Comunicações Ópticas
Prof. H. Salgado

Raman amplification

Deben Lamon
Jelle Stuyvaert

Ano lectivo 2007 – 2008
# Contents

1 Raman amplification ........................................ 1
   1.1 History ............................................ 1
   1.2 Stimulated Raman scattering .......................... 1
   1.3 Pump and signal equations ............................... 2
      1.3.1 Raman gain spectrum ............................ 3
      1.3.2 Single-pump Raman amplification ................. 4
      1.3.3 Multiple-pump Raman amplification ............... 8
   1.4 Performance limiting factors ......................... 10
      1.4.1 Spontaneous Raman scattering ...................... 10
      1.4.2 Rayleigh backscattering ........................ 13
      1.4.3 Pump-noise transfer ............................. 14
      1.4.4 Polarization mode dispersion .................... 16
   1.5 Ultrafast Raman amplification ......................... 20

2 Distributed Raman amplification ......................... 22
   2.1 Benefits ........................................... 22
   2.2 Challenges .......................................... 23
      2.2.1 Polarization dependence ........................ 23
      2.2.2 Spatial overlap of pump and signal mode ........ 25
      2.2.3 Nonlinearities .................................. 26
      2.2.4 Rayleigh reflections ............................. 27
      2.2.5 Time response .................................. 28
   2.3 Backward pumping .................................... 29
      2.3.1 Wavelength multiplexed pumps .................... 30
      2.3.2 Broadened pumps ................................ 30
      2.3.3 Time-division-multiplexed pumps ................. 31
   2.4 Advanced pumping configurations ..................... 32
      2.4.1 Higher order pumping ............................. 32
      2.4.2 Quiet pumps .................................... 33

3 Discrete Raman amplification ............................ 35
   3.1 Basic configuration and model ......................... 35
   3.2 Gain fibers and materials ............................ 37
   3.3 Design issues ........................................ 37
      3.3.1 Maximum Raman gain as a function of fiber length 37
      3.3.2 Figure of merit of gain fiber ..................... 37
      3.3.3 Efficiency and linearity ........................ 39
      3.3.4 Pump-mediated noise ............................. 40
      3.3.5 ASE noise figure ............................... 40
      3.3.6 Nonlinear effects and double Rayleigh backscattering noise 41
      3.3.7 Optimum fiber length and number of stages ........ 42
      3.3.8 Transient effects ................................ 43
   3.4 Dispersion-compensating Raman amplifiers ............ 44
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 Wideband operation by WDM pumping</td>
<td>44</td>
</tr>
<tr>
<td>3.5.1 Wide flat composite gain</td>
<td>45</td>
</tr>
<tr>
<td>3.5.2 Pump SRS tilt – Effect of saturation</td>
<td>45</td>
</tr>
<tr>
<td>3.5.3 Signal SRS tilt – How to define gain</td>
<td>45</td>
</tr>
<tr>
<td>3.5.4 Control of gain</td>
<td>46</td>
</tr>
<tr>
<td>3.5.5 Flattening other parameters</td>
<td>47</td>
</tr>
</tbody>
</table>

Bibliography 48
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>COPT</td>
<td>Comunicações Ópticas (Optical Communications)</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensated Fiber</td>
</tr>
<tr>
<td>DCRA</td>
<td>Dispersion-Compensating Raman Amplifiers</td>
</tr>
<tr>
<td>DRBS</td>
<td>Double Rayleigh BackScattering</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifier</td>
</tr>
<tr>
<td>FOM</td>
<td>Figure Of Merit</td>
</tr>
<tr>
<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>MPI</td>
<td>MultiPath Interference</td>
</tr>
<tr>
<td>NZDSF</td>
<td>NonZero Dispersion Shifted Fiber</td>
</tr>
<tr>
<td>OFC</td>
<td>Optical Fiber Communications</td>
</tr>
<tr>
<td>OSNR</td>
<td>Optical Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>PDG</td>
<td>Polarization-Dependent Gain</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarization Mode Dispersion</td>
</tr>
<tr>
<td>RFL</td>
<td>Raman Fiber Laser</td>
</tr>
<tr>
<td>RIN</td>
<td>Relative Intensity Noise</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SLA</td>
<td>Super Large Area</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOP</td>
<td>State Of Polarization</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>SPS</td>
<td>Signal-Pump-Signal</td>
</tr>
<tr>
<td>SRS</td>
<td>Stimulated Raman Scattering</td>
</tr>
<tr>
<td>TDM</td>
<td>Time-division multiplexing</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
</tr>
</tbody>
</table>
Preface

The work Raman amplification is executed as part of the subject Optical Communications or Comunicações Opticas (COPT), taught by professor H. Salgado in the fifth year of the Integrated Master in Electrotechnic and Computer Engineering in the Faculty of Engineering of the University of Porto.

The main objective of this work is to provide an overview of an optical phenomenon or component which is not treated as subject matter in COPT. We chose Raman amplification since (i) even though it is a physical phenomenon, the realisation of it involves a high level of technology; (ii) it is beyond the scope of any course in our education; and (iii) it has a high number of engineering concepts due to the many factors that need to be considered when designing a Raman amplifier. Furthermore, it is the dissertation area of one of the authors.

This work consists of three chapters. Chapter 1 describes the basic theory behind Raman amplifiers. It starts with a very brief historical overview of research work in the area of Raman amplification, after which the fundamental phenomenon, stimulated Raman scattering (SRS), is explained. It introduces a set of two coupled pump and signal equations that govern power transfer from pump to signal leading to signal amplification. To provide physical insight, these equations are first solved approximately in an analytic form in the case in which a single pump laser provides Raman gain. The more realistic case of multiple pump lasers is then addressed to illustrate how such a scheme can provide gain over a wide signal bandwidth. Furthermore, several practical issues that must be addressed for Raman amplifiers are pointed out. More specifically, it considers the impact of spontaneous Raman scattering, double Rayleigh backscattering (DRBS), pump-noise transfer and polarization-mode dispersion (PMD).

In chapter 2 the performance of distributed amplifiers is considered. The benefits of this scheme are discussed including improved noise performance, upgradability of existing systems, amplification at any wavelength, broadband amplification and shaping of the gain curve. This is followed by a discussion of the challenges of Raman amplification, including double Rayleigh backscattering, nonlinear impairments resulting from amplification, pump-signal cross talk and signal-pump-signal cross talk. Finally advanced pumping schemes such as forward, bidirectional higher order pumping and low noise pumps are discussed.

Evenly important is the discussion of discrete amplifiers in chapter 3. Here, there is more flexibility in the choice of gain fiber as compared to distributed amplifiers. Therefore the Raman properties of fibers with different dopants are discussed. This is followed by several design issues affecting the performance of the amplifier including fiber length, pump-noise transfer, amplified spontaneous emission (ASE), nonlinear effects and double Rayleigh backscattering noise. Special attention is paid to dispersion compensating Raman amplifiers (DCRA), which provide both amplification and dispersion compensation simultaneously. The chapter closes with a discussion on wideband operation.
Chapter 1

Raman amplification

1.1 History

Research on Raman amplification in optical fibers started early in the 1970s. The benefits from Raman amplification in the transmission fiber were already being investigated in the mid-1980s. However, Raman gain requires more pump power, roughly tens of milliwatts per dB of gain, as compared to the tenths of a milliwatt per dB required by erbium-doped fiber amplifiers (EDFAs) for small signal powers. This disadvantage, combined with the scarcity of high power pumps at appropriate wavelengths, meant that Raman amplifier research subsided during the commercialization of EDFAs in the early 1990s.

Then, in the mid-1990s, the development of suitable highpower pumps sparked renewed interest (figure 1.1). Researchers were quick to demonstrate some of the advantages that Raman amplifiers have over EDFAs, particularly when the transmission fiber itself is turned into a Raman amplifier. This, in turn, fueled further advances in Raman pump technology. Figure 1.2 shows the exponential increase since 1994 in the capacity-distance product of transmission experiments reported at the postdeadline session of the Optical Fiber Communications (OFC) conference. The experiments are categorized by the length of the fiber spans (less than 80-km for submarine-type applications, and greater than or equal to 80-km for terrestrial-type). A number of technologies contributed to these advances:

- dispersion management,
- higher modulation rates,
- fiber engineering and
- advanced modulation formats

Demonstrations that used Raman amplification are circled. The first occurred in 1999, and now Raman amplification is an accepted technique for enhancing system performance.

1.2 Stimulated Raman scattering

Stimulated Raman scattering is the fundamental nonlinear process that turns optical fibers into broadband Raman amplifiers. Although Raman amplification in optical fibers was observed as early as 1972, until recently SRS was mainly viewed as a harmful nonlinear effect because it can also severely limit the performance of multichannel lightwave systems. Three important points are (i) SRS can occur in any fiber; (ii) because the pump photon is excited to a virtual level, Raman gain can occur at any signal wavelength by proper choice of the pump wavelength; and (iii) the Raman gain process is very fast (order of 10 ps).

Compared to a EDFA, the main advantages of Raman amplification are an improved noise figure and improved gain flatness. However, additional issues arise in Raman amplification that are not present in EDFA. These include double Rayleigh backscattering or multipath interference, pump-noise transfer and noise figure tilt.
Figure 1.1: Numbers of published papers (conferences and journals of the OSA and IEEE) and submitted U.S. patents each year since 1980 in the fields of EDFAs and Raman amplifiers.

Figure 1.2: Capacity-distance products of postdeadline transmission experiments OFC Conference since 1994. Experiments are categorized by the length of their fiber spans. Those using Raman amplification are circled.

1.3 Pump and signal equations

In any molecular medium, spontaneous Raman scattering can transfer a small fraction (typically $< 10^{-6}$) of power from one optical field to another field whose frequency is downshifted by an amount determined by the vibrational modes of the medium. This phenomenon was discovered by Raman in 1928 and is known as the Raman effect. As shown schematically in figure 1.3, it can be viewed quantum-mechanically as scattering of a photon of energy $h\omega_p$ by one of the molecules to a lower-frequency photon of energy $h\omega_s$. The energy difference is used by an optical phonon that is generated during the transition of the molecule from an excited vibrational state. This red-shifted radiation is called the Stokes-line. A blue-shifted component, known as the anti-Stokes line, is also generated but its intensity is much weaker than that of the Stokes line.

\[ \text{Note this is distinct from scattering caused by acoustic phonons, which is referred to as Brillouin scattering.} \]
because the anti-Stokes process requires the vibrational state to be initially populated with a phonon of right energy and momentum. In what follows, we ignore the anti-Stokes process as it plays virtually no role in fiber amplifiers.

Although spontaneous Raman scattering is weak enough that it can be ignored when an optical beam propagates through a fiber, for intense optical fields, the nonlinear phenomenon of SRS can occur in which the Stokes wave grows rapidly inside the medium such that most of the power of the pump is transferred to it. SRS was first observed in silica fibers in 1972.

### 1.3.1 Raman gain spectrum

The most important parameter characterizing Raman amplifiers is the Raman gain coefficient $g_r$. It describes how the Stokes power grows as pump power is transferred to it through SRS. On a more fundamental level, $g_r$ is related to the imaginary part of the third-order nonlinear susceptibility. In a simple approach, valid under the CW or quasi-CW conditions, the initial growth of a weak optical signal is governed by

$$\frac{dI_s}{dz} = \gamma_r(\Omega) I_p I_s$$  \hspace{1cm} (1.1)

where $\gamma_r(\Omega)$ is related to $g_r$, $\Omega \equiv \omega_p - \omega_s$ represents the Raman shift and $\omega_p$ and $\omega_s$ are the optical frequencies associated with the pump and signal fields having intensities $I_p$ and $I_s$, respectively.

Figure [1.4](#) shows the Raman gain coefficient for bulk silica as a function of the frequency shift $\Omega$ when the pump and signal are copolarized (solid curve) or orthogonally polarized (dotted curve). The peak gain is normalized to 1 in the copolarized case so that the same curves can be used for any pump wavelength $\lambda_p$. The peak value scales inversely with $\lambda_p$ and is about $6 \times 10^{-14}$ m/W for a pump near 1.5 µm.

The most significant feature of the Raman gain spectrum for silica fibers is that the gain exists over a large frequency range (up to 40 THz) with a broad peak located near 13.2 THz. This behaviour is due to the noncrystalline nature of silica glasses where molecular vibrational frequencies spread out into bands that overlap and create a continuum. Another important feature is the polarization dependence of the Raman gain. The gain nearly vanishes when pump and signal are orthogonally polarized.

In single-mode fibers, the spatial profile of both the pump and the signal beams is dictated by the fiber and does not change along the entire fiber length. For this reason, one often deals with the total optical power defined as

$$P_j(z) = \iint_{-\infty}^{\infty} I_j(x,y,z) \, dx \, dy$$ \hspace{1cm} (1.2)

where $j = p$ or $s$. Equation [1.1](#) can be written in terms of optical powers as

$$\frac{dP_s}{dz} = (\gamma_r/A_{eff}) P_p P_s \equiv g_r P_p P_s$$ \hspace{1cm} (1.3)

where the effective core area is defined as

$$A_{eff} = \frac{\iint_{-\infty}^{\infty} I_p(x,y,z) \, dx \, dy \, \iint_{-\infty}^{\infty} I_s(x,y,z) \, dx \, dy}{\iint_{-\infty}^{\infty} I_p(x,y,z) I_s(x,y,z) \, dx \, dy}$$ \hspace{1cm} (1.4)

This complicated expression simplifies considerably if we assume that the field-mode profile $F(x,y)$ is nearly the same for both the pump and the signal. In terms of this mode profile, $A_{eff}$ can be written as

$$A_{eff} = \left( \frac{\iint_{-\infty}^{\infty} |F(x,y,z)|^2 \, dx \, dy}{\iint_{-\infty}^{\infty} |F(x,y,z)|^4 \, dx \, dy} \right)^2$$ \hspace{1cm} (1.5)
Figure 1.3: Schematic illustration of the Raman-scattering process from a quantum-mechanical viewpoint. A stokes photon of reduced energy $\hbar \omega_s$ is created spontaneously when a pump photon of energy $\hbar \omega_p$ is lifted to a virtual state.

Figure 1.4: Raman gain spectrum for bulk silica measured when the pump and signal are copolarized (solid curve) or orthogonally polarized (dotted curve). The peak gain is normalized to 1 in the copolarized case.

If we further approximate the mode profile by a Gaussian function of the form $F(x, y, z) = \exp\left[-\left(x^2 + y^2\right)/w^2\right]$, where $w$ is the field-mode radius, and perform the integrations in equation 1.5, we obtain the simple result $A_{eff} \approx \pi \omega^2$. Since the field-mode radius $w$ is specified for any fiber, $A_{eff}$ is a known parameter. Figure 1.5 shows $g_r$ for a DCF, a nonzero dispersion fiber (NZDF) and a superlarge area (SLA) fiber with $A_{eff} = 15, 55$ and $105 \text{ } \mu \text{m}^2$, respectively. In all cases, the fiber was pumped at $1.45 \text{ } \mu \text{m}$ and provided gain near $1.55 \text{ } \mu \text{m}$.

The main point to note is that a DCF is nearly 10 times more efficient for Raman amplification. This is expected from its reduced effective core area, but is also due to a higher doping level of germania in DCFs ($\text{GeO}_2$ molecules exhibit a larger Raman gain peaking near $13.1 \text{ } \text{THz}$).

1.3.2 Single-pump Raman amplification

Consider the simplest situation in which a single CW pump beam is launched into an optical fiber used to amplify a CW signal. Equation 1.3 is modified to include fiber losses and the fact that the pump power does not remain constant along the fiber. When these effects are included,
the Raman amplification process is governed by the following set of two coupled equations

\[
\frac{dP_s}{dz} = g_r P_p P_s - \alpha_s P_s \quad (1.6)
\]

\[
\xi \frac{dP_p}{dz} = \frac{\omega_p}{\omega_s} g_r P_p P_s - \alpha_p P_p \quad (1.7)
\]

where \( \alpha_s \) and \( \alpha_p \) account for fiber losses at the Stokes and pump wavelengths, respectively. The parameter \( \xi \) takes values \( \pm 1 \) depending on the pumping configuration. The minus sign should be used in the backward-pumping case.

The frequency ratio \( \omega_p/\omega_s \) appears in equation (1.7) because the pump and signal photons have different energies. One can readily verify that, in the absence of losses,

\[
\frac{d}{dz} \left( \frac{P_s}{\omega_s} + \xi \frac{P_p}{\omega_p} \right) = 0 \quad (1.8)
\]

Noting that \( P_j/\omega_j \) is related to photon flux at the frequency \( \omega_j \), this equation merely represents the conservation of total number of photons during the SRS process.

Equations (1.6) and (1.7) are not easy to solve analytically because of their nonlinear nature. In many practical situations, pump power is so large compared with the signal power that pump depletion can be neglected by setting \( g_r = 0 \) in equation (1.7) which is then easily solved. As an example, \( P_p(z) = P_0 \exp(-\alpha_p z) \) in the forward-pumping case (\( \xi = 1 \)), where \( P_0 \equiv P_p(0) \), the input pump power at \( z = 0 \). If we substitute this solution in equation (1.6), we obtain

\[
P_s(L) = P_s(0) \exp(g_r P_0 L_{\text{eff}} - \alpha_s L) = G(L) P_s(0) \quad (1.9)
\]

where \( G(L) \) is the net signal gain, \( L \) is the amplifier length and \( L_{\text{eff}} \) is an effective length defined as

\[
L_{\text{eff}} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \quad (1.10)
\]

The solution (1.9) shows that, because of pump absorption, the effective amplification length is reduced from \( L \) to \( L_{\text{eff}} \).

The backward-pumping case can be considered in a similar fashion. In this case equation (1.7) should be solved with \( g_r = 0 \) and \( \xi = -1 \) using the boundary condition \( P_p(L) = P_0 \). The result is \( P_p(z) = P_0 \exp[-\alpha_p (L - z)] \). The integration of equation (1.6) yields the same solution given in equation (1.9) indicating that the amplified signal power at a given pumping level is the same in both the forward- and the backward-pumping case.
The case of bidirectional pumping is slightly more complicated because two pump lasers are located at the opposite fiber ends. The pump power in equation 1.6 now represents the sum

\[ P_p = P_f + P_b \]

where \( P_f \) and \( P_b \) are obtained by solving (still ignoring pump depletion)

\[ \frac{dP_f}{dz} = -\alpha_p P_f \]  (1.11)

\[ \frac{dP_b}{dz} = -\alpha_p P_b \]  (1.12)

Solving these equations, we obtain total pump power \( P_p(z) \) at a distance \( z \) in the form

\[ P_p(z) = P_0 \left\{ r_f \exp \left( -\alpha_p z \right) + (1 - r_f) \exp \left[ -\alpha_p (L - z) \right] \right\} \]  (1.13)

where \( P_0 \) is the total pump power and \( r_f = P_L/P_R \) is the fraction of pump power launched in the forward direction. The integration of equation 1.6 yields the signal gain

\[ G(z) = \frac{P_s(z)}{P_s(0)} = \exp \left( g_r \int_0^z P_p(z) \, dz - \alpha_s z \right) \]  (1.14)

Figure 1.6 shows how the signal power changes along a 100 km long distributed Raman amplifier as \( r_f \) is varied from 0 to 1. In all cases the total pump power is chosen such that the Raman gain is just sufficient to compensate for fiber losses, that is, \( G(L) = 1 \).

One may ask which pumping configuration is the best from the system standpoint. The answer is not so simple and depends on many factors. This will be discussed in detail once we know more about system impairments, though we can already point out the following. The forward pumping is superior from the noise viewpoint. However, for a long-haul system limited by fiber nonlinearities, backward pumping may offer better performance because the signal power is the smallest throughout the link length in this case.

The total accumulated nonlinear phase shift induced by self-phase modulation (SPM) can be obtained from

\[ \phi_{nl} = \gamma \int_0^L P_s(z) \, dz \]

\[ = \gamma P_s(0) \int_0^L G(z) \, dz \]  (1.15)

where \( \gamma = 2\pi n_2 / (\lambda_s A_{eff}) \) is the nonlinear parameter responsible for SPM. The increase in the nonlinear phase shift occurring because of Raman amplification can be quantified through the ratio

\[ R_{nl} = \frac{\phi_{nl \text{ with pump on}}}{\phi_{nl \text{ with pump off}}} \]

\[ = L_{eff}^{-1} \int_0^L G(z) \, dz \]  (1.16)

Figure 1.7 shows how this ratio changes as a function of the net gain \( G(L) \) for a 100 km long distributed Raman amplifier for different combinations of forward an backward pumping. Clearly, the nonlinear effects are the least in the case of backward pumping and become enhanced by more than 10 dB when forward pumping is used.

It is useful to introduce the concept of on-off Raman gain using the definition

\[ G_A = \frac{P_s(L) \text{ with pump on}}{P_s(L) \text{ with pump off}} \]

\[ = \exp (g_r P_0 L_{eff}) \]  (1.17)

Clearly, \( G_A \) represents the total amplifier gain distributed over a length \( L_{eff} \). If we use a typical value of \( g_r = 3W^{-1}/km \) for a DCF from figure 1.5 together with \( L_{eff} = 1 \) km, the signal can be
amplified by 20 dB for $P_0 \approx 1.5$ W. Figure 1.8 shows an experiment of the variation of $G_A$ with $P_0$ observed in which a 1.3 km long fiber was used to amplify the 1.064 µm signal by using a 1.017 µm pump. The amplification factor increases exponentially with $P_0$ initially, as predicted by equation (1.17) but starts to deviate for $P_0 > 1$ W. This is due to gain saturation occurring because of pump depletion. The solid lines in figure 1.8 are obtained by solving equations (1.6) and (1.7) numerically to include pump depletion. The numerical results are in excellent agreement with the data and serve to validate the use of equations (1.6) and (1.7) for modeling Raman amplifiers.

An approximate expression for the saturated gain $G_s$ in Raman amplifiers can be obtained by solving equations (1.6) and (1.7) analytically with the assumption $\alpha_s = \alpha_p \equiv \alpha$. This approximation is not always valid but can be justified for optical fibers in the 1, 55 µm region. We assume forward pumping ($\xi = 1$), but omit the calculations and advance immediately to the result, that is

$$G_s = \frac{(1 + r_0) G_A^{1 + r_0}}{1 + r_0 G_A^{1 + r_0}}$$  \hspace{0.5cm} (1.18)

where $r_0$ is related to the signal-to-pump power ratio at the fiber input as

$$r_0 = \frac{\omega_s P_s(0)}{\omega_p P_p(0)}$$  \hspace{0.5cm} (1.19)
and $G_A$ is the on-off Raman gain introduced in equation 1.17. Typically, $P_s(0) \ll P_p(0)$. For example $r_0 < 10^{-3}$ when $P_s(0) < 1$ mW while $P_p(0) \approx 1$ W. Under such conditions, the saturated gain of the amplifier can be approximated as

$$G_s = \frac{G_A}{1 + r_0 G_A}$$

(1.20)

The gain is reduced by a factor of 2 or 3 $dB$ when the Raman gain amplifier is pumped hard enough that $r_0 G_A = 1$. This can happen for $r_0 = 10^{-3}$ when the on-off Raman gain approaches $30 \, dB$. This is precisely what we observe in figure 1.8.

Figure 1.9 shows the saturation characteristics by plotting $G_s/G_A$ as a function of $G_A r_0$ for several values of $G_A$. The saturated gain is reduced by a factor of two when $G_A r_0 \approx 1$. This condition is satisfied when the power in the amplified signal starts to approach the input pump power $P_0$. In fact, $P_0$ is a good measure of the saturation power of Raman amplifiers.

1.3.3 Multiple-pump Raman amplification

Starting in 1998, the use of multiple pumps for Raman amplification was pursued for developing broadband optical amplifiers required for wavelength-division multiplexing (WDM) lightwave systems operating in the 1,55 $\mu m$ region. Massive WDM systems (80 or more channels) typically require optical amplifiers capable of providing uniform gain over a 70 to 80 $nm$ wavelength range.

Multiple-pump Raman amplifiers make use of the fact that the Raman gain exists at any wavelength as long as the pump wavelength is suitably chosen. Thus, even though the gain spectrum of a single pump is not very wide and is flat over a few nanometers (see figure 1.4), it can be broadened and flattened considerably by using several pumps of different wavelengths. Superposition of several such spectra can produce relatively constant gain over a wide spectral region when pump wavelengths and power levels are chosen judiciously. Figure 1.10 shows a numerical example when six pump lasers operating at wavelengths in the range of 1420-1500 $nm$ are employed.

The individual pump powers (vertical bars) are chosen to provide individual gain spectra (dashed curves) such that the total Raman gain of 18 $dB$ is nearly flat over a 80 $nm$ bandwidth.

![Figure 1.8: Variation of amplifier gain $G_A$ with pump power $P_0$. Different symbols show the experimental data for three values of input signal power. Solid curves show the theoretical prediction.](image-url)
Figure 1.9: Gain-saturation characteristics of Raman amplifiers for several values of the unsaturated amplifier gain $G_A$.

Figure 1.10: Numerically simulated composite Raman gain (solid trace) of a Raman amplifier pumped with six lasers with different wavelengths and input powers (vertical bars). Dashed curves show the Raman gain provided by individual pumps.

(solid trace). Pump powers range from 40 to 200 mW. The choice of pump power and wavelength is far from easy and requires a thorough understanding of several system impairments. That is why we will address this item later.

Broadband Raman amplifiers are designed using a numerical model that includes pump-pump interactions, Rayleigh backscattering and spontaneous Raman scattering (these factors will be discussed later on). Such a model considers each frequency component separately and requires the solution of a large set of coupled equations of the form

$$\frac{dP_f(\nu)}{dz} = \int_{\mu>\nu} g_r(\mu, \nu) [P_f(\mu) + P_b(\mu)] \times [P_f(\nu) + 2h \nu n_{sp}(\mu - \nu)] d\mu$$

$$- \int_{\mu>\nu} g_r(\mu, \nu) [P_f(\mu) + P_b(\mu)] \times [P_f(\nu) + 4h \nu n_{sp}(\nu - \mu)] d\mu$$

$$- \alpha(\nu) P_f(\nu) + f_r \alpha_r P_b(\nu)$$

(1.21)
where $\mu$ and $\nu$ denote optical frequencies and the subscripts $f$ and $b$ denote forward- and backward-propagating waves, respectively. The parameter $n_{\text{sp}}$ is defined as

$$n_{\text{sp}} (\Omega) = \left[ 1 - \exp \left(-\frac{\hbar \Omega}{k_BT}\right) \right]^{-1} \quad (1.22)$$

where $\Omega = |\mu - \nu|$ is the Raman shift and $T$ denotes absolute temperature of the amplifier. In equation 1.21 the first and second terms account for the Raman-induced power transfer into and out of each frequency band. The factor of 2 in the first term accounts for the two polarization modes of the fiber. An additional factor 2 in the second term includes spontaneous emission in both the forward and the backward directions. Fiber losses and Rayleigh backscattering are included through the last two terms and are governed by the parameters $\alpha$ and $\alpha_r$, respectively. $f_r$ represents the fraction of backscattered power that is recaptured by the fiber mode. A similar equation holds for the backward-propagating waves.

1.4 Performance limiting factors

The performance of modern Raman amplifiers is affected by several factors that need to be controlled. We focus on spontaneous Raman scattering, double Rayleigh backscattering and pump-noise transfer. We also consider briefly the impact of polarization mode dispersion on the performance of a Raman amplifier.

1.4.1 Spontaneous Raman scattering

Spontaneous Raman scattering adds to the amplified signal and appears as a noise because of random phases associated with all spontaneously generated photons. It depends on the phonon population in the vibrational state, which in turn depends on the temperature of the Raman amplifier. If we neglect pump depletion, it is sufficient to replace equation 1.6 with

$$\frac{dA_s}{dz} = \frac{g_r}{2} P_p (z) A_s - \frac{\alpha_s}{2} A_s + f_n (z, t) \quad (1.23)$$

where $A_s$ is the signal field defined such that $P_s = |A_s|^2$, $P_p$ is the pump power and the Langevin noise source $f_n (z, t)$ takes into account the noise added through spontaneous Raman scattering. Since each scattering event is independent of others, this noise can be modeled as a Markovian stochastic process with Gaussian statistics such that $\langle f_n (z, t) \rangle = 0$ and its second moment is given by

$$\langle f_n (z, t) f_n (z', t') \rangle = n_{\text{sp}} h \nu_0 g_r P_p (z) \delta (z - z') \delta (t - t') \quad (1.24)$$

where $n_{\text{sp}}$ is the spontaneous-scattering factor introduced earlier and $h \nu_0$ is the average photon energy. The two delta functions ensure that all spontaneous events are independent of each other.

Equation 1.23 can easily be integrated to obtain

$$A_s (L) = \sqrt{G (L)} A_s (0) + a_{\text{ASE}} (t) \quad (1.25)$$

where $G (L)$ is the amplification factor defined earlier in equation 1.9 and the total accumulated noise from spontaneous Raman scattering is given by

$$a_{\text{ASE}} (t) = \sqrt{G (L)} \int_0^L f_n (z, t) \sqrt{G (z)} \quad (1.26)$$

with

$$G (z) = \exp \left( \int_0^z [g_r P_p (z') - \alpha_s] \, dz' \right) \quad (1.27)$$
This noise is often referred to as amplified spontaneous emission because of its amplification by the distributed Raman gain. It is easy to show that it vanishes on average ($\langle a_{\text{ASE}}(t) \rangle = 0$) and its second moment is given by

$$\langle a_{\text{ASE}}(t) a_{\text{ASE}}(t') \rangle = G(L) \int_0^L dz \int_0^L \frac{(f_n(z,t) f_n(z',t'))}{\sqrt{G(z) G(z')}} dz' = S_{\text{ASE}} \delta(t-t')$$  \hspace{1cm} (1.28)

where

$$S_{\text{ASE}} = n_{sp} h \nu_0 g_r G(L) \int_0^L \frac{P_p(z)}{G(z)} dz$$  \hspace{1cm} (1.29)

The presence of the delta function in equation 1.28 is due to the Markovian assumption implying that $S_{\text{ASE}}$ is constant and exists at all frequencies (white noise). In practice, the noise exists only over the amplifier bandwidth and can be further reduced by placing an optical filter at the amplifier output. Assuming this to be the case, we can calculate the total ASE power after the amplifier using

$$P_{\text{ASE}} = 2 \int_{-\infty}^{\infty} S_{\text{ASE}} H_f(\nu) d\nu = 2 S_{\text{ASE}} B_{\text{opt}}$$  \hspace{1cm} (1.30)

where $B_{\text{opt}}$ is the bandwidth of the optical filter. The factor of 2 in this equation accounts for the polarization modes of the fiber. Indeed, ASE can be reduced by 50% if a polarizer is placed after the amplifier. Assuming that a polarizer is not used, the optical signal-to-noise ratio (SNR) of the amplified signal is given by

$$\text{SNR}_o = \frac{P_s(L)}{P_{\text{ASE}}} = \frac{G(L) P_{\text{in}}}{P_{\text{ASE}}}$$  \hspace{1cm} (1.31)

It is evident from equation 1.29 that both $P_{\text{ASE}}$ and $\text{SNR}_o$ depend on the pumping scheme through pump-power variations $P_p(z)$ occurring inside the Raman amplifier. As an example, figure 1.11 shows how the spontaneous power per unit bandwidth $P_{\text{ASE}}/B_{\text{opt}}$ and the optical SNR vary with the net gain $G(L)$ for several different pumping schemes assuming that a 1 mW input signal is amplified by a 100 km long, bidirectionally pumped, distributed Raman amplifier. The fraction of forward pumping varies from 0 to 100%. The other parameters were chosen to be $\alpha_s = 0.21 \text{ dB/km}$, $\alpha_p = 0.26 \text{ dB/km}$, $n_{sp} = 1.13$, $h\nu_0 = 0.8 \text{ eV}$ and $g_r = 0.68 \text{ W}^{-1}/\text{km}$.

The optical SNR is the highest in the case of purely forward pumping (about 54 dB or so) but degrades by as much as 15 dB as the fraction of backward pumping is increased from 0 to 100%. This can be understood by noting that the spontaneous noise generated near the input end experiences losses over the full length of the fiber in the case of forward pumping, whereas it experiences only a fraction of such losses in the case of backward pumping. Mathematically, $G(z)$ in the denominator in equation 1.29 is larger in the forward pumping case, resulting in reduces $S_{\text{ASE}}$.

The preceding discussion shows that spontaneous Raman scattering degrades the SNR of the signal amplified by a Raman amplifier. The extent of SNR degradation is generally quantified through the amplifier noise figure $F_n$ defined as

$$F_n = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}}$$  \hspace{1cm} (1.32)

In this equation, SNR is not the optical SNR but refers to the electric power generated when the optical signal is converted into an electric current. In general, $F_n$ depends on several detector
Figure 1.11: (a) Spontaneous spectral density and (b) optical SNR as a function of net gain $G(L)$ at the output of a 100 km long, bidirectionally pumped, distributed Raman amplifier assuming $P_{in} = 1 \text{ mW}$.

parameters that include, but are not limited to, shot noise, signal-ASE and ASE-ASE beating. Without going into much detail, the noise figure becomes

$$F_n = 2n_{sp}g_r \int_0^L \frac{P_p(z)}{G(z)} dz + \frac{1}{G(L)}$$

(1.33)

This equation shows that the noise figure of a Raman amplifier depends on the pumping scheme.

It provides reasonably small noise figures for “lumped” Raman amplifiers for which fiber length is $\approx 1 \text{ km}$ and the net signal gain exceeds 10 $\text{ dB}$. When the fiber within the transmission link itself is used for distributed amplification, the length of the fiber section typically exceeds 50 km and pumping is such that net gain $G(z) < 1$ throughout the fiber length. In this case, $F_n$ predicted by equation (1.33) can be very large and exceed 15 $\text{ dB}$ depending on the span length. This does not mean distributed amplifiers are noisier than lumped amplifiers. To understand this apparent contradiction, consider a 100 km long fiber span with a loss of 0.2 $\text{ dB/km}$. The 20 $\text{ dB}$ span loss is compensated using a hybrid scheme in which a lumped amplifier with 5 $\text{ dB}$ noise figure is combined with the Raman amplification through backward pumping. The on-off gain $G_A$ of the Raman amplifier can be varied in the range 0-20 $\text{ dB}$ by adjusting the pump power. Clearly $G_A = 0$ and 20 $\text{ dB}$ correspond to the cases of pure lumped and distributed amplifications, respectively.

The solid line in figure 1.12 shows how the noise figure of such a hybrid amplifier changes as $G_A$ is varied from 0 to 20 $\text{ dB}$. When $G_A = 0$, equation (1.33) shows that the passive fiber has a noise figure of 20 $\text{ dB}$. This is not surprising since any fiber loss reduces signal power and thus degrades the SNR. When the signal is amplified by the lumped amplifier, and additional 5 $\text{ dB}$ degradation occurs, resulting in a total noise figure of 25 $\text{ dB}$. This value decreases as $G_A$ increases, reaching a level of about 17.5 $\text{ dB}$ for $G_A = 20 \text{ dB}$ (no lumped amplification). The dashed line shows the noise figure of the Raman-pumped fiber span alone as predicted by equation (1.33). The total noise figure is higher because the lumped amplifier adds some noise if span losses are only partially compensated by the Raman amplifier. The important point is that total noise figure drops below the 20 $\text{ dB}$ level (dotted line) when the Raman gain exceeds a certain value.

To emphasize the noise advantage of distributed amplifiers, it is common to introduce the concept of an effective noise figure using the definition

$$F_{eff} = F_o \exp (-\alpha L)$$

(1.34)
where $\alpha$ is the fiber-loss parameter at the signal wavelength. In decibel units, $F_{\text{eff}} = F_n - \zeta$, where $\zeta$ is the span loss in dB. The effective noise figure is simply the noise figure that one would require from a discrete amplifier placed after a passive fiber of the same length as the Raman amplifier assuming that the Raman amplifier and the imaginary transmission span should perform equally well. As seen from figure 1.12, $F_{\text{eff}} < 1$ (or negative on the decibel scale) by definition. It is this feature of distributed amplification that makes it so attractive for long-haul WDM lightwave systems. For the example shown in figure 1.12, $F_{\text{eff}} \approx -2.5 \, \text{dB}$ when pure distributed amplification is employed. Note, however, the noise advantage is almost 7.5 dB when the noise figures are compared for lumped and distributed amplification schemes.

As seen from equation 1.33, the noise figure of a Raman amplifier depends on the pumping scheme used because $P_p(z)$ can be quite different for forward, backward and bidirectional pumping. In general, forward pumping provides the highest SNR and the smallest noise figure, because most of the Raman gain is then concentrated toward the input end of the fiber where power levels are high. However, backward pumping is often employed in practice because of other considerations such as the transfer of pump noise to signal.

1.4.2 Rayleigh backscattering

The phenomenon that limits the performance of distributed Raman amplifiers most turned out to be Rayleigh backscattering. Rayleigh backscattering occurs in all fibers and is the fundamental loss mechanism for them. Although most of the scattered light escapes through the cladding, a part of backscattered light can couple into the core mode supported by a single-mode fiber. Normally, this backward-propagating noise is negligible because its power level is smaller by more than 40 dB compared with the forward-propagating signal power. However, it can be amplified over long lengths in fibers with distributed Raman gain.

Rayleigh backscattering effects the performance of Raman amplifiers in two ways. First, a part of backward-propagating ASE can appear in the forward direction, enhancing overall noise. This noise is relatively small and is not of much concern for Raman amplifiers. Second, double Rayleigh backscattering of the signal creates a cross-talk component in the forward direction that has nearly the same spectral range as the signal (in-band cross talk). It is this Rayleigh-induced noise, amplified by the distributed Raman gain, that becomes the major source of power penalty in Raman-amplified lightwave systems. Figure 1.13 shows schematically the phenomenon of double Rayleigh backscattering of the signal. Density fluctuations at the location $z_2$ inside the transmission fiber reflect a small portion of the signal through Rayleigh backscattering. This backward-propagating field is reflected a second time by density fluctuations at the location $z_1$. 

![Figure 1.12: Total noise figure as a function of the on-off gain of a Raman amplifier when a 20 dB loss of a 100 km long fiber span is compensated using a hybrid amplification scheme. Dashed line shows the noise figure of Raman-pumped fiber alone. Dotted line shows 20 dB span loss.](image-url)
and thus ends up propagating in the same direction as the signal. Of course, \( z_1 \) and \( z_2 \) can vary over the entire length of the fiber and the total noise is obtained by summing over all possible paths. For this reason, the Rayleigh noise is also referred to as originating from multiple-path interference.

The calculation of the noise produced by double Rayleigh backscattering is somewhat complicated because it should include not only the statistical nature of density fluctuations but also any depolarizing effects induced by birefringence fluctuations. Without going into much detail and when we ignore the depolarizing effects, we obtain the following expression for the fraction of input power that ends up coming out with the signal at the output end caused by double Rayleigh backscattering

\[
f_{DRS} = \frac{P_{DRS}(L)}{P_s(L)} = (f_r \alpha_r)^2 \int_0^L G^{-2}(z) \, dz \int_z^L G^2(z') \, dz'
\]

where \( \alpha_r \) is the Rayleigh scattering loss and \( f_r \) is the fraction that is recaptured by the fiber mode. Figure 1.14 shows how \( f_{DRS} \) increases with on-off Raman gain \( G_A \) using \( f_r \alpha_r = 10^{-4} \), \( g_r = 0.7 \, W^{-1}/km \), \( \alpha_s = 0.2 \, dB/km \), \( \alpha_p = 0.25 \, dB/km \) and backward pumping for a 100 km long Raman amplifier. The crosstalk begins to exceed the \(-35 \, dB \) level for the 20 \, dB Raman gain needed for compensating fiber losses. Since this crosstalk accumulates over multiple amplifiers, it can lead to large power penalties in long-haul lightwave systems.

### 1.4.3 Pump-noise transfer

All lasers exhibit some intensity fluctuations. The situation is worse for semiconductor lasers used for pumping a Raman amplifier because the level of power fluctuations in such lasers can be relatively high owing to their relatively small size and a large rate of spontaneous emission. As seen from equation 1.14, the gain of a Raman amplifier depends on the pump power exponentially. It is intuitively expected from this equations that any fluctuation in the pump power would be magnified and result in even larger fluctuations in the amplified signal power. This is indeed the case and this source of noise is known as pump-noise transfer. Details of the noise transfer depend on many factors including amplifier length, pumping scheme and the dispersion characteristics of the fiber used for making the Raman amplifier.

Power fluctuations of a semiconductor laser are quantified through a frequency-dependent quantity called the relative intensity noise (RIN). It represents the spectrum of intensity or power fluctuations and is defined as

\[
\frac{\sigma_p^2}{(P_0)^2} = \int_0^\infty RIN_p(f) \, df
\]

where \( \sigma_p^2 \) is the variance of pump-power fluctuations and \( \langle P_0 \rangle \) is the average pump power. When pump power is included, the amplified signal also exhibits fluctuations and one can introduce the RIN of the amplified signal as

\[
\frac{\sigma_s^2}{(P_s(L))^2} = \int_0^\infty RIN_s(f) \, df
\]

The pump-noise transfer function represents the enhancement in the signal noise at a specific frequency \( f \) and is defined as

\[
H(f) = RIN_s(f) / RIN_p(f)
\]

To calculate the noise transfer function \( H(f) \), one must include the fact that the pump and the signal have different wavelengths and thus do not travel along the fiber at the same speed due to dispersion. For this reason, the pump-noise transfer process depends on the pumping scheme,
the amplifier length and the dispersion parameter $D$ of the fiber used to make the amplifier. Mathematically, equations 1.6 and 1.7 are modified to include an additional term and take the form

$$\frac{\partial P_s}{\partial z} + \frac{1}{\nu_{gs}} \frac{\partial P_s}{\partial t} = g_r P_p P_s - \alpha_s P_s \quad (1.39)$$

$$\xi \frac{\partial P_p}{\partial z} + \frac{1}{\nu_{gp}} \frac{\partial P_p}{\partial t} = -\frac{\omega_p}{\omega_s} g_r P_p P_s - \alpha_p P_p \quad (1.40)$$

where $\nu_{gs}$ and $\nu_{gp}$ are the group velocities for the signal and pump, respectively. These equations can be solved with reasonable approximations to calculate the noise transfer function $H(f)$.

Figure 1.15 compares the calculated frequency dependence of $H(f)$ in the forward- and backward-pumping configurations for two types of Raman amplifiers pumped at 1450 nm to provide gain near 1550 nm. Solid curves are for a discrete Raman amplifier made with a 5 km long DCF with $\alpha_p = 0.5 \, dB/km$ and a dispersion of $D = -100 \, ps/(km \, nm)$ at 1.55 $\mu m$. Dashed curves are for a distributed Raman amplifier made with a 100 km long NZDF with $\alpha_p = 0.25 \, dB/km$ and a dispersion of 4.5 $ps/(km \, nm)$ at 1.55 $\mu m$. The on-off Raman gain is 10 $dB$ in all cases.

In the case of forward pumping, RIN is enhanced by a factor of nearly 6 in the frequency range of 0-5 $MHz$ for the DCF and the frequency range increases to 50 $MHz$ for the NZDF because of its relatively low value of $D$. However, when backward pumping is used, RIN is actually reduced at all frequencies except for frequencies below a few kilohertz. Notice that $H(f)$ exhibits an
oscillatory structure in the case of a DCF. This feature is related to a relatively short length of discrete amplifiers.

In general, the noise enhancement is relatively small in the backward-pumping configuration and for large values of D. This behaviour can be understood physically as follows. The distributed Raman gain builds up as the signal propagates inside the fiber. In the case of forward pumping and low dispersion, pump and signal travel at nearly the same speed. As a result, any fluctuation in the pump power stays in the same temporal window of the signal. In contrast, when dispersion is large, the signal moves out of the temporal window associated with the fluctuation and sees a somewhat averaged gain. The averaging is much stronger in the case of backward pumping because the relative speed is extremely large (twice that of the group velocity). In this configuration, the effects of pump-power fluctuations are smoothed out so much that almost no RIN enhancement occurs. For this reason, backward pumping is often used in practice even though the noise figure is larger for this configuration. Forward pumping can only be used if fiber dispersion is relatively large and pump lasers with low RIN are employed.

1.4.4 Polarization mode dispersion

In the scalar approach used so far, it has been implicitly assumed that both pump and signal are copolarized and maintain their state of polarization (SOP) inside the fiber. However, unless some kind of polarization-maintaining fiber is used for making Raman amplifiers, residual fluctuating birefringence of most fibers changes the SOP of any optical field in a random fashion and also leads to PMD. It turns out that the amplified signal fluctuates over a wide range if PMD changes with time and the average gain is significantly lower than that expected in the absence of PMD.

Vector theory of Raman amplification

After extensive calculations based on the third-order nonlinear polarization and with the assumptions of neglecting pump depletion and the signal-induced cross-phase modulation (XPM) because the pump power is much larger than the signal power in practice, we can derive the following vector equation capable of including the PMD (SPM and XPM) effects.

\[ \frac{ds}{dz} = \frac{g_r}{2} (1 + \mu/3) P_p(z) s_0 \hat{p} - \Omega_r b \times s \]  

(1.41)

where \( s \) is derived with a specific transformation from the signal expression in the Stokes space and \( s_0 = |s| \) is the magnitude of vector \( s \), \( \hat{p} \) is the input SOP of the pump and \( b \) is related to \( \beta \).
after two rotations (one on the Poincaré sphere and one deterministic), where the birefringence vector $\beta$ includes the PMD effects. Furthermore, the Raman gain $g_r$ and the parameter $\mu$ are defined as

$$g_r = \frac{\omega_p^2 \omega_s \text{Im} [\tilde{a}(\Omega)]}{c^2 k_s k_p A_{\text{eff}}}$$  \hspace{1cm} (1.42)

$$\mu = \frac{\text{Im} [\tilde{b}(\Omega)]}{\text{Im} [\tilde{a}(\Omega)]}$$  \hspace{1cm} (1.43)

and $\Omega_r$ is the Raman shift. $\omega_s$ and $\omega_p$ are the signal and pump frequencies, respectively, while $k_s$ and $k_p$ are its propagation constants, $c$ is the speed of light and $A_{\text{eff}}$ is the effective area as defined in equation 1.4. $\tilde{a}(\omega)$ and $\tilde{b}(\omega)$ are the Fourier transforms of the Raman response functions (related to nuclear motion) $a(t)$ and $b(t)$, respectively. Physically $\mu$ represents the ratio of the Raman gain for copolarized and orthogonally polarized pumps, respectively. Equation 1.41 applies for both the forward and the backward pumping schemes, but the $z$ dependence of $P_p(z)$ and the magnitude of $\Omega$ depend on the pumping configuration. More specifically, $\Omega = \omega_p - \omega_s$ in the case of forward pumping but it is replaced with $\Omega = - (\omega_p + \omega_s)$ in the case of backward pumping. In the absence of birefringence ($b = 0$), $s$ remains oriented along $\pm \hat{p}$ and we recover the scalar case.

**Average Raman gain and signal fluctuations**

Equation 1.41 can be used to calculate the power $P_s$ of the amplified signal as well as its SOP at any distance within the amplifier. In the presence of PMD, $b(z)$ fluctuates with time. As a result, the amplified signal $P_s(L)$ at the output of the amplifier also fluctuations. Such fluctuations would affect the performance of any Raman amplifier. We focus on the forward-pumping case for definiteness.

The average value of the signal gain $G_{av}$ and the variance of signal power fluctuations $\sigma^2_s$ are defined as

$$G_{av} = \frac{\langle P_s(L) \rangle}{P_s(0)}$$  \hspace{1cm} (1.44)

$$\sigma^2_s = \frac{\langle P^2_s(L) \rangle}{\langle P_s(L) \rangle^2} - 1$$  \hspace{1cm} (1.45)

It is also useful to introduce the diffusion length $L_d$, defined as

$$L_d = \frac{3}{D_p \Omega^2}$$  \hspace{1cm} (1.46)

The diffusion length is a measure of the distance after which the SOPs of the two optical fields, separated in frequency by $\Omega$, become decorrelated. $D_p$ is the PMD parameter of the fiber.

When PMD effects are large and $L_d \ll L$, the average gain is given by

$$G_{av} = \exp \left[ \frac{1}{2} (1 + 3\mu) g_r P_{in} L_{\text{eff}} - \alpha_s L \right]$$  \hspace{1cm} (1.47)

Compared to the scalar case in section 1.3, PMD reduces the Raman gain coefficient by a factor of $(1 + 3\mu)/2$, exactly the average Raman gain coefficients in the copolarized and orthogonally polarized cases. Since $\mu \ll 1$, $g_r$ is reduced by about a factor of 2. It should however be stressed that the on-off Raman gain $G_A$ is reduced by a large factor when $g_r$ is halved because of the exponential relation between the two.

If we introduce an angle $\theta$ as the relative angle between the pump-signal SOPs with the definition $s_0 \cos (\theta) = s \cdot \hat{p}$, we can conclude that signal fluctuations have their origin in fluctuations of the angle $\theta$ between these vectors associated with the pump and signal. We will not go into further detail.
To illustrate the impact of PMD on the performance of Raman amplifiers, we focus on a 10 km long Raman amplifier pumped with 1 W of power using a single 1.45 μm laser. The Raman gain coefficient $g_r = 0.6 \text{ W}^{-1}/\text{km}$ while $\mu = 0.012$ near the signal wavelength 1.55 μm. Fiber losses are taken to be 0.273 dB/km and 0.2 dB/km at the pump and signal wavelengths, respectively. Figure 1.16 shows how $G_{av}$ and $\sigma_s$ change with the PMD parameter $D_p$ when the input signal is copolarized (solid curves) or orthogonally polarized (dashed curves) with respect to the pump. The curves are shown for both the forward- and backward-pumping schemes. When $D_p$ is zero, the two beams maintain their SOP and the copolarized signal experiences a maximum gain of 17.6 dB while the orthogonally polarized signal has 1.7 dB loss, irrespective of the pumping configuration. The loss is not exactly 2 dB because a small signal gain exists for the orthogonally polarized input signal. As the PMD parameter increases, the gain difference between the copolarized and the orthogonally polarized cases decreases and disappears eventually.

The level of signal fluctuations in figure 1.16 increases quickly with the PMD parameter, reaches a peak and then decreases slowly to zero with further increase in $D_p$. The location of the peak depends on the pumping scheme as well as on the initial polarization of pump. The noise level can exceed 20 % for $D_p = 0.05 \text{ ps}/\sqrt{\text{km}}$ in the case of forward pumping. If a fiber with low PMD is used, the noise level can exceed 70 % under some conditions. These result suggest that forward-pumped Raman amplifiers will perform better if a fiber with $D_p > 0.1 \text{ ps}/\sqrt{\text{km}}$ is used. The curves for backward pumping are similar to those for forward pumping but shift to smaller $D_p$ values and have a higher peak. In spite of an enhanced peak, the backward pumping produces the smallest amount of fluctuations for all fibers for which $D_p > 0.01 \text{ ps}/\sqrt{\text{km}}$. Note that the curves in the case of backward pumping are nearly identical to those for forward pumping except that they are shifted to the left. As a result, the solid and dashed curves merge at a value of $D_p$ that is smaller by about a factor of 30. This difference is related to the definition of $\Omega$ in equation 1.41. In the case of backward pumping, $\Omega = \omega_p + \omega_s$ is about 30 times larger than the value of $\Omega = \omega_p - \omega_s$ in the forward pumping case.

In practice, fibers used to make a Raman amplifier have a constant value of $D_p$. Figure 1.17 shows $G_{av}$ and $\sigma_s$ as a function of amplifier length for a fiber with $D_p = 0.05 \text{ ps}/\sqrt{\text{km}}$. All other parameters are the same as in figure 1.16. The solid and dashed lines correspond to copolarized and orthogonally polarized cases, respectively (the two lines are indistinguishable in the case of backward pumping). Physically, it takes some distance for the orthogonally polarized signal to adjust its SOP through PMD before it can experience the full Raman gain. Within the PMD diffusion length (around 175 m in this case of forward pumping), fiber loss dominates and the signal power decreases. Beyond the diffusion length, Raman gain dominates and the signal power increases. The gain difference seen in figure 1.16 between the copolarized and the orthogonally polarized cases comes from this initial difference. In the case of backward pumping, the PMD diffusion length becomes so small (about 0.2 m) that this difference completely disappears. The level of signal fluctuations depends strongly on the relative directions of pump and signal propagation. In the case of forward pumping, $\sigma_s$ grows monotonically with the distance, reaching 24 % at the end of the 10 km fiber. In contrast, $\sigma_s$ is only 0.8 % even for a 10 km long amplifier in the case of backward pumping, a value 30 times smaller than that occurring in the forward pumping case.

### Polarization-dependent gain

The PMD effects in Raman amplifiers can be quantified using the concept of polarization-dependent gain (PDG), a quantity defined as the difference between the maximum and the minimum values of $G$ realized while varying the SOP of the input signal. The gain difference $\Delta = G_{\text{max}} - G_{\text{min}}$ is itself random because both $G_{\text{max}}$ and $G_{\text{min}}$ are random. It is useful to know the statistics of $\Delta$ and its relationship to the operating parameters of a Raman amplifier because they can identify the conditions under which PDG can be reduced to acceptable levels.

Without going into much detail on the calculations, we state that the probability density of
the PDG magnitude $\Delta$ is expressed as

$$p(\Delta) = \frac{\Delta}{2\sigma_\parallel \sigma_\perp} \exp \left[ -\frac{\Delta^2 (r - 1) - r\Delta_0^2}{2\sigma^2} \right] \times \left[ \text{erf} \left( \frac{\Delta (r - 1) + r\Delta_0}{\sqrt{2}\sigma} \right) + \text{erf} \left( \frac{\Delta (r - 1) - r\Delta_0}{\sqrt{2}\sigma} \right) \right]$$

(1.48)

where $\sigma = \sigma_\perp (r - 1)$, $r = \sigma_\parallel^2 / \sigma_\perp^2$ and $\text{erf}(x)$ is the error function. Furthermore, $\sigma_\parallel^2$ and $\sigma_\perp^2$ are the variances of the PDG vector $\Delta$ in the direction parallel and perpendicular to $\hat{p}$, respectively while $\Delta_0 = |\langle \Delta \rangle|$.

Figure 1.18 shows how $p(\Delta)$ changes with $D_p$ in the case of forward pumping. All parameters are the same as in figure 1.16. The PDG values are normalized to the average gain $G_{av}$ (in $dB$) so that the curves are pump-power independent. In the limit $D_p \rightarrow 0$, $p(\Delta)$ becomes a delta
function located at the maximum gain difference (almost $2G_{av}$) as little gain exists for the orthogonally polarized signal. As $D_p$ increases, $p(\Delta)$ broadens quickly because PMD changes the signal SOP randomly. If $D_p$ is relatively small, the diffusion length $L_d$ is larger than or comparable to the effective fiber length $L_{eff}$ and $p(\Delta)$ remains centered at almost the same location but broadens because of large fluctuations. Its shape mimics a Gaussian distribution. When $D_p$ is large enough that $L_{eff} \gg L_d$, $p(\Delta)$ becomes Maxwellian and its peaks shifts to smaller values.

The mean value of PDG $\langle \Delta \rangle$ and the variance of PDG fluctuations $\sigma^2_\Delta$ can be calculated using the PDG distribution. Figure 1.19 shows how these two quantities vary with the PMD parameter for the same Raman amplifier used for figure 1.16. Both $\langle \Delta \rangle$ and $\sigma^2_\Delta$ are normalized to the average gain $G_{av}$. As expected the mean PDG decreases monotonically as $D_p$ increases. It is not exactly $2G_{av}$ when $D_p = 0$ because the gain is not zero when pump and signal are orthogonally polarized. Note however that $\langle \Delta \rangle$ can be as large as 30 % of the average gain for $D_p > 0.05 \text{ ps}/\sqrt{\text{km}}$ in the case of forward pumping and it decreases slowly with $D_p$ after that, reaching a value of 8 % for $D_p = 0.2 \text{ ps}/\sqrt{\text{km}}$. In the case of backward pumping, the behaviour is nearly identical to that in the case of forward pumping except that the curve shifts to a value of $D_p$ smaller by about a factor of 30.

As seen in figure 1.19 the root mean square (RMS) value of PDG fluctuations increases rapidly as $D_p$ becomes nonzero, peaks to a value close to 56 % of $G_{av}$ for $D_p$ near $0.01 \text{ ps}/\sqrt{\text{km}}$ in the case of forward pumping and then begins to decrease. Again, fluctuations can exceed 7 % of the average gain level even for $D_p = 0.1 \text{ ps}/\sqrt{\text{km}}$. A similar behaviour holds for backward pumping. Both the mean and the RMS values of DPG fluctuations decrease with $D_p$ inversely for $D_p > 0.03 \text{ ps}/\sqrt{\text{km}}$.

1.5 Ultrafast Raman amplification

The CW regime considered so far assumes that both the pump and the signal fields are in the form of CW beams. This is rarely the case in practice. Although pumping is often continuous in lightwave systems, the signal is invariably in the form of a pulse train consisting of a random sequence of 0 and 1 bits. Fortunately, the CW theory can be applied to such systems, if the signal power $P_s$ is interpreted as the average channel power, because the Raman response is fast enough that the entire pulse train can be amplified without any distortion. However, for pulses shorter than 10 ps or so, one must include the dispersive and nonlinear effects that are likely to affect the amplification of such short pulses in a Raman amplifier.

The situation is quite different when a Raman amplifier is pumped with optical pulses and
Figure 1.18: The probability density distribution of PDG as a function of $D_p$ under the conditions of figure 1.16. The PDG value is normalized to the average gain $G_{av}$.

Figure 1.19: (a) Mean DPG and (b) variance $\sigma_\Delta$ (both normalized to the average gain $G_{av}$) as a function of PMD parameter under forward- and backward-pumping conditions.

is used to amplify a pulsed signal. Because of the dispersive nature of silica fibers, the pump and signal pulses travel with different group velocities, $\nu_{gp}$ and $\nu_{gs}$, respectively, because of their different wavelengths. Thus, even if the two pulses were overlapping initially, they separate after a distance known as the walk-off length. The CW theory can still be applied for relatively wide pump pulses (width $T_0 > 1$ ns) if the walk-off length $L_W$, defined as

$$L_W = \frac{T_0}{|\nu_{gp} - \nu_{gs}|}$$

(1.49)

exceeds the fiber length $L$. However, for shorter pump pulses for which $L_W < L$, Raman amplification is limited by the group-velocity mismatch and occurs only over distances $z \approx L_W$ even if the actual fiber length $L$ is considerably larger than $L_W$. At the same time, the nonlinear effects such as SPM and XPM become important and affect considerably the evolution of the pump and signal pulses. We will not go into further detail, since this subject falls out of the scope of this text.
Chapter 2

Distributed Raman amplification

The term distributed amplification refers to the method of cancellation of the intrinsic fiber loss. As opposed to discrete amplification, which will be discussed in chapter [3], the loss in distributed amplifiers is counterbalanced at every point along the transmission fiber in an ideal distributed amplifier. The transmission fiber is, in itself, turned into an amplifier.

This makes it more challenging to optimize the fiber design with respect to amplifier performance because the fiber at the same time has to be optimized for signal transmission, that is, with constraints to the group velocity dispersion and the nonlinearities at the signal wavelengths.

In addition, when evaluating the performance of a distributed amplifier, further noise sources need attention compared to the noise sources known from conventional lumped amplified transmission systems. These new noise sources include effects due to Rayleigh scattering, nonlinear interaction between pump and signal channels and pump and signal cross talk. These noise sources become relevant because gain is accumulated over tens of kilometers in distributed amplifiers and especially the Raman process has a very fast response time on the order of femtoseconds, enhancing the pump and signal cross talk.

2.1 Benefits

Even though the intrinsic loss of a transmission fiber is extremely low, about 0.2 dB/km at 1550 nm, the loss is responsible for one of the major limitations when transmitting light through an optical fiber. To overcome the loss, amplification is needed. This may be achieved all optically through Raman amplification. One of the major benefits, only obtainable through the use of distributed amplification, is that signal gain may be pushed into a transmission span preventing the signal from decaying as much as it otherwise would have if no amplification was provided within the span. As a consequence, the signal-to-noise ratio does not drop as much as it would have in a system based on transmission through a passive fiber followed by a discrete amplifier.

An expression for the noise figure $F_n$ can be derived from the noise power $P_{ASE}$ related to the amplified spontaneous emission. When the loss rate at the pump $\alpha_p$ and signal $\alpha_s$ are equal, $\alpha = \alpha_p = \alpha_s$ the noise figure may be evaluated analytically. Considering the case of a transparent amplifier (the net gain $G = 1$), this corresponds to a noise figure of

\[
F_n = 1 + 2 \frac{\eta r \alpha}{g_r P_L^2} (G_A - 1) \tag{2.1}
\]

where $\eta r$ is the thermal equilibrium phonon number, $g_r$ the Raman gain coefficient, $P_L$ the pump power at the end ($z = L$) of the fiber span and $G_A$ is the on-off Raman gain as defined in equation [1.17].

At the limit when the amplifier length approaches infinity ($L \to \infty$), the noise figure in decibels approximates

\[
F_n|dB \to G_A|dB + 10 \log \left(2 \frac{\eta r \alpha}{g_r P_L^2}\right) \tag{2.2}
\]
This equation shows that for large fiber lengths the noise figure grows nearly decibel for decibel in the on-off Raman gain, whereas when the length approaches zero \((L \to 0)\) the noise figure approaches 0 dB.

The noise figure as a function of the on-off Raman gain for a transparent backward pumped Raman amplifier is displayed in figure 2.1. The figure displays the noise figure both when assuming that the loss rate at the pump wavelength equals the loss at the signal wavelength, \(\alpha_p = \alpha_s = 0.20 \text{ dB/km}\) and more realistically when the loss rate at the pump is \(\alpha_p = 0.25 \text{ dB/km}\) and the loss rate at the signal wavelength is \(\alpha_s = 0.20 \text{ dB/km}\). The pump and signal wavelengths are chosen to match the gain peak in the Raman gain spectrum \((\lambda_p = 1455 \text{ nm} \text{ and } \lambda_s = 1555 \text{ nm})\). Finally, figure 2.1 also illustrates the ideal noise figure achieved in the limit where the loss is counterbalanced along every point of the span. This limit is

\[
F_n|_{dB} \approx 10 \log (2\alpha_sL + 1)
\]

Here, \(\exp (\alpha_sL)\) is the gain necessary to counterbalance the loss. If, for example, a transmission fiber is 100 km long with a loss rate of 0.2 \text{ dB/km}, the span loss equals 20 dB, resulting in an asymptotic value in the noise figure of 10 dB.

From the two curves in figure 2.1 illustrating the noise figure for realistic loss rates and equal loss rates, it is obvious that assuming the same loss rate may be acceptable to obtain simple insight into amplifier behaviour. However, accurate predictions clearly require the use of accurate values of loss rates.

Comparing the three graphs on figure 2.1, the effect of excursions in the signal power becomes clear. As the on-off Raman gain, or in analogy the length of the fiber span, increases the signal excursions along the span deviate more and more from the ideal distributed amplification. This causes an 8 dB penalty for the realistic case relative to the ideal distributed amplifier when the span length equals 100 km or 20 dB on-off Raman gain.

The improvement in noise figure, when comparing a Raman amplifier against a passive fiber followed by a discrete amplifier strongly depends on the amplifier length. Assuming that the amplifier is transparent and the noise figure of the discrete amplifier is ideal, the expected improvement as a function of the on-off Raman gain is displayed in figure 2.2.

It is obvious that by pumping in the forward direction, the accumulated spontaneous emission will be reduced. This is illustrated in figure 2.3 which displays the noise figure of a transparent 100 km long Raman amplifier. That is, the gain is adjusted exactly to counterbalance the intrinsic fiber loss, where the ratio of backward to forward pump power is varied. The value 0 on the x-axis corresponds to a purely forward-pumped amplifier whereas the value 1 corresponds to a conventional purely backward-pumped amplifier.

Figure 2.3 illustrates an improvement of approximately 10 dB when using forward pumping as opposed to backward pumping in the example of a 100 km long amplifier. However, the benefits in signal-to-noise ratio do not take into account the possible drawback due double Rayleigh backscattering, nonlinear effects or possible cross-coupling between the signal and the pump. The latter is most detrimental when the pump and signal copropagate in the same direction, that is, in the forward-pumped Raman amplifier configuration.

2.2 Challenges

Although the distributed Raman amplification process offers several advantages, it is also accompanied by challenges. Most of these can be overcome by choosing an amplifier design that mitigates the challenges.

2.2.1 Polarization dependence

One of the challenges is the polarization dependence of the Raman gain. The Raman scattering is strongly polarization dependent. A standard single-mode fiber, in which both the pump and the signal propagate in the fundamental mode, supports two orthogonal polarization states in
Figure 2.1: The noise figure versus the on-off Raman gain or similarly the length of a transparent span. The lower trace (1) represents the ideal lower limit, whereas the middle trace (2) represents the case in which the loss rate at the pump equals the loss rate at the signal wavelength $0,2 \text{ dB/km}$. Finally the upper trace (3) is the realistic case in which the loss rate at the pump is $\alpha_p = 0,25 \text{ dB/km}$ and the loss rate at the signal is $\alpha_s = 0,2 \text{ dB/km}$. All traces assume room temperature.

Figure 2.2: The improvement in noise figure versus fiber length on-off Raman gain. The improvement is relative to a passive span succeeded by an ideal discrete erbium-doped fiber amplifier. The on-off gain may be directly translated to fiber length by dividing the values on the x-axis with the signal loss rate.

each mode. Thus, even though the fiber is single mode, the pump and signal may propagate in orthogonal polarizations. In this case the gain coefficient almost vanishes, in contrast to propagation when pump and signal have the same polarizations. This is clearly visible from the Raman susceptibility shown in figure 2.4. Curves $a$ and $c$ are the real part of the susceptibility whereas curves $b$ and $d$ are the imaginary part, which is proportional to the Raman gain coefficients.

To overcome this polarization dependence, Raman amplifiers are typically pumped using unpolarized pump beams. As a result the Raman gain coefficient is somewhat the average of curves $b$ and $d$. 

24
2.2.2 Spatial overlap of pump and signal mode

The Raman gain also depends on the spatial overlap of the pump and signal mode. On one hand, this allows for a fiber designed for optimum spatial overlap between the pump and signal modes and the core. On the other hand, the spatial overlap restricts the design space because single-mode propagation of both pump and signal is desired.
To illustrate this, figure 2.5 displays the Raman gain coefficient as a function of the radius of the core $a$ in a step index fiber with an extremely high germanium concentration ($\approx 20 \text{ mol\%}$). A change in the core radius is analogous to a change in the normalized frequency $V$, defined as

$$V = \frac{2\pi}{\lambda_s} a \sqrt{n_1^2 - n_2^2}$$  \hspace{1cm} (2.4)

Where $\lambda_s$ is the wavelength of the signal and $n_1$ and $n_2$ are the refractive indices of the core and cladding, respectively. A pump at 1450 nm and a signal at 1555 nm is assumed. When $V$ exceeds 2.405 the fiber becomes multimode.

In figure 2.5 the Raman gain coefficient is illustrated for the case in which the pump and signal are in the same polarization. In the figure, the diameter of the core is varied to describe the single-mode and multimode operation. For a core diameter below 3,6 $\mu$m the fiber is single mode for both pump and signal. In this region the maximum Raman gain coefficient is found for a core diameter close to 2,8 $\mu$m. This is the geometry that provides the maximum overlap of both the pump and the signal mode and their overlap to the core.

When the diameter of the core is between 3,6 and 3,8 $\mu$m the pump becomes multimode whereas the signal is still single mode. As a consequence the Raman gain coefficient may now assume two different values depending on whether the pump is in the fundamental mode or in the higher order mode. This is the case even when the pump and signal are in the same polarization state.

Finally, when the diameter of the core exceeds 3,8 $\mu$m both the pump and the signal become multimode. Thus the Raman gain coefficient may now assume several values because of the degeneracy of the pump and signal modes. Assuming that the pump and signal are in the same polarization state and the same trigonometric mode, the data in figure 2.5 are found for the Raman gain coefficients as a function of the core radius of the fiber. If the core radius exceeds 5.7 $\mu$m, even more modes are guided and the description gets further complicated.

Figure 2.5 shows that there is a strong dependence in the Raman gain coefficient due to the mode profile of the pump and signal. In addition, the figure illustrates the complexity with respect to the Raman gain in dealing with more than the fundamental mode of pump and signal. However, in the following we assume that both the pump and the signal are in the fundamental mode.

### 2.2.3 Nonlinearities

The refractive index of germano-silicate fibers changes with the intensity of the light propagating through the fiber. The rate of change is characterized by the so-called intensity-dependent refractive index, which for a typical transmission fiber is $3,2 \times 10^{-20} \text{ m}^2/\text{W}$.

The nonlinear propagation effects relevant to the evolution of the electric field amplitude involve a cubic term in the electric field. In a communication system with multiple signal channels, the nonlinear effects are typically classified by the number of field amplitudes involved in the process, each associated with its own frequency.

The term self-phase modulation is used if all three fields belong to the same frequency as the channel of interest. As a result of SPM the phase of a given signal channel is modulated by the signal itself. In the absence of group velocity dispersion, SPM causes broadening of the pulse in the frequency domain. In a typical transmission system, the interplay of group velocity dispersion and SPM is complicated.

A phase change appearing on a channel may also be caused by signals, a tone, or two other channels. In this case this is referred to as cross-phase modulation. The phase modulation caused by other signal channels causes a signal distortion and hence a degradation of the system performance. The XPM is strongly dependent on walk-off between the signal channel and the channels causing the XPM. Thus it depends on the channel’s spacing, the group-velocity dispersion and the polarization of the channels.

Finally, if all three amplitudes in the cubic nonlinear term belong to channels other than the considered, one refers to four-wave mixing (FWM). In this process power is transferred to new
Figure 2.5: Calculated Raman gain coefficients versus the normalized frequency at the signal wavelength. Each curve is labeled according to the mode of the pump and signal. For example, $G_{1101}^{1101}$ is the gain coefficient corresponding to the pump being in the $LP_{01}$ mode. The relatively large gain coefficients are due to the high index contrast between core and cladding, that is, a large content of germanium in the center.

frequencies from the signal channels. The appearance of additional waves and the depletion of the signal channels will degrade the system performance through both cross talk and depletion. The efficiency of the FWM depends on channel dispersion and channel spacing.

For completeness it should be noted that there are other nonlinear effects that may impact the system performance including Raman scattering among channels. In this process, signal channels will experience gain from channels at lower wavelengths whereas other channels will be depleted by channels at higher wavelengths. This will cause a gain tilt that to first order may be counterbalanced by proper design of the pump configuration of the Raman amplifier. However, since the channels are copropagating with each other, the Raman scattering among the channels will cause extra noise since the channel-by-channel Raman gain will fluctuate according to the bit pattern in the channels. Both the statistics of the signal modulation and the number of channels are two important numbers.

2.2.4 Rayleigh reflections

A fraction of the intrinsic loss in an optical fiber is due to Rayleigh scattering. In this process light is elastically scattered. That is, the frequency of the scattered light is identical to that of the incoming light. However, a small part of the scattered light is recaptured, half of which propagates in the direction of the launched light and the other half propagates in the opposite direction. In a typical transmission fiber of ideally infinite length, the back-reflected power measured at the input end of a fiber is approximately 30 dB lower than the launched power.

The part that propagates in the opposite direction of the signal may again undergo a reflection and now after two reflections it propagates in the same direction as the signal. This second reflection, also referred to as double Rayleigh backscattering, causes a severe penalty as this double-reflected signal is directly at the same frequency as the original signal but appears like an echo of the signal and interferes with the original signal. Naturally, the penalty contains multiple reflections rather than two and is therefore also referred to as the multipath interference (MPI).

Thus far, only reflections of the signal were discussed. However, in a real communication system, the Rayleigh process cannot distinguish signal from noise. The implication of this is that the spontaneous emission contains a contribution caused by Rayleigh reflections of the
noise propagating in the opposite direction relative to the signal. This is referred to as the single-reflected backward-propagating ASE.

There is a drawback to Raman amplifiers for large on-off Raman gains because of Rayleigh reflections when comparing against systems using discrete amplification due to the long lengths of the amplifier over which gain is accumulated. The penalty from Rayleigh reflections may be reduced by applying bidirectional pumping.

2.2.5 Time response

It is demonstrated that the Raman response time is in the order of tens of femtoseconds. This very fast response time enables mutual interactions between the pump and the signal in addition to cross-coupling between two signal channels mediated by the pump. Both of these interactions are crucial when considering forward pumping in which pump and signal propagate in the same direction. In addition, they are especially critical in distributed Raman amplifiers because the amplifying fiber is the transmission fiber and thus a modification of the walk-off between pump and signal achieved through a modified dispersion will not only mitigate the penalties but also impact the dispersion of the signal.

Pump-signal cross talk

Because of the very short response time, any fluctuations in pump power slower than the response time can cause gain fluctuations if the pump and signal are propagating in the same direction. This results in additional noise on the signal. If, on the other hand, the pump and signal are counterpropagating, the signal passes the pump that propagates in the opposite direction. This introduces a strong averaging of the accumulated gain and hence reduces the effect of pump-signal cross talk. In the copumped Raman amplifier the signal and pump propagate through the fiber in the same direction and only the effect of walk-off between pump and signal causes averaging. The direct coupling of pump fluctuations to signal fluctuations is demonstrated in figure 2.6.

The efficiency of the averaging effect is strongly correlated to the frequency of the fluctuations in the pump. In the limit in which the frequency is very low, all variations in the pump power are directly transferred, whereas in the other limit in which the frequencies are much higher than the time of a bit slot, no fluctuations will be transferred to the signal.

Signal-pump-signal cross talk

In the Raman process, the amplitude modulation of the encoded signals is impressed upon the pump. Thus even a perfectly fictive noise free pump, that is, no fluctuations in wavelength or amplitude, will become noisy during the Raman amplification process. Thereby, induced noise on the pump may be transferred to other signals through the Raman process, in the following denoted as signal-pump-signal (SPS) cross talk.

The amount of SPS cross talk depends on

- **The relative directions of the pump and signal beams** This may be simply understood by dividing the signal-pump-signal cross talk process into two parts. In the first part a footprint of a given signal channel is transferred to the pump. This is then, in the second part, transferred to another signal channel. The second part corresponds to the situation of simple pump-signal cross talk. Following this argument, it is clear that the cross talk is most severe for copumped amplifiers as compared to counterpumped amplifiers.

- **The walk-off between pump and signal** The relative propagation speed difference between the pump and the signal as well as between the signals themselves causes averaging of signal-pump-signal cross talk, similar to the discussion of pump-signal cross talk. This results in a limited cross-talk bandwidth over which the SPS cross talk occurs.
The amount of pump depletion The signal-pump-signal cross talk also depends on the pump depletion and the size of the applied Raman gain. In general, the smaller the pump depletion and the smaller the Raman gain, the smaller the SPS cross talk. Thus, conventionally copumped Raman amplifiers are limited to applications with small levels of Raman gain and small degrees of pump depletion.

The statistics of signals including the number of channels It is the collective modulation of the $N_{ch}$ signal channels that serves as the noise source for SPS cross talk. Thus it is important to consider the statistics of the $N_{ch}$ transmitted channels as for example the probability that a mark ("1") is simultaneously transmitted on all $N_{ch}$ channels. This probability decreases as the number of channels increases. Assuming that all the signal channels interact equally strong with the pump, the RIN of the collective signal may be evaluated theoretically as the variance of the collective signal power relative to the squared mean value of the power. Such calculations show that the RIN decays quadratically. That is, it is beneficial to have many channels. To minimize the signal-pump-signal cross talk it has been proposed to constrain the Raman gain to values well below the saturation point.

2.3 Backward pumping

To realize Raman amplification, the pump lasers have to fulfill several conditions. Since the Raman process is polarization dependent, the preferred pump needs to be unpolarized. In addition, the spectrum of a particular pump should be relatively broad, a few nanometers, to avoid the onset of Brillouin scattering. Finally, because of the relative low gain coefficient of the Raman gain, pump powers on the order of a few hundreds of milliwatts are required.
Even with the constraints described above regarding the pumping configuration and the pump laser, there are several free parameters including the number of pump wavelengths, the actual pump wavelengths and the power in each pump wavelength. The majority of research within selecting pumping configurations and pump lasers has been concentrating on achieving as wide and as flat a gain spectrum as possible. Only little effort has focused on creating both flat gain and flat noise spectrum.

The backward-pumping configuration is preferred because pump-signal crosstalk is then considerably averaged out.

2.3.1 Wavelength multiplexed pumps

When combining multiple discrete pumps, the task is to adjust the wavelength and amplitude of each pump laser in order to minimize the peak-to-peak variations in the gain spectrum and to broaden the gain spectrum or to optimize the noise spectrum. Finally, in the design of an amplifier with a fixed total bandwidth there is a trade-off between using many pumps to minimize the peak-to-peak variations and using as few pumps as possible for simplicity and cost.

As an example, a gain of 10.9 dB ± 0.5 dB over 1530 to 1565 nm is demonstrated in a 2100 m long dispersion compensating fiber. This is obtained by using 5 pump wavelengths.

The profile of the gain spectrum can be adjusted for maximum flatness by carefully selecting the pump wavelengths and adjusting the power in the individual pump wavelengths. It is obvious this is not a trivial procedure and a practical approach to optimizing the pump wavelengths and their power settings is desired both in the process of designing the amplifier and also as a feature in an already realized amplifier configuration.

The design process typically involves a theoretical optimization with the goal being to return pump wavelengths and pump power levels for a given specified amplifier performance. Many factors must be considered in the design of the amplifier and the systems that use them. A thorough understanding of some of the key factors is required including pump-to-pump power transfer, signal-to-signal power transfer, pump depletion, Rayleigh scattering and spontaneous emission. There are several approaches regarding numerical solutions to this task. However, we will not treat them here.

The maximize the chance for success in flattening the gain shape, knowledge of the Raman gain spectrum and the fact that power is transferred from the shortest pump wavelength to the longest pump wavelength is essential. In addition, it has been proposed to reduce the number of adjustable parameters by collectively controlling the shortest wavelengths and only a single, or a few, longer wavelengths.

In a specific example illustrated in figure 2.7, four short wavelength pumps are grouped and collectively controlled and the longest wavelength pump is adjusted independently of the others. Using this pump method, three examples are given in which the gain is adjusted to three different values, 6, 1 dB, 4, 0 dB and 2, 0 dB, respectively, by adjusting the setting of the controller for group #1 and the power group #2. The flatness achieved is ±0, 46 dB, ±0, 34 dB and ±0, 21 dB for the three settings.

2.3.2 Broadened pumps

The use of multiple pump wavelengths may be less attractive from a commercial point of view because of complexity and cost. A possible solution is a setup in which the spectral width of the applied pump is broadened before it is coupled into the Raman amplifier.

As an example, a 50 nm broadband pump was constructed by using the spontaneously emitted light from and erbium-doped fiber amplifier followed by a gain equalization filter and a booster amplifier. The emitted pump power was 23, 5 dBm. By using this pump together with a fiber with a strong Raman efficiency, a 30 nm broadband amplifier was constructed with a 13 dB average net gain and peak-to-peak gain variations of less than 2 dB.

One of the constraints in this method is the wavelength of the pump. To address this, spectral broadening can also be obtained by launching the pump laser first into a fiber with
its zero dispersion wavelength matched to the wavelength of the pump laser and then into the amplifier. In this scheme, the pump spectrum is defined by the fiber design of the pump fiber and the seed laser, as opposed to the wavelength band of the ASE source, typically an EDFA.

In this example, the pump laser had an initial $3 \, dB$ bandwidth of 0.63 nm at 1455 nm. After propagation through a 25 km zero-dispersion fiber, the $3 \, dB$ bandwidth of the pump was 14.23 nm when the pump power was 800 mW. Comparing the Raman gain spectra with and without the broadening, a significant change is found. From figure 2.8 it is noted that the peak to peak variations in the gain spectrum has been significantly reduced and in addition, the achieved gain spectrum is broadened as was expected.

### 2.3.3 Time-division-multiplexed pumps

As a result of multiple pumps at relatively high power levels, hundreds of milliwatts, propagating in the same direction, four-wave mixing components may be generated. The strength of the four-wave mixing components depend particularly on the fiber dispersion and the actual wavelengths of the pumps.

One possible solution to improve the noise caused by four-wave mixing is changing the fiber dispersion at the pump wavelengths to a relatively large value. As a second solution, four-wave mixing may be avoided and pump-to-pump interactions eliminated by sweeping the frequency of one pump laser or by time division multiplexing (TDM) of a multiple of pump lasers each at different wavelengths.

Instead of using a single-frequency laser, a single but frequency-tunable laser is employed as a pump source. The tunable laser is periodically swept according to some wavelength pattern with the time spent at a particular wavelength determining the amount of Raman gain arising from that wavelength. If the pattern repetition rate is chosen high enough, the (counterpropagating) signal does not experience any significant temporal gain variations, but does experience the composite Raman gain of all pump wavelengths making up the sweep pattern, in analogy to a multiwavelength continuous Raman system. This method only works for backward pumping.
Figure 2.8: Measured Raman gain spectra of a 25 km long fiber. The trace labeled conventional refers to the use of a fiber raman laser pump source, linewidth 0.6 nm. The trace labeled enhanced is the gain spectrum obtained from a broadened pump laser, linewidth 14.23 nm.

2.4 Advanced pumping configurations

In an ideal configuration of a distributed amplifier, the intrinsic fiber attenuation is counterbalanced along every point of a transmission span resulting in no signal power variations along the span. A realistic approach to an ideal distributed Raman amplifier is obtained by using a bidirectionally Raman pumped amplifier, that is, the combined use of forward and backward pumping.

It has been demonstrated that bidirectional pumping would result in a reduced accumulation of spontaneous emission, in addition to reduced penalties from Rayleigh scattering. On the other hand the path average power will increase when compared to a backward-pumped Raman amplifier and fixed-signal input power. In addition, but practically most challenging, an extra noise contribution arises from pump-signal cross talk and signal-pump-signal cross talk when comparing bidirectional pumping against backward pumping.

For completeness, an advantage of bidirectional pumping compared to backward or forward pumping is the ability to transmit signals in both the forward and the backward direction, that is, bidirectional pumping and bidirectional signal transmission. Finally, rather than launching very high power from one end, now the power requirement is split between two launch sites.

The above benefits and drawbacks have to be accounted for in a final evaluation of a pumping configuration.

One of the major obstacles in using forward pumping is the pump-signal cross talk as well as signal-pump-signal cross talk. Both phenomena result in an additional noise contribution that may exceed the benefits otherwise obtained from the uniform gain distribution. However, two methods have been proposed to realize forward pumping.

2.4.1 Higher order pumping

There are significant benefits in moving the gain from the end of a fiber span into the span, for example in improved signal-to-noise ratio and in reduced double Rayleigh backscattering cross talk. One way to push the gain into the span is by amplifying the pump within the span using distributed amplification of the pump. Thus method thus relies on using another pump wavelength shifter another 13.2 MHz from the first pump wavelength. This method is called second-order pump or cascaded Raman pumping.

The second order pump may be launched from the same end as the first pump or from the same end as the signal. Both configurations are displayed in figure 2.9. In the latter case the remaining first pump is amplified close to the signal input end and as a result the first pump now provides gain for the signal both at the input and at the output end of the fiber span. In this case the signal power evolves as in a bidirectional pumped amplifier. However, when compared
to a conventionally bidirectionally pumped amplifier, pump-signal and signal-pump-signal cross talk is avoided.

Higher order pumping can push the Raman gain even further into the span, leading to a further improvement of the noise performance. In one configuration, a low-power 1455 nm pump is launched in the opposite direction as the signal. This weak pump is launched together with a second low-power pump at 1356 nm. A high-power third pump at 1257 nm amplifies the 1356 nm pump, which peaks in power about 15 km from the input end. The 1455 nm pump is amplified by the 1356 nm pump and assumes a maximum value approximately 25 km from the input end. A system demonstration using a 100 km span shows an improvement of 2.5 dB compared to conventional Raman pumping configuration when using third-order pumping. This improvement is achieved on the cost of applying a 3 W pump laser at 1276 nm.

2.4.2 Quiet pumps

For the purpose of forward pumping it is essential to have both a high degree of wavelength stabilization and a stable and low noise output intensity, the latter characterized by RIN. These requirements need to be fulfilled while retaining a high-output power level and multimode operation. The latter is desired to avoid stimulated Brillouin scattering. Finally, the output of the pump should preferably be unpolarized.

A multimode pump laser with an internal Bragg grating incorporated into the laser cavity can be used as a quiet pump. With this method only a few longitudinal modes are contained within the output beam and the mode spacing in this laser is relatively large. Figure 2.10 illustrates the power spectrum of a laser with an internal grating and the relative large mode spacing is clear.

The RIN of the laser with the output power spectrum in figure 2.10 is shown in figure 2.11. From the figure, the RIN as low as −160 dB/Hz, which is about 30 dB lower than the RIN of a Fabry Perot laser with an external grating.

Bidirectional pumping was used in an experimental demonstration of a 1,28 Tbit/s (32 × 40 Gbit/s) unrepeatered transmission through a 240 km long fiber span consisting of conventional nonzero dispersion fiber. In the transmission, the losses were compensated solely by bidirectionally pumped distributed Raman amplification. That is, the pump power in the transmission span was chosen exactly so that the Raman gain was sufficient to counterbalance the 24 dB intrinsic fiber losses. The forward pump provided approximately 8 dB of gain. The Raman pumping modules were multiplexed depolarized semiconductor lasers operating at wavelengths of 1427 nm and 1455 nm. The RIN values of the pump modules were around −140 dB/Hz. The bidirectional pumping configuration resulted in a 6 dB improvement in the optical signal-to-noise ratio when compared against either co- or counterpumping. In the system there was no significant transfer of RIN from the pump to the signal.

Forward pumping may also be used to flatten the spectral dependence of the noise figure. In conventional counterpumped Raman amplifiers, pump power is transferred from the short pump wavelengths to the longer wavelengths during propagation. Thus, the gain for the longer signal wavelengths is pushed further into the transmission span. As a result the longer signal wavelengths perform the best. To eliminate this difference in performance between the longest and shortest wavelength channels, bidirectional pumping will, in addition to improved noise performance, also lead to the possibility of flattening the spectral dependency of the noise figure by applying forward pumping for the poorest performing channels.

This has been demonstrated on a 76 km long Raman amplifier. The fiber in the experiment was a standard single-mode fiber. By using five pump wavelengths in the backward direction, totaling 580 mW and three pump wavelengths in the forward direction, totaling 90 mW, a noise figure of 15, 2 dB ± 0, 4 dB was achieved over an 80 nm bandwidth.
Figure 2.9: Configurations of second order pumping. In (a) the first- and second-order pumps are copropagating but both are counterpropagating the signal, whereas in (b) the first- and second-order pumps are counterpropagating against each other.

Figure 2.10: Output spectrum of internal-grating stabilized multimode pump laser.

Figure 2.11: Comparison of relative intensity noise between a usual external fiber Bragg grating stabilized laser and the internal-grating stabilized laser.
Chapter 3

Discrete Raman amplification

This chapter focuses on the issues surrounding Raman amplifiers in a discrete module, or discrete Raman amplifiers. Because of the small scattering cross-section, Raman amplification may better fit in a distributed amplifier rather than a discrete one. However, discrete Raman amplifiers have many attractive aspects over rare-earth-doped amplifiers such as an erbium-doped fiber amplifier including arbitrary gain band, better adjustability of gain shape and better linearity. It is thus important to understand the design issues of discrete Raman amplifiers, so that one can optimize the design for a particular application.

3.1 Basic configuration and model

Figure 3.1 shows the basic configuration of discrete Raman amplifiers. It generally comprises a gain fiber, a wavelength-division-multiplexed (WDM) coupler for combining the pump and the signal and isolators at the input and output ends. The orientation of the pump can be either forward or backward with respect to the signal propagation. Even bidirectional pumping is possible. In general, there are several derivatives or combinations of these simple configurations for various applications. In a dual-stage Raman amplifier, two amplifier stages are concatenated.

The important parameters representing discrete Raman amplification are (i) the wavelength and input power level of the signal, (ii) the wavelength and input power level of the pump and (iii) the type and length of the gain fiber. As for the gain fiber, the following properties in signal and pump wavelength bands are required to design the amplifier in detail: (i) the attenuation coefficient, (ii) the Raman gain coefficient for the given pump wavelengths, (iii) the Rayleigh backscattering coefficient and (iv) the nonlinear coefficient. The wavelength dependence of each property should be given as precisely as possible for the accurate design over the entire signal and pump band.

An optimal discrete Raman amplifier is designed and found by changing these parameters for various configurations. The targeted optical characteristics of a discrete Raman amplifier are usually gain, noise figure, output signal power level, optical signal-to-noise ratio (OSNR), double Rayleigh backscattering noise power, nonlinear phase shift and pump-to-signal power conversion efficiency. FOR WDM signals, the dependence of the above characteristics on wavelength or signal channel should also be optimized.

We use the theory as developed in chapter 1. More specific the equations 1.6 and 1.7 for single-pump amplification and equation 1.21. However, we note a significant difference in definition of the effective area $A_{\text{eff}}$ in equation 1.4 needed in, among other, the calculation of the nonlinear phase shift $\gamma = 2\pi n_2 / (\lambda_s A_{\text{eff}})$. In this chapter, the effective area is defined as

$$A_{\text{eff}} = \left[ \frac{\iint I_s(x,y,z) \, dx \, dy}{\iint [I_s(x,y,z)]^2 \, dx \, dy} \right]^2$$

where $I_s$ is the intensity of the signal wave in the optical fiber and $\iint dx \, dy$ denotes the integral over the entire transverse plane.
Figure 3.1: Schematic configurations of (a) single-stage counterpumped, (b) single-stage copumped, (c) single-stage bidirectional and (d) dual-stage discrete Raman amplifiers.
3.2 Gain fibers and materials

There is only a limited number of fiber types that are commercially available. Almost all of them are based on germano-silicate glass. The designs and fabrication of optical fibers are limited by many fundamental trade-offs of the design issues and the basic material properties. The Raman properties of other glass materials have also been investigated, but we will focus on germano-silicate fibers.

For thorough design, the properties of gain fibers associated with Raman amplification need to be known exactly. Figure 3.2 plots the measured Raman gain efficiency spectra of standard single-mode fiber (SNF), nonzero dispersion shifted fiber (NZDSF) and dispersion-compensating fiber (DCF). In this plot, a 1511 nm pump laser is used for the measurement.

To perform a full numerical computation using equation 1.21, one also needs to know the spectra of the attenuation coefficient and the Rayleigh backscattering coefficient, as well as the gain spectrum. Figure 3.3 shows an example of the spectra of attenuation and Rayleigh backscattering coefficients for different fibers. In general, DCF has a higher concentration of germanium and a smaller core area than SMF and NZDSF. This leads to higher attenuation and Rayleigh backscattering coefficients. The attenuation coefficient of DCF increases rapidly toward 1400 nm. This comes from the OH absorption peak around 1385 nm. One also needs to know the value of the nonlinear phase shifts. In most cases, the nonlinear coefficient can be treated as a constant over the entire low loss wavelength range of the fiber.

3.3 Design issues

In the following sections, various numerical simulations based on the models mentioned in chapter 1 will be conducted. The default set of parameters used for these simulations is listed in table 3.1 unless otherwise mentioned.

3.3.1 Maximum Raman gain as a function of fiber length

Once the gain fiber and pump power are given, the net gain $G$ can be written explicitly from equation 1.14 as a function of the fiber length (refer to equations 1.9 and 1.10)

$$G(z) = \exp \left( g_r P_0 \frac{1 - \exp \left(-\alpha_p z\right)}{\alpha_p} - \alpha_s z \right)$$

(3.2)

though it is valid only under the small signal approximation. Figure 3.4 plots the net gain versus the fiber length for a fixed pump power based on the parameters in table 3.1. As can be seen from the figure, the Raman gain is dominant for shorter fiber length and the net gain increases with increasing fiber length, while the fiber attenuation plays a more important role for longer fiber length and the net gain decreases. In between the net gain has a maximum at a distance

$$z = -\frac{1}{\alpha_p} \ln \left( \frac{\alpha_s}{g_r P_0} \right)$$

(3.3)

where the small signal approximation is used as well.

3.3.2 Figure of merit of gain fiber

The effective length, as defined in equation 1.10 asymptotically becomes for long enough fiber

$$L_{eff} | z \rightarrow \infty = \frac{1}{\alpha_p}$$

(3.4)

In this limit, the on-off gain will be

$$G_A | z \rightarrow \infty = \exp \left( g_r P_0 \right) = \exp (FOMP_0)$$

(3.5)
Figure 3.2: The measured Raman gain efficiency spectra of single-mode fiber (SMF), nonzero dispersion shifted fiber (NZDSF) and dispersion compensating fiber (DCF).

Figure 3.3: An example of the (a) attenuation spectra and (b) Rayleigh backscattering coefficients for SMF, NZDSF and DCF.

where the figure of merit (FOM) for a fiber with regard to the applicability to a discrete amplifier is defined as

\[ FOM = \frac{g_r}{\alpha_p} \]  \hspace{1cm} (3.6)
Table 3.1: List of parameters used in the numerical simulations conducted in the following sections

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump wavelength [nm]</td>
<td>1451.779</td>
</tr>
<tr>
<td>Signal wavelength [nm]</td>
<td>1550.116</td>
</tr>
<tr>
<td>Pump power [mW]</td>
<td>400</td>
</tr>
<tr>
<td>Input signal power [mW]</td>
<td>0.01</td>
</tr>
<tr>
<td>Attenuation coefficient at 1452 nm [dB/km]</td>
<td>0.64</td>
</tr>
<tr>
<td>Attenuation coefficient at 1550 nm [dB/km]</td>
<td>0.45</td>
</tr>
<tr>
<td>Peak of Raman gain efficiency pumped at 1452 nm [W^{-1}/km]</td>
<td>3.3</td>
</tr>
<tr>
<td>Fiber length [km]</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3.4: Net gain versus fiber length.

By knowing FOM, the efficiency of the fiber for discrete Raman amplifiers can be estimated and compared. The unit of FOM is \( W^{-1} \).

### 3.3.3 Efficiency and linearity

Let us turn to the relation between the pump-to-signal power conversion efficiency (PCE) and the linearity of amplification. PCF [%] is defined as

\[
PCE = \frac{P_s(L) - P_s(0)}{P_0} \times 100
\]

\[
= \frac{(G(L) - 1) P_s(0)}{P_0} \times 100
\]

(3.7)

where \( P_s(L), P_s(0) \) and \( P_0 \) are the output and input signal power and the launched pump power, respectively. Figure 3.5 plots the relation between PCE and Raman gain efficiency. The dashed line indicates the PCE obtained by using equation (3.7). Here the counterpumped configuration is used and it is assumed that an arbitrary Raman gain efficiency can be used. For a given Raman gain efficiency, the pump power is adjusted so that the net gain of the amplifier is 18 dB. The simulation parameters other than the efficiency and the pump power are fixed at the values in table 3.1. As can be seen from the figure, the PCE increases with increasing Raman gain efficiency.

The PCE of Raman amplifiers appears very low as compared with EDFAs, which can easily achieve several tens percent of PCE. However, the PCE of a Raman amplifier can be increased by using higher input power, because the gain of the Raman amplifier has a larger saturation power than EDFA. Therefore, for example, PCE increases with the number of WDM signal channels. Figure 3.6 shows the PCE as a function of the total input signal power while the net gain is kept at 18 dB by changing the pump power. The dashed line indicates the PCE obtained by using equation (3.7). The other values of the simulation parameters are as shown in table 3.1.
Incidentally, it is noted that the small signal approximation should not be used to investigate how to increase PCE beyond 0 dBm input signal power, as the pump depletion term is not negligible under the large PCE. It is interesting to see the PCE increases monotonically with increasing input signal power. Due to gain saturation, larger input signal means larger pump power. Indeed, PCE could increase up to 13% if the input signal power were 0 dBm or 32 channels of −15 dBm.

3.3.4 Pump-mediated noise

As already discussed in chapter 1, temporal fluctuations of the pump laser will increase the noise of the signal, especially in the compumping scheme. The relative intensity noise transfer function consists of several parameters such as on-off Raman gain, loss and dispersion coefficients of fiber and the wavelength difference between pump and signal. Although the amount of Raman gain determines the maximum transfer, the other parameters affect the shape of the function. Figure 3.7 shows examples of RIN transfer functions in which the characteristics of the gain fibers listed in table 3.1 are used. In general, the shorter gain fiber leads to a significant chirped oscillation as shown in the case of DCF in figure 3.7. To put it more precisely, the amplitude of the oscillation is determined by the total attenuation of the fiber at the pump wavelength. Thus, the frequency at which the RIN transfer is 3 dB lower than the maximum is raised when the gain fiber is shortened.

3.3.5 ASE noise figure

The noise figure was defined in equation 1.32. Figure 3.8 plots the ASE noise figure as a function of the fiber length, for (a) counterpumping and (b) copumping, respectively. These figures also plot the net gain as a function of the fiber length. The values of the simulation are shown in table 3.1 except for the fiber length. From the figures, it is found that the difference between the two schemes is not significant for relatively short fiber length. On the other hand, for longer fiber lengths the difference becomes remarkable. This is because the accumulation of noise along the fiber is different in the two cases. The signal power in the counterpumping scheme experiences a lower level than that in the copumping scheme. This results in a worse noise figure in the counterpumping scheme for longer fiber lengths. The desirable characteristics of a fiber to obtain high net gain and low noise figure are high Raman gain coefficient, small effective area, low attenuation coefficient and short fiber length.
3.3.6 Nonlinear effects and double Rayleigh backscattering noise

Because a long fiber length is required for a Raman amplifier compared with EDFAs, it is necessary to account for the nonlinear effects and the DRBS effects that occur inside the Raman amplifier. These effects are particularly important for Raman amplifiers, as they tend to persist because the gain is distributed over a long length of the fiber.

The nonlinear effects are complicated and difficult to thoroughly examine, as they depend on many system parameters such as the fiber dispersion, the signal pulse parameters and the modulation formats of the signal. However, at least if the total nonlinear phase shift of the signal, defined in equation 1.15, inside the Raman amplifier could be sufficiently reduced, it would be desirable in general. The total nonlinear phase shift can be reduced by decreasing at either the path average power of the signal, the length of the fiber or the nonlinear coefficient.

The DRBS effects mainly causes multipath interference of the signal and results in an intensity noise via conversion of phase noise. The DRBS signal is amplified twice. Therefore, the MPI noise due to DRBS scales as the length of the fiber and the Raman gain. Using equation 1.21 the signal power evolution can be calculated from which the integral in equation 1.15 can be performed to obtain the total nonlinear phase shift. Also, the power ratio of the output signal to the DRBS noise can be calculated. Figure 3.9 plots the nonlinear phase shift and the signal-to-DRBS noise ratio versus fiber length for (a) a counterpumping scheme and (b) a copumping scheme, while the net gain was kept constant at 18 dB by adjusting the pump power. The other conditions are as shown in table 3.1. The nonlinear phase shift is larger and
incremental with the length for the copumping case. The effect of MPI is almost the same for both cases. Both the nonlinear and the MPI effects become larger for longer fiber length. Therefore, shorter fiber length would be desirable in order to avoid these effects.

The relationship between MPI cross talk and the Raman gain for co-, counter- and bidirectional pumping schemes is shown in figure 3.10. The fiber lengths used here were 5 km and 10 km and the Raman gain was changed by changing the pump power. The MPI cross talk grows as the Raman gain increases. The bidirectional pumping shows slightly smaller MPI cross talk. This difference becomes larger when the net loss of the gain fiber is larger, for example, when the fiber is longer.

3.3.7 Optimum fiber length and number of stages

From the above discussions, a shorter fiber length would be desirable for various reasons. The nonlinear effects, the MPI cross talk, the noise figure and the linearity of amplification are better for shorter fiber length. One serious drawback however is efficiency. One way to circumvent this fundamental dilemma is to adopt a multistage scheme. By inserting an optical isolator, the MPI effects will be mitigated, as the DRBS portions will be isolated between the stages and not cumulative over the entire length. This scheme therefore can realize a larger Raman gain than the single stage scheme within the same limit of the MPI cross talk.

A drawback of the multistage configurations is the risk of increasing nonlinear effects. Because of the additional losses due to isolators and couplers, the multistage amplifiers tend to require larger on-off Raman gain than the single stage one for the same net gain. This results in the
Figure 3.9: Nonlinear phase shift and MPI cross talk versus fiber length for (a) counterpumping and (b) copumping.

Figure 3.10: MPI cross talk versus Raman gain for co-, counter- and bidirectional pumping.

larger path average power and hence the larger nonlinear phase shift. It is therefore important to carefully choose and optimize the configuration of the amplifier by understanding the priority trade-offs in the performance.

3.3.8 Transient effects

Suppose that the total input power would suddenly decrease by a large fraction of power, say 3 dB for example. In such a situation, if the amplifier operates at a saturated regime, the gain
has to change accordingly before and after the sudden decrease in the input power. A finite response time of the amplifier may then result in a transient response in the gain. Although the stimulated Raman scattering is nearly instantaneous, the time delay due to the propagation of the signal and pump through the kilometers-long gain fiber causes a relatively slow response as a whole system of amplification. In one experiment, the transient response of a counterpumped discrete Raman amplifier comprising 13.9 km of DCF as the gain medium was measured. The result showed that the transient response to 50% modulation of the input signal power lasted for approximately 50 µs as shown in figure 3.11.

The magnitude of the gain change in the transient response depends on the degree of gain saturation. In other words, if the amplifier operates in a linear gain regime, the transient change in the gain will not be as large. Therefore, in order to avoid the transient effect, it is again desirable to use a short length of fiber to make the gain as linear as possible.

### 3.4 Dispersion-compensating Raman amplifiers

In high bitrates and long-haul optical transmissions, the effect of the group velocity dispersion (GVD) becomes nonnegligible. The signal pulse having a finite bandwidth tends to spread because each frequency component has a different group velocity. In practice, it is necessary to compensate for the GVD of most commercially available fibers in the transmissions at the bit rates of 10 Gb/s or higher. As this is a linear process, the pulse spreading due to GVD can be offset by applying the same magnitude but opposite sign of the GVD. One of the most practical and effective ways to compensate for the GVD is the use of dispersion-compensating fibers. DCFs in WDM applications usually have an opposite sign of both dispersion and dispersion slope to compensate for the GVD over a wide band.

One critical drawback of the use of DCF is the loss added to the system due to the attenuation of the DCF. In optically amplified transmission links, the loss always turns out to be the noise. In order to mitigate the noise due to the loss of the DCF module, the DCF is usually placed between two EDFA stages. In spite of such a configuration, the noise figure increases with the larger loss of the DCF. For a loss larger than 10 dB, the noise figure increases significantly. If the dispersion and loss of a DCF are assumed $-150$ ps/(nm km) and $0.5$ dB/km, respectively, about 10 dB of DCF loss is required to compensate 170 km of standard single mode fiber. In EDFAs for WDM applications, the DCF is not the only interstage device in general, but a gain flattening filter, a variable optical attenuator, add-drop components and so on are also used, adding their losses as interstage devices. Since only the DCF among these interstage devices can be a gain medium, it could be inevitable to reduce DCF loss by using Raman amplification.

The design issues of a dispersion-compensating Raman amplifier are not just the same as those discussed in the previous sections. Because the DCF is usually used to compensate for the dispersion of the transmission fiber, the length of the DCF is determined by the amount of the cumulated dispersion in the transmission line. On the other hand, a discrete Raman amplifier has to be carefully designed to optimize the overall performance with respect to efficiency, ASE noise, nonlinearity, MPI and so on. Therefore, the DCF used in a DCRA might be slightly different from the passive DCF. A critical parameter is the fiber length. Ideally speaking, the length of the DCF should be simultaneously optimized as a discrete Raman amplifier and a dispersion-compensating element. In general, the length of the DCF should be as short as possible.

### 3.5 Wideband operation by WDM pumping

The previous sections have mainly been focused on using one pump wavelength. This section attempts to extend the previous discussions to the case of mult wavelength pumping, or WDM pumping, for wide and flat gain operation of discrete Raman amplifiers. The design issues are basically the same, but the wavelength dependence of each property has to be optimally designed as well.
Figure 3.11: Stimulated transient effect with a 50% amplitude modulation on the input signal. In addition to the overshoot at the leading edge, an undershoot at the trailing edge of the signal pulse appears.

3.5.1 Wide flat composite gain

First, let us define a WDM-pumped discrete Raman amplifier in order to facilitate our following discussions. Figure 3.12 shows the schematic diagram of the discrete Raman amplifier comprising five-wavelength WDM pumps and DCF as the gain fiber. The spectral of the Raman gain efficiency, attenuation coefficient and Rayleigh backscattering coefficient of the DCF are those shown in figures 3.2 and 3.3, respectively. The number of WDM signals is assumed to be 92 channels in the range from 1530 nm to 1605 nm with 100 GHz spacing.

Figure 3.13 plots the on-off Raman gain spectra for the total input signal powers of $-30$, $-10$, 0 and −10 dBm, respectively. The launched pump powers of the pumping wavelengths are fixed for all plots, which are 375 mW, 167 mW, 93 mW, 99 mW and 71 mW for 1424 nm, 1438 nm, 1452 nm, 1466 nm and 1495 nm pump wavelengths, respectively. The change in the gain spectra derives mainly from the gain saturation and the stimulated Raman scattering among signals. The average net gain is 18 dB and the flatness is better than 1 dB for total input signal power of $-30$ dBm.

Figure 3.14 plots the Raman gain and output signal spectra under the same conditions as figure 3.13. Comparing the two curves shown in figure 3.14, it is found that the signal output spectra are not of the same profile as that of the on-off Raman gain, where the difference around 1600 nm for +10 dBm input looks larger than $-30$ dBm input. This is due to not only the spectral profile of fiber attenuation coefficients but also Raman interactions between signals. The interactions between the WDM signals and WDM pumps are complicated. Indeed, the on-off Raman gain spectra are inseparable from the signal power level spectra through saturation and they in turn influence the degree of Raman interactions between the signals. In this sense, when one designs Raman amplifiers for WDM signals, it is important to optimize the relevant parameters with regard to the signal power level spectra rather than the on-off Raman gain spectra.

3.5.2 Pump SRS tilt – Effect of saturation

As shown in figure 3.13, the on-off gain tends to have a tilt in the spectrum when the composite gain is saturated. This is because each of the WDM pumps is differently depleted through the amplification process, resulting in different contributions from each pump wavelength.

3.5.3 Signal SRS tilt – How to define gain

The system would become even more complicated when the so-called signal stimulated Raman scattering tilt is taken into account. The signal SRS tilt is the phenomenon in which the WDM signals interact with each other through the stimulated Raman scattering process and as a result the energy in the shorter wavelength signals is transferred to the longer wavelength signals. The energy transfer causes a tilt in the optical spectra of the WDM signals.

Because this process is via the stimulated Raman scattering, the amount of tilt, or in other
words the on-off Raman gain, depends on the power and the number of the signals. This fact also suggests that the signal output power spectrum is as important as the on-off Raman gain. Furthermore, in the presence of signal SRS tilt, care should be taken to clearly define the Raman gain with appropriate parameters given when discussing such Raman amplifiers.

### 3.5.4 Control of gain

In the WDM pumping, the pump power allocation is an important parameter to determine the composite Raman gain spectra. In practice, each of the pump powers has to be controlled possibly through some feedback. In order to control the gain, it is necessary to precisely know how much pump power is required to achieve the desirable gain. One proposed method is to measure the spontaneous Raman scattering by each pump laser beforehand and prepare a table of the pump-power allocations for the reference to realize desirable gain shapes. Another approach is to predict the necessary pump powers based on a simple linearized model with numerical iterations.
3.5.5 Flattening other parameters

For wideband operation, not only the gain and output signal power but also the other characteristics such as noise figure, optical SNR, DRBS-MPI and nonlinear phase shift should be flattened. In designing the wideband discrete Raman amplifiers, one has to optimize all the parameters over the entire signal range while watching the trade-off among them.
Bibliography
