ABSTRACT

This dissertation addresses some of the key aspects associated with the operation of optical communication systems: emission, transmission and amplification.

The path of an optical signal is followed from the transmitter to the receiver, being characterized in a first phase the light emitter: a semiconductor laser. Direct modulation is analyzed through the current injection. The threshold current for which the laser is on emission is defined, and, then discussed the behavior for different current injection. It has been made also a short introduction to electro-optic modulation.

During the transmission, it is analyzed initially the problem of group velocity dispersion, which will disturb the signal propagation in ideal conditions, without taking into account the fiber attenuation. Then the fiber attenuation is added and the impact of this factor in the propagation of impulses is checked. For this study, a simulator that encompasses the process of calculating the propagation of pulses in the linear regime was developed.

In the last chapter it is going to be discussed the amplification of the signal with the resource of EDFA amplifiers. It is going to be studied the EDFA’s design, taking into account the balance between the needed gain and the optimal length of the fiber to amplify a WDM (Wavelength Domain Multiplexing) signal. It will also be studied the use of Raman amplifiers in fiber optic systems and there will be analyzed their features and benefits.

Index Terms — Fiber Optics, Semiconductor Lasers, Pulse Propagation, Linear Regime, EDFA’s, Raman Amplifiers

1. INTRODUCTION

There has been all over the time an enormous need to establish long distance communications, and it happens that nowadays those communications are essentially implemented over fix and mobile telephones, internet and television.

The invention of the optical fiber is due to Narinder Singh Kapany, a scientist born in India. Kapany, basing his work on the studies of an English physics, John Tyndall (1820 – 1893), who stated that light could describe a curved path inside a certain material (in fact the material he was talking about was water), has been able to conclude his experiences by 1952 and invent the optical fiber.

1.1. Historical Perspective: Different Generations of Optical Fibers

The first tests that have been made concerning communications over an optical fiber were far from successful. The losses associated to the transmission of light pulses were too high, therefore limiting the transmission distances.

The first commercial generation of optical communications systems appeared by 1980. We are talking about multimodal fibers that operated on the first window (0.8 μm), with a binary rate of 45 Mb/s and that involved a distance between repeaters in the order of 10 km.[3]

The second commercial generation appeared by 1987, operating on the second window (1.3 μm) with attenuation values below 1 dB/km and a minimum distortion.

The first commercial generation of optical communications systems appeared by 1990. These systems operated on the third window (1.55 μm), with binary rates up to 10 Gb/s.

During 1990 the third commercial generation of optical communications systems became available. These systems operated on the third window (1.55 μm), with binary rates up to 10 Gb/s.

The main problem of these latest systems refers to the electronic repeaters usage, known as 3R repeaters, involving typical distances between them around 60 – 70 km. This problem has been solved through the availability of optical amplifiers, which directly amplify the signals in the optical domain, without the need to use the electrical domain, against what 3R repeaters do. This has been the step that
allowed the entrance into the photonic era (all-optical transmission).

By 1990 the first amplifying fibers doped with erbium, known as EDFA’s (erbium doped fiber amplifiers), were developed and became commercially available. They operated on the third window, they had a considerable bandwidth and they used semiconductors lasers for the pumping action. EDFA’s allowed the distance between amplifiers to rise to 60 – 100 km.

The fourth generation of optical communications systems is the first one to be truly photonic. In this generation there is the usage of optical amplification, in order to permit greater distances between amplifiers and to improve systems transparency. Besides that it was also used a multiplexing technique in the wavelength domain, or WDM (wavelength division multiplexing), in order to increase the binary rate.

Now we are moving towards the fifth generation of optical communications systems. The problem with losses was solved by the introduction of amplifying fibers, so that dispersion became the most important one to be solved. Various techniques have been considered in order to find a solution for this problem: dispersion compensation, as a way to improve existing systems; dispersion management, as a foundation to new systems development and soliton systems, as a revolution in the optical communications systems domain. In all cases there exist some common factors, such as the optical amplification over long distances (usage of EDFA’s on the third window) and the rise of the binary rate (usage of WDM and the corresponding dispersion management).

2. SEMICONDUCTOR LASERS

A semiconductor laser is a semiconductor optical cavity where it is present an active environment capable of amplifying an optical signal. While the active environment works like a laser amplifier, the cavity provides the feedback mechanism that causes the conversion from amplification into oscillation and, besides that, the cavity is where the selection of the laser oscillating frequencies occurs.

The fast evolution of computers processing capabilities allows the consideration of elaborated mathematical models that reproduce very accurately the behavior of semiconductor lasers, as well as to overcome the growing complexity of numerical methods of calculation.

2.1. Laser Model: Stationary Regime

The produced models are based on Maxwell’s laws that can be reduced to the dominated by rate equations, which in stationary regime [6],

\[ \frac{dS}{dt} = \frac{dN}{dt} = 0 \]  

has the following appearance

\[ G_0 S_0 + \beta p R_{sp}^{(0)} = \frac{S_0}{\tau_p} \]  

\[ G_p S_0 + \frac{N_0}{\tau_c} = \frac{I_b}{q} \]

where \( N_0 \) and \( S_0 \) correspond respectively to the number of electrons and photons.

Taking into consideration both the most relevant laser attributes and the above information, we can obtain the threshold current:

\[ I_{th} = q \frac{N_{th}}{\tau_c} \]

Under this model, the population of electrons is constant (ie, not a function of current injection).

\[ N_{th} = N_t + \frac{1}{G_s \tau_p} \]  

For a simulation of a laser, we will study three cases: in the first one we consider \( I_o=1.1 I_{th} ; I_m=I_{th} \); in the second \( I_o=2 I_{th} ; I_m=I_{th} \) and in the third \( I_o=0.8 I_{th} ; I_m=3 I_{th} \)

1\(^{st}\) Case : \( I_o=1.1 \times I_{th} ; I_m=I_{th} \): \( I(t)=1.1 I_{th} + I_{th} \cdot \text{rect} \left( \frac{t-T/2}{T} \right) \)

![Fig. 2.1: Injection current for T=0.5ns](image)
Evolução do número de fotões na cavidade laser

Fig. 2.2: Evolution of the number of photons for $T=0,5\text{ns}$.

Fig. 2.3: Evolution of the number of electrons, $N$ normalized to $N_0$ ($I_0 > I_{th}$) for $T=0,5\text{ns}$

We can see, based on the previous simulations, that the laser is behaving correctly, as expected, because the injection current has a value that is superior to the oscillation threshold and so there is a population inversion, which means that only exists emission of photons above the value of the threshold current, necessary to the stimulated emission. When we observe the previous figures, we can verify that the number of electrons quickly rises, in an opposite way when compared to the number of photons, when the injection current $I_0$ is applied, due to the passage of the electrons from the valence to the conduction band.

The growth of the number of electrons will later cause a rise of the stimulated emission rate which provokes a fast growth of the number of photons. This rise originates a radioactive recombination that is characterized by the reduction of the number of electrons inside the cavity, in consequence of the transition of the electrons from the valence to the conduction band. This process is going to originate once more a rise of the number of electrons while the number of photons decreases, as stated before, and these events will occur in succession. We can then understand the oscillatory behavior between electrons and photons inside the laser’s cavity. When the current impulse $T$ ends, the oscillation tends to stabilize, and the number of both electrons and photons are going to converge to constant values.

2$^\text{nd}$ Case: $I_0=2 \times I_{th}$; $I_m=I_{th}$;

$$I(t)= 2 \ I_{th} + I_{th} \cdot \text{rect} \left( \frac{t-T/2}{T} \right)$$

Fig. 2.4: Injection current for $T=0,5\text{ns}$

Fig. 2.5: Evolution of the number of photons for $T=0,5\text{ns}$.

Fig. 2.6: Evolution of the number of electrons, $N$ normalized to $N_0$ ($I_0 > I_{th}$) for $T=0,5\text{ns}$

The occurrences in the second case are practically the same that we found in the first one, because both injection currents have an intensity superior to the threshold current, though in this second case it happens that the number of both electrons and photons tend to stabilize comparatively faster, due to the fact that the injection current has a superior value.

3$^\text{rd}$ Case: $I_0=0.8 \times I_{th}$; $I_m=3 \times I_{th}$

$$I(t)= 0.8 \ I_{th} + 3 \ I_{th} \cdot \text{rect} \left( \frac{t-T/2}{T} \right)$$
After solving some equations, we get:
\[ \beta + i \beta = 0 \]
\[ \beta = 0 \text{ and } \alpha = 0 \]

The stimulated and spontaneous emission provoke the balance of photons, making the whole process to repeat all over again, and the number of both electrons and photons will stabilize since the moment the current pulse ends. At this point \( N \) is going to tend to \( N_0 \) and \( S \) to 0. As \( N_0 \) is not reached no photons can be created and so the existing ones are absorbed by the material.

### 3. PULSE PROPAGATION IN LINEAR REGIME

The impulses that are propagating in an optical fiber, in the linear regime, suffer a time enlargement due to the dispersion of the group velocity (GVD), which causes inter-symbolic interference.

If \( A(0,t) \) is an impulse at the entry of the fiber, \( z = 0 \), and considering that the electric field in that point is linearly polarized along the \( x \) axis, then we have [3]:

\[ E(x,y,0,t) = \hat{s} E(x,y,0,t) \]  \hspace{1cm} (3.1)

Starting from the previous equation and bearing in mind [3], we obtain:

\[ E(x,y,z,t) = E_0 F(x,y) A(z,t) \exp[i(\beta_0 z - \omega_0 t)] \]  \hspace{1cm} (3.2)

Now we are going to calculate the function \( A(z,t) \) starting from \( A(0,t) \). After solving some equations [3], we reach

\[ \frac{\partial A}{\partial z} = i \sum_{m=1}^{\infty} \frac{\beta}{m!} A_m(z,t) - \frac{\alpha}{2} A(z,t) \]  \hspace{1cm} (3.3)

and then

\[ \frac{\partial A}{\partial z} + \sum_{m=1}^{\infty} \frac{i m^{-1} \beta_m}{m!} \frac{\partial^m A}{\partial t^m} + \frac{\alpha}{2} A = 0. \]  \hspace{1cm} (3.4)

Discarding all terms of superior order, we finally get

\[ \frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{1}{6} \beta_3 A + \frac{\alpha}{2} A = 0 \]  \hspace{1cm} (3.5)

#### 3.1 Numerical Resolution

In order to make the numerical simulation of the impulse propagation in the linear regime, using the Matlab tool, we consider to be negligible both the losses and the dispersive effects, that means \( \beta_1 = 0 \) and \( \alpha = 0 \).

Then equation (3.5) becomes:

\[ \frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} = 0. \]  \hspace{1cm} (3.6)
In order to normalize the impulse propagation equation in the linear regime, we have considered the following change of variables:

\[ \zeta = \frac{z}{L_D} \]  

(3.7)

\[ \tau = \frac{t - \beta z}{\tau_0} \]  

(3.8)

\[ L_D = \frac{\tau_0^2}{|\beta|} \]  

(3.9)

where \( L_D \) is the dispersion length and \( \tau \) and \( \zeta \) respectively are dimensionless variables that correspond to time and space.

Next we are going to rewrite the former equations in terms of these new variables. We start with the linear differential equation that governs the impulse propagation inside the fiber. Let us then establish a relation among the operators that were used:

\[ \frac{\partial}{\partial \zeta} = \frac{1}{L_D} \frac{\partial}{\partial \zeta} - \frac{\beta}{\tau_0} \frac{\partial}{\partial \tau} \]  

(3.10)

\[ \frac{\partial}{\partial \tau} = \frac{1}{\tau_0} \frac{\partial}{\partial \tau} \]  

(3.11)

Writing again the linear equation in a more simplified way, we obtain:

\[ \frac{\partial A}{\partial \zeta} + i \frac{1}{2} \text{sgn}(\beta) \frac{\partial^2 A}{\partial \tau^2} = 0 \]  

(3.12)

If we apply the Fourier transformation to the previous equation and considering \( \zeta \) to be a normalized frequency so that:

\[ \zeta = \Omega \tau_0 = (\omega - \omega_0) \tau_0 \]  

(3.13)

we get

\[ \frac{\partial A(\zeta, \xi)}{\partial \zeta} = i \left( \frac{1}{2} \text{sgn}(\beta) \xi \right) A(\zeta, \xi) \]  

(3.14)

which solution is

\[ A(\zeta, \xi) = A(0, \xi) \exp \left[ i \left( \frac{1}{2} \text{sgn}(\beta) \xi \right) \zeta \right] \]  

(3.15)

In order to calculate the spectral value of the impulse at any position \( \zeta \) based on its initial characteristics, it will be necessary to perform the next three steps of a numeric resolution:

1- FFT calculation

\[ A(0, \xi) = FFT \{ A(0, \tau) \} \]  

(3.16)

2- \( A(\zeta, \xi) \) calculation

\[ A(\zeta, \xi) = A(0, \xi) \exp \left[ i \left( \frac{1}{2} \text{sgn}(\beta) \xi \right) \zeta \right] \]  

(3.17)

3- IFFT calculation

\[ A(\zeta, \xi) = IFFT \{ A(\zeta, \xi) \} \]  

(3.18)

We are going to simulate the behavior of a fiber and the effect that DVG has upon the impulse that travels along the fiber, in the case of being a Gaussian one. The value of the DVG parameter, \( \beta \), that is going to be used, is \(-20 \) (ps²/km).

3.2. Gaussian Impulse

Let’s consider the Gaussian impulse given by[3]:

\[ A(0, t) = \exp \left[ - \frac{1 + iC}{2} \left( \frac{t}{\tau_0} \right)^2 \right] \]  

(3.19)

with \( m = 1 \) and \( C = -2; 0; 2 \)

The parameter \( m \) controls how sharp the fall is going to be. The greater its value is, more similar to a square one the impulse seems to be. Let us bear in mind that, when \( m = 1 \), we get a Gaussian pulse.

For the impulse given by equation (3.19) and in the case that the chirp parameter equals zero, \( C=0 \), the expression becomes:

\[ A(0, t) = \exp \left[ - \frac{1}{2} \left( \frac{t}{\tau_0} \right)^2 \right] \]  

(3.20)

In figure 3.1 the Gaussian impulse with \( C=0 \) is graphically presented, both at the entry and at the end of the optical fiber.
Figure 3.1: Gaussian impulse at the entry and at the end of the optical fiber (C=0).

In figure 3.2 we can see the evolution of the Gaussian impulse along the optical fiber (C=0).

Figure 3.2 - Evolution of the Gaussian impulse along the optical fiber (C=0).

In figure 3.3 we can see the evolution of the spectrum of the Gaussian impulse along the optical fiber, when C=0.

Figure 3.3 - Evolution of the spectrum of the Gaussian impulse during its propagation (C=0).

Now let’s see the effect of chirp. In the case that the chirp parameter is C=2, the expression (3.19) becomes

$$A(0,t) = \exp\left[-\frac{1+2i}{2} \left( \frac{t}{t_0} \right)^2 \right] \quad (3.21)$$

In figure 3.4 the Gaussian impulse with C=2 is graphically presented, both at the entry and at the end of the optical fiber.

Figure 3.4 – Gaussian impulse at the entry and at the end of the optical fiber (C=2).

In figure 3.5 we can see the evolution of the Gaussian impulse along the optical fiber (C=2).

Figure 3.5 - Evolution of the Gaussian impulse along the optical fiber (C=2).

In figure 3.6 we can see the evolution of the spectrum of the Gaussian impulse when C=2.

Figure 3.6 - Evolution of the spectrum of the Gaussian impulse during its propagation (C=2).

Through the analysis of the previous graphs we notice that the introduction of a positive chirp, at the beginning of the connection, does not causes initially an enlargement of the impulse, however its impact is limited because it can only be introduced at the entrance of the fiber, and it ends when we reach the maximum narrowing of the pulse. Beyond this point we recover the control of the dispersive effect that keeps causing an enlargement of the pulse, so that we obtain results that are worse when compared to those corresponding to the pulse without chirp at the end of the connection.
In the case that the value of the chirp parameter is $C = -2$, the expression (3.60) becomes

$$A(0,t) = \exp\left[ -\frac{1-2i}{2} \left( \frac{t}{t_0} \right)^2 \right]$$

(3.22)

In figure 3.7 the Gaussian impulse when $C = -2$ is graphically presented, both at the entry and at the end of the optical fiber.

In figure 3.8 we can see the evolution of the Gaussian impulse along the optical fiber ($C = -2$).

In figure 3.9 we can see the evolution of the specter of the Gaussian impulse when $C = -2$.

We can verify that the presence of a negative chirp provokes a raise of the width of its spectral component. This phenomenon causes a worse situation than the one that was present in the impulse without chirp, so its application reveals to be inadequate.

### 3.2 - Attenuation

Next we are going to address the impact of the fiber attenuation regarding the propagation of the pulses that travel along the fiber.

According to equation (3.6) and leaving apart only the dispersive effect, that means $\beta_i = 0$, we get

$$\frac{\partial A}{\partial \zeta} + \beta_1 \frac{\partial A}{\partial t} + i \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + A \frac{\alpha}{2} = 0$$

(3.23)

and bearing in mind the equations from (3.7) to (3.18) we come to [2][5]

$$\frac{\partial A}{\partial \zeta} + i \frac{1}{2} \frac{\partial^2 A}{\partial t^2} + A \frac{\alpha}{2} \frac{L_d}{L_d} = 0$$

(3.24)

If we apply the Fourier Transform to the previous equation and considering $\zeta$ to be a normalized frequency such that

$$\zeta = \Omega \tau_0 = (\omega - \omega_0) \tau_0$$

(3.25)

we find

$$\frac{\partial A(\zeta, \xi)}{\partial \zeta} = i \left[ \frac{1}{2} \frac{\partial^2 A}{\partial t^2} \right] A(\zeta, \xi)$$

(3.26)

which solution is

$$A(\zeta, \xi) = A(0, \xi) \exp \left\{ \left[ \frac{1}{2} \frac{\partial^2 A}{\partial t^2} \right] \zeta \right\}$$

(3.27)

Next we are going to perform some more simulations in order to analyze the impact of the optical fiber attenuation on the pulses propagation:

Considering the value of the fiber attenuation $\alpha = 0.2$ dB/km, the value of the dispersion length in the fiber $L_d = 1000$ km and a value of $\zeta = 0.01$ (that is, we are facing a fiber that is 10 km long, according to equation 3.7), we obtain:

![Figure 3.10 – Spectrum evolution of the gaussian pulse for $\zeta = 0.01$, $Ld=1000km$ and $\alpha = 0.2dB/km$](image)
If we increase the fiber attenuation to the value $\alpha = 1$ dB/km, we get:

![Figure 3.11 – Spectrum evolution of the gaussian pulse for $\zeta = 0.01$, $L_d=1000$km and $\alpha = 1$dB/km](image)

Considering the value of the fiber attenuation $\alpha = 0.2$ dB/km, the value of the dispersion length in the fiber $L_d = 2000$ km and a value of $\zeta = 0.001$ (that is, we are facing a fiber that is 2 km long, according to equation 3.7), we obtain:

![Figure 3.12 – Spectrum evolution of the gaussian pulse for $\zeta = 0.001$, $L_d=2000$km and $\alpha = 0.2$dB/km](image)

If we increase the fiber attenuation to the value $\alpha = 1$ dB/km, we get:

![Figure 3.13 – Spectrum evolution of the gaussian pulse for $\zeta = 0.001$, $L_d=2000$km and $\alpha = 1$dB/km](image)

We find that propagation is influenced by the inter-symbolic interference that, by its turn, directly depends on dispersion and on impulse enlargement. It has been possible to verify the impact of the *chirp* parameter at the level of dispersion correction and to check that for positive *chirp* values that interference becomes more intense. There is a compromise between the negative *chirp* and the *chirp* absence: under the presence of negative *chirp* there is a less enlargement of the pulse until a certain distant point, beyond which its lack produces better results.

We can conclude that the ideal solution would consist of manipulating the use of *chirp*, however it is impossible to materialize that solution, since in this case we should have a linear chirp effect, that does not exist in the real world. By definition, *chirp* is a dynamic deviation in the frequency domain provoked by the internal modulation of the laser. Now, being dynamic, we are not able to use it as linear in a concrete situation.

Following the fiber attenuation introduction, we notice from the obtained simulations, that when the parameter $\alpha$, corresponding to the fiber attenuation, becomes higher, the amplitude of the Gaussian impulses starts considerably decreasing, and that for very long distances and for very high attenuation values, the pulse presents a very short amplitude. Considering the attenuation value to be 0.2 dB, the attenuation influence on the pulse propagation will not be very important, and the results that we get are very similar to those that were obtained before related to the ideal case ($\alpha = 0$).

4. OPTICAL AMPLIFIERS

The optical amplifiers only operate in the optical domain, without any conversions to the electrical domain. In this chapter we will analyze the behavior of two different types of amplifiers that are used with optical fibers: the erbium doped fiber amplifiers, EDFA’s, and the Raman amplifiers.

4.1 Erbium Doped Fiber Amplifiers (EDFA’s)

Prior to 1990 the main telecommunication services were based on electrical transmission. By the end of 1980 decade the third commercial generation of optical communication systems started to appear. These systems operated in the third window (1.55μm), with binary rates up to 10 Gb/s [7].

The most important problem regarding the third generation systems is due to the usage of electronic repeaters, known by 3R regenerators, which presented typical distances between them of 60 – 70 km.

This problem has been solved by the appearance of the erbium doped fiber amplifiers or EDFA’s, in which the pumping is made by semiconductor lasers. This caused a great revolution regarding the conception of optical communication systems. EDFA’s, whose commercialization started to occur during 1990, allowed the distance between amplifiers to rise up to 60-100 km, besides the ability to
directly amplify signals in the optical domain, without the need of the electrical domain, in an opposite way compared to what happens with the usage of 3R regenerators. This has been the step to entrance the photonic era.

An EDFA is an optical fiber, doped with erbium ions, that works in the third window, around 1550nm. These ions present a radioactive decay in which the lifetime of the excited state due to pumping is large enough. The inserted power is maximal at the pumping moment, then starts to decrease as time passes, and is progressively distributed among the various channels that are present, provoking gain in the fiber through the amplification originated in those channels. This action is performed by a laser that excites the ions so that they move to upper energy levels.

4.1.1. Amplification gain

The amplification’s gain is given by gain coefficient that can be calculated with following expression[7]:

\[
g_k = (\alpha_k + \gamma_k) \frac{N_2}{\rho} - a_k \tag{4.1}
\]

where \(a_k\) is the absorption coefficient represented by

\[
a_k = \Gamma_k \sigma_m \rho
\tag{4.2}
\]

\(\Gamma_k\) is the optical confinement factor, \(\sigma_m\) is the efficient section of emission and \(\rho\) is the effective ray of erbium ions concentration. In parallel, the parameter \(\gamma_k\) is the emission coefficient given by

\[
\gamma_k = \Gamma_k \sigma_m \rho = \eta_k a_k
\tag{4.3}
\]

where \(\eta_k\) is the coefficient that relates the efficient sections of emission and absorption

4.1.2. Amplification of a WDM signal

The amplification of a WDM signal can be translated through the following equation:

\[
\frac{dp_k}{dz} = g_k p_k
\tag{4.4}
\]

with

\[
g_k = \frac{\alpha_k}{1 + \sum_j \eta_j} \left(1 + \sum_{j \neq k} \frac{\eta_k - \eta_j}{1 + \eta_j} p_j \right)
\tag{4.5}
\]

4.1.3. Optimal length

The optimal length of the EDFA, \(L_{opt}\), is the value for which is guaranteed the maximum gain in the end of the amplification for one determined input power, that is, it verifies the expression:

\[
\left. \frac{dp}{dz} \right|_{z=L_{opt}} = 0.
\tag{4.6}
\]

The optimal length can be obtained by

\[
L_{opt} = \frac{1}{\alpha_p U_s} ( \frac{1}{\alpha_s} - \frac{1}{\alpha_p} ) \left[ \ln G + (G-1) p_0 \right]
\tag{4.7}
\]

In figure 4.1 we can see a WDM signal with four channels represented at different colors. Although identical input power, we can see different gains and maximums for each channel centered at different wavelength.

![Figure 4.1: Evolution of the power introduced in a WDM signal throughout the length of the amplification](image)

We can see that an EDFA is very sensible to its length and the wavelength of transmission. Depending on the type of signal to amplify, it is necessary to choose a specific optimal length to optimize the behavior of the EDFA.

4.2. Raman amplifiers

4.2.1. Raman scattering

Spontaneous Raman scattering (SRS) occurs in optical fibers when a pump wave is scattered by the silica molecules. Some pump photons give up their energy to create other photons of reduced energy at a lower frequency; the remaining energy is absorbed by silica molecules, which end up in an excited vibrational state.

The Raman scattering process becomes stimulated if the pump power exceeds a threshold value. SRS can occur in both the forward and backward directions in optical fibers. In the case of forward SRS, the feedback process is governed by the following set of two coupled equations [1]:

\[
\frac{dI_p}{dz} = -g_R I_p I_s - a_p I_p
\tag{4.8}
\]

\[
\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s
\tag{4.9}
\]
where \( g_R \) is the SRS gain. In the case of backward SRS, a minus sign is added in front of the derivative in Eq. (4.9).

### 4.3.2. Raman Gain and Bandwidth

The Raman-gain spectrum of silica fibers is shown in figure 4.2:

![Raman Gain Spectrum](image)

Figure 4.2: a) Raman gain spectrum of fused silica at \( \lambda_p = 1 \) μm. b) energy levels participating in the SRS process [1].

The Raman-gain spectrum of silica fibers is shown in Figure 4.2; its broadband nature is a consequence of the amorphous nature of glass. The Raman-gain coefficient \( g_R \) is related to the optical gain \( g(z) \), as \( g = g_R I_p(z) \), where \( I_p \) is the pump intensity. In terms of the pump power \( P_p \), the gain can be written as

\[
g(\omega) = g_R(\omega) \left( \frac{P_p}{a_p} \right)
\]

(4.10)

where \( a_p \) is the cross-sectional area of the pump beam inside the fiber.

More specifically, vibrational energy levels of silica molecules merge together to form a band. As a result, the Stokes frequency \( \omega_s \) can differ from the pump frequency \( \omega_p \) over a wide range. The maximum gain occurs when the Raman shift \( \Omega_R \equiv \omega_p - \omega_s \) is about 13 THz.

The threshold power \( P_{th} \) is defined as the incident power at which half of the pump power is transferred to the Stokes field at the output end of a fiber of length \( L \). It is estimated from [1]

\[
g_R P_{th} L_{\text{eff}}/ A_{\text{eff}} \approx 16 \tag{4.11}
\]

where \( g_R \) is the peak value of the Raman gain, \( L_{\text{eff}} \) can be approximated by \( 1/ \alpha \) [1]. If we replace \( A_{\text{eff}} \) by \( \pi w^2 \), where \( w \) is the spot size, \( P_{th} \) for SRS is given by

\[
P_{th} \approx 16 \alpha (\pi w^2)/ g_R \tag{4.12}
\]

SRS is not a limiting factor for single-channel lightwave systems. However, it affects the performance of WDM systems considerably.

SRS can be used to advantage while designing optical communication systems because they can amplify an optical signal by transferring energy to it from a pump beam whose wavelength is suitably chosen. SRS is especially useful because of its extremely large bandwidth. Indeed, the Raman gain is used routinely for compensating fiber losses in modern lightwave systems.

The measured gain profile of a Raman amplifier is shown in figure 4.3:

![Measured Gain Profile](image)

Figure 4.3: Measured gain profile of a Raman amplifier with nearly flat gain over an 80-nm bandwidth. Pump frequencies and powers used are shown on the right [1].

The wide bandwidth of the fiber with Raman amplifiers makes them attractive for applications regarding optical fiber communications. However it is necessary a relatively high amount of pumping power in order to obtain a high amplification factor. If longer fibers are to be used, the power needed can be reduced, but in this case the fiber losses must be included.

### 5. CONCLUSIONS

The direct modulation of a semiconductor laser, through the usage of an injection current, is a process that reveals to be insufficiently adequate to high transmission rates. In such a case it is better to use electro-optical modulation.

The group velocity dispersion is a limiting factor of the optical communications systems, so that compensation mechanisms must be utilized. Besides that, both chirp and attenuation also contribute to a reduction of the performance of such systems.

EDFA’s and Raman amplifiers have demonstrated to be a good solution regarding attenuation issues and they also have the advantage of working only in the optical domain.
REFERENCES