, copumping cannot be used any more and the Raman amplified multispans

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is purely counterpumping. A pump laser with RIN less than -120 dB/Hz is necessary for bidirectional pumping scheme with negligible Q-penalty. Our analysis provides a useful tool for the optimization process of bidirectional Raman pumping multispan long-haul transmission system including the requirement of pump RIN.

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5 Double-Pass Fiber Raman Amplifiers

5.1 INTRODUCTION

As described in previous Chapters, to provide sufficient cost-efficient network capacity for future bandwidth demand, higher bit-rate and higher channel density systems are being rapidly developed. Among the various competing candidates for next generation optically amplified transmission systems, Raman amplifier has been proven to be an effective amplifying device for providing relative flat gains over wide bandwidth in the C band and L bands [1-9]. The design issue of the ultra-broadband FRA with multiple pumps has been investigated in Chapter 3 by using our proposed numerical simulation algorithms. We also studied the optimal operation conditions of distributed bi-directional pumping Raman amplification for multi-span long-haul system in Chapter 4. Due to its feasibility and flexibility, FRA is being deployed in almost every new long-haul or ultralong-haul fiber optic transmission systems, making it one of the widely used nonlinear optical devices in telecommunications [10].

Raman amplifiers can appear in a distributed manner to decrease the noise accumulation and enhance the system power margin (as discussed in Chapter 3 and Chapter 4). At the same time, we can configure the Raman amplifier in lumped or

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discrete structure, or optionally in a hybrid amplifying structure when used in combination with erbium-doped fiber amplifiers (EDFAs). Discrete Raman amplifiers (DCRAs), mostly in the form of a pumped DCF, overcome the bandwidth limitations created by the discrete energy levels of erbium in EDFAs [10-16]. Moreover, appropriately designed all-Raman systems combining distributed and discrete amplifiers could reduce numbers of discrete components compared with EDFA-based systems. Thus, the DCRA will be a key component in optical communication networks and will be studied in this Chapter.

The DCF is a particular convenient gain medium [11, 13, 18], as it can be used not only as a dispersion compensating medium but as an amplifying medium with a Raman gain efficiency 5 to 10 times larger than that of SSF as well (as measured in our experiments). By using a modest amount pump power, the DCRA can be used to offset the loss of the dispersion compensation module and to extend new gain bandwidth such as S band (1480 – 1530 nm) or U band (1625 – 1675 nm). However, there are two problems associated with DCF as an amplification medium. One is that the DCF length is fixed when it is used to compensate the dispersion of a specific fiber span. On the other hand, when the amplifier acts only as a discrete amplifier to open new bandwidth window, rather than being used for dispersion compensation, the fiber length can only be adjustable within a limited range to avoid additional dispersion accumulation. Therefore DCF is normally limited to be less than 10 km as an amplifying device. The short DCF length reduces the amount of available gain for a given pump power thus decreases the pump efficiency. The high pump power needed for sufficient signal amplification increases the fiber nonlinearity and the system costs. At this power level (such as ~ 1 W) some fiber components such as connectors, wavelength-division-multiplexers (WDMs) are highly vulnerable to

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damage. As the optical power level rises, nonlinear phenomena start to become important, and these include the effects of the “fiber fuse” phenomenon. This effect, named because of its similarity in appearance to burning fuse, can lead to the catastrophic destruction of various types of optical fibers [17, 18]. Thus, an optimum gain distribution of amplifier must be found and the improvements in pump efficiency are needed to make the discrete Raman amplifiers competitive with the performance of new types of EDFAs [7]. In order to release the pump power requirement and improve the Raman amplification efficiency, many efforts have been done to develop the novel types of fibers to enhance the Raman gain efficiency [19-21]. Various dopants such as germanium, erbium and tellurium with heavy metal-oxides are used to modify the Raman gain spectrum. Moreover, researchers investigate the application of index guiding highly nonlinear photonic crystal fibers (PCFs) on Raman amplification. Recent experiments and theoretical analysis have proven the possibility to achieve significant Raman gain in short length PCF, which is quite meaningful to the compact nonlinear fiber devices [22-24]. However, these novel fibers add additional cost and the splice loss between amplified fibers and transmission fibers is quite large. Thus they are not suited for the upgrade of the existed SSMF/NZDF fiber link.

In this Chapter, we investigate the gain/pump efficiency improvement and the noise performance in a novel design structure of double-pass DCRA system, in which narrow or wideband reflector is used to retroreflect the signal or pump light. Different geometries are discussed without additional expense of extra pump lasers. The system is evaluated with regard to the gain enhancement, noise figure, and fiber nonlinearity in comparison with the typical backward pumping Raman amplifier. The requirement of components according to the performance optimization is also illustrated. Section

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5. 2 presents the novel DCRA design and the analytic model to describe the gain and noise performance considering the effect of signal/pump double-pass geometry. The MPI noise due to the Rayleigh scattering and external reflection is discussed in detail. In addition, experiments are implemented to validate the modeling method and prove the feasibility of double-pass DCRA. Section 5. 3 discusses the requirements of various components in this system such as pump stability, fiber dispersion, and reflection ratio of reflector. In Section 5. 4, the fiber nonlinear effect in this DCF-based double-pass DCRA is analyzed to compare the nonlinear impairments with the conventional counterpumped Raman amplifier. Furthermore, we numerically study the 10 Gb/s NRZ signal qualities in the transmission span employing double-pass DCRA. Bit error rate (BER) performance related to the input signal power and Raman gain of DCRA is discussed to evaluate the impact of this device in practical optical communication system. Discussions and conclusions are given in Section 5. 5.

5. 2 SYSTEM DESIGN AND THEORETICAL MODEL

Figure 5. 1 shows the schematic of the double-pass DCRA used in theoretical analysis and experiments. The input signal from a tunable laser source (TLS) is injected into 3-km DCF through the optical circulator (OC) port 1. The dropped signal from circulator co-propagates with the pump power in the DCF and is reflected to counter-propagate with the pump. Both narrow band FBG and wideband chirp-FBG (CFBG) (Reflection ratio $R > 99\%$) can be used here as the reflector. In addition, the CFBG can provide a flexibility to compensate the dispersion of fiber span dynamically [25]. Thus the length of gain medium is not restricted by the required amount of accumulated dispersion in transmission lines. Moreover, a wideband reflector or FBG

at pump wavelength can be deployed at the fiber end to reflect the residual part of the pump power to increase the gain efficiency further [25, 26].

Figure 5. 1: Schematic system setup of double-pass DCRA.

5. 2. 1 Raman Gain Characteristics with Small Pump Depletion

At the steady state operating condition, there are four types of lightwaves traveling in the amplifier, 1) forward propagating signal; 2) forward pump; 3) the reflected signal; 4) reflected propagating pump, respectively, which determine the gain profile of the double-pass DCRA. Recall the power analysis model described in Chapter 2, the power evolution of lightwaves can be described by the following coupled equations with the convenient notations [27-30]:

$$\pm \frac{dP_{SK}}{dz} = -\alpha_s P_{SK} + C_R \cdot P_{SK} P_{Pf} \quad (5.1)$$

$$\pm \frac{dP_{PK}}{dz} = -\alpha_p P_{PK} - C_R \cdot \sum P_{SK} \cdot P_{PK} \quad (5.2)$$

Here, $P_{SK} = P_{Sf}$ or P_{Sb} is the forward or backward signal power, and $P_{PK} = P_{Pf}$ or P_{Pb} is the forward/backward pump power, respectively. α_s or α_p is the fiber loss at the signal or pump wavelength. z is the propagation distance from the fiber input and $C_R = g_R / A_{eff} \cdot K$ is the effective Raman gain coefficient where g_R is the Raman gain

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coefficient between signal and pump, A_{eff} is the effective fiber area and K is the polarization scrambling factor between pump and signal light, which are consistent with previous chapters. The temperature dependence is not considered because it is negligible [3, 30] when considering the gain profile. The Rayleigh backscattering induces MPI noise and ASE induced system noise can be included additively (see below).

In this double-pass system, by neglecting the pump depletion and using the specific boundary condition $P_{pf}(L) = P_{pb}(L)$, the pump power distribution $P_p(z)$ can be derived as:

$$\begin{aligned} P_p(z) &= P_{pf}(z) + P_{pb}(z) \\ &= P_{pf}(0) \exp(-\alpha_p z) + P_{pb}(L) \exp[-\alpha_p (L - z)] \end{aligned} \quad (5.3)$$

Where $P_{pf}(0)$ is the input pump power, and $P_{pb}(L) = P_{pf}(0) \exp(-\alpha_p L)$. It is an equivalent bidirectional-pumping scheme. Using the boundary condition $P_{sf}(L) = P_{sb}(L)$, the forward and backward-transmission ON-OFF signal gain can be derived analytically as:

$$\begin{aligned} G_{Rf}(z_1, z_2) &= \exp\{C_R P_{pf}(0) [\exp(-\alpha_p z_1) - \exp(-\alpha_p z_2)] / \alpha_p\} \\ &\quad \cdot \exp\{C_R P_{pb}(L) [\exp(\alpha_p (z_2 - L)) - \exp(\alpha_p (z_1 - L))] / \alpha_p\} \end{aligned} \quad (5.4)$$

$$\begin{aligned} G_{Rb}(z_1, z_2) &= \exp\{C_R P_{pf}(0) [\exp(\alpha_p (z_2 - L)) - \exp(\alpha_p (z_1 - L))] / \alpha_p\} \\ &\quad \cdot \exp\{C_R P_{pb}(L) [\exp(-\alpha_p z_1) - \exp(-\alpha_p z_2)] / \alpha_p\} \end{aligned} \quad (5.5)$$

Where L is total fiber length. Thus the output signal will experience the total ON-OFF Raman gain of $G_{Rf}(0, L) \cdot G_{Rb}(0, L)$ (Note that $G_{Rb}(z_1, z_2)$ is the Raman gain experienced from z_2 to z_1).

5. 2. 2 ASE Noise Characteristics

With the same notation, the ASE noise spectral density in each state of polarization of double pass system can be described as $\pm dN_{SK}^{ASE} / dz = -\alpha_s N_{SK}^{ASE} + C_R \cdot (N_{SK}^{ASE} + hv) \cdot P_{Pf}$.

Using the Raman gain equation (5. 4) and (5. 5), the backward and forward ASE noise spectral density can be obtained:

$$N_{Sb}^{ASE}(z) = N_{Sf}^{ASE}(L)A(0, L)G_{Rb}(0, L) + hv \int_0^{L-z} C_R \cdot [P_{Pb}(L) \exp(-\alpha_p x) + P_{Pf}(0) \exp(-\alpha_p (L-x))] \cdot A(0, x)G_{Rb}(L-x, L)dx \quad (5. 6)$$

$$N_{Sf}^{ASE}(L) = hv \int_0^L C_R \cdot [P_{Pf}(0) \exp(-\alpha_p x) + P_{Pb}(L) \exp(-\alpha_p (L-x))] \cdot A(x, L)G_{Rf}(x, L)dx \quad (5. 7)$$

Where $A(z_1, z_2) = \exp[-\alpha_s(z_2 - z_1)]$ is the passive fiber loss, thus the forward net gain G_f from distance z_1 to z_2 is $A(z_1, z_2)G_{Rf}(z_1, z_2)$ and the backward net gain G_b from distance z_2 to z_1 is $A(z_1, z_2)G_{Rb}(z_1, z_2)$.

5. 2. 3 MPI Noises Induced by The Rayleigh Scattering

Figure 5. 2: Signal and noise (ASE and MPI) flows of double-pass DCRA.

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Unlike the white noise random process feature of ASE, the MPI noises induced by Rayleigh backscattering are distributed over the same wavelength band of the transmitted signal, which is generated by the beating of multiple differently delayed replicas of the signal itself [31, 32]. The contribution from signal-MPI beat noise is more serious in our system with the introduction of external reflection. We will examine the Rayleigh-backscattered (RB) and double-Rayleigh-backscattered (DRB) light of forward and backward propagating signals. The flows of signal and RB/DRB light are shown in Fig. 5. 2. We derive the RB and DRB noise power separately as:

$$P_{sf}^{RB}(0) = rP_{sf}(0)G_b(0, L) \int_0^L G_f(0, z) / G_b(z, L) dz \quad (5.8)$$

$$P_{sf}^{DRB}(L) = r^2 P_{sf}(0) G_f(0, L) \cdot \int_0^L \frac{1}{G_f^2(0, z)} \int_z^L G_f^2(0, x) dx \cdot dz \quad (5.9)$$

$$P_{sb}^{RB}(L) = rP_{sb}(L)G_f(0, L) \int_0^L G_b(z, L) / G_f(0, z) dz \quad (5.10)$$

$$P_{sb}^{DRB}(0) = r^2 P_{sb}(L) G_b(0, L) \cdot \int_0^L \frac{1}{G_b^2(z, L)} \int_z^L G_b^2(x, L) dx \cdot dz \quad (5.11)$$

Where $P_{sb}(L) = P_{sf}(L) = P_{sf}(0)G_f(0, L)$, G_f and G_b are net gains, r is the Rayleigh – backscattering coefficient. Since the Rayleigh scattering of light occurs continuously in fibers, $P_{sb}^{RB}(L)$ and $P_{sf}^{DRB}(L)$ will be reflected by the FBG and experience the Raman gain. Considering all these factors, we can obtain a general expression of noise figure (NF) of the double-pass DCRA in which ASE and MPI noises are generated simultaneously. In the beat noise limited detection, one can write the effective NF of DCRA [34, 35] as:

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$$NF = \frac{1}{G_{ON-OFF}} \left[\frac{2N_{sb}^{ASE}(0)}{h\nu} + \frac{(5/9)P_{RB}(0)}{h\nu(B_e^2 + B_o^2/2)^{1/2}} + 1 \right] \quad (5.12)$$

Here G_{ON-OFF} is the overall ON-OFF Raman gain and $P_{RB}(0)$ is the total MPI noise at the output port. Notice that ASE light is randomly polarized but the degree of polarization of Rayleigh backscattered light is 5/9. If we replace the ON-OFF gain G_{ON-OFF} by the net gain $G = G_f \cdot G_b = G_{ON-OFF} \exp(-2\alpha_s L)$, which includes the transmission loss, equation (5.12) represents the real total NF of the amplification system.

5.3 PERFORMANCE OF DOUBLE-PASS DCRA

5.3.1 Theoretical Results

The double-pass DCRA is designed to cost-effectively compensate the dispersion and loss of conventional single-mode fiber (SMF) or nonzero dispersion fiber (NZDF). The parameters of different fiber types are listed in Table 5.1. Nowadays, the transmission systems require amplifier spacing at least 80 km in NZDF with five to six spans between electrical regeneration, while the span of standard telecommunication SMF is about 40-50 km. In double-pass geometry, the DCF length required for 80 km NZDF span is less than 2 km regardless of the use of CFBG. It is well known that the effective length of pump L_{eff} determines the effective fiber length for the Raman interaction and is defined as $[1 - \exp(-\alpha_p L)] / \alpha_p$. Since the length of DCF is quite short, the pump reflector is certainly needed to increase the effective Raman interaction length and improve the gain efficiency. In order to compare with the experimental results, we design and implement the DCRA module to compensate

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the 40 km SMF span. 3 km DCF is needed in the double-pass scheme and the L_{eff} is about 2.4 km.

Parameter Fiber type	α @1550 nm [dB/km]	D@1550 nm [ps/km/nm]	n_2 / A_{eff} [W^{-1}]	r [km^{-1}]	C_R [1/W/km]
SMF	0.18	+16.3	—	0.6×10^{-4}	0.34
DCF	0.49	-102	14.5×10^{-10}	2.7×10^{-4}	3.20
NZDF	0.22	+4.4	—	1.03×10^{-4}	0.56

Table 5. 1: α : attenuation loss, D : dispersion, r : Rayleigh backscattering coefficient,

C_R : effective Raman gain coefficient for 1455 nm pumping, n_2 / A_{eff} : nonlinear

coefficient, where n_2 is the nonlinear refractive index.

If the input light power of signal at 1554 nm in SMF is -10 dBm, after passing through a SMF of 40 km, the signal power at the input of the DCF is -17.2 dBm. First, we analyzed the gain performance of double-pass DCRA without the pump reflector. A pump light upshifted 13.2 THz from the signal frequency was used to provide the maximum Raman gain. Figure 5. 3 shows the calculated signal and pump power distributions along the DCF for our double-pass configuration and the traditional single-pass backward pumping amplifier. Both cases were simulated to provide the same net gain of 17.2 dB. The double-pass amplifier was pumped with 458 mW and the backward pumping single-pass amplifier was pumped with 848 mW.

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Figure 5. 3: Signal and pump power distributions along the 3-km DCF for double- and single-pass schemes.

Clearly, the double-pass configuration achieved the same gain performance with 46% less pump power in the same fiber length. The normalized pump power transmitted in the single- and double-pass system (calculated by numerical simulation) is shown in Fig. 5. 4. The pump power calculated by neglecting pump depletion in double-pass geometry is also plotted, which matches the numerical results very well. We can observe that although the gain-efficiency is much higher in double-pass system, a significant fraction of pump power exits at the end of DCF. The fact that over 60% unused pump power in the 3-km double-pass system suggests that the gain-efficiency could be improved by adding a pump light reflector.

Figure 5. 4: Normalized pump power distribution along the amplifier fiber for single- and double-pass system. Simulation and analytical results (dotted line) are compared for double-pass system.

5. 3. 2 Tested Data of Components Used in System

We then calculated the gain of the double-pass DCRA with the pump reflector using the theoretical models given in equations (5. 3), (5. 4), (5. 5) and compared the analytical results with the experimental results. The experimental configuration is illustrated in Fig. 5. 1. One 1455 nm Raman fiber laser (RFL) with Relative Intensity Noise (RIN) < -124 dB/Hz was employed as the CW Raman pump source and was injected through a WDM coupler. The measured 3 dB gain bandwidth of this pump was 20 nm and the peak Raman gain wavelength is 1554 nm. The FBGs were replaced by a wideband reflector (reflectivity > 90% from 1260 to 1650 nm) to simplify the setup. Thus both the signal and pump wave can be reflected. For

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comparison, we implemented the experiments where only one FBG is used to reflect the signal light. It is worth noting that the average total polarization mode dispersion (PMD) value of our DCF is measured as 0.82 ps, which is high enough to neglect the polarization dependence of the Raman gain [35] and it is reasonable to avoid the depolarization of the pump source.

Since the performance of our system in experiments is highly dependent on the parameters of optical components used in the double-pass DCRA, we tested the data of some key components and listed their data as follows:

Figure 5. 5: Reflection spectrum of the FBG used in the double-pass DCRA.

1) Parameter of FBG:

The Gaussian-apodized FBG used in our system is centered at 1554 nm with a 0.2 nm stop-bandwidth and a side-lobe suppression ratio larger than 20 dB. The reflection spectrum of the FBG is shown in Fig. 5. 5.

2) Polarization independent 3-port circulator:

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The tested data of 3-port OC is listed in the following Table 5. 2

Wavelength Range		1525 - 1575	nm
Insertion Loss	1→ 2	0.66	dB
	2→ 3	0.47	
Isolation	2→ 1	57	dB
	3→ 2	58	
Polarization Dependent Loss (PDL)	1→ 2	0.04	dB
	2→ 3	0.06	
Directivity	1→ 3	64	dB
	3→ 1	70	
Return Loss	1	56	dB
	2	57	
	3	56	
Polarization Mode Dispersion (PMD)		< 0.05	ps
Operating Temperature		0 ~ 70	°C
Storage Temperature		-40 ~ 85	

Table 5. 2: Data sheet of polarization independent 3-port OC

3) Tested data of Raman pump:

The high power 1455 nm RFL is used as our Raman pump source. The RFL is driven by the electrical current. Its maximum output light power exceeds 1 W and the threshold electrical driven current is 0.55 A. We measured and gave its operation parameters in Fig 5. 6 and in Table 5. 3.

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Figure 5. 6: Pump output light power versus dive current (1455 nm Raman pump)

Drive current (A)	Output light power (dBm)	Output light power (mw)
0.55	13	19.953
0.6	16.8	47.863
0.65	18.72	74.473
0.7	20.3	107.15
0.75	21.4	138.04
0.8	22.33	171
0.85	23.23	210.38
0.9	23.85	242.66
0.95	24.38	274.16
1	24.95	312.61
1.1	25.83	382.82
1.15	26.2	416.87
1.2	26.5	446.68
1.3	27.14	517.61
1.4	27.72	591.56
1.5	28.23	665.27
1.6	28.72	744.73
1.7	29.13	818.46
1.8	29.51	893.31

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1.9	29.82	959.4
2	30.1	1023.3

Table 5. 3: Data sheet of 1455 nm Raman pump source.

5. 3. 3 Experimental Results

Figure 5. 7: Comparison of Raman net gains in single- and double-pass system.

In Fig. 5. 7, Raman net gains in the same 3-km DCF were plotted for single- and double-pass system using wideband fiber mirror. The double-pass system with only FBG at signal wavelength is also examined. The insertion loss of the reflector and the connector were taken into account. The input signal condition was the same as that in Fig. 5. 3 and the signal linewidth is controlled as 50 MHz to suppress the Brillouin scattering. With the pump reflection, 3 ~ 5 dB gain increase was obtained when the pump power exceeded 300 mW in the double-pass geometry. Our theoretical model presented a good prediction of the gain performance especially at the high gain region

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and the double-pass amplifier exhibited much higher gain efficiency compared with the typical single-pass amplifier. Due to the considerable pump depletion, there were relatively large discrepancies between the theoretical and experimental results when the pump power was less than 100 mW in double-pass DCRA.

Figure 5. 8: ASE and RB/DRB noise power versus Raman gain of double-pass DCRA.

Input signal is -17.2 dBm at 1554 nm.

In order to evaluate the noise performance of double-pass system, we plotted the ASE and all of the RB/DRB noise powers versus Raman gain in Fig. 5. 8. The input signal condition was assumed to be the same as that in Fig. 5. 3. The ASE noise power was integrated within the optical filter bandwidth of 0.2 nm. For comparison, we also plotted the ASE noise power of traditional backward pumped 6-km DCF single-pass system. It was clear that the ASE noise in our double-pass system was suppressed by the equivalent bi-directional pumping scheme. But the MPI noises due to the reflection played an important role in the double-pass system. As shown here, the

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double-Rayleigh-backscattered light was quite weak because of the short fiber length and very low input signal power. However, the RB light of signal induced by the reflection of FBG was a key component when considering the noise performance. The output RB noise of forward signal $P_{sf}^{RB}(0)$ in equation (5. 8) is of the same order as ASE, but the output RB noise of backward signal $P_{sb}^{RB}(0)$ in equation (5. 10) increases with the Raman gain rapidly and overwhelms ASE power at the high gain region. That is, the MPI noise is the main limitation factor of the double-pass Raman amplifier.

Figure 5. 9: Total NF with/without considering the MPI noise

We compare the total NF performance versus Raman ON-OFF gain with and without considering MPI noise contribution in Fig. 5. 9. When calculating the NF, we use the optical signal bandwidth $B_o = 10$ GHz and the receiver electrical bandwidth $B_e = 10$ GHz [33, 34]. In general, the NF can be reduced with the increasing distributed Raman gain, which fits to the curve of ASE-induced-NF in Fig. 5. 9. But unlike the

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NF in traditional DCRA, the NF in the double-pass system increases drastically due to the MPI impairments when the Raman gain exceeds 14 dB, limiting the high gain usage of the double-pass DCRA. Although the total NF is less than 8.5 dB at the 20 dB Raman gain, the trade-off between the pump gain efficiency and NF tolerance must be taken into consideration according to the system requirements.

5.4 DESIGN ISSUES OF DOUBLE-PASS DCRA

This section discusses the design issues of some key components in the double-pass systems. Requirements and conditions complied with the system performances are specified to make the double-pass DCRA a practical and feasible amplifier module.

5.4.1 Optimization of The Signal Reflector

Figure 5.10: Total NF with different reflection ratio (R) of signal reflector.

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Since most of the Rayleigh-backscattering induced noise is due to the RB light of backward propagating signal (shown in Fig. 5. 8), we can try to vary the reflection ratio of FBG to control the reflected power of backward amplified signal and hence reduce the total NF in high gain region. The tunable FBGs provide more flexibility to control the dispersion and net gain of the double-pass DCRA module. Figure 5. 10 shows the total NF for reflection ratio of $R = 1, 0.75, 0.5$ of FBG, respectively.

The lower the reflection ratio, the higher the NF at the zero gain operating point due to the additional insertion loss of FBG. By increasing the pump power and consequently, the ON-OFF Raman gain, we observed the NF reduction in high gain region and hence, the minimum NF can be achieved at the higher gain. The minimum NF of $R = 0.75$ or 0.5 can be obtained when the DRA is operating at the ON-OFF gain of 11 or 13 dB. It is clear that we can achieve less NF and higher Raman gain simultaneously by reducing the reflection ratio of FBG. Note that the required pump power in this case increases as well (such as the input pump power at $R = 0.5$ is 15% larger than that at $R = 1$). Indeed, if we set $R = 0$ which indicates the absence of a reflector, signal will be received at the reflector end and the DRA is a typical single-pass amplifier system. The RB noise has no effect on the system noise performance but the advantages of double-gain and high pump efficiency are sacrificed.

5. 4. 2 Pump-RIN Transfer

Traditionally, Raman amplifiers are operated in the backward pumping geometry to minimize the pump-to-signal crosstalk and polarization-dependant gain. However, with the available low-noise pump sources, the co-pumping and bi-directional pumping schemes are feasible in practice [36-38]. Ultra-dense WDM channel spacing and ultra-long amplifier span have been achieved with the benefits of the Raman

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copumping [37, 38]. Because there is a certain amount of copumping in our double-pass DCRA, it is important to consider the effects of pump-to-signal RIN transfer. Although the counterpumping scheme has a larger tolerance of pump RIN compared with the copumping scheme, the chromatic dispersion in the fiber causes the signal and pump wavelength to “walk off” and average the noise transfer from pump to signal. Analysis shows that fibers with high dispersion between the signal and pump wavelengths present a greater potential for the use in copumped Raman amplified systems [39]. As illustrated in Chapter 2, we follow the analysis procedures in ref. [39] to study the performance degradation due to RIN transfer in copropagating Raman pump using the parameters listed in Table. 1; and obtain the estimated quality factor (Q factor) penalty in our DCF with varying Raman gain. The results are presented in Fig. 5. 11.

Figure 5. 11: Estimated Q penalty for different values of pump RIN at the copumping situation.

From Fig. 5. 11, we can observe that the copumped Raman amplification can tolerate up to -112 dB/Hz without suffering a 0.1 dBQ penalty with 20 dB Raman gain and the double-pass DCRA can be made feasible using the pump sources with $RIN < 112$ dB/Hz. Thus it is suitable to use our pump source ($RIN \leq -124$ dB/Hz) in this double-pass geometry with respect to system performances.

5.5 Nonlinear Impairments in Double-Pass DCRA

The double-pass DCRA has been proven to outperform the conventional counterpumped DCRA in the gain efficiency. The decrease of pump power requirements is extremely meaningful to make the Raman amplification competitive with the performance of EDFAs and recent tellurium-doped fiber amplifiers (TDFAs) [5, 40]. However, nonlinear impairments can occur for relatively high signal powers in DCF with small-effective area even inside rather short fibers (in our case, 3-km DCF). Interchannel effects such as FWM or XPM are mitigated by the high local dispersion of the DCF, but self-phase modulation can still lead to signal distortion. The integrated nonlinear phase of a signal power evolution $P_s(z)$ over a fiber segment of length L is given by $\phi(L) = \int_0^L \gamma \cdot P_s(z) dz$ where $\gamma = \frac{\omega n_2}{c A_{eff}}$ is the fiber nonlinear coefficient, ω is the center angular frequency of signal [33, 41]. We assume that different signal power evolutions on a transmission fiber of given constant dispersion produces the same signal distortion if they have the same integrated nonlinear phase. Our double-pass DCRA can be viewed as a bidirectional-pumping amplifier with a signal propagation distance twice the fiber length. A fair comparison can be made between the double-pass DCRA and the typical backward-pumping DCRA with the

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same total dispersion experienced. Since $P_s(z) = P_s(0)G(0, z)$, where $G(0, z)$ is the net gain, the signal nonlinear phase accumulation in double-pass system can be modeled using equation (5. 3), (5. 4), (5. 5) in the equivalent light path illustrated in Fig. 5. 12.

Figure 5. 12. Equivalent light path of double-pass DCRA.

Similar with the discussion in Chapter 3, we define the $G(0, z) = \exp(-\alpha_{eq}z)$ where α_{eq} is the equivalent local loss-amplification factor and it can be derived as follows:

$$\begin{aligned} \alpha_{eq}(z) = \alpha_s - \{ & C_R \cdot P_{pf}(0) \exp(-\alpha_p z) + \\ & C_R \cdot P_{pb}(L) \cdot \exp[-\alpha_p(L-z)] \} \\ & \dots z \in [0, L] \end{aligned} \quad (5. 13)$$

$$\begin{aligned} \alpha_{eq}(z) = \alpha_s - \{ & C_R \cdot P_{pf}(0) \exp[-\alpha_p(L-z)] \\ & + C_R \cdot P_{pb}(L) \exp(-\alpha_p z) \} \\ & \dots z \in [L, 2L] \end{aligned} \quad (5. 14)$$

Where the parameters are defined in Section 5. 2, and the equivalent local loss-amplification factor of typical backward pumping DCRA can be given as [42-44]:

$$\Gamma_{eq}(z) = \alpha_s - C_R \cdot P_p(2L) \cdot \exp[-\alpha_p(2L-z)] \quad (5. 15)$$

Where $P_p(2L) = \ln(G_{ON-OFF})/(gL_{eff})$ is the input pump power at the fiber output port that supply the same gain as the double pass geometry. The calculated equivalent fiber loss-amplification factor of double-pass DCRA is shown in Fig. 5. 13, and the equivalent fiber loss of typical backward pumping DCRA is plotted as well for comparison.

Figure 5. 13: Fiber equivalent loss of transmitted signal in double- and single-pass DCRA system with 20 dB ON-OFF Raman gain. The nonlinearity enhancement R_{NL} is plotted versus distance.

It is evident that both amplifiers provide 20 dB ON-OFF gain. A flat distribution of Raman gain in double-pass system is achieved. Since there is a significant forward pumping in double-pass geometry, the fiber nonlinearity of this type amplifier will be larger than that of the conventional counterpumped DCRA with the same input conditions. For the constant nonlinear impairments, we define R_{NL} to be the ratio of

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overall nonlinear phase of signal experienced in the double-pass DCRA relative to that experienced in the typical counterpumped DCRA,

$$R_{NL}(2L) = \frac{\phi_{double-pass}(2L)}{\phi_{backward}(2L)} = \frac{\int_0^{2L} \exp[-\alpha_{eq}(z) \cdot z] dz}{\int_0^{2L} \exp[-\Gamma_{eq}(z) \cdot z] dz} \quad (5.16)$$

The signal input power of double-pass system should be $P_{in}/R_{NL}(2L)$, where P_{in} is the input power of conventional single-pass system, to insure the same cumulative nonlinearity. The R_{NL} as a function of transmission distance is plotted in Fig. 5. 13. The initial increase of R_{NL} (in dB) is due to the forward pumping and the decrease near the fiber end is caused by the backward gain of counterpumping. Less than 1.5 dB power nonlinearity enhancements can be obtained in the double-pass DCRA with 20 dB ON-OFF gain (about 17 dB net gain). This indicates the possibility to employ the double-pass DCRA as a preamplifier in a transmission system where the signal is attenuated during the transmission in span.

Figure 5. 14: Schematic configuration of 100 km SSMF transmission span.

A comprehensive numerical simulation of the signal transmission characteristics in the fiber span employing double-pass DCRA is demonstrated in the following section. The system is configured as a cascade of four spans. As shown in Fig. 5. 14, in each span, the signal propagates in the 100 km SSMF span and acquires the loss and

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dispersion compensation in the DCRA module configured in double-pass geometry. 8 km DCF is employed as gain medium and the ideal dispersion and dispersion slope compensation is assumed. Pseudonym-random-binary-sequence (PRBS) 64-bit nonreturn-to-zero (NRZ) signals are assumed for intensity modulation at 10 Gb/s. The frequency and temporal traces of the input signal are represented in Fig. 5. 15:

Figure 5. 15: Frequency (upper case) and temporal (lower case) representations of 64-bit 10 Gb/s NRZ signal.

For our simulation, the total signal envelope A propagated through the fiber span is modeled by the modified nonlinear Schrödinger equation (NLSE) [40-44]

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$$j \frac{\partial A}{\partial z} - \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - j \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + \gamma |A|^2 A = -j \frac{\alpha}{2} A \quad (17)$$

where β_2 is the group velocity dispersion (GVD) coefficient, and β_3 is the third order dispersion, respectively. The waveform evolutions can be obtained by numerically solving this equation with the split-step Fourier method (SSFM). Since the signal quality degradation caused by the pump depletion and RIN transfer is negligible according to the discussion in Section 5.3 and 5.4, we can replace the attenuation coefficient α by the equivalent local loss-amplification factor α_{eq} defined in equation (5.13), (5.14) to incorporate the Raman amplification. We consider the effects of the double-pass DCRA on the single channel signal transmission properties. The signal is output by means of a bandpass optical filter with 3-dB bandwidth 40 GHz, then photodetected and filtered by a 12-GHz bandwidth low-pass electrical filter. The demodulated eye diagram can be obtained and the BER can be estimated by following the steps in ref. [42, 43].

At the receiver, the signal and delayed signal will beat together thus the phase noise is converted into intensity noise by the incoherent mixing (since the Rayleigh scattered pulse signal is produced along the long length of amplifier cavity) [45]. In order to incorporate the MPI noise effect in the performance estimation, we study the electrical properties of Rayleigh scattered light. Figure 5.16 shows the electrical power spectrum of 10-Gb/s NRZ signal back-to-back, signal after transmission and the Rayleigh backscattered light, respectively, as measured by electrical spectrum analyzer. The measured signal transmits through 50 km SSMF span and amplified by the counterpumped 3-km DCF, in which 10 dB Raman gain is applied. The intensity noise of Rayleigh component presents a wideband white noise feature and it has a

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similar power level with transmitted signal component in the high frequency region (above 40 GHz). This property suggests that a low-pass electrical filter would be necessary for the double-pass DCRA system and we can include the MPI noise in the system by adding a wideband electrical noise source at the receiver side.

Figure 5. 16: The electrical power spectrum of 3 types of light: back-to-back 10-Gb/s NRZ signal source, signal after transmission, and Rayleigh scattered signal light, respectively.

The total loss in one span is about 26 dB (18 dB in SSMF and 8 dB in DCF). We calculate the BER and Q-factor with respect to the signal mean power injected through the SSMF span for transmission and present the results in Fig. 5. 17, where Raman gains of different values are only applied in the double-pass DCRA. At low input power where ASE noise dominates, the performance is better with increasing input power while it starts to degrade when the input power exceeds an optimum

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value, as a result of the fiber nonlinearity overwhelming the signal-to-noise ratio (SNR) improvement. For the error free condition (BER of 10^{-12}), the power margin achieved by using double-pass DCRA is significant with the increasing Raman gain (8 dB power margin result can be obtained when 11 dB Raman gain is applied). Furthermore, the minimal BER performance is obtained for a particular combination of input signal power and Raman gain (16 dB Raman gain and 0 dBm input signal). Since the Raman amplification is provided only in the DCF module, the nonlinear penalty is mainly due to the SPM effects where high input power and high Raman gain are present. The degradation of BER performance at high Raman gain regime is also due to the MPI noise because it is more strongly dependent on Raman gain and hence results in the noise floor [46]. The Rayleigh-scattered light is proportional to the transmitted signal power and the enhanced MPI noise degrades the total noise performance at the high power signal input condition, which should be avoided in the real applications.

(a)

(b)

Figure 5. 17: BER (a) and Q -factor (b) as a function of the mean input signal power for the transmission span with different ON-OFF Raman gain in double-pass DCRA.

In order to explore the optimal BER performance for the transmission span using the double-pass DCRA, we estimate the BER with respect to the input signal power in the span and the ON-OFF Raman gain in the DCRA. The contour map of calculated BER is plotted in Fig. 14. The best BER of the system can be achieved when the ON-OFF Raman gain in DCRA is 18 dB and the input signal power is 0 dBm (indicated by the gray square). The corresponding input signal at the DCF is about -18 dBm to ensure a low level MPI noise.

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Figure 5. 18: Contour map of the $\log_{10}(\text{BER})$ as a function of the ON-OFF Raman gain in DCRA and the input signal power.

5.6 CONCLUSIONS

The DCFs are excellent gain mediums for discrete Raman amplifiers because of high Raman gain efficiency due to small effective area and high Ge concentration. Compared with the conventional discrete EDFAs, the DCRA can be used to develop an all-Raman amplified system not limited to EDFA bands and to give additional flexibility to extend the available bandwidth. Since cost/efficiency relation for Raman amplifiers is one of the major concerns for wide commercial use, we investigated the DCRA with a double-pass configuration to provide gain/pump efficiency improvement and acceptable noise performance. We developed a theoretical model for the transmitted signal, pump, and the enhanced MPI noise due to the Rayleigh

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scattering and reflection in the double-pass system. Experiments are implemented by using 3-km DCF to prove the feasibility of our model. Both theoretical and experimental results represent significant enhancement in gain efficiency. With the appropriate FBG, in the same length of DCF the double-pass DCRA generates the same net gain with 46% less pump power compared to the typical backward pumped DCRA and achieves double dispersion compensation ability. For a fixed dispersion compensation management, the double-pass geometry reduces the required DCF length/cost and makes the gain distribution more evenly in the DCRA. With cascaded FBG or wideband reflector covering pump wavelength, a large amount pump power can be reused and 3 ~ 5 dB gain increase can be obtained with the same pumping conditions. We also prove that MPI noise is the dominating source of noise impairments in our double-pass DCRA system. From the NF performance we can see that the MPI noise limits the usage of our double-pass system in the very high gain regime. The trade-off between high gain/efficiency and MPI noise impairments has been discussed with regard to the reflection ratio of the external reflector. The wideband white noise feature of MPI in the electrical domain suggests that a low pass electrical filter is needed to maintain the signal quality in transmission.

In order to evaluate the system transmission property with the noise and nonlinear impairments, a 4×100 km SSMF span with double-pass DCRA has been simulated for 10 Gb/s NRZ signal channel. The optimal performance was discussed according to the Raman gain and input signal power level. For large input power and high Raman gain, the quality penalty originates from both the nonlinear effect and the MPI noise. The compact, low cost, high-efficient double-pass DCRA module is quite convenient for all-Raman amplified dispersion managed system, where low input power and moderate Raman gain in the DCRA are preferred to ensure the best signal quality.

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6 Dynamic Properties of Double-Pass DCRA

6.1 INTRODUCTION

Similar to the SRS process, stimulated Brillouin scattering (SBS) is a nonlinear process in which frequency-downshifted (Stokes) radiation is amplified in a medium by parametric coupling with a pump and an electrostriction-induced ultrasonic wave (electrostriction represents the tendency of materials to densify in regions of high optical intensity) [1-3]. Since the SBS limits the maximum optical signal power that can be launched in the fiber for transmission, researchers have investigated the effects of distributed Raman gain on SBS for the stable operation of Raman amplifiers [4, 5]. The threshold features of Raman-enhanced Brillouin Stokes and the Brillouin Stokes combs in high Raman gain region have been studied in typical forward- and backward-pumping Raman amplifiers [6-8].

In Chapter 5, we have demonstrated a highly efficient double-pass discrete Raman amplifier using DCF and high reflectivity FBG (or fiber mirror) with affordable noise performance [9-11]. Compared with the typical counterpumped Raman amplifiers, nearly 50% pump power can be saved while the same Raman gain and double-dispersion-compensation performance can be obtained with the same length of DCF fiber. However, Brillouin Stokes-shifted light may be enhanced in this configuration

because of the equivalent bi-directional Raman gain [4, 9] and the external reflector feedback [12, 13]. Therefore it is important to study the SBS effects in fiber amplifier systems using the double-pass geometry in this chapter.

Besides the gain and noise performances, amplifier transients during channel add/drop or the total input power variations must be suppressed in order to maintain the transmission quality of dynamic networks. All-optical feedback is one of the promising techniques to stabilize the gain of amplifier in dynamic operation. The automatic gain control in Raman amplifiers using additional lasing line has been investigated theoretically and experimentally [14, 15]. Furthermore, gain clamping in L-Band EDFA using a FBG has been proposed to stabilize the gain of fiber amplifier [16] and partially gain-clamped single and double-pass L-Band EDFA using FBG has been investigated experimentally [17]. However, there has been no study on gain control mechanisms in double-pass discrete Raman amplifiers.

In this chapter, we investigate the SBS features in double-pass Raman amplifier, which are quite different from those in a typical Raman-pumped system. We observe that the signal and first order Brillouin Stokes' power reduction contribute to the generation of Stokes and anti-stokes comb through power transfer. We also analyze the dynamics of cascaded Brillouin Stokes generation to investigate their impacts on the Raman gain efficiency. The appropriate operation conditions of signal and pump in our double-pass Raman amplifiers are explored. In order to suppress the SBS and stabilize the Raman amplifier, an all-optical gain-clamping (GC) scheme is proposed and implemented by using a FBG and a wideband reflector to form a fiber laser. The high lasing power within the linear resonant cavity makes the DRA operate in saturation regime and provides a uniform gain and noise performance for large signal

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variation and eliminates the Brillouin scattering of signal wavelength. This is the first experimental demonstration of an FBG-based all-optical gain-clamped double-pass Raman amplifier (AO-GC-DRA).

6.2 SBS IN DOUBLE-PASS DCRA

6.2.1 Theoretical Backgrounds

SBS is a nonlinear effect that manifests through the generation of backward propagating frequency-shifted Brillouin Stokes wave [2, 4]. The process of SBS can be described as the interaction between intense pump light and the acoustic waves in a fiber medium. The pump field generates an acoustic wave through the process of electrostriction [5] (electrostriction represents the tendency of materials to densify in regions of high optical intensity). The excited acoustic waves generate an index grating that copropagates with the pump at the acoustic velocity in the material and the moving grating reflects the pump light and causes the backscattered Stokes light to be downshifted in frequency through the Doppler effect. The frequency shift with respect to the pump is given by $\Delta\nu_B = 2nV_A / \lambda_p$, where λ_p , n , and V_A are the wavelength of the incident pump, the refractive index of the core, and the sound velocity of the material, respectively [18-22].

Due to the high gain coefficient and large interaction length in the optical fiber, SBS is one of the dominant nonlinear effects. SBS has detrimental consequences for signal transmission in optical fiber since it limits the maximum optical power that can be launched into the fiber [2-4]. It is therefore essential for a system designer to understand the impact of SBS on the performance of telecommunications. Recently

the Raman amplifiers based on the SRS have attracted considerable attention because of their potential for providing a relatively flat gain over a wide bandwidth with low noise figure [23-25]. Thus, understanding the impairments of SBS in the Raman amplifiers is important. Since the fiber loss is replaced by the distributed gain in Raman amplifier, both the Brillouin pump and Stokes wave experience gain thus the SBS threshold is drastically reduced. Moreover, higher-order Stokes can be generated through cascaded SBS. Kobayakov et al. have analyzed the SBS in Raman-pump optical fibers using a theoretical approach [4]. The threshold power of the first Brillouin Stokes in distributed Raman gain is inversely proportional to the path-average integral of Raman gain [4]. Also, the generation of a Brillouin Stokes comb in Raman amplifier has been reported recently, the threshold features and the dynamics of multi-Stokes generation have been investigated [6-8].

In order to investigate the features of SBS in double-pass Raman amplifier, which are quite different from those in typical Raman-pumped fiber, we implement experiments to observe the threshold features of the first order Brillouin Stokes and the generation of reflected Stokes comb. The dynamics of Brillouin pump and first Brillouin Stokes waves are analyzed in detail.

6. 2. 2 Experimental Results

The experimental configuration is the same as that shown in Fig. 5. 1. The input signal with linewidth of 700 KHz (act as Brillouin pump) from a tunable laser source (TLS) is injected into 3-km DCF through the optical circulator (OC) port 1. The 1455 nm Raman fiber laser (RFL) with Relative Intensity Noise (RIN) < -124 dB/Hz is employed as the CW Raman pump source. It is injected through a wavelength division multiplexer (WDM). The 3 dB Raman gain bandwidth of RFL is 21 nm and

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the peak gain wavelength is 1554 nm. A wideband mirror with reflectivity $> 90\%$ instead of the narrowband FBG is placed at the fiber end to further improve the pump efficiency [26]. The signal and the Brillouin scattering light experience double-amplification and output through OC port 3. We omit the depolarization of the pump source because the average total PMD value of our DCF is measured as 0.82 ps, which is high enough to neglect the polarization dependence of the Raman gain [27].

Figure 6. 1: Comparison of net Raman net gains in single- and double-pass system.

The signal is -25 dBm at 1554 nm. The inset shows the FBS generation when pump is 660 mW.

Let us recall the gain performance of double-pass DRA firstly in comparison with the typical counterpumped single-pass system first. In Fig. 6. 1, Raman net gains in the same 3-km DCF are plotted for single- and double-pass system. The CW input signal is -25 dBm at 1554 nm. More than 30 dB Raman net gain can be obtained when the power of RFL is 620 mW. It's quite clear that the high gain efficiency and low pump power consumption in double-pass scheme make this amplifier a promising candidate

for the cost-effective Raman amplification. However, with further increase of the Raman pump power, the strong first order Brillouin stokes (FBS) light generates and the signal (Brillouin pump-BP) power decreases due to the Brillouin-induced power transfer. An example of power transfer is shown in the inset of Fig. 6. 1 when the pump power is 660 mW.

Although the double-pass geometry allows the copumping when the signal first enters the amplifier, the high dispersion of DCF will average the RIN transfer thus performance degradation due to RIN transfer can be negligible provided our stable pump source [11, 28]. Figure 6. 2 shows the net Raman gain (a) and total noise figure (NF) (b) as a function of injected pump power with different signal (1554 nm) input power levels in our double-pass system. In this experiment, we have tried to amplitude modulate (AM) the signal at 300 MHz before the circulator to suppress the SBS effect. Although more than 30 dB Raman net gain can be achieved at small signal condition, the net gain decreases with the increasing signal input at the same pump power, which is consistent with the results in ref. [29]. Unlike the typical single-pass amplifier, the MPI noise caused by the reflected-Raman-amplified Rayleigh backscattering [9] is the major limitation factor. We measured the Rayleigh-induced noise using the expanded time-domain-extinction method [30] and added it to the ASE NF using the general NF expression equation (5. 12). The ASE noise is measured using the interpolation-source subtraction method [31]. As the MPI-induced noise is strongly dependent on Raman gain, it will degrade the OSNR, increase the receiver sensitivity penalty, and eventually result in a noise floor. The measured total NF increases at high Raman gain region, which is consistent with the previous theoretical results [9]. At the same time, strong Brillouin scattering are observed when

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pump power exceeds 660 mW regardless of the input signal power although we implemented the intensity modulation.

Figure 6. 2: Experimental net gain (a) and total NF (b) versus input pumping power with different input signal power. Signal wavelength: 1554 nm.

In order to explore the dynamics of Brillouin Stokes light, we observe the evolutions of the output amplified signal (BP), the first Brillouin Stokes (FBS) and the ON-OFF Raman gain versus the pump power when a -17 dBm 1554 nm signal is injected into the double-pass system. The results are shown in Fig. 6. 3. (a). Although the input BP power is still quite low, the FBS appears when Raman pump is 270 mW (16 dB ON-OFF Raman gain) and increases with the increasing of signal power. FBS shows exponential growth at the pump power of 500 mW and increases linearly until pump power reaches 630 mW. Similar with the results in the ref. [7], the FBS experiences a 10 dB reduction when pump power is higher than 620 mW and a cascaded Brillouin-Stokes comb is generated. For the Raman amplification, the ON-OFF gain of transmitted signal saturates at 30 dB after the comb generation. The gain-competition between the multi-Stokes and the wideband Raman amplification contribute to the comb generation.

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Figure 6. 3: (a) Signal, first Brillouin Stokes and Raman gain versus pump power when -17 dBm signal input. (b) Comb generation when -17 dBm signal input. (c) Pump threshold of Brillouin comb generation. Resolution: 0.01 nm.

An example of comb generation with -17 -dBm-signal input before and after the pump threshold is shown in Fig. 6. 3. (b). It is quite clear that not only the FBS but also the second-order Stokes decreases to support the comb generation, which is different from the previous report [7, 8]. The linewidth of Stokes lines are the same because of the reflection-enhanced Brillouin scattering. The comb threshold with respect to the input signal and Raman pump power is measured and illustrated in Fig. 6. 3. (c). The needed pump power increases linearly with the decreasing injected signal power.

Figure 6. 4: Evolutions of output signal power, first Brillouin stokes and Raman gains versus input signal power.

We then study the SBS feature in our double-pass Raman amplifier as a function of input signal power with fixed pump power and plot the results in Fig. 6. 4. Before the exponential boost of FBS, we can observe that the Raman gain maintains a stable value at small-signal conditions. Above the FBS threshold, the signal output power saturates and the Raman gain of signal decreases with the increasing of input power.

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The higher order Stokes and anti-Stokes appear successively and increase because of both the Raman effect and power transfer from signal. A very interesting phenomenon is that more than 6 dB reduction of output signal appears abruptly if the input power exceeds 0 dBm. The output signal remains at low power level (-3 dBm) even with higher input. At this moment neighboring Stokes and anti-Stokes lines increase but other low-power higher order Stokes are suppressed. The power transfer and gain-competition are represented in Fig. 6. 5. The average power and spectral coverage of the comb can be enlarged with higher input signal and RFL power.

Figure 6. 5: Signal power transfer at input signal threshold with pump power at 410 mW. Resolution: 0.01 nm.

The observed novel features are partly due to the feedback induced by the wideband reflector in our double-pass system. Firstly, the higher order Stokes will generate due to the reduction in Brillouin threshold as a result of the external feedback [2, 12-13] and the Raman amplification. Secondly, the instability caused by the

counterpropagating signal waves manifests as the spontaneous growth of side modes in the pump spectrum at $\nu_s \pm \nu_B$, where ν_s is the signal frequency. As the instability threshold is significantly smaller than the Brillouin threshold, the scattered light can exhibit rich frequency spectra of multiple harmonics of the fundamental acoustic wave frequency [12]. All these factors contribute to the comb generation in the Raman gain region when there is a small signal. Since the signal and multi-Stokes lines can copropagate in DCF, anti-Stokes components are generated through FWM between copropagating signal and Stokes waves [2]. Although the local dispersion of DCF is quite high ($D = -110$ ps/km/nm), the coherence length $L_{coh} = 2\pi / (\Omega_s^2 |\beta_2|)$ can be 12 km where the frequency shift $\Omega_s / (2\pi)$ is the acoustic wave frequency 10 GHz, and the dispersion parameter is given by $D = -2\pi c \beta_2 / \lambda^2$. Thus significant FWM occurs in the short DCF even no perfect phase matching provided. The anti-Stokes lines consume the signal light power thus the FBS can exceed the signal power at the end. From Fig. 6. 4, we can conclude that the Brillouin Stokes comb generates only with enough Raman pump power (here the pump threshold is 500 mw) no matter how high the signal power is. The high Raman pump power gives a flat floor for the cascaded Stokes and enhances the tendency of power transfer from higher frequency to lower frequency. At lower pump power conditions, the Raman gain just decreases the Brillouin scattering threshold.

6.3 Dynamics of Gain-Clamped DCRA

The strong SBS Stokes comb generation can be attributed to the wideband Raman gain region and the reflection-enhanced signal-Stokes power transfer. It is clear from above results that the Brillouin Stokes consumes the pump power of RFL and makes

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the Raman amplification of signal unstable. Although the multi-Stokes cascaded Brillouin scattering is interesting and meaningful for the development of multiwavelength fiber lasers, it is a detrimental effect in Raman amplified telecommunication system and need to be suppressed. However, the SBS in the double-pass system is enhanced significantly because of the distributed Raman gain and the instability caused by the counterpropagating signal in the double-pass geometry [12]. Since we have concluded that the Brillouin Stokes comb can be stimulated only with enough Raman pump power, the SBS might be suppressed under saturation regime in which Raman pump power is depleted by all-optical feedback.

The all-optical feedback is one of the promising techniques to stabilize the gain of amplifier in dynamic operation. It can be achieved by introducing a lasing light inside the amplifier gain medium. X. Zhou *et al.* did some theoretical investigations of all-optical gain control by using an additional lasing line and filter [14]. The experimental approaches are implemented to stabilize the performance of S-band discrete Raman amplifier [15]. Furthermore, gain clamping in L-Band EDFA using a FBG has been proposed to stabilize the gain of fiber amplifier and partially gain-clamped single and double-pass L-Band EDFA using FBG has been investigated experimentally [16, 17]. Actually, the automatic all-optical gain control is quite useful for the small or medium size metro-area network (MAN) or broadband access network with variable traffic pattern and dynamic channel add/drop operations. Amplifier transients during channel add/drop or total input power variations must be suppressed in order to maintain the transmission quality of dynamic networks. However, there has been no study on gain control mechanisms in double-pass discrete Raman amplifiers up till now.

6.3.1 Experimental Setup of Gain-Clamped Double-Pass DCRA

In order to suppress the SBS and stabilize the Raman amplifier, an all-optical gain-clamping (GC) scheme is proposed and implemented by using a FBG and a wideband reflector to form a fiber laser. The high lasing power developed within the linear resonant cavity makes the DRA operate in saturation regime, provides a uniform gain and noise performance for large signal variations (both in power and in wavelength) and eliminates the Brillouin scattering of signal wave. We believe that it is the first application of FBG-based all-optical feedback gain-clamping in a double-pass discrete Raman amplifier.

Figure 6.6: GC scheme to stabilize the signal gain and eliminate the SBS.

The experimental configuration (shown in Fig. 6. 6) of all-optical gain-clamped double-pass DCRA is based on the typical double-pass system described in Fig. 5. 1. A FBG with a reflectivity $> 99\%$ at 1539 nm and a stop band of 0.2 nm is placed between the WDM and DCF. The ASE light within the stop band of FBG will resonate in the fiber cavity to form a lasing light. The intensity of lasing light depends on the reflectivity of FBG and the Raman gain efficiency at the FBG central wavelength.

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6.3.2 Experimental Results

The dynamics of GC (gain and noise performances versus input power) are analyzed in Fig. 6.7. The pump power is fixed at 410 mW to sustain a saturation operation. Clearly, the gain-clamped double-pass amplifier maintains a stable and higher than 21 dB ON-OFF gain (14 dB net gain), for the input signal power ranging from -25 dBm to 3 dBm, while keeping gain variation below 0.17 dB. For comparison, we plot the gain variation versus input signal power without the GC. Although the Raman gain at small signal input is above 24 dB (17 dB net gain), the gain experiences a significant reduction with the increasing signal power and strong Brillouin scattering generation. The cascaded Brillouin Stokes sidebands consume the pump power and significantly degrade the noise performances. On the contrary, the noise figure (NF) in double-pass system with GC can be clamped at a flat level until the input signal exceeds 0 dBm. The Rayleigh-induced MPI noise is measured using the same method described above and added to the ASE NF using the general NF expression. The larger NF in higher input power conditions is mainly due to the enhanced MPI noise in this double-pass geometry since the Rayleigh backscattering is proportional to the input signal power [9-11].

With the lasing light in GC amplifier, net amplification experienced by the signal and the MPI noise is clamped. The pump depletion due to the resonant cavity suppresses the total NF of GC-DRA at the large power signal input. The variation of NF is below 1.5 dB in GC-DRA. Thus, our 3-km double-pass GC-DRA exhibits a stable ~14 dB net gain and a total dispersion of -660 ps/nm, with a NF less than 6 dB for a 30-dB input dynamic range. At the same time, the SBS is suppressed efficiently in the simple gain clamped system. Since the amplification module is in saturation status due to the

lasing light, further increase of the pump power can only enhance the clamping effect and no SBS generation is observed. This gain module is suitable for compensation of dispersion and loss in a 40-km span of standard single mode fiber (SSMF) with considerable gain margin and high efficiency.

Figure 6. 7: Gain and NF as a function of input signal power for signal wavelength 1554 nm. Solid: without GC. Hollow: with GC. Input pump power is 410 mW.

Figure 6. 8 shows the gain and total NF as a function of signal wavelength for input signal power of -20 dBm with the pump power of 410 mW. More than 10 dB net gain can be obtained from 1542 to 1568 nm. Although the peak gain at 1554 nm decreases 4 or 5 dB compared to the results in Fig. 6. 2. (a), the 3-dB gain bandwidth of this amplifier is broadened to 25 nm. The total NF can be maintained at a flat level from 1547 to 1570 nm with a variation within 0.3 dB.

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Figure 6. 8: Gain and NF as function of input signal wavelength. Pump power is 410 mw and the input signal power is -20 dBm. Solid: ON-OFF gain. Hollow: Total NF.

6.4 CONCLUSIONS

In summary, we investigated the SBS properties and the dynamic performance in the high efficient double-pass DRA system. Distributed Raman gain and the reflector-induced feedback significantly decrease the threshold of Brillouin scattering of signal light. Moreover, cascaded Brillouin Stokes comb generates simultaneously due to the wideband Raman gain spectrum and the power transfer from signal wavelength. The dynamics of SBS are analyzed and the threshold of comb generation is measured according to the pump and input signal conditions. In order to suppress the detrimental SBS effect in double-pass system, we proposed and demonstrated a simple GC scheme by using a single FBG and fiber mirror to form an oscillation in the double-pass cavity. The proposed configuration is also used to control the

amplifier transient effects in double-pass DCRA with optical feedback mechanism. Based on the all-optical feedback mechanism, we achieved a flat Raman net gain of more than 14 dB with large input power variations and only 0.17 dB gain ripple over 30-dB input signal dynamic range when pump power is fixed at 410 mW. Actually, the high pump efficiency of double-pass configuration (30 dB net gain achieved at the pump power of 640 mW) provides a large margin for gain clamping. The NF can be flattened over a wide range of input signal power/wavelength. At the same time, the SBS is eliminated successfully in the all-optical GC DRA system without the complex phase/amplitude modulation. Thus, the gain-clamping technique eliminates the Raman-reflection-enhanced Brillouin scattering and provides a stable and efficient Raman-amplification module for the dispersion-managed fiber transmission system.

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7 Raman-Assisted FWM All-Optical Wavelength Conversion

7.1 INTRODUCTION

Different from previous chapters, this chapter investigates the Raman-based all-optical wavelength conversion, which is a key technology in the realization of all optical networks together with the all-optical Raman amplification. It is well known that the WDM technology has becoming the key technique for the ultra-high capacity optical networks. Due to the significant increase of Internet traffic recently, the large amount of data traffic requires huge bandwidth. Furthermore, the manufacturing technology of WDM components is matured, and their costs are going cheaper. Based on the application environment and the technical evolution, implementation of WDM technology to short-haul or metro area is increasing now. In contrast with long-haul network, metropolitan-area network (MAN) has various traffic patterns including the asymmetric traffic pattern, so the flexibility of networks is very important [1, 2]. According to the network operation environment, wavelength converter is a crucial component to improve the flexibility and increase the capacity of optical fiber networks [3].

Various strategies have been investigated to achieve the all-optical wavelength conversion. The mechanisms such as cross-gain modulation (XGM), XPM, and FWM are heavily explored in two kinds of media: SOA and optical fibers [4-11]. As one of the nonlinear process, the use of parametric four-wave mixing (FWM) for wavelength conversion has attracted considerable attention since 1990s because of its potential application in WDM lightwave systems [7, 12-16]. In the parametric process, the idler wave can only be generated through FWM when the pump and signal are present simultaneously. Thus, the pseudorandom data sequence carried by the signal wave can be transferred to the idler wave at a new frequency through the parametric FWM when a continuous-wave (CW) pump beam is injected. Since the origin of parametric process in fibers lies in the nonlinear response of material's bound electrons to an applied optical field, the instantaneous feature ($\sim$ fs scale) of parametric FWM makes it ideal for ultrafast, high-speed optical signal wavelength conversion. In effect, FWM transfers the signal data to the idler at a new wavelength with perfect fidelity. The signal quality can be even improved by reducing the intensity noise [12-16].

It is well known that the efficient FWM process depends on appropriate phase-matching conditions [12]. In practice, the phase-matching condition in single-mode fibers can be satisfied by using fiber birefringence or nonlinear SPM effect near the zero-dispersion wavelength (ZDW). At the same time, in order to enhance the conversion efficiency, the SRS is considered to obtain a large frequency shift because of the broadband Raman gain spectrum [14-16]. As discussed in previous chapters, fiber Raman amplification has been used to manage the OSNR and optimize the reach of fiber spans [17]. Recent studies show that timing jitter is reduced by up to a factor of two when distributed amplification is employed [18, 19]. Due to the unique

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properties of Raman-FWM based wavelength conversion, various Raman-assisted FWM based wavelength converters are reported [14-16, 20-21].

In this chapter, we concentrate on the design of Raman-FWM based wavelength converters theoretically and experimentally. According to the different phase-matching techniques and gain mediums, two types of fiber-based Raman-FWM wavelength converter are developed. Section 7. 2 introduces the principle of parametric FWM and its phase-matching condition. Section 7. 3 demonstrates the Raman-resonant FWM method in which the 500 m birefringent fiber is used to maintain the phase-matching condition and the group-velocity matching. Based on our proposed novel model, the power intensity and temporal properties of the converted wave (10 Gb/s and 20 Gb/s, from C-band to L-band) are illustrated using numerical simulation. In section 7. 4, we propose and implement an efficient wavelength conversion using distributed Raman gain and the Raman-assisted parametric four-wave mixing in 1 km of HNLFs. The system is implemented in a double-pass Raman amplifier described in Chapter 5, in which a tunable optical bandpass filter and a wideband reflector are used to form a laser oscillation in the normal dispersion region of HNLF. The phase-matching condition is achieved using SPM-induced nonlinearity. The lasing light acts as the parametric pump to enable the wideband wavelength conversion around the pump wavelength. We compare the two schemes and summarize this chapter in section 7. 5.

7. 2 Parametric FWM

FWM is a third-order nonlinearity in silica fiber that is analogous to intermodulation distortion in electrical systems and has been studied extensively because it can be quite promising for generating new frequency waves [12]. When wavelength channels

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are located near the ZDW, three optical frequencies (ν_i, ν_j, ν_k) will mix to produce a fourth intermodulation product ν_{ijk} given by:

$$\nu_{ijk} = \nu_i + \nu_j - \nu_k, \quad \text{with } i, j \neq k \quad (7.1)$$

This process corresponds to the case in which two photons at frequencies ν_i and ν_j are annihilated with simultaneous creation of two photons at frequencies ν_k and ν_{ijk} such that $\nu_{ijk} + \nu_k = \nu_i + \nu_j$. When this new frequency falls within the transmission window of the original frequencies of WDM system, it will experience amplification and cause severe crosstalk (similar with SRS).

Figure 7. 1: Two optical waves at frequencies ν_1 and ν_2 mix to generate two third-order sidebands.

Figure 7. 1 shows a simple example for two waves at frequencies ν_1 and ν_2 acting as the FWM pumps. When they copropagate along the fiber and at the same polarization state, they mix and generate sidebands at $\nu_3 = 2\nu_1 - \nu_2$ and $\nu_4 = 2\nu_2 - \nu_1$. Similarly, three co-propagating waves will create nine new optical sideband waves at frequencies given by equation (7. 1). These waves will travel along with the original pump waves and grow at the expense of pump strength depletion. The FWM in which

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two photons annihilate themselves to produce two sidebands photons can occur provided the total momentum is conserved. This momentum conservation requirement leads to the phase-matching condition. That is:

$$\begin{aligned}\kappa &= k_3 + k_4 - k_1 - k_2 \\ &= 2\pi(n_3\nu_3 + n_4\nu_4 - n_1\nu_1 - n_2\nu_2)/c = 0\end{aligned}\tag{7.2}$$

where the propagation constant is $k_j = n_j\omega_j/c$, n_j is the refractive index and $\omega_j = 2\pi\nu_j$. The main difference between the parametric FWM and the SRS/SBS is that the phase-matching condition is automatically satisfied in the inelastic stimulated scattering process due to the participation of the nonlinear medium. However, the specific phase-matching condition in FWM requires a proper choice of pump frequency and refractive index.

A special case is that there exists a FWM process which is easier to occur when the central pump wavelength $\nu_1 = \nu_2$. For this degenerate case a strong pump wave at ν_1 creates two sidebands located symmetrically at frequencies ν_3 and ν_4 with frequency shift

$$\Delta\nu = \nu_1 - \nu_3 = \nu_4 - \nu_1\tag{7.3}$$

The optical wave associated with higher frequency photons is called anti-Stokes and that with lower frequency photons is called Stokes wave. Notice that the Stokes and anti-Stokes waves are often called the signal and idler waves, when the input signal with frequency ν_3 is amplified through FWM.

7.3 Raman-Resonant FWM Based Wavelength Converter

7.3.1 Theoretical Model of Raman-Resonant FWM

Figure 7. 2: Theoretical Energy-level diagram (a) and schematic diagram (b) of dual-wavelength pumped fiber Raman-FWM converter.

The low frequency parametric Stokes wave generated by FWM will experience Raman gain through subsequent Raman amplification when the frequency shift falls into the Raman gain band [16-18]. We can expect that Raman-resonant-FWM scheme will be a very promising wavelength conversion technique with very high conversion speed, good SNR, voluntary modulation format (by FWM), and a high conversion efficiency, ultrabroad conversion range based on the Raman gain spectrum.

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The Raman conversion scheme based on dual-wavelength-pumped four-wave-mixing was proposed by using solid-state lasers to get the anti-Stokes, first-Stokes wave in different cases where the phase matching conditions were satisfied by choices of a suitable angular configuration of the incident beams [13,14]. A fiber-Raman-converter model [15] using the same principle was also presented with which the wavelength conversion from 1.31 to 1.42 μm can be realized. Even the 1.31 to 1.55 μm conversion for optical fiber communications is feasible when these types of fiber-Raman converters are cascaded twice. Application of this concept to a fiber results in a convenient wavelength converter that can be used for information transfer between different fibers. The theoretical and schematic diagrams of dual-wavelength-pumped fiber Raman converter are shown in Fig. 7. 2. An external intense secondary pump laser (refer to as P2) and its associated first Stokes wave (S2) are used to assist the Raman conversion process from a weak primary pump laser with bit sequence (P1) to the associated first Stokes wave (S1). As in Fig. 7. 2. (a), the conversion of the weak primary pump wave P1 to the corresponding first Stokes wave S1 is achieved by photons prepared by the intense secondary pump wave P2 and its corresponding first Stokes wave S2. As in Fig. 7. 2. (b), the primary pump wave P1, which includes optical information in the form of pulse train, is incident to fiber Raman converter with the P2 laser and the S2 laser through a fiber coupler. The Stokes wave S1 converted from the P1 signal is generated by the Raman-resonant FWM process. Therefore, when we use a tunable laser source as the S2 laser, we can obtain a wide-range tunable wavelength conversion device.

However, the previous schemes may not be suitable in practical optical networks. This is because, (i) the walk-off length for the FWM is restricted by the group-velocity mismatch between the signal and pump so high power solid-state laser must

be used to achieve enough interaction strength, which is not convenient in today's WDM systems; (ii) the nonlinear phase distortion caused by the high input signals and power intensity which deteriorate the network performance [15]. Thus, we propose a novel model of Raman-resonant FWM fiber wavelength converter with high power pumping LDs, where not only the phase-matching but also the group-velocity matching (to greatly extend the interaction fiber length) can be achieved by the birefringent fiber.

7.3.2 The Phase-Matching and Group-Velocity Matching Techniques

Once the Stokes signal is parametrically generated, not only phase-matching (PM) but also group-velocity matching (GVM) of four waves is required to obtain long interaction length and achieve efficient FWM and subsequent Raman amplification [12, 16]. We can make use of the modal birefringence which results in different effective refractive indices for waves propagating with orthogonal polarization. Actually, the phase-matching condition can be written as:

$$\Delta k = \Delta k_M + \Delta k_w + \Delta k_{NL} = 0 \quad (7.4)$$

where Δk_M , Δk_w , and Δk_{NL} represent the mismatch due to the material dispersion, waveguide dispersion, and the nonlinear effects, respectively. By neglecting the nonlinear contribution, it is possible to achieve phase matching by polarizing different waves along differently principal axes of the fiber. When the wavelengths of all four waves are shorter than the zero-dispersion wavelength of fibers, the phase-matching condition is obtained when Δk_M (positive) and Δk_w cancel each other (note that Δk_w can be made negative) [12]. Furthermore, the birefringence between the fast and slow fiber axes can compensate for the difference of group velocities between the Stokes

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pulses and the pump component, which is polarized perpendicular to the Stokes polarization, to acquire excellent GVM [16]. The FWM generated Stokes pulse will experience subsequent Raman amplification by the perpendicular pump pulse in GVM condition. The GVM compensated by the fiber birefringence occurs in the positive dispersion regime where the Stokes pulse is polarized along the slow fiber axis and one of the pump pulse components is polarized along the fast fiber axis. Thus, in our model, for both matching conditions, the S2 and S1 waves are polarized along the slow axis (x-axis) while the P1 and P2 waves are polarized along the fast axis (y-axis). If the effective indices are written as $\tilde{n} = n + \Delta n$, where n is the material index while the Δn is the change in the material refractive index due to waveguiding, the Δk_M and Δk_W become

$$\Delta k_M = (n_4 k_4 - n_3 k_3) - (n_2 k_2 - n_1 k_1) \quad (7.5)$$

$$\Delta k_W = \Delta n_4 k_4 + \Delta n_1 k_1 - \Delta n_2 k_2 - \Delta n_3 k_3 = -\delta n \cdot \Delta k \quad (7.6)$$

where n_i is the refractive index ($i=1,2,3,4$ represents S1, P1, S2 and P2, respectively), $k_i = 2\pi/\lambda_i$ is the wave number in vacuum, $\delta n = \Delta n_x - \Delta n_y$ is the birefringent refractive index difference, where Δn_x and Δn_y are the changes in the refractive indices for the modes polarized along the slow and fast axes of the fiber, $\Delta k = k_4 - k_2 = k_3 - k_1$. By selecting an appropriate value of δn , it is possible to make $\Delta k_M + \Delta k_W = 0$ and hence obtain the phase-matching condition for FWM.

In this scheme, the walk-off length L_W of P1 and S1 waves is characterized as:

$$L_W = c \cdot T_0 / (\tilde{n}_{P1} - \tilde{n}_{S1}) \quad (7.7)$$

where c is the speed of light in vacuum, T_0 is the pulse width of P1 wave. With a specific value of δn , $L_w = c \cdot T_0 / (\Delta N - \delta n)$, $\Delta N = n_{p1} - n_{s1}$. Compared with the conventional FWM scheme in ref. [3], the walk-off length L_w in our group-velocity matched model increases with a factor of $\Delta N / (\Delta N - \delta n)$ (in normal dispersion regime).

7.3.3 Numerical Model of Converter

Based on the group-velocity matching and phase matching condition, the propagation of the four waves in the birefringent fiber is governed by the nonlinear *Schrödinger* equation (NLSE) described in Chapter 2, section 2.5. GVD, fiber loss, SPM, and XPM are incorporated into our model. Because the employed LDs are operating at the wavelength band of $1.4 \mu m$ to $1.5 \mu m$, they can act as the Raman pumps of the converted wave inside C- and L-band (thus increase the efficiency of the conversion process). Also we consider the polarization dependence in Raman effect and XPM as illustrated in Chapter 2. That is the Raman gain coefficient between the orthogonal pump and Stokes is just one tenth of that between the parallel pump and Stokes. When we approximate the transverse overlap between the propagating waves as the effective fiber core area A_{eff} (it is valid for single-mode fiber), the coupling equations for the above four waves are described as follows [12, 15]:

$$\frac{\partial A_1}{\partial z} = (\hat{D}_1 + \hat{M}_1) \cdot A_1 + \frac{g_{21}}{5} (|A_2|^2 A_1 + A_2 A_4^* A_3) + 2 \cdot g_{31} |A_3|^2 A_1 \quad (7.8)$$

$$\frac{\partial A_2}{\partial z} = (\hat{D}_2 + \hat{M}_2) \cdot A_2 + \frac{g_{12}}{5} (|A_1|^2 A_2 + A_1 A_3^* A_4) + 2 \cdot g_{42} |A_4|^2 A_2 \quad (7.9)$$

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$$\frac{\partial A_3}{\partial z} = (\hat{D}_3 + \hat{M}_3) \cdot A_3 + \frac{g_{43}}{5} (|A_4|^2 A_3 + A_4 A_2^* A_1) + 2 \cdot g_{13} |A_1|^2 A_3 \quad (7.10)$$

$$\frac{\partial A_4}{\partial z} = (\hat{D}_4 + \hat{M}_4) \cdot A_4 + \frac{g_{34}}{5} (|A_3|^2 A_4 + A_3 A_1^* A_2) + 2 \cdot g_{24} |A_2|^2 A_4 \quad (7.11)$$

where A_i is the propagating optical field amplitude, z is the coordinate in the propagation direction, $\tau = t - z/c$ is the retardation time.

$\hat{D}_i = -\frac{1}{v(\lambda_i)} - \frac{j}{2} \beta_2(\lambda_i) \frac{\partial^2}{\partial \tau^2} - \frac{\alpha_i}{2}$ is the differential operator accounting for dispersion

and absorption (α_i is the birefringent fiber loss for different waves, λ_i is the wavelength of different waves. $v(\lambda_i)$ is the group velocity, $\beta_2(\lambda_i)$ is the linear group velocity dispersion given by $-(\lambda_i^2 D_i / 2\pi c)$ where D_i is the dispersion parameter).

$\hat{M}_i = j\gamma_i [|A_i|^2 + 2 \sum_{k \neq i} |A_k|^2]$ accounts for SPM and XPM. γ_i is the nonlinear coefficient

defined by $n_2 \omega_i / c A_{eff}$, where $\omega_i = 2\pi \nu_i$ is the angular frequency, and the nonlinear

index coefficient $n_2 = 2.7 \times 10^{-20} \text{ m}^2 / \text{W}$. The Raman interaction factor is given by

$g_{ik} = C_R(\nu_i - \nu_k)$ for $\nu_i > \nu_k$ and $g_{ik} = -C_R(\nu_k - \nu_i)$ for $\nu_i < \nu_k$, (also k

$= S1, P1, S2$ and $P2$ but it's different from i) where $C_R(\Delta \nu)$ is the effective Raman

gain coefficient measured in Chapter 2 under polarization scramble conditions. The

second terms on the right-hand side of above equations correspond to the dual-

wavelength-pumped Raman-resonant FWM and the first terms on the right-hand side

correspond to the conventional stimulated Raman scattering.

7.3.4 Numerical Simulations and Discussions

In this section, we numerically demonstrate the feasibility of our proposed fiber Raman converter for optical information. As an example, we consider the fiber

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Raman converter using 500 m birefringent fibers. P2 wave is obtained from the 1400 nm high power laser diode or fiber Raman laser; S2 is a tunable laser diode where its wavelength ranges from 1430 nm to 1480 nm (S-band) and the input signal light wavelength is 1530 nm. In this Raman-resonant FWM process, the Raman frequency shift between the P1 wave and the S1 wave depends on the frequency difference between the P2 wave and the corresponding Stokes wave S2. Thus, the wavelength conversion can cover a very wide wavelength band where the tuning range is determined by the S2 wave as the appropriate phase matching and group-velocity matching conditions are satisfied. Hence, we expect to have wavelength conversion between C-band and L-band.

We assumed a highly birefringent germania-doped silica fiber as the Raman medium. The fiber model [15, 16] is characterized by a core/cladding index difference of 0.001 and a 2.0 μm core radius. Since the fiber core area is similar with that of HNLF, we use the effective Raman gain coefficient of HNLF measured in Chapter 2. The material refractive index dispersion features is well approximated by the Sellmerier equation [12]:

$$n^2(\omega) = 1 + \sum_{j=1}^3 \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2} \quad (7.12)$$

where $\omega_j = 2\pi c / \lambda_j$, the Sellmerier coefficients B_j and λ_j are found to be: $B_1 = 0.80686642$, $B_2 = 0.71815848$, $B_3 = 0.85416842$, $\lambda_1 = 0.068972606 \mu\text{m}$, $\lambda_2 = 0.15396605 \mu\text{m}$, and $\lambda_3 = 11.841931 \mu\text{m}$. When the S2 wavelength is tuned to be 1.45 μm , the Raman shift frequency is 7.39 THz, and an effective Raman gain coefficient C_R of $3.9 \text{ W}^{-1} \text{ km}^{-1}$ is obtained. With the signal pump P1 at 1530 nm, a 1.59 μm S1 Stokes wave can be generated. By calculating the refractive index and

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satisfying the phase matching and group-velocity matching condition based on equation (7. 5), (7. 6), and (7. 12), a birefringent refractive index difference of 6.55×10^{-4} is required for both matching conditions. If the input light and pump wavelength are changed, we can tune the fiber birefringence in a wide range to get the associated frequency shift and matching conditions. Tuning of the fiber birefringence may be achieved by a temperature change or by external stress [16]. In this way, our Raman converter can work over a very wide bandwidth within the transmission window.

In our analysis we have assumed Gaussian pulse shape with repetition rate of 10 Gb/s for the input signal, the peak power of the input signal, pump and tunable laser diodes are 5 mw, 1 w, 100 mw, respectively. Figure 7. 3 shows the spatial and temporal evolution and Fig 7. 4 presents the peak power evolutions of all the four waves. The S1 wave is generated from the Raman-resonant FWM and it is amplified by the subsequently Raman interaction of P1 and S2 waves. At first, the parametrically FWM-Raman process diminishes the direct Raman amplification, thus the S1 wave is generated and increases drastically until after around 100 m of fiber. As the fiber extends longer, the FWM efficiency will decrease because of the increase of the group-velocity mismatch, then the Raman amplification will dominate the process and the S1 can be amplified directly by the S2 and P1 waves. Note that the P1 wave also acquires signal gain by Raman amplification of P2 and the pulse widths of P2 and S2 are much wider than those of P1 and S1 wave.

From the power evolutions, we can observe that the power of S1 is about 2 mW at the end of propagation, which is high enough for optical fiber transmission. If we increase

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the fiber length, the power of S1 will be increased along the fiber, but the GVM will be worse.

(a) P1 wave evolution.

(b) S1 wave evolution.

(c) P2 wave evolution.

(d) S2 wave evolution.

Figure 7. 3: Spatial and temporal power evolution of propagating waves. The repetition rate of P1 is 10 Gb/s when periodic boundary conditions are used to model a regularly spaced pulse train.

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Figure 7. 4: Peak power evolutions of four waves. The fiber length is 500 m, the initial value for P1 at 1530 nm, P2 at 1400 nm, S2 at 1450 nm are 5 mW, 1 W, 100 mW, respectively. The repetition rate of P1 is 10 Gb/s, the S1 wave is 1.59 μm

The intensity-temporal profiles of the converted S1 wave (at the fiber output end) and the control P1 wave (at the fiber input end) are demonstrated in Fig. 7.5 (P1 is 10 Gb/s) and Fig. 7. 6 (P1 is 20 Gb/s) to show the pulse properties and conversion feasibility in dispersion region. It can be seen that the information (intensity and phase profiles) of P1 is imprinted on the S1 wave. Although the conversion efficiency will decrease as the bit rate increases, the decrease of conversion efficiency in our model can be compensated by the Raman amplifications from S2 and P2 waves. Clearly, the width of pulses will be broadened because of dispersion effects, and also they will be broadened further at higher repetition rate. The distortion of the profile and overlap of the pulse will occur if higher bit rates are used.

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Figure 7. 5: Temporal profiles of converted $S1$ wave and the initial $P1$ wave with 20 Gb/s repetition rate. All of the conditions are the same as those in Fig. 7. 3.

Figure 7. 6: Temporal profiles of converted $S1$ wave and the initial $P1$ wave with 20 Gb/s repetition rate. All of the conditions are the same as those in Fig. 7. 3.

7.3.5 The Tunability of Fiber Raman-Resonant FWM Converter

One of the advantages of this fiber Raman converter is that a tunable wavelength conversion can be realized by selecting an appropriate wavelength of S2 wave and an appropriate refractive index difference. When we choose another wavelength of S2, the Raman gain coefficient will change (apart from the Raman gain spectra peak), thus the output power of S1 signal will be different. To convert the wavelength efficiently with a small Raman gain, we can use a much longer fiber with increased dispersion effects. Decreasing the dispersion in fibers is the key issue to obtain a practical fiber Raman converter.

7.4 Raman-Assisted FWM-based Double-Pass Wavelength

Converter

Besides the birefringent fiber-based phase-matching technique, another approach is to implement the degenerate FWM in DSF near ZDW where the nearly phase matching FWM occurs within the coherence length [12, 20-21]. A high power laser source at the ZDW area is often needed as a pump to stimulate the conversion process between Stokes and anti-Stokes waves [21]. Because of the gain variations due to the phase-mismatch, wavelength converters based on the dual-pump parametric amplification has been proposed to realizing broadband features [20]. In order to employ the wide range amplification property of stimulated Raman scattering (SRS), a Raman assisted parametric frequency conversion scheme has been demonstrated [13]. However, such devices cannot provide an arbitrary new converted wavelength in wideband wavelength range while keeping the polarization independence. In this section, we propose and implement a simple scheme of a highly efficient wavelength converter utilizing the interaction between the parametric-FWM and the SRS in highly

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nonlinear fibers (HNLFs). A double-pass Raman amplifier is used to form a fiber Raman oscillator in which a tunable optical bandpass filter (TOBPF) and a wideband Faraday rotator mirror (FRM) are used to generate a lasing light in the normal dispersion region of HNLF in order to seed the Raman-parametric wavelength conversion. We achieve the wavelength conversion with an efficiency larger than 0 dB over 50-nm signal bandwidth. Arbitrary new wavelength in the tunable range of the filter can be obtained for a given input signal.

7.4.1 Technical Concepts

It is well known that the SRS can be strongly affected by parametric FWM interactions in silica fibers [22]. As the fiber Raman amplifiers (FRAs) and fiber Raman lasers based on SRS are increasingly important in high capacity optical fiber telecommunications, it is essential to study the influence of parametric process on the Raman effects and take advantage of the interaction of these two nonlinear processes useful to achieve high efficiency Raman amplification. Also, as such amplifiers generate an idler wave around the parametric pump, they also can be used for wavelength conversion. The pioneering theoretical study has shown that the Raman gain depends on the phase-matching condition between the pump and Stokes wavelength in optical fibers [23]. The FWM can suppress or enhance SRS under appropriate conditions. An experimental investigation performed in photonic crystal fibers demonstrates that a threefold increase of Raman gain can be obtained under phase-matching conditions [24].

Let us recall some theoretical results of the interactions between FWM and SRS for a better understanding of our experiments. SRS is characterized by a down-conversion of a pump photon into a low-frequency Stokes photon through excitation of a

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vibrational mode of the transmission medium [12]. An up-conversion process that generates an upshifted anti-Stokes wave is also possible through the parametric FWM.

Figure 7. 7: Illustration of parametric-Raman interaction. Wavelength conversion occurs between Stokes and anti-Stokes.

As shown in Fig. 7. 7, the anti-Stokes is located symmetrically to the Stokes wave around the parametric pump wavelength. This FWM-influenced Raman scattering is highly dependent on the dispersion of the pump wavelength. On one hand, significant Raman gain improvements can be obtained for the Stokes and anti-Stokes if the Raman pump wavelength is in the anomalous dispersion region [23, 24]. The Raman pump acts as a parametric pump in this case and the Raman gain variation is associated with chromatic dispersion. The phase matching can be achieved under appropriate conditions due to the cancellation of linear phase-mismatch and nonlinear SPM [22-24]. Although this phenomenon is quite useful to improve the Raman amplification efficiency significantly on the Stokes sideband, the depleted parametric pump power cannot feed an efficient wavelength conversion between Stokes and anti-Stokes. On the other hand, if the pump wavelength is located in the normal dispersion region, the parametric suppression of the seeded Stokes exponential amplification takes place and the anti-Stokes idler generation and amplification occur even phase matching condition is not satisfied perfectly. In this case, a sequence of data

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transmitted by the Stokes light is transferred to the anti-Stokes light. Similarly, the seeded anti-Stokes light containing data sequence can transfer the energy downshifted to the Stokes idler due to the Raman effects and Raman-assisted FWM. With this method, efficient wavelength conversion between Stokes and anti-Stokes light can be achieved around the pump wavelength. The modulation-instability-induced amplitude noise associated with the wavelength conversion is avoided since the parametric pump light is located inside the normal dispersion region. To maintain the nearly phase matching condition when the pump wavelength is within normal dispersion region, a flat dispersion slope of the nonlinear fiber is necessary.

The dispersion-shifted HNLF used in our work for optical signal processing owns quite large Raman gain coefficient ($g_R = 5.9 \text{ W}^{-1}\text{km}^{-1}$) and nonlinear coefficient ($\gamma = 10 \text{ W}^{-1}\text{km}^{-1}$). The measured Raman gain coefficient of our HNLF is illustrated in Fig. 2. 6. The zero dispersion wavelength (ZDW) of the HNLF is at 1559 nm with dispersion slope of $0.02 \text{ ps/nm}^2/\text{km}$ and a cut-off wavelength below 1200 nm. The typical loss is less than 0.75 dB/km from 1550-1650 nm. In order to obtain the frequency conversion between Stokes and anti-Stokes, the pumping wavelength should be selected carefully to provide partial suppression of Raman gain of Stokes light and maintain a small phase mismatch. Due to the interaction between parametric-FWM and stimulated Raman scattering, the mixed Raman gain coefficient g experienced by the Stokes light can be given by [23, 24]:

$$g = 2\gamma\Re[\sqrt{K(2q - K)}] \quad (7.13)$$

Where $K = -\Delta k / (2\gamma P_0)$ is the linear phase mismatch ($\Delta k = \beta_2 \Omega^2$) normalized to the nonlinearity-induced mismatch ($2\gamma P_0$). Here β_2 is the dispersion at the pump wavelength, Ω is the angular frequency shift between pump and Stokes light, and P_0

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is the peak power of the pump. $q = 1 - f_R - \tilde{f}h_R(-\Omega)$ where $\tilde{h}_R(\Omega)$ is the Fourier transform of the complex Raman susceptibility and $f_R \cong 0.18$ measures the fractional contribution of Raman effect. $\Re$ represents the real part of the formula. The well-known equation (7.13) reveals the relationship between the parametric-Raman gain and fiber dispersion. The peak gain coefficient for a Stokes frequency shift, $\Omega/(2\pi) = 13.2$ THz, of HNLF versus pump wavelength is shown in Fig. 7.8 with different pump power. Note that we normalize the gain coefficient g to the standard peak value g_R . FWM suppresses the Raman gain when pump is near the ZDW but there exists a significantly enhanced Raman gain when the pump wavelength is in the anomalous-dispersion region. As we mentioned above, suppression of Raman gain at Stokes light leads to the efficient wavelength conversion when the pump wavelength is in normal dispersion region.

Figure 7.8: Normalized gain coefficient g/g_R versus pump wavelength at Stokes shift of 13.2 THz.

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From above figure, it is clear that the efficient suppression of Raman gain can be achieved with a large pump power ($P_0 = 10$ W). The gain evolution near the ZDW becomes sharper and weaker when the pump power is much lower. In order to employ the FWM-Raman induced wavelength conversion at the frequency range $\Omega/(2\pi) = 13.2$ THz, we must use quite high power pump laser, which makes the system very expensive, fragile, and undesirable. However, the phase matching is also relevant to the Stokes shift $\Omega_s/(2\pi)$. If Ω_s is not too large, the required pump power can be low to obtain an efficient conversion. Thus we calculate and plot the contour map of Raman gain suppression as a function of pumping wavelength and Stokes shifts in Fig. 7. 9 when pump power is 100 mW.

Figure 7. 9: Contour map of Raman gain suppression effects versus the pump wavelength and the Stokes shift when pump is 0.1 W.

The suppression factor is defined as the ratio between the parametric-Raman gain coefficient and the normal Raman gain at the same Stokes shift. The smaller the suppression factor, the stronger the suppression effect. It is verified that significant

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Raman gain suppressions can be obtained when the Stokes shifts is less than 3 THz (25 nm), which leads to about 50 nm useful bandwidth for the efficient conversion between Stokes and anti-Stokes waves around an appropriate parametric pump wavelength.

7. 4. 2 Experimental Results and Discussions

Figure 7. 10: Experimental setup. FRM: Faraday rotator mirror.

We implement the wavelength conversion in a double-pass Raman amplifier as depicted in Fig. 7. 10. The TOBPF with 3-dB bandwidth of 0.65 nm can be tuned in the C-band (1530-1565 nm). The HNLF is pumped by a 1455 nm Raman fiber laser (RFL) through the WDM and the peak Raman gain coefficient of HNLF occurs at 1555 nm. By using the optical circulator 1 (OC1), the wideband FRM and the TOBPF are able to form a laser which acts as the parametric pump light for efficient wavelength conversion. The signal from the tunable laser source (TLS) is injected through the optical circulator 2 (OC2) to be a control light and its linewidth is set as 50 MHz to suppress the stimulated Brillouin scattering (SBS). The converted idler wave is monitored at the output of the circulator OC2. Note that the FRM optimized for 1556 nm is able to eliminate the PDG and achieve a polarization independent conversion. The lasing light (parametric pump) in the HNLF is measured to be 21

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dBm when the RFL's power is 450 mW. The converted idler waves located inside the Raman gain spectrum of the RFL can be amplified by the distributed Raman gain provided by RFL to obtain a further efficiency enhancement. Note that the double-pass configuration used here can further enhance the pumping efficiency and relax the Raman pump power requirements [25-27].

Figure 7. 11 shows an example of the spectrum at the output of our system when the input signal is -8 dBm at 1543 nm (Fig. 7. 11. (a)) and 1567 nm (Fig. 7. 11. (b)). The parametric pump wavelength is 1555 nm by adjusting the filter's central wavelength. It is shown that highly efficient wavelength conversion is realized between Stokes and anti-Stokes light around the pump wavelength. To verify the feasibility of wavelength conversion, we implemented time domain experiments. The input signal is externally modulated by a LiNbO₃ Mach-Zehnder modulator with 2.5 Gb/s nonreturn-to-zero (NRZ), $2^{31}-1$ pseudorandom bit stream (PRBS). The converted idler is filtered by a 0.4 nm fiber Bragg grating-based bandpass filter and detected by a 7 GHz bandwidth Photodetector. The eye diagrams of the 1543 nm input signal and the corresponding idler output from OC2 are shown in Fig. 7. 11. (c). The measured Q-factors of the input signal and converted wave are 9.2 and 7.3, respectively. Note that under Gaussian approximation, the BER with the optimum setting of the decision threshold depends only on the Q parameter and $\text{BER} \approx 10^{-9}$ when $Q = 6$. Thus the results show that the present scheme is applicable for the converted signal transmission with a forward-error correction (FEC) technique. From the eye diagram, the high noise appears when "1" is transmitted and this performance degradation is most probably due to the relative-intensity-noise (RIN) fluctuation in the double-pass cavity.

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Figure 7. 11: Example of converted waves at the output with a control signal at 1543 nm (a) and 1567nm (b). Resolution is 0.2 nm. The eye diagrams of 1543 nm input signal and its idler output are shown in (c).

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The wavelength conversion efficiency over a wide bandwidth is measured (idler power at the output of the HNLF/signal power at the input of HNLF) by monitoring the output with an optical spectrum analyzer and the results are plotted in Fig. 7. 12 at different input signal power levels. As can be seen from Fig. 7. 12, we obtain a conversion efficiency greater than 0 dB for over 50 nm signal bandwidth (1530 – 1580 nm) with an input signal power of –8 dBm. When the signal shifts toward the pump from the 1580 nm, the linear phase mismatch reduces such that a strong FWM-Raman gain of idler wave occurs. However, with further shift, the FWM is perfectly phase-matched because of the flat dispersion slope. Cascaded FWM happens through the beat between pump and idler wave hence the conversion efficiency at the idler wave decreases. A maximum efficiency can be observed in Fig. 7. 12. If the input signal power increases, the control signal itself will act as a FWM pump and generate its sideband since the phase matching can be nearly satisfied due to the flat dispersion slope. The wavelength conversion efficiency decreases accordingly as in Fig. 7. 12.

Figure 7. 12: Idler conversion efficiency measured with different signal power levels.

Pump wavelength is 1555 nm.

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Figure 7.13: Tunable idler wavelength (left axis and conversion efficiency (right axis) as a function of pump wavelength.

Besides wide wavelength operation ranges, our wavelength converter can also provide an arbitrary new wavelength when the phase-mismatch is not serious. Although the wavelength conversion with wide pump tuning range has been reported previously [21], the parametric pump wavelength in our system can be adjusted simply by tuning the TOBPF. Also, the distributed Raman amplification in the double-pass system is beneficial to the Raman-assisted FWM. Actually, we observe from Fig. 7. 9 that efficient Stokes Raman gain suppression can be obtained to support the wavelength conversion when pump wavelength is adjusted in normal dispersion region. For a given input control signal, the pump wavelength can be tuned continuously using the TOBPF thus the frequency shift between pump light and control signal can be adjusted. Through the Raman-assisted parametric FWM, the wavelength of converted idler wave can be adjusted continuously around the pump light. When the input control signal is -8 dBm at 1564 nm, by tuning the TOBPF to keep the pump

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wavelength inside the normal dispersion region, we obtained the idler wavelength and its conversion efficiency versus the pump wavelength, as plotted in Fig. 7. 13. When the pump wavelength shifts from 1558 nm to 1552 nm, an idler from 1540 nm to 1552 nm can be adjusted continuously with a conversion efficiency larger than -3 dB. The flat dispersion slope enables the efficient wavelength conversion within the tunable range of the TOBPF.

7.5 CONCLUSIONS

As one of the nonlinear effects in optical fibers, SRS is promising for all-optical signal processing due to its broad amplification bandwidth and nearly instantaneous response time (less than 100 fs). It's evident to employ Raman effects together with parametric FWM to achieve the all-optical wavelength conversion. Phase matching and dispersion properties are essential to design an efficient Raman-assisted FWM wavelength converter. In this chapter, two types of Raman-FWM wavelength converter are demonstrated according to the different phase matching scheme and gain mechanisms.

In order to improve the performance of dual-pump Raman-resonant FWM wavelength converter, a novel wavelength conversion scheme based on the group-velocity matched fiber Raman-resonant FWM has been proposed by using a long fiber (i.e. $L = 500m$) in the converter and employing a high power laser diode. With the appropriate arrangement of pump and Stokes waves in the polarization-preserving birefringent fibers, we have presented a novel simulation model, and numerically demonstrated the power and temporal evolutions of the converted and pump signals. The results of pulse broadening and conversion efficiency have also been discussed.

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The scheme is compact and practical for applications in flexible and reconfigurable wavelength-reuse networks.

The Raman-resonant FWM scheme actually uses the Raman effect to amplify the input signal and the converted wave. The conversion process is initiated by the FWM itself. However, the Raman scattering and the FWM can interact significantly under proper phase-matching conditions. The reinforced Raman-FWM gain coefficient of Stokes wave can be tailored by adjusting the pump power and the fiber dispersion. This interaction can be used to achieve a threefold increase of Raman gain for the efficient Raman fiber amplifier or laser. The Raman gain of Stokes can also be suppressed to provide the amplification of anti-Stokes wave. Thus efficient wavelength conversion is feasible between the Stokes and anti-Stokes while the central pump acts as the Raman-FWM hybrid pump source. After theoretical analysis, we propose and demonstrate a simple scheme to achieve a highly efficient wavelength converter through the FWM-Raman interaction in HNLFs based on our proposed double-pass system [27]. Wavelength conversion with efficiency larger than 0 dB over 50 nm signal bandwidth is realized. A new wavelength idler with conversion efficiency greater than -3 dB can be adjusted arbitrarily with over 15 nm wavelength ranges. Actually, the Raman-assisted parametric FWM in the double-pass Raman amplifier enables the wideband tunable wavelength conversion with high efficiency. To achieve the wavelength conversion in an even wider bandwidth, the pump light source with much higher power must be developed to increase the nonlinear contribution.

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7.6 REFERENCES

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8 Conclusions and Recommendations for Future Works

8.1 CONCLUSIONS

This thesis has presented the investigation of fiber Raman amplification (FRA) for next generation optical fiber telecommunication systems and networks. In order to reduce system cost and achieve a stable, efficient Raman amplification, we have proposed and developed various design techniques, which include the theoretical analysis model, novel numerical simulation algorithms, optimal pumping schemes and novel structures of Raman fiber amplifiers. Furthermore, the unique applications of the distributed Raman gain in the all-optical parametric FWM wavelength conversion have been investigated. Undoubtedly, Raman amplification will be an essential feature of every ultra-high-capacity, ultra-long-haul, and flexible fiber optical communication networks.

We have developed the explicit theoretical model under small-signal approximation to explore the properties of CW Raman amplification. Raman gain distribution along the fiber span and the noise accumulation were calculated under co-pumping, counter-pumping and bidirectional pumping schemes using our measured effective Raman gain coefficients. By using the numerical simulation, we have validated the feasibility

of the analytical model, which is accurate when signal power is less than 0 dBm and Raman ON-OFF gain is less than 25 dB. Given the same gain, Raman amplification can reduce the ASE accumulation significantly compared with the lumped EDFA. Co-gain of Raman amplifier amplifies the signal near the fiber input end, improves the ASE noise performance and leads to a better OSNR_{ASE} . However, the high average signal power evolution raises the issue of nonlinear penalty. For counter-gain, the signal is amplified near the fiber output end. The higher ASE noise accumulation results in a worse OSNR_{ASE} compared with the copumping scheme. Besides the ASE noise, the MPI noise due to the DRB of the signals is enhanced by the distributed Raman gain, which dominates the noise performance at high gain regime. The MPI noise actually limits the maximum Raman gain that can be applied in fiber system. The bidirectional pumping scheme is able to reduce the MPI noise and make the Raman gain distribution uniformly hence is expected to be the optimal choice. However, the performance degradations due to RIN transfer, interchannel FWM and PDG must be considered when large amounts of co-gain are used.

The ultra-broadband multi-pumping FRA, which employs several pump lasers at appropriate wavelengths and power allocation, was investigated and designed using numerical simulations. We have proposed a novel simulation model using the equivalent attenuation coefficient α_{eq} . The semi-analytical method can enlarge the step size significantly without loss of accuracy. This technique has been successfully used in designing a 100-channel wideband FRA with ± 0.5 dB gain ripple. In order to solve the two-point boundary condition problem in the counterpumped Raman amplifier efficiently, we have developed a nonlinear shooting method based on the Newton-Raphson formula and the multistep predictor-corrector integration algorithm. The gain performance of the two-point boundary condition counterpumped wideband

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Raman amplifier is simulated with high accuracy. With the quite fast/stable convergence rate, we can get the accuracy of the order $10^{-3} \sim 10^{-4}$ in a very complicated system (8 pump- and 101 signal-channels) with just 4 iterations.

We then conducted the optimal design of bidirectionally pumped FRA for multispan long-haul fiber transmission system. The evolutions of copropagating ASE, DRB-induced MPI and RB-backward-propagating ASE noise versus ON-OFF Raman gain were compared under different pumping schemes. The RB-backward-propagating ASE noise power will exceed the forward-propagating ASE if the ON-OFF Raman gain is above 35 dB and lead to deterioration of OSNR_{ASE} . Based on the Q-analysis model, we optimized the operation conditions of bidirectionally Raman pumped long-haul multispan fiber system versus the copumping percentage and total Raman gain. The nonlinearity enhancement was considered. The optimal Q-factor was found to be 21.5 dB with 40% copumping and 19.5 dB total Raman gain for NRZ, and 22 dB with 40% copumping and 22 dB total Raman gain for RZ system. However, by considering the pump RIN-transfer, the corresponding copumping percentage and Raman gain have to decrease to suppress the RIN penalty. Furthermore, we have demonstrated the relationship between the pump RIN intensity and the optimal operation conditions of Raman amplification systems.

We have proposed and implemented a DCRA with a double-pass configuration to provide gain/pump efficiency improvement and acceptable noise performance. We have developed the theoretical model for the transmitted signal, pump, and the enhanced MPI noise in double-pass DCRA. Moreover, we have conducted the experiments to validate our analytical model. Due to the significant enhancement in gain efficiency, the same net gain with 46% less pump power compared to the typical

backward pumped DCRA can be achieved with double dispersion compensation ability. A large amount of pump power can be reused and 3 ~ 5 dB gain increase can be obtained with the same pumping conditions when the pump wavelength reflector is used. At the same time, the MPI noise is proved to be the dominating source of noise impairments in double-pass system, which limits the very high gain usage of double-pass DCRA. After discussing the requirements of components in double-pass system, we evaluated the transmission performance of a 10 Gb/s NRZ signal over a 4×100 km SSMF span with double-pass DCRA. The optimal performance was discussed according to the nonlinear effect and the MPI noise.

We have investigated the Brillouin scattering phenomena in the double-pass DCRA in which the threshold of SBS is reduced by the distributed Raman gain and the reflector-induced feedback. We have analyzed the dynamics of SBS and the threshold of comb generation by adjusting the pump and input signal conditions. Moreover, we have proposed and demonstrated an all-optical feedback gain-clamping scheme to suppress the SBS generation and control the amplifier transient effects. The automatic gain control mechanism is achieved by using a lasing oscillation in the double-pass cavity formed by the FBG and fiber mirror. When pump power was fixed at 410 mw, a flat Raman net gain of more than 14 dB was achieved with large input power variations. Only 0.17 dB gain ripple over 30-dB input signal dynamic range was obtained. The NF can be flattened over a wide range of input signal power/wavelength. Also, the SBS is eliminated successfully in the all-optical GC DRA system without the complex phase/amplitude modulation.

We have studied the all-optical wavelength conversion using Raman-assisted FWM. Firstly, a novel wavelength conversion scheme based on the group-velocity matched

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fiber Raman-resonant FWM has been proposed using birefringent fibers. The input signal and the converted wave are amplified by the consequent Raman effect. With the appropriate phase-matching conditions in the polarization-preserving fibers, we numerically demonstrated the power and temporal evolutions of the converted wave and pump wave for 10 Gb/s and 20 Gb/s systems. Secondly, with the theoretical analysis of the mutual influence of FWM on Raman scattering, we proposed and demonstrated a simpler scheme to achieve a highly efficient wavelength converter through the Raman-assisted FWM interaction in HNLFs based on our proposed double-pass system. Wavelength conversion with efficiency larger than 0 dB over 50 nm signal bandwidth around the central pump wavelength was realized. An idler wave with conversion efficiency greater than -3 dB can be adjusted arbitrarily with over 15 nm wavelength ranges. Thus, Raman-assisted parametric FWM in the double-pass Raman amplifier enables the wideband tunable wavelength conversion with high efficiency.

8.2 Recommendations for Future Works

Although an intensive investigation of FRA has been conducted in this thesis, with the rapid technological developments, there still exists some interesting research possibilities that are worth doing for future works.

8.2.1 Raman Amplification Based on PCF

Recently, great excitement has been generated by the demonstration of air-silica photonic crystal fibers (PCFs), or holey fibers (HFs), microstructured fibers (MFs), which have a large variation of refractive index within the lightguiding region [1].

Unlike conventional optical fibers, PCFs can be made from single material. Waveguiding in these structures can be due to the difference of effective index between a defected region, which forms the core, and the arrangement of air holes, which surround the core and act as the cladding. PCFs are particularly attractive for photonic components because the optical properties can be engineered during fabrication. Through the fiber design, the mode size can be tailored by appropriate air-hole geometrical arrangement, which in turn change the light intensity inside the fiber to alter the effective nonlinearity. An effective mode area as small as $1.3 \mu\text{m}^2$ has successfully been fabricated with an effective nonlinearity coefficient as high as $70 \text{ W}^{-1} \text{ km}^{-1}$ at 1550 nm [2], i.e. around 70 times more nonlinear than SSF. The combination of highly nonlinear material composition and small core/high numerical aperture (NA) allows a dramatic increase of the fiber nonlinearity. A highly nonlinear PCF with loss as low as 2.6 dB/m at 1550 nm and with a nonlinear coefficient as high as $640 \text{ W}^{-1} \text{ km}^{-1}$ has been fabricated [3]. These results provide a promising future for the nonlinear fiber devices based on PCF. Thus, it is natural to explore the possibility of using the highly nonlinear PCF to construct a compact FRA with enhanced amplification performance, which is expected to overcome the typical drawbacks of using conventional fiber: long fiber length (tens of kilometers) and related Rayleigh scattering [4]. The key issue is to determine the Raman effective area defined in equation (2. 19) to take into account the overlap between pump and signal profiles. The doping concentration in the core area should also be considered. The numerical simulation based on full-vector finite-element method (FEM) is needed to calculate the distribution of pump and signal fields on the entire PCF cross-section. Because the Raman effective area is a function of wavelength, one promising application is to

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design an appropriate effective area distribution by tailoring the air-hole arrangement. Hence the effective Raman gain coefficient can be flattened across a broad bandwidth.

8. 2. 2 Polarization Properties of Raman Amplification

The theoretical treatment of Raman amplifiers in this thesis is based on the scalar approach and neglects the polarization dependence of Raman scattering. It is reasonable for a fiber with a relatively large polarization mode dispersion (PMD), in which the polarization dependent gain (PDG) in Raman amplifier can be suppressed by the depolarization of pump laser and the changes of states of polarization (SOPs) induced by PMD [5]. Although the PMD is able to mitigate the PDG of Raman amplifier, it introduces the polarizations and signal distortions. For high-speed fiber optic communications, low PMD fiber is preferred and obtainable with modern fiber fabrication technology [6]. Thus the initial SOPs of signal channels may remain correlated for a long transmission distance of the low-PMD fibers. The signal-signal Raman interaction will dominate the PDG, especially under pump depletion conditions and copumping scheme. It is then important to study the polarization induced Raman gain fluctuations and statistics in the newly installed fiber link. A vector theory of Raman amplification including the fiber birefringence and the input SOPs of pump and signals should be developed for multi-channel WDM system.

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