Optical Fiber Systems with Dispersion Compensation

Ana Filipa Fazenda Cabete
Instituto Superior Técnico, Technical University of Lisbon, Portugal.
anafilipacabete@gmail.com

Abstract

Pulse propagation in optical fibers, associated dispersion phenomenon and effective techniques that are able to solve this degrading effect are addressed.

The work begins with a brief description of the several types of dispersion, including these into the equation that governs pulse propagation on linear regime for a single-mode fiber. Studies of dispersive effects (group velocity dispersion and higher order dispersion) are carried out for various types of pulses.

The main techniques used to compensate the dispersive effects in the linear regime are analyzed. The first one is based on dispersion compensating fibers, which operation mode is described and, for several pulses, simulations are done considering the group velocity dispersion, higher order dispersion and both simultaneously. Another compensation approach is using fiber Bragg gratings. In this topic, theoretical foundations essential for understanding the Bragg gratings are described along with uniform and non-uniform Bragg gratings parameters simulations.

Finally, optical fibers are analyzed as non-linear transmission media. As in the linear regime, the equation that governs the pulse propagation in the nonlinear regime is derived. Dispersive effects of this type of regime are identified, namely the group velocity dispersion and self-phase modulation, which equilibrium determines the propagation of a special type of pulses, the Soliton. Simulations for this type of pulses are presented, as well as the study of one of the most common non-linear regime dispersion compensation technique: the dispersion decreasing fibers.

Keywords: Pulse Propagation in Optical Fibers, Group Velocity Dispersion, Higher Order Dispersion, Dispersion Compensation, Dispersion Compensating Fibers, Fiber Bragg Gratings, Self-Phase Modulation, Solitons, Decreasing Dispersion Fibers.

1 INTRODUCTION

A communication system is a link between two points through which information is transmitted using a carrier. An optical communication system uses the electromagnetic waves from the optical spectrum, contained between the far infrared (100µm) and the ultraviolet (0.05µm) to carry the information. The basic components of an optical communication system are: an optical transmitter, that converts the electrical signal into optical signals sending them to the optical fiber that represents the transmission media and an optical receiver, that receives the optical signal converting it to an electrical signal [1].

The work developed by the physicists Daniel Colladon and Jacques Babinet was essential to the development of optical fiber based communication systems. In the decade of 1840, they were the first to demonstrate the possibility of redirecting light through refraction, the fundamental principle for light propagation in optical fibers. The experiment conducted by John Tyndall in 1854, gave him the credit for Colladon’s and Babinet’s ideas. In the second half of the twentieth century, optical fibers suffered major breakthroughs. In 1952, a partnership between Brian O’Brien and Narinder Kapany resulted in the development of the first communication system to ever use glass fibers, transmitting information through pulses of light. In the 1960s, optical communication systems faced two major obstacles. First, there was a need for a source capable of generating optical pulses. Secondly, the inexistence of an adequate transmission media. The first problem was solved with the development of Laser, that allowed carrying up to 10000 times more information than the highest radio frequencies used. Still, it wasn’t an adequate media for free space propagation due to the sensibility to environmental conditions. In 1966, Charles Kao and George Hockman proposed optical fibers as the ideal light propagation media [2], as long as losses were of the order of 20 dB/km. This goal was reached by Robert Maurer, Donald Keck and Peter Schultz in 1970, making viable the use of optical fibers in communication systems.

In the last decades several generations of optical fiber communication systems were developed. The development of optical amplifiers allowed the amplification of signals without the use of electronics. Erbium doped fiber amplifiers (ED-FAs) [2] were the ones that mattered the most, allowing the increase in the distance between repeaters. Currently the fourth generation uses optical amplification to extend the distance between amplifiers and wavelength division multiplexing (WDM) technique that allows higher bit rates [2]. The fifth generation is highly anticipated. Having solved the losses problems by using amplifying fibers, dispersion has become the greater problem to be addressed. To eliminate this problem, several techniques have been developed, such as compensating dispersion systems, dispersion management systems and soliton based systems [2]. All this solutions make use of optical amplification, WDM and dispersion
Optical fibers revolutionized the communication systems. The need to increase the traffic capacity, results from the generalization of new technologies. Given all the advantages and capabilities of optical fibers, it is possible to assess that the use of these devices as a mean of transmission (FTTx networks), is the most appropriate way to meet these requirements.

2 PULSE PROPAGATION IN A OPTICAL FIBER

Besides fiber losses ($\alpha$), that reduce the available optical power increasing the bit error rate (BER) in the reception limiting the maximum distance between transmitter and receiver, the dispersion is another major degrading phenomena that affects pulse propagation. The time dispersion limits the bandwidth because it causes broadening of the optical pulse. In long distance communication systems it can cause pulses to interfere with each other (intersymbolic interference (ISI)) [2] and consequently information loss. The main advantage of single mode fibers (SMF), the ones that are relevant for this work, is that intermodal dispersion is absent only by one single mode. However, in this type of fibers there is still a dispersion source entitled group velocity dispersion (GVD).

2.1 Time Dispersion in SMF

For a monomodal fiber, the group velocity relates with the group index $n_g$ by

$$v_g = \frac{c}{n_g}.$$  \hspace{1cm} (1)

Considering the fact that the frequency dependence causes a time delay, one has

$$D = -\frac{2\pi c}{\lambda^2} \beta_2,$$  \hspace{1cm} (2)

where $D$ is the dispersion coefficient and $\beta_2$ is the GVD coefficient responsible for the pulse broadening inside the fiber. It is given by

$$\beta_2 = \frac{d^2\beta}{d\omega^2}.$$  \hspace{1cm} (3)

The GVD is the result of different spectral components of the pulse traveling at a slightly different group velocities due to the variation of the refractive index of the fiber core and cladding with the frequency. The dispersion coefficient includes both the material dispersion ($D_M$) and the waveguide dispersion ($D_W$). The first one is a consequence of existing changes in the cladding’s refractive index with the wavelength and the waveguide dispersion occurs because of the light-confinement problem in the fiber core. These contributions are given by

$$D_M = M_2 = \frac{1}{c} \frac{\partial N_2}{\partial \lambda}$$  \hspace{1cm} (4)

$$D_W = M_2 \Delta \frac{d(\nu b)}{d\nu} - \frac{N_2^2}{n_2 \lambda c} \left[ \nu \frac{d^2(\nu b)}{d\nu^2} \right].$$  \hspace{1cm} (5)

where $c$ is the light velocity, $N_2$ is the group index of the cladding, $\nu$ is the normalized frequency and $b$ is the normalized propagation constant.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{Total dispersion $D$, material dispersion $D_M$ and waveguide dispersion $D_W$, in a conventional SMF [1].}
\end{figure}

$D_M$ has a positive slope and $D_W$ a negative slope. $D \approx 0$ when the fiber is operating near the zero dispersion wavelength $\lambda_{ZD}$. However, the dispersion effects do not disappear completely. In this case, and when the pulse is ultrashort, one has to consider the effects of the higher order dispersion (HOD), which is governed by the dispersion slope $S = \frac{\partial D}{\partial \lambda}$, which equals

$$S = \frac{4\pi c}{\lambda N} \beta_2 + \left( \frac{2\pi c}{\lambda^2} \right)^2 \beta_3 = \frac{S_D}{4} \left[ 1 + 3 \left( \frac{\lambda_{ZD}}{\lambda} \right)^4 \right].$$  \hspace{1cm} (6)

When $\lambda = \lambda_{ZD}$ and $\beta_2 = 0$, $S$ is proportional to the higher order dispersion coefficient $\beta_3$, which equals

$$\beta_3 = \frac{\partial \beta_2}{\partial \omega}.$$  \hspace{1cm} (7)

2.2 Pulse Propagation Equation in the Linear Regime

The pulse propagation equation in the linear regime is derived in order to determine the shape of the pulse at the end of the link.

Assuming that the refractive index is invariant and considering one pulse $A(0,t)$ at the input of the fiber with the carrier frequency of $\omega_0$, the field equations are

$$E(x, y, 0, t) = \hat{x} F(x, y) B(0, t),$$  \hspace{1cm} (8)

$$B(0, t) = A(0,t) \exp(-i\omega_0 t).$$  \hspace{1cm} (9)

Applying the properties of Fourier transform, the amplitude can be written as

$$B(z, t) = A(z,t) \exp[i(\beta_0 z - \omega_0 t)].$$  \hspace{1cm} (10)
To find the basic propagation equation it is useful to determine $A(z, t)$ in terms of $A(0, t)$. Considering losses (attenuation coefficient $\alpha$), it is obtained the following equation

$$\frac{\partial A}{\partial z} + \sum_{m=1}^{\infty} \frac{i^{m-1}}{m!} \beta_m \frac{\partial^m A}{\partial t^m} + \frac{\alpha}{2} A = 0. \quad (11)$$

Ignoring the fourth and greater propagation terms ($m \geq 4$) and $\alpha$, it is reached

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{1}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial t^3} = 0. \quad (12)$$

This differential equation can be rewritten applying the following normalized variables

$$\zeta = \frac{z}{L_D}, \tau = \frac{t - \beta_1 z}{\tau_0}, L_D = \frac{\tau_0^2}{|\beta_2|}. \quad (13)$$

Then it is obtained

$$\frac{\partial A}{\partial \zeta} + i \frac{1}{2} \beta_2 \frac{L_D}{\tau_0^2} \frac{\partial^2 A}{\partial \tau^2} - \frac{1}{6} \beta_3 \frac{L_D}{\tau_0^3} \frac{\partial^3 A}{\partial \tau^3} = 0. \quad (14)$$

### 2.3 Merit Figure

The pulse broadening caused by dispersion, has influence on the intersymbolic interference. As a consequence, the bit rate is affected. To study the repercussions in this parameter, it is essential to determine the effective width of the pulse, given by

$$\sigma(z) = \sqrt{(t^2) - \langle t \rangle^2}, \quad (15)$$

where the angle brackets refer to averaging with respect to intensity.

Being $V$ the normalized spectral width, considering $V \ll 1$ a reasonable approach for an monomodal laser with a small spectral width and ignoring the HOD, for a gaussian pulse the following equation represents the broadening factor

$$\left(\frac{\sigma}{\sigma_0}\right)^2 = \left(1 + \frac{\beta_2 L}{2\sigma_0^2}\right)^2 + \left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2, \quad (16)$$

where $C$ is the chirp parameter and $L$ the fiber length. Assuming a broadening coefficient $\eta = \frac{\sigma}{\sigma_0}$, the correspondent bit rate is $B$.

Figure 2 shows the effects of the chirp parameter on the broadening coefficient of the pulse along the fiber. For the anomalous region ($\beta_2 < 0$), a negative chirp causes a faster broadening of the pulse. However, for a positive chirp one can observe a pulse contraction in its initial stage. Later on, the effect of the chirp is overruled by the GVD effect.

### Figure 2: Pulse broadening evolution with the normalized distance $\zeta$.

Being

$$x = \frac{\beta_2 L}{2\sigma_0^2} = 2\gamma_0^2 |\beta_2| (B^2 L), \quad (17)$$

and applying it to the equation (16), it is reached the final equation that represents the figure of merit

$$B^2 L = \frac{-C + sgn(\beta_2) \sqrt{\eta^2(1 + C^2) - 1}}{2\gamma_0^2\beta_2(1 + C^2)}. \quad (18)$$

This product is dimensionless and given two or more links, this factor allows to verify which one is the best (the bigger this factor is, the better is the link). It is possible to adjust the values of $B^2$ and $L$ in order to have the best link possible.

### 2.4 Group Velocity Dispersion Effect

This section focuses on the study of the GVD effect on pulses, namely chirped gaussian ones.

#### 2.4.1 Gaussian pulse

A chirped gaussian pulse is described by the following equation

$$A(0, t) = \exp\left[-\frac{1 + iC}{2} \left(\frac{t}{t_0}\right)^2\right]. \quad (19)$$

In order to identify the GVD effects in gaussian pulses, the simulations done for three different chirp values are presented.
Observing the above images, it is possible to conclude that there is a substantial reduction in the pulse amplitude along the fiber. So, for distances bigger than the ones used, the results will be even more degraded. This happens because of the broadening phenomenon that comes with the GVD influence. For $C < 0$ the chirped gaussian pulse broadens faster than the same type of pulse in the absence of frequency chirp ($C = 0$). In the $C > 0$ situation, it is verified that the chirp initially compensates the GVD effects that later in the propagation become dominant.

2.5 Higher Order Dispersion Effect

This section focuses on the study of the HOD effect on pulses, namely gaussian ones.

2.5.1 Gaussian pulse

Although the contribution of GVD dominates in most cases of practical interest, it’s sometimes necessary to include the higher order dispersion, governed by $\beta_3$ [3]. This parameter can’t be ignored in situations where ultra-short pulses are considered (characteristic width $< 5 \text{ps}$) and in cases where the pulse wavelength is very close to the zero dispersion wavelength $\lambda_{ZD}$ ($\beta_2 = 0$) [1].

For this case, it’s considered $L_D' = \frac{\tau_0}{|\beta_3|}$. For one link distance $z = 5L_D'$ and width $\tau_0 = 1 \text{ps}$, Figure 7 represents gaussian pulse shapes for three distinct cases: initial pulse, $L_D' = L_D$ and $\beta_2 = 0$.

The presence of HOD effects changes the pulse shape, causing deformations. For $\beta_2 = 0$, the pulse becomes asymmetric when comparing to the initial pulse presenting strong oscillations in its extreme. When considering $L_D' = L_D$, the pulse is still distorted and remains asymmetric.

It is also important to examine the HOD effects in a chirped gaussian pulse. The next figure, represents the deterioration of a gaussian pulse with the chirp parameter.
The $\beta_3$ parameter is affected by a $C^2$ factor, so for symmetric values of $C$ the evolution of chirp gaussian pulses is similar [4]. Considering Figure 8, it is possible to conclude that the greater $C$ value is, more significant the effects of HOD will be.

3 DISPERSSION COMPENSATION IN LINEAR REGIME

In this section two of the techniques used for compensating the dispersion phenomenon are presented: Dispersion Compensating Fibers (DCF) and Fiber Bragg Gratings (FBG).

3.1 Dispersion Compensating Fibers

The broadening of pulses that occur due to GVD, can be compensated using DCF. This technique allows full dispersion compensation as long as the average optical power of the signal is low enough so that nonlinear effects can be neglected. This technique combines segments of optical fiber with different characteristics in order to reduce the average dispersion of the entire fiber link to zero.

Considering the pulse propagation along two segments of fiber, the correspondent pulse envelope is given by

$$A(L, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A(0, \omega) \exp \left[ \frac{i}{2} \omega^2 (\beta_{21} L_1 + \beta_{22} L_2) - i\omega t \right] d\omega,$$

(20)

where $L = L_1 + L_2$ and $\beta_{2j}$ is the dispersion coefficient of the fiber segment $L_j (j = 1, 2)$. The DCF is such that the factor in $\omega^2$ is cancelled, meaning that

$$\beta_{21} L_1 + \beta_{22} L_2 = 0.$$

(21)

The results obtained for a gaussian pulse are presented in the Figures 9, 10 and 11.

3.2 Fiber Bragg Gratings

Due to recent studies, it is possible to change the refraction index inside the fiber core through ultraviolet light absorption. This photosensitivity allows the fabrication of phase structures inside the fiber core. This enables the formation of phase structures, the Bragg gratings [5].

Bragg gratings are a periodic disturbance of the refraction index along the fiber length. They are formed by a set of elements spaced a certain distance. These segments of optical fiber reflect only the wavelengths that satisfy the Bragg condition and transmit all the others. This way, a FBG acts like a reflective optical filter [1]. This because of the existence of a stop band, the frequency region where the most part of the incident light is reflected back [1]. The Bragg wavelength, where the stop band is centered, is given by

$$\lambda_B = 2\tilde{n}\Lambda,$$

(22)

where $\Lambda$ is the grating period and $\tilde{n}$ is the average mode index. For $\lambda_B$, maximum reflectivity occurs. To analyze the behavior of these structures, it is used the couple-mode equations that describe the coupling between the waves that are transmitted (forward waves) and the ones that are reflected backwards (backward waves).
### 3.2.1 Uniform FBG

A FBG is considered uniform if all its spacial properties remain constant throughout its length. Along the uniform FBG, the two waves referred are given by

\[
\frac{\partial A_f}{\partial z} = i\delta A_f + i\kappa_g A_b \\
-\frac{\partial A_b}{\partial z} = i\delta A_b + i\kappa_g A_f
\]

where \( A_b \) and \( A_f \) are the spectral amplitudes of the two waves, \( \delta \) is the detuning from the Bragg wavelength and \( \kappa_g \) is the coupling coefficient. Solving analytically the couple-mode equations, the expressions obtained for the reflection coefficient \( r_g \) and its phase \( \phi_g \) are

\[
r_g = \frac{A_b(0)}{A_f(0)} = \frac{i\kappa_g \sin(q_g L_g)}{q_g \cos(q_g L_g) - i\delta \sin(q_g L_g)}
\]

\[
\phi_g = -\arctan \left[ \frac{\text{Im}(r_g)}{\text{Re}(r_g)} \right],
\]

where \( q_g^2 = \delta^2 - \kappa_g^2 \) and \( L_g \) is the FBG length.

By observing the above figure, it’s possible to conclude that in the stop band region the greater the \( \kappa_g L_g \) product, the more reflectivity approaches its maximum value 100%. However, it is verified the presence of secondary maximums that are justified by the existence of multiple reflections in the FBG extremes. To solve this problem apodisation techniques are used.

From the reflected signal phase, the group delay \( \tau_g \) is given by

\[
\tau_g = \frac{\delta \phi_g}{2\pi c} = -\frac{\lambda^2}{2\pi c} \frac{\partial \phi_g}{\partial \lambda},
\]

and the grating induced dispersion is

\[
D_g = \frac{\partial \tau_g}{\partial \lambda} = -\frac{2\pi c}{\lambda^2} \frac{\partial^2 \phi_g}{\partial \omega^2} = -\frac{2\pi c}{\lambda^2} \beta_{2g},
\]

where \( \beta_{2g} \) is the dispersion coefficient related to the group velocity in FBG.

In Figure 13, it is observed that in the stop band the phase variation is almost linear. So, this region will correspond to a minimum group delay value as can be seen in Figure 14. Consequently, the dispersion value is lower (Figure 15). From this, it’s possible to state that the grating induced dispersion exists only outside the stop band and the bigger the \( \kappa_g L_g \) product is, the higher the dispersion value will be.

Another important parameter is the bandwidth of the grating, given by [6]

\[
\Delta \lambda = \frac{2\lambda_B^2}{2\pi L_g \pi} \sqrt{(\kappa_g L_g)^2 + (\pi)^2}.
\]

The smaller the grating length \( L_g \), the bigger the band-
width will be. However, this fact leads to an undesirable situation related to the fact that the value of the maximum reflectivity decreases. Although FBG are used for dispersion compensation, they have a very narrow stop band width which forbids its use for very high bit rates [1].

### 3.2.2 Chirped FBG

Chirped FBG (CFBG) are used for dispersion compensation when considering high bit rates. This type of device enables variation of the Bragg condition throughout its length by varying the physical grating period \( \Lambda(z) \) or by changing the effective mode index \( \tilde{n} \). The grating period variation has a linear characteristic, given by the expression [7]

\[
\Lambda(z) = \Lambda(0) + C\Lambda z, \tag{30}
\]

where \( \Lambda(0) \) represents the grating spacial period in one of its extremes and \( C\Lambda \) the aperiodicity coefficient.

Hence, it is possible to obtain a linear aperiodicity which is caused by an increase in the Bragg wavelength. Consequently, a shift on the stop band center occurs, changing it to progressively lower frequencies as the spacial period increases. Different frequency components of an incident optical pulse are reflected at different points, depending on where the Bragg condition is satisfied. This way, for a situation that corresponds to anomalous GVD, the high frequency components of the pulse are the first to be reflected and the lower frequency ones are reflected later [1]. The remaining wavelengths are reflected normally.

A CFBG has a wider bandwidth than a uniform FBG. This fact is related to the fact that the Bragg condition is verified, in CFBG, for a bigger number of spectral components.

The group delay \( \tau_g \) in CFBG is given by [1]

\[
\tau_g = \frac{2\tilde{n}L_g}{c}. \tag{31}
\]

The dispersion in a CFBG, where the optical period varies linearly along its length, is given by

\[
D_g = \frac{2\tilde{n}L_g}{c\Delta\lambda}, \tag{32}
\]

where \( \Delta\lambda = 2\tilde{n}L_gC\Lambda \) represents the difference between the spectral components reflected at the CFBG extremes. Then, it is obtained

\[
D_g = \frac{1}{cC\Lambda}. \tag{33}
\]
the aperiodicity coefficient (Figure 19). This way, it is possible to use a CFBG with length in the order of centimeters to compensate the GVD effects in a SMF with approximately hundreds of kilometers.

4 DISPERSION COMPENSATION IN NONLINEAR REGIME

All the former studies were made considering an optical fiber as a linear propagation medium. It happens that not always this devices have this type of behavior. In fact, when considering high optical powers or long transmission distances, nonlinear effects appear and cannot be neglected. When the electromagnetic field intensity increases, there is a consequent change of the optical fiber refraction index [8]. This nonlinear effect is known as the Kerr effect. In this, it is noticed a nonlinear phase deviation $\phi_{NL}$ which is called self-phase modulation (SPM). So, in this regime, SPM phenomenon and GVD limit the system performance by causing spectral broadening of optical pulses. However, for the anomalous region a fascinating manifestation occurs when there is a balance between both GVD and SFM: the appearance of a special type of pulse, the soliton. This section focuses on pulse propagation in the nonlinear regime, identifying the behavior of systems based on optical solitons and presenting one of the most common solutions in dispersion compensation for this regime, the dispersion decreasing fibers (DDF).

4.1 Optical Solitons

Using normalized variables, the expression that rules the pulse propagation in nonlinear dispersive regime is given by

$$i \frac{\partial u}{\partial \zeta} - \frac{1}{2} \text{sgn}(\beta_2) \frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = -i \frac{\Gamma}{2} u + ik \frac{\partial u}{\partial \tau^3}. \quad (34)$$

Neglecting the losses ($\Gamma = 0$) and the HOD ($k = 0$), equation (34) is reduced to

$$i \frac{\partial u}{\partial \zeta} - \frac{1}{2} \text{sgn}(\beta_2) \frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0, \quad (35)$$

which represents the nonlinear Schrodinger (NLS) equation.

Through the inverse scattering transform (IST) method, it’s possible to prove that the NLS equation accepts solutions like [9]

$$\mu(\zeta, \tau) = \text{sech}(\tau) \exp \left[ i \frac{\zeta}{2} \right]. \quad (36)$$

Any incident pulse has the following shape

$$\mu(0, \tau) = N \text{sech}(\tau), \quad (37)$$

where $N = L_D/L_{NL}$, $L_D$ is the dispersion length and $L_{NL}$ is the nonlinear length. The first order solution ($N = 1$) corresponds to the fundamental soliton. This type of pulse has a special property related to the fact that its shape remains constant along propagation (Figure 20). Unlike of what happens with the fundamental soliton, the second and third order solitons ($N = 2$ and $N = 3$, respectively) change its shape along propagation (Figure 21). Nevertheless, a periodic evolution is observed recovering totally its original shape in a soliton period $\zeta_0 = \frac{\pi}{2}$.

![Figure 20: Fundamental soliton evolution along the optical fiber.](image)

![Figure 21: Third order soliton evolution along the optical fiber.](image)

In the above case, it can be seen that the pulse width contracts until a maximum value, where the SPM effects are dominant on GVD ones. Next, the situation is reversed, having the dispersion effects ruling on the SPM ones. Consequently, broadening and a decrease in the pulse amplitude is verified. Finally, the several pulse components join and recover completely the initial pulse shape. This happens when the propagation distance equals the soliton period.

Although the higher order solitons can be used for compressing pulses, the fundamental soliton is the most interesting one for current communications systems, because it does not suffer distortion during its propagation.

4.2 Decreasing Dispersion Fibers

The existence of solitons in an optical fiber depends on the balance between GVD and SPM. This same balance, however, can be broken by fiber loss presence. To solve this problem, a dispersion decreasing fiber (DDF) can be used [3].
It is known that the relation between $L_D$ and $L_{NL}$ is given by

$$N^2 = \frac{L_D}{L_{NL}}, \quad (38)$$

and for the fundamental soliton one has $N = 1$. Therefore,

$$\beta_2 = \tau_0^2 \gamma P, \quad (39)$$

where $P = P_0 \exp(-\alpha z)$. Then, it is possible to conclude that

$$\beta_2 = |\beta_2| \exp(-\alpha z), \quad (40)$$

with $\beta_2 = \tau_0^2 \gamma P_0$ and $\gamma$ being the nonlinear coefficient. Equation (40) describes the ideal profile for $\beta_2$ along the fiber in order to solve this problem. However, in practical terms this solution is not easy to implement and so it is common to apply a staircase approximation to equation (40).

Through the results, it can be verified that between 4 and 6 step levels there is an improvement on the amplitude oscillation of the fundamental soliton. For a considerable number of step levels, the approximation becomes almost linear overlapping the ideal function of $\beta_2$. Thus, it may be concluded that the larger the number of step levels used, the better the approximation to the real function and hence the more efficient compensation will be. However, the fact of increasing the number of step levels to improve the approximation requires an increased processing capability [10].
5 CONCLUSION

In this paper the optical fiber dispersion phenomenon, its degrading influences and a few compensating techniques were addressed.

For a SMF, $\beta_2$ (GVD) is responsible for the pulse broadening and ISI that limits the bit rate. Regarding the GVD effects on pulse propagation, a decrease in the pulse amplitude and an increase in its width are expected. Moreover when considering gaussian pulses with chirp parameter $C$, it can be verified that there is an additional broadening effect. However, when considering ultra short pulses or when the GVD coefficient is null, the HOD effects ruled by $\beta_3$ can not be neglected. For this case, a gaussian pulse shows changes in its shape, becoming asymmetric when comparing to the initial pulse and oscillations in the extremes. Chirp parameter in this case also contributes for the pulse deterioration.

Regarding dispersion compensation techniques, the DCF was the first to be addressed. It was proven that it is possible to reduce to zero the average value of dispersion as the pulse initial shape was fully recovered when considering GVD and HOD effects separately. FBG is another technique commonly used. Uniform Bragg gratings act like an optical filter, reflecting only the wavelengths that satisfy the Bragg condition. The most important parameters were studied. This type of Bragg gratings are not efficient for very high bit rates and consequently, CFBG are used. In these, through refractive index changes or by grating period variation it is possible to reflect different wavelengths at different places in the grating. The main parameters were studied, concluding that a CFBG with length in the order of centimeters is able to compensate the GVD effects in a SMF with approximately hundreds of kilometers.

In the nonlinear regime, high electromagnetic field intensities cause a refraction index variation (nonlinear optical Kerr effect). This effect allows the appearance of the SPM phenomenon. Under certain circumstances, it is possible to have an balance between GVD and SPM, allowing the propagation of a special type of pulses, the solitons. These pulses maintain their shape throughout the fiber propagation, which makes them very desirable when considering its application in optical systems. When GVD and SPM effects are not balanced due to fiber losses, it is required a compensation technique. For this goal, the DDF technique was studied. Using a staircase approximation for the ideal dispersion profile, it was shown that the compensation was efficient.

From this study, it was shown that dispersion phenomenon has a deep influence on optical systems and must be considered all times.

6 REFERENCES

[10] Santos, N. M. V-D. N., Dissertação sobre Métodos variacionais aplicados ao estudo das fibras ópticas e técnicas de compensação de dispersão, Setembro 2011.