Characterization of Fiber Bragg Grating for Dispersion Compensation

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July 2004
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Acknowledgments

We would like to thank Professor Henrique Salgado for his orientation, patience and advices through the project.

We are grateful to Instituto de Engenharia de Sistemas e Computadores (INESC-Norte) for providing a laboratory and all necessary equipment, and to its Human Resources, that were always helpful. We are also grateful to Professor Antonio Teixeira, of Instituto de Telecomunicações for showing their own system, and for the given hints. Also for the hints given, in order to control the Network Analyzer, we are thankful to Professor Henrique Miranda.

For being the first person to actual use our characterization system and for the feedback given, we thank Rosa Romero.

Last but not the least, we are grateful for the support given by the program PRODEP III Medida 3.
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Chapter 1

Introduction

1.1 Background and Motivation

Fiber Bragg gratings (FBG) have been a subject of research with several applications. They are used as sensors, as wavelength stabilizers for pump lasers, in narrowband WDM add/drop filters and also as filters for dispersion compensation. This last one can be achieved with a special FBG type: chirped gratings. In chirped FBG the period variation of the refraction index is not constant. Gratings with linear variation are the ones with application for dispersion compensation.

Light propagating within the fibers with a wavelength twice the grating period is reflected. Used as a dispersion compensator, the grating period could be reduced linearly down the length of grating (i.e. chirped mode). Therefore, the shorter wavelength is reflected at a point farther into the device than the longer wavelength. As intramodal dispersion reflects the fact that the shorter (blue) wavelength of the pulse travel faster than the longer (red) wavelength, this wavelength-dependent time delay can be used to produce negative dispersion being perfect to compensate dispersion in optical telecommunications systems. Using fiber Bragg gratings for dispersion compensation is a promising approach, because they are passive optical components, fiber compatible, have low insertion losses and low costs.

The Optoelectronics and Electronic Systems Unit of INESC Porto has the ability to fabricate Bragg gratings. Therefore one of main areas of research of UOSE is related to FBGs. This focus area has brought the necessity to characterize them and to test their performance at the several possible applications of FBGs. Until now, all FBGs have to be sent to Institute of Telecommunications, at University of Aveiro. Thus, this is a desired setup that saves money and specially time.

The development of FBG, by INESCN has been quite limited by the lack of an automated system to characterize all the fabricated FBG. The development of this characterization system is a step forward in the studies of FBG. Now INESCN is
completely autonomous in FBGs production. And, in few months, with the fabrication setup for chirped FBG being available, the importance of our system will be even greater.

1.2 Report Organization

This report is divided in chapters which gives a structured view of the developed work done in this project. Although some chapters are strongly related, all necessary links between them are referenced in order to give readers a possibility to choose the topics of interest. In this introductory chapter the main purposes and motivations of the project are presented, and the state of the art of the technology at the present time is briefly described.

The report may be organized grouping some chapters. Since this is a project where "dispersion" and "fiber Bragg gratings" are key terms, chapter 2 and chapter 3 explain these concepts. In chapter 2 dispersion in optical fibers is discussed, describing the several causes of dispersion and its impacts in bandwidth limitation of optical telecommunications systems. Chapter 3 gives an overview of fiber Bragg gratings, where fundamental notions about the fabrics of this device and its applications are given. One special type of fiber Bragg gratings – chirped gratings – are better analyzed due to their importance in dispersion compensation.

The developed characterization setup is an important part of this project and it is fully described in chapters 4 and 5. In chapter 4 the physical hardware is explained. At first it is discussed the measurement method, comparing it with other existent methods, and next all the developed measurement setup is described, presenting all the used hardware and the principal characteristics of each one that are critical to the setup. The developed software is described in chapter 5. This chapter is closely related with the previous chapter because here it is described how the PC controls all the equipment in the data acquisition. Readers may read only the initial sections of this chapter, where is made a general approach to the software, showing its principal characteristics and its general workings. In the second half all the software is fully discussed and are described all options taken in its implementation that leaded to its high performance.

In chapter 6 are presented measurements done with the developed setup. At first it is discussed two different approaches to the software development, analyzing results obtained in each approach. At next there are presented several measurements obtained with the final software version, discussing how each parameter influences measurement results. Conclusions about all work that was done are made in chapter 7. In this chapter is summarized the setup specifications. It is also described the most important results and it is discussed the system performance.
Appendix A gives some important notes about Network Analyzer that expands some subjects discussed. In appendix B is presented a small example of a data log file that the software may create and opens. A briefly explanation of a small software that automatically acquires data from the Network Analyzer and stores in a disk file is explained in chapter C. Finally, the presentation poster is shown in appendix D.
Chapter 2

Dispersion in Optical Waveguides

2.1 Introduction

When fiber was firstly studied for communication applications, the world assumed that it possessed infinite bandwidth and would meet communication needs for ever. As the need arose to transmit information over longer and longer distances, the fiber optic community developed additional wavelength “windows” that allowed longer transmission. The 1550 nm region, with a loss of only 0.2 dB/km, seemed like the answer. Millions of kilometers of fiber were installed around the world creating a high-speed communication network. However, as data rates in optical networks increased, it was needed to pay increasing attention to peculiarities in the fiber-optic medium.

Telecommunication systems modulates the intensity of a light source in order to transmit information. Information is modulated and sent as a series of pulses representing binary encoded data. Data can be transmitted with few errors, as long as these pulses travel through the fiber without changing their shape. But usually, as they travel along the fiber, the pulses start to spread, loosing their original shape and overlap each other, becoming indistinguishable at the receiver input. Dispersion is the general term applied to this cause, and the effect is known as intersymbol interference.

Dispersion was initially a problem when multimode step-index fiber, the first optical fibers, were introduced. Multimode graded-index fiber improved the situation, but even when they are well graded there are severe limitations to the information capacity of multimode fibers. It was single-mode fiber that eliminated multipath dispersion and left only intramodal dispersion and polarization mode dispersion to be dealt with by engineers. Therefore single-mode fibers are the fiber type which are used in high-speed communication networks, as, for example, in fiber Bragg gratings production. Thus, this chapter discusses dispersion in single-mode optical fibers. At first the basics of bandwidth in optical fibers are introduced, relating it with the pulse dispersion. Next it is discussed the several dispersion causes in single-mode fibers.
2.2 Bandwidth

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. As already explained, in a dispersive medium, each pulse broadens and overlaps with its neighbors – intersymbol interference.

For no overlapping of the light pulses on an optical fiber link, the digital bit rate $B_T$ must be less than the reciprocal of the broadened (through dispersion) pulse duration $(2\tau)$. Hence:

$$B_T \leq \frac{1}{2\tau} \quad (2.1)$$

This statement assumes that the pulse broadening due to dispersion on the channel is $\tau$, and therefore the input pulse duration is also $\tau$. Hence Equation 2.1 gives a conservative estimate of the maximum bit rate that may be obtained on an optical fiber link. Unlike the relationship given in Equation 2.1, this analysis allows for the existence of a certain amount of signal overlap on the channel, whilst avoiding any signal to noise ratio penalty which occurs when intersymbol interference becomes pronounced. The maximum bit rate is given approximately [18] by:

$$B_T(\text{max}) \approx \frac{0.2}{\sigma} \text{bits}^{-1} \quad (2.2)$$

$\sigma$ may be assumed to represent the root mean square (rms) impulse for the channel. This equation gives a good approximation for other pulse shapes which may occur on the channel resulting from various dispersive mechanisms within the fiber.

The conversion of bit rate to bandwidth in Hertz depends on the digital coding format used in information transmission. For metallic conductors when is employed a nonreturn to zero code, the binary used level is held for the whole bit period $\tau$. In this case there are two bit periods in one wavelength (i.e. two bits per second per Hertz). Hence the maximum bandwidth $B$ is one half of the maximum data rate or:

$$B_T(\text{max}) = 2B \quad (2.3)$$

![Figure 2.1: Bandwidths before (B) and after (B_T) modulation.](image)
However, when a return code is considered the binary one level is held for only part (usually half) the bit period. For this signalling scheme the data rate is equal to the bandwidth in Hertz (i.e. one bit per second per Hertz) and thus:

\[ B_{T}(\text{max}) = B \] (2.4)

The bandwidth for metallic conductors is also usually by the electrical 3 dB points (i.e. the frequencies at which the electrical power has dropped to one half of its constant maximum value). However, when the corresponding 3 dB optical bandwidth of a fiber is considered it is significantly larger than the 3 dB electrical bandwidth. Hence, when the limitations in the bandwidth of a fiber due to dispersion are stated (i.e. optical bandwidth \( B_{opt} \)), it is usually with regard to a return to zero code where the bandwidth in Hertz is considered equal to the digital bit rate. However when electro-optical devices and optical fiber systems are considered it is more usual to state the electrical 3 dB bandwidth.

![Optical and electrical bandwidth relation.](image)

The number of optical signal pulses which may be transmitted in a given period, and therefore the information-carrying capacity of the fiber, is restricted by the amount of pulse dispersion per unit length. These dispersion causes will be discussed later. In the absence of mode coupling or filtering, the pulse broadening increases linearly with fiber length and thus the bandwidth is inversely proportional to distance. This leads to the adoption of a more useful parameter for the information-carrying capacity of an optical fiber which is known as bandwidth-length product (i.e. \( B_{opt} \times L \)). The typical best bandwidth-length products for the three fibers are 20 MHz km, 1 GHz km and 100 GHz km for multimode step index, multimode graded index and single-mode step index fibers respectively.
2.3 Phase and Group Velocities

Light consists of electromagnetic waves, or in other words, it is an appearance where disturbances in the electric and in the magnetic field would spread through space. $\beta$ is the propagation constant which monochromatic light travels through a fiber, and it is fundamental to understanding how the optical fiber transmits light. The propagation constant is given by:

$$\beta = \frac{2\pi}{\lambda} n_1 = \frac{n_1 \omega}{c} \quad (2.5)$$

where $n_1$ is the index of refraction of an infinite medium, $\lambda$ is the optical wavelength of the light in a vacuum, $\omega = 2\pi f$ is the angular frequency of the wave and $c = \lambda f$ is the velocity of light. The index of refraction is the ratio of the velocity of light in free space to the velocity of light in a fiber material and it is always greater than or equal to one. It depends on such characteristics as the size and shape of the core/cladding regions, the fiber’s material properties, as well as any stress-causing birefringence.

Within all electromagnetic waves there are points of constant phase. For plane waves these points form a surface which is named as wavefront. In a monochromatic light wave propagating along a waveguide these points of constant phase travel at a phase velocity $v_p$ given by:

$$v_p = \frac{\omega}{\beta} = \frac{c}{n_1} \quad (2.6)$$

However, in real world light energy is generally composed of a sum of plane waves components of different frequencies, being impossible to produce perfectly monochromatic light waves. These group of waves with slightly different frequencies propagate through a fiber resulting in packet of waves.

![Figure 2.3: Phase and group velocities.](image)

In figure 2.3 it can be seen at bottom the result from a combination of two waves of nearly equal frequency propagation together. In non-dispersive media, the phase
velocity equals the group velocity. However, in dispersive media (like optical fibers) this envelope of the wake package does not travel at the phase velocity of the individual waves but is observed to move at a group velocity \( v_g \) given by:

\[
v_g = \frac{d\omega}{d\beta} = \frac{1}{\omega_v} = \frac{v_p}{1 - (\omega/v_p)(dv_p/d\omega)} \tag{2.7}
\]

The group velocity is of greatest importance and concerns in the study of the transmission characteristics of optical fibers as it relates to the propagation characteristics of observable groups or packets of light. A light pulse, for example, propagates through a dispersive medium with a speed \( v_g \). As a result of the dispersion the pulse is necessarily distorted as well as being attenuated during its travel, so \( v_g \) as to be based on the mean pulse arrival time, what complicates the issue.

In single-mode optical fibers both the propagation constant and the group velocity depend on the state of polarization and the wavelength of the light. When the group velocity depends on the wavelength of light, the fiber has intramodal dispersion. When the group velocity depends on the state of polarization, the fiber has polarization mode dispersion.

### 2.4 Intramodal Dispersion

The speed of transmission of electromagnetic waves through transparent materials is influenced by the interaction of the waves with the atoms of the material. One of media among others is glass \((SiO_2)\). Due to its optical transparency and the inexhaustible resource of \(SiO_2\) in the earth’s crust, glass is the preferred material for optical waveguides.

Intramodal dispersion may occur in multimode and single-mode index fibers, and represents the fact that different colors or wavelengths travel at different speeds, even within the same mode. This happens with real-world transmitters, which always have a range of optical wavelengths. Every laser has finite optical bandwidth, and the speed of light in fused silica (fiber) varies with the wavelength of the light. If the fiber system’s spectral source emitted a single frequency of light, this ”spectral dispersion” would be eliminated. Since a pulse of light from the laser usually contains several wavelengths, these wavelengths tend to get spread out in time after travelling some distance in the fiber. The refractive index of fiber decreases as wavelength increases, so longer wavelengths travel faster. The net result is that the received pulse is wider than the transmitted one, or more precisely, is a superposition of the variously delayed pulses at the different wavelengths. This phenomenon constitutes an important factor limiting the bandwidth of optical fibers, as explained at section 2.2.

A further complication is that when lasers are being turned on, have a tendency
to shift slightly in wavelength, adding some frequency modulation to the signal. This effect, called "chirp", causes the laser to have an even wider optical line width.

The delay differences between the different spectral components of the transmitted signal may be the result of the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

### 2.4.1 Material Dispersion

Pulse broadening due to material dispersion results from the wavelength-dependent index of refraction in the bulk material, which makes up the fiber, as seen in figure 2.4. It is this property that Newton exploited when he conducted his experiments with glass prisms, showing that white sunlight is actually made up of many different colors.

It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero ($\frac{d^2n}{d\lambda^2} \neq 0$).

A plane electromagnetic wave of frequency $f$ may be represented as propagating in the $z$-direction through a refractive medium by writing the amplitude of its electric field component in the $y$-direction as the real part of $E_y$, where

$$E_y(z,t) = E_0 e^{-az} e^{-j(\omega t - \beta z)} \quad (2.8)$$

and where $E_0$ is the field constant, $a$ is the attenuation coefficient, and $j^2 = -1$. 

---

**Figure 2.4:** Refractive index of pure fused silica.
This behaviour may equally well be represented by defining a complex refractive index, \( n^* \), such that

\[
n^* = n +jn' = (c/\omega)(\beta + ja)
\]  

(2.9)

Thus the real part of the refractive index is still given by \( n = (c/\omega)\beta \), as in equation 2.6, while the imaginary part becomes

\[
n' = (c/\omega)a
\]  

(2.10)

It so happens that the same physical processes that cause the refractive index to vary with frequency also give rise to attenuation of electromagnetic waves. Thus the refractive index in a dispersive medium is both a function of frequency and complex. These physical processes can be described qualitatively for a typical dielectric medium, using a classic model.

The electric field component of the propagating optical electromagnetic wave produces polarization in atoms of the material such that they or their electronic structures oscillate at the wave frequency. The effect of the oscillating charge is to radiate new waves at the same frequency and these interfere with the original wave in such a way that the resultant wave has a net phase shift with respect to the original. Because this is happening continuously, the total phase shift is proportional to the propagation distance and the resultant wave appears to travel with a lower phase velocity.

To define the time dispersion in a bulk media it is necessary to use parameters defined at section 2.3 and, referring to equation 2.7, to define group index of the guide, \( N_g \):

\[
v_g = d\lambda/d\beta \cdot d\omega/d\lambda =
\]

\[
= d\lambda \left( n_1 \frac{2\pi}{\lambda} \right)^{-1} \left( -\frac{\omega}{\lambda} \right) =
\]

\[
= -\frac{\omega}{2\pi\lambda} \left( \frac{1}{\lambda} \frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2} \right)^{-1} =
\]

\[
= \frac{c}{(n_1 - \lambda \frac{dn_1}{d\lambda})} =
\]

\[
= \frac{c}{N_g}
\]  

(2.11)

In a dispersive medium, \( N_g \) is different from the ordinary refractive index, or phase index, \( n \).
The dispersive properties of optical materials are traditionally expressed in terms of the variation of the refractive index with free space wavelength: \( n\lambda \). It is therefore needed to express \( v_g \) and \( N_g \) in terms of \( n \) and \( \lambda \). Note first that
\[
N_g = \frac{c}{v_g} = c \frac{d\beta}{d\omega} = c \frac{d}{d\omega} \left( \frac{\omega n}{c} \right) = \frac{d(\omega n)}{d\omega} = n + \frac{\omega}{d\omega} \frac{dn}{d\lambda} \quad (2.12)
\]
Now
\[
\frac{d}{d\omega} = \frac{dn d\lambda}{d\lambda d\omega} \quad (2.13)
\]
and with \( \omega = 2\pi c/\lambda \),
\[
\frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2} \quad (2.14)
\]
Substituting these expressions into equation 2.12 gives
\[
N_g = n + 2\pi c \frac{dn}{d\lambda} \left( \frac{-\lambda^2}{2\pi c} \right) = n - \lambda \frac{dn}{d\lambda} \quad (2.15)
\]
Thus
\[
v_g = \frac{c}{N_g} = \frac{c}{n - \lambda \frac{dn}{d\lambda}} \quad (2.16)
\]
A pulse of light, then, travels a distance \( L \) through a medium in a time, \( \tau_m \), given by
\[
\tau_m = \frac{L}{v_g} = \frac{N_g L}{c} = \left[ n - \lambda \frac{dn}{d\lambda} \right] \frac{L}{c} \quad (2.17)
\]
If the light contains a range of free space wavelengths and if the medium is dispersive, the pulse spreads out as it propagates and arrives over a range of times. The spectral linewidth of an optical source is frequently defined as the range of wavelength over which the spectral power exceeds 50\% of the peak spectral power. This is the Full-Width-at-Half-Maximum (FWHM) or Full-Width-at-Half-Height (FWHH) spectral width. It is also possible to define \( \text{rms} \) spectral linewidths, \( \sigma_\lambda \) and \( \sigma_\omega \), for the spectral distribution with respect to wavelength or with respect to the optical angular frequency
\[
\sigma_\lambda = \frac{\int_0^\infty (\lambda - \bar{\lambda})^2 \Phi_\lambda(\lambda) d\lambda}{\int_0^\infty \Phi_\lambda(\lambda) d\lambda} = \frac{\int_0^\infty \lambda^2 \Phi_\lambda(\lambda) d\lambda}{\int_0^\infty \Phi_\lambda(\lambda) d\lambda} - \bar{\lambda}^2 \quad (2.18)
\]
where \( \Phi_\lambda(\lambda) \) is the spectral power density at the wavelength \( \lambda \) and \( \bar{\lambda} \) is the mean wavelength which is given by
\[
\bar{\lambda} = \frac{\int_0^\infty \lambda \Phi_\lambda(\lambda) d\lambda}{\int_0^\infty \Phi_\lambda(\lambda) d\lambda} \quad (2.19)
\]
The rms spread of angular frequencies, $\sigma_\omega$, is defined in a similar way. $\sigma_\lambda$ is normally used as the measurement of spectral linewidth. It is sometimes convenient to deal with the fractional rms spectral linewidth, $\gamma_\sigma = \sigma_\lambda/\lambda = \sigma_\omega/\omega$.

A pulse then, after propagating for a distance, $L$, through a dispersive medium, broadens into a pulse of rms which may be obtained from the expansion of equation 2.17 in a Taylor series about $\lambda$ where:

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{2d^2\tau_m}{d\lambda^2} + \ldots \tag{2.20}$$

As the first term in equation 2.20 usually dominates, especially for sources operating over 0.8 to 0.9 $\mu$m wavelength range, then,

$$\sigma_m \approx \sigma_\lambda \frac{d\tau_m}{d\lambda} \sigma_\lambda = \frac{L}{c} \frac{d}{d\lambda} \left( n - \lambda \frac{dn}{d\lambda} \right) \sigma_\lambda = \frac{L}{c} \left| -\lambda \frac{d^2 n}{d\lambda^2} \right| \sigma_\lambda \tag{2.21}$$

The material dispersion for optical fibers is sometimes quoted as a value for $|\lambda^2(d^2 n/d\lambda^2)|$ or simply $|d^2 n/d\lambda^2|$. However, it may be given in terms of a material dispersion parameter $D_m$ which is defined as:

$$D_m = \frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} \tag{2.22}$$

and it is usually measured in $[ps/(km \cdot nm)]$.

### 2.4.2 Waveguide Dispersion

The waveguide of the fiber may also create intramodal dispersion and it is explained by Maxwell’s equations. This results from the normalized frequency $V$ dependence that characterizes a waveguide ($V = ka(n_1^2 - n_2^2)^{1/2}$) relating to wavelength of the transmitted wave light.

Considering the refraction index of the fiber independence from wavelength (material dispersion null), the propagation group delay of any mode is a non-linear function of $V$, as shown in figure 2.5. For any constant value $V$, each mode has a different propagation group delay, leading to signal distortion.

The ray approximation typically shows little squiggly lines bouncing off the core-cladding interface due to total internal reflection. In single-mode waveguides, this oversimplified view is incorrect because a significant amount of the optical power is actually carried in the cladding, as well as in the core. Furthermore, solution of Maxwell’s equations shows that the diameter of this mode increases with increasing wavelength,
as it can be observed in figure 2.6. Longer wavelength (red) light extends further into cladding than shorter wavelength (blue) light. Thus, the fundamental mode in standard single-mode fiber is slightly larger at 1550 nm, for example, than at 1310 nm, and this causes it to see a slightly different effective group index.

Figure 2.6: Different wavelength beams propagating through the fiber.

Thus, the total effective group index is a function of material dispersion, as well as the geometry of the core/cladding region.

For a single-mode whose propagation constant is $\beta$, the fiber exhibits waveguide dispersion when $\left(\frac{d^2\beta}{d\lambda^2}\right) \neq 0$. Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion ($\approx 0.1$ to $0.2$ ns km$^{-1}$). However, with single-mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant and, at some wavelengths, it can even compensate material dispersion.
2.4.3 Overall Single-Mode Fiber Dispersion

The pulse broadening in single-mode fibers results almost entirely from intramodal or chromatic dispersion as only a single-mode is allowed to propagate. Hence the bandwidth is limited by the finite spectral width of the source. Unlike the situation in multimode fibers, the mechanisms giving intramodal dispersion in single-mode fibers tend to be interrelated in a complex manner. The transit time of specific group delay $\tau_g$ for a light pulse propagating along a unit length of a single-mode fiber may be given as the inverse of the group velocity $v_g$. So, from equation 2.7, $\tau_g$ can be defined as:

$$\tau_g = \frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c} \frac{d\beta}{dk}$$  \hspace{1cm} (2.23)

where $k$ is the propagation constant for the mode in the vacuum. Referring to equation 2.11, $\tau_g$ can appear as:

$$\tau_g = \frac{N_g}{c}$$  \hspace{1cm} (2.24)

Moreover, the effective group index may be written in terms of effective refractive index $n_{eff}$ defined as:

$$N_g = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$$ \hspace{1cm} (2.25)

$\beta$ may be expressed in terms of the relative index difference $\Delta$ and the normalized propagation constant $b$ by the following approximate expression:

$$\beta = k[(n_1^2 - n_2^2)b + n_2^2]^{1/2} \simeq kn_2[1 + b\Delta]$$ \hspace{1cm} (2.26)

Furthermore, approximating the relative refractive index difference as $(n_1 - n_2)/n_1$, for a weakly guiding fiber where $\Delta \ll 1$, it can be used the approximation:

$$\frac{n_1 - n_2}{n_2} \simeq \frac{N_{g1} - N_{g2}}{N_{g2}}$$ \hspace{1cm} (2.27)

where $N_{g1}$ and $N_{g2}$ are the group indices for the fiber core and cladding regions respectively. Substituting equation 2.26 for $\beta$ into equation 2.23 and using approximate expression given in equation 2.27 it can be obtained the group delay per unit distance as:

$$\tau_g = \frac{1}{c} \left[ N_{g2} + (N_{g1} - N_{g2}) \frac{d(Vb)}{dV} \right]$$ \hspace{1cm} (2.28)

The dispersive properties of the fiber core and the cladding are often about the same and therefore the wavelength dependence of $\Delta$ can be ignored. Hence the group delay can be written as:
\[ \tau_g = \frac{1}{c} \left[ N_g^2 + n_2 \Delta \frac{d(Vb)}{dV} \right] \quad (2.29) \]

The initial term is constant and it gives the dependence of the group delay on wavelength caused when a uniform plane wave is propagating in an infinitely extended medium with a refractive index which is equivalent to that of the fiber cladding. However, the second term results from the waveguide properties of the change in group delay arising from the changes in power distribution between the parameter which plays a major part in the theory of single-mode fibers. The factor \( d(Vb)/dV \) can be expressed as:

\[ \frac{d(Vb)}{dV} = b \left[ 1 - \frac{2 J_v^2(ua)}{J_{v+1}(ua) J_{v-1}(ua)} \right] \quad (2.30) \]

where \( u = \sqrt{(2\pi n_1/\lambda)^2 - \beta^2} \) and \( a \) is fiber radius. For a fixed value of \( V \), the group delay is different for every guide mode. When a light pulse is launched into a fiber, it is distributed among many guided modes. These various modes arrive at the fiber end at different times depending on their group delay, so that a pulse spreading results.

The total first order dispersion parameter or the intramodal dispersion of a single-mode fiber, \( D_T \), is given by the derivative of the specific group delay with respect to the vacuum wavelength \( \lambda \) as:

\[ D_T = \frac{d\tau_g}{d\lambda} \quad (2.31) \]

In common with the material dispersion parameter it is usually expressed in units of ps nm\(^{-1}\) km\(^{-1}\). When the variable \( \lambda \) is replaced by \( \omega \), then the total dispersion parameter becomes:

\[ D_T = -\frac{\omega}{\lambda} \frac{d\tau_g}{d\omega} = -\frac{\omega}{\lambda} \frac{d^2\beta}{d\omega^2} \quad (2.32) \]

The fiber exhibits intramodal dispersion when \( \beta \) varies nonlinearly with wavelength. \( \beta \) may be expressed in terms of the relative refractive index difference \( \Delta \) and the normalized propagation constant \( b \) as:

\[ \beta = kn_1 [1 - 2 \Delta (1 - b)]^{\frac{1}{2}} \quad (2.33) \]

The \( rms \) pulse broadening caused by intramodal dispersion downs a fiber of length \( L \) is given by the derivative of the group delay with respect to wavelength as:

\[ Total \ rms \ pulse \ broadening = \sigma_L \left| \frac{d\tau_g}{d\lambda} \right| = \frac{\sigma_L 2\pi}{c\lambda^2} \frac{d^2\beta}{dk^2} \quad (2.34) \]

where \( \sigma_{\lambda} \) is the source \( rms \) spectral linewidth centred at a wavelength \( \lambda \).
Detailed calculation of the first and second derivative with respect to \( k \) gives the dependence of the pulse broadening on the fiber material’s properties and the normalized propagation constant \( b \). This gives rise to three interrelated effects which involve complicated cross-product terms. However, the final expression may be separated into three composite dispersion components in such a way that one of the effects dominates each term. The dominating effects are as follows:

1. The material dispersion parameter \( D_M \) defined by \( \lambda/c|d^2n/d\lambda^2| \) where \( n = n_1 \) or \( n_2 \) for the core cladding respectively.

2. The waveguide dispersion parameter \( D_W \), which may be obtained from equation 2.32 by substitution from equation 2.29 for \( \tau_g \), is defined as:

\[
D_W = -\left(\frac{n_1 - n_2}{\lambda c}\right) V \frac{d^2(Vb)}{dV^2}
\]  

(2.35)

where \( V \) is the normalized frequency for the fiber. Since the normalized propagation constant \( b \) for a specific fiber is only dependent on \( V \), then the normalized waveguide dispersion coefficient \( V d^2(Vb)/dV^2 \) also depends on \( V \). This latter function is another universal parameter which plays a central role in the theory of single-mode fibers.

3. A profile dispersion parameter \( D_P \) which is proportional to \( d\Delta/d\lambda \).

Although material and waveguide dispersion tend to be dominant in single-mode fibers, the composite profile should not be ignored. However, the profile dispersion parameter \( D_P \) can be quite small, especially at long wavelengths and hence is often neglected in rough estimates of total dispersion within single-mode fibers.

Strictly speaking, in single-mode fiber with a power law refractive index profile the composite dispersion terms should be employed. Nevertheless, it is useful to consider the total first order dispersion \( D_T \) in a practical single-mode fiber as comprising:

\[
D_T = D_M + D_W + D_P
\]

(2.36)

which is simply the addition of the material dispersion \( D_M \), the waveguide dispersion \( D_W \) and the profile dispersion \( D_P \) components. However, in standard single-mode fibers the total dispersion tends to be dominated by the material dispersion of fused silica. This parameter is shown plotted against wavelength in figure 2.7. It may be observed that the characteristic goes through zero at a wavelength of 1.27 \( \mu \)m. This zero material dispersion point can be shifted anywhere in the wavelength range 1.2 to 1.4 \( \mu \)m by addition of suitable dopants. For instance, the zero material dispersion point shifts from 1.27 \( \mu \)m to approximately 1.37 \( \mu \)m as the GeO\(_2\) dopant concentration is
increased from 0 to 15%. However, the zero material dispersion point alone does not represent a point of zero pulse broadening since the pulse dispersion is influenced by both waveguide and profile dispersion.

With zero material dispersion the pulse spreading is dictated by the waveguide dispersion coefficient \( V d^2(Vb)/dV^2 \), which is illustrated in figure 2.5 as a function of normalized frequency for \( HE_{11} \) mode. It may be seen that in the single-mode region where the normalized frequency is less than 2.405 the waveguide dispersion is always positive and has a maximum at \( V = 1.15 \). In this case the waveguide dispersion goes to zero outside the true single-mode region at \( V = 3.0 \). However, a change in the fiber parameters (such as core radius) or in the operating wavelength alters the normalized frequency and therefore the waveguide dispersion.

![Dispersion characteristics of standard single-mode fiber](image)

**Figure 2.7:** Dispersion characteristics of standard single-mode fiber.

The total fiber dispersion, which depends on both the fiber material composition and dimensions, may be minimized by trading off material and waveguide dispersion whilst limiting the profile dispersion (i.e. restricting the variation in refractive index with wavelength). For wavelengths longer than the zero material dispersion point, the material dispersion parameter is positive whereas the waveguide dispersion parameter is negative, as shown in figure 2.7. However, the total dispersion \( D_T \) is approximately equal to the sum of the material dispersion \( D_M \) and the waveguide dispersion \( D_W \) following equation 2.35. Hence for a particular wavelength, designated \( \lambda_0 \), which is slightly larger than the zero material dispersion point wavelength, the waveguide dispersion compensates for the material dispersion and the total first order dispersion parameter \( D_T \) becomes zero (see figure 2.7). The wavelength at which the first order dispersion is zero \( \lambda_0 \) may be selected in the range 1.3 to 2 \( \mu \text{m} \) by careful control of the fiber core diameter and profile.

In figure 2.7 it may be noted that the zero material dispersion point occurs at a wavelength of 1.27 \( \mu \text{m} \) but that the influence of waveguide dispersion shifts the total
dispersion minimum towards the longer wavelength giving a $\lambda_0$ of 1.32 $\mu$m.

The wavelength at which the first order dispersion is zero $\lambda_0$ may be extended to wavelength of 1.55 $\mu$m and beyond by a combination of three techniques. These are:

1. lowering the normalized frequency ($V$ value) for the fiber;
2. increasing the relative refractive index difference $\Delta$ for the fiber;
3. suitable doping of the silica with germanium.

This allows bandwidth-length products for such single-mode fibers to be in excess of 100 GHz km$^{-1}$ at the slight disadvantage of increased attenuation due to Rayleigh scattering within the doped silica.

For single-mode fibers optimized for operation at a wavelength of 1.3 $\mu$m, the CCITT (Consultative Committee for International Telegraphy and Telephony) recommends that the maximum value of intramodal dispersion $D_T$ shall not be exceed 3.5 ps nm$^{-1}$ km$^{-1}$ in the wavelength range 1.285 to 1.330 $\mu$m. Moreover, for the same fiber $D_T$ should be less than 20 ps nm$^{-1}$ km$^{-1}$ at the wavelength of 1.55. Hence, although the wavelength of zero first order intramodal dispersion (i.e. $D_T = 0$) is often called the zero-dispersion wavelength, it is more correct to refer to it as the wavelength of minimum dispersion because of the significant second order dispersion effects.

The variation of the intramodal dispersion with wavelength is usually characterized by the second order dispersion parameter of dispersion slope $S$ which may be written as:

$$ S = \frac{dD_T}{d\lambda} = \frac{d^2\tau_g}{d\lambda^2} \quad (2.37) $$

Whereas the first order dispersion parameter $D_T$ may be seen to be related only to the second derivative of the propagation constant $\beta$ with respect to angular frequency in equation 2.32, the dispersion slope can be shown to be related to both second and third derivatives following:

$$ S = \frac{(2\pi c)^3}{\lambda^4} \frac{d^3\beta}{d\omega^3} + \frac{4\pi c}{\lambda^3} \frac{d^2\beta}{d\omega^2} \quad (2.38) $$

It should be noted that although there is a zero first order dispersion at $\lambda_0$, these higher order intramodal effects impose limitations on the possible bandwidths that may be achieved with single-mode fibers. For example, a fundamental lower limit to pulse spreading in silica-based fibers of around $2.50 \times 10^2$ ps nm$^{-1}$ km$^{-1}$ is suggested at a wavelength of 1.273 $\mu$m. These secondary effects such as birefringence arising from ellipticity or mechanical stress in the fiber core may cause dispersion, especially in the case of mechanical stress of between 2 and 40 ps km$^{-1}$. If mechanical stress is avoided, pulse dispersion around the lower limit may be obtained in the longer wavelength region.
(i.e. 1.3 to 1.7 µm). By contrast the minimum pulse spread at a wavelength of 0.85 µm is around 100 ps nm⁻¹ km⁻¹.

An important value of the dispersion slope \( S(\lambda) \) is obtained at the wavelength of minimum intramodal dispersion \( \lambda_0 \) such that:

\[
S_0 = S(\lambda_0)
\]

where \( S_0 \) is called the zero-dispersion slope which, from equations 2.31 and 2.37, is determined only by the third derivative of \( \beta \). Typical values for the dispersion slope for standard single-mode fiber at \( \lambda_0 \) are in region 0.085 to 0.092 ps nm⁻² km⁻¹. Moreover, for such fibers the CCITT has recently proposed that \( \lambda_0 \) lies in the range 1.295 to 1.322 µm with \( S_0 \) less than 0.0995 ps nm⁻² km⁻¹. The total intramodal dispersion at an arbitrary wavelength can be estimated when the two parameters \( \lambda_0 \) and \( S_0 \) are specified according to:

\[
D_T(\lambda) = \frac{\lambda S_0}{4} \left[ 1 - \left( \frac{\lambda_0}{\lambda} \right)^4 \right]
\]

2.5 Polarization Mode Dispersion

Polarization mode dispersion (PMD) is another complex optical effect that can occur in single-mode optical fibers. Single-mode fibers with nominal circular symmetry about the core axis support the propagation of two perpendicular polarizations of the original transmitted signal. These two states of polarization (which are orthogonal) define the endpoints of an axis through the center of the Poincare sphere. The polarization dispersion vector is defined as a vector originating at the center of the Poincare sphere and pointing toward one of the principal states of polarization.

So single-mode fibers are therefore bimodal supporting \( HE_{11}^x \) and \( HE_{11}^y \) modes where the principal axes \( x \) and \( y \) are determined as said before. Thus the fiber behaves as a birefringent medium due to the difference in the effective refractive indices, and hence phase velocities, for these two orthogonally polarized modes. Figure 2.8 illustrates this condition. The modes therefore have different propagation constants \( \beta_x \) and \( \beta_y \) which are dictated by the anisotropy of the fiber cross section. When the fiber cross section
is independent of the fiber length $L$ in the $z$ direction, then the modal birefringence $B_F$ for the fiber is given by:

$$B_F = \frac{\beta_x - \beta_y}{2\pi/\lambda} \quad (2.41)$$

Light polarized along one of the principal axes will retain its polarization for all $L$. The difference in phase velocities causes the fiber to exhibit a linear retardation $\Phi(Z)$ which depends on the fiber length $L$ in the $z$ direction and is given by:

$$\Phi(Z) = (\beta_x - \beta_y)L \quad (2.42)$$

assuming that the phase coherence of the two mode components is maintained. The phase coherence of the two mode components is achieved when the delay between the two transit times is less than the coherence time of the source. The coherence time for the source is equal to the reciprocal of the uncorrelated source frequency width $(1/\delta f)$.

It may be shown that birefringent coherence is maintained over length of fiber $L_{bc}$ (i.e. coherence length) when:

$$L_{bc} \simeq \frac{c}{B_F\delta f} = \frac{\lambda^2}{B_F\delta\lambda} \quad (2.43)$$

where $\delta\lambda$ is the source linewidth.

However, when phase coherence is maintained (i.e. over the coherence linewidth) equation 2.33 leads to polarization state which is generally elliptical but which varies periodically along the fiber. The characteristic length $L_B$ corresponding to this process is known as the beat length. It is given by:

$$L_B = \frac{\lambda}{B_F} \quad (2.44)$$

Substituting $B_F$ from equation 2.32 gives:

$$L_B = \frac{2\pi}{(\beta_x - \beta_y)} \quad (2.45)$$

If a fiber was perfectly round and free from all stresses, both polarization modes would propagate at exactly the same speed, resulting in zero PMD. However, real fibers are not perfect, having geometric irregularities in core or internal stresses on it. In addition, external factors, such as bending, twisting, or pinching of the fiber, can also lead to birefringence.

This factor leads to coupling of energy from one polarization to other, so the two perpendicular polarizations may travel at different speeds. And, consequently, the two perpendicular polarizations arrive at the end of the fiber at different times. The fiber is said to have a fast axis, and a slow axis.
These perturbations along the fiber are difficult to eradicate as they may easily occur in the fiber manufacture and cabling. The energy transfer is at a maximum when the perturbations have a period $\Lambda$, corresponding to the beat length, and defined by:

$$\Lambda = \frac{\lambda}{B_F}$$  \hspace{1cm} (2.46)

However, the cross polarization effect may be minimized when the period of the perturbations is less than a cutoff period $\Lambda_c$ (around 1 mm). Hence polarization maintaining fibers may be designed by either:

1. High (large) birefringence: the maximization of the modal birefringence, which, following equation 2.44, may be achieved by reducing the beat length $L_B$ to around 1 mm or less; or

2. Low (small) birefringence: the minimization of the polarization coupling perturbations with a period of $\Lambda$. This may be achieved by increasing $\Lambda_c$ giving a large beat length of around 50 m or more.

In a uniformly birefringent fiber, as mentioned previously, the orthogonal fundamental modes have different phase propagation constants $\beta_x$ and $\beta_y$. Hence the two modes exhibit different specific group delays or $\tau_{gx}$ and $\tau_{gy}$. A delay difference $\delta\tau_g$ therefore occurs between the two orthogonally polarized waves such that:

$$\delta\tau_g = \tau_{gx} - \tau_{gy} = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right|$$  \hspace{1cm} (2.47)

where $\delta\tau_g$ is known as the polarization mode dispersion. Measured values in polarization mode dispersion range from significantly less than 1 ps km$^{-1}$ in conventional single-mode fibers to greater than 1 ns km$^{-1}$ in high birefringence polarization maintaining fibers. However, in specific low birefringence fibers, that is, spun fiber, polarization mode dispersion is negligible.

Since the two fundamental modes generally launched into single-mode fiber have different group velocities, the output from a fiber length $L$ will comprise two elements separated by a time interval $\delta\tau_gL$. For high birefringence fibers, the product $\delta\tau_gL$ provides a good estimate of pulse spreading in long fiber lengths. In this case the 3 dB bandwidth $B$ is given by:

$$\beta = \frac{0.9}{(\delta\tau_gL)}$$  \hspace{1cm} (2.48)

However, for short fiber lengths and fiber lengths longer than a characteristic coupling length $L_c$, the pulse spreading is proportional to $(LL_c)^{1/2}$ instead of simply $L$. 
Moreover, the maximum bit rate $B_T(max)$ for digital transmission in relation to polarization mode dispersion may be obtained from:

$$B_T(max) = \frac{G}{0.55}$$ (2.49)

Like intramodal dispersion, PMD causes digital transmitted pulses to spread out as the polarization modes arrive at their destination at different times. Intramodal dispersion is typically a much larger impairment than PMD, and can be a significant effect even at relatively low data rates on long fibers (depending on the transmitter type). For most fibers, PMD is not a serious problem until data rates exceed 10 Gbps in not too old fibers. Unlike intramodal dispersion, however, PMD on long fibers cannot be corrected with passive devices because the PMD changes randomly over time. This means that both the amount of dispersive group delay changes, and the orientation of the principal axes. It is this dynamic characteristic of PMD that makes it such a difficult problem for high-speed optical networks.

### 2.5.1 Polarization Maintaining Fiber

As said before, in specific applications with transmission systems of coherence type, polarization control is fundamental. One single-mode fiber type of great interest to coherence systems is the single-mode fiber with polarization maintaining, which is defined as a fiber that maintains the light’s polarization through the fiber. This single-mode fiber has different birefringences to the two polarizations propagation, isolating one from another. This may be achieved with a elliptical core instead of conventional circular core or inserting the birefringence characteristic by components in core and cladding, with different thermal expansion coefficients.

### 2.6 Summary

Fiber does not have infinite bandwidth. This bandwidth limit is defined due to distortion on pulses. The source sends data as series of pulses that, as they travel through the fiber, broaden, loosing their shape and overlapping their neighbors – intersymbol interference.

Intensive research have been done in order to eliminate dispersion causes. In that way, single-mode fibers substituted multimode fibers, eliminating multipath dispersion, a strong source of dispersion. But other dispersion causes remain in single-mode fibers, which still limits the bandwidth. Even with the different modal velocities solved there is intramodal dispersion. The pulse is constituted by several waves of different frequencies that travel at different velocities in the fiber – material dispersion. Waveguide dispersion is also wavelength-dependent and occurs because light does not only
propagates in the core. The amount of optical power that travels in the cladding (with a different velocity) varies with wavelength. Therefore these two dispersion causes are related and with some techniques it can be found special conditions (material and wavelength selected) where one source has the opposite effect of the other, cancelling each other.

With the last two effects annulated, polarization-mode dispersion is now critical. If an optical pulse passes through a fiber with varying birefringence along its length, its polarization states will vary, and therefore the group velocity of each of the two polarization modes will also vary.
Chapter 3

Fiber Bragg Gratings

3.1 Introduction

Optical fibers came to revolutionise telecommunications. Its success is mainly due to its low transmission loss, high optical damage threshold, and low optical nonlinearity. These properties made long-distance communication an actual reality. Having long communications, the bandwidth available in single-mode fiber must meet the ever increasing demand for higher data rates.

The technological advances made in the field of photosensitive optical fibers are relatively recent; nevertheless, an increasing number of fiber devices based on this technology are coming into the market. They can provide to the network designer the option of deployment of wavelength-division-multiplexed (WDM) systems, as well as channel selection.

3.2 Photosensitivity of optical fibers

Optical fibers have good optical properties for light transmission. The property of glass denies the electric interference to light propagation, although an exposure to ultra-violets (UV) radiation contributes to the change of the refractive index of the fiber. The periodically change of the refractive index along the fiber, based on simple exposure to UV radiation, is known as a Fiber Bragg Grating (FBG). Due to that change, it presents a reflection band centred at the Bragg wavelength

$$\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda$$

being $n_{\text{eff}}$ the effective index of the of the core and $\Lambda$ the period of the grating.

An uniform imprinted grating can be represented as a uniform sinusoidal modulation of the refractive index along the core:

$$n(z) = n_{\text{core}} + \delta n \left[ 1 + \cos \left( \frac{2\pi z}{\Lambda} \right) \right]$$
where \( n_{\text{core}} \) is the unexposed core refractive index and \( \delta n \) is the photoinduced change in the index.

The maximum reflectivity of the grating occurs when the wavelength is \( \lambda_{\text{Bragg}} \). At this wavelength, the peak reflectivity \( R_{\text{max}} \) for the grating of length \( L \) and coupling coefficient \( \kappa \) is given by

\[
R_{\text{max}} = \tanh^2(\kappa L)
\]  

(3.3)

The full bandwidth \( \Delta \lambda \) over which the maximum reflectivity prevails is

\[
\Delta \lambda = \frac{\lambda_{\text{Bragg}}^2}{\pi n_{\text{eff}} L} \left[ (\kappa L)^2 + \pi^2 \right]^{1/2}
\]

(3.4)

For uniform gratings, the coupling coefficient \( \kappa \) is given by

\[
\kappa = \frac{\pi \delta n \eta}{\lambda_{\text{Bragg}}}
\]

(3.5)

with \( \eta \) being the fraction of optical power contained in the fiber core. Under the assumption that the grating is uniform in the core, \( \eta \) can be approximated by

\[
\eta \approx 1 - V^{-2}
\]

(3.6)

where \( V \) is the \( V \) number of the fiber (see section 2.4.2).

There are several types of Bragg gratings. The typical grating profile is the uniform (figure 3.1), this type of grating reflects a single wavelength, it has an huge application in sensors field for instance.

![Uniform Profile FBG](image1)

**Figure 3.1:** Uniform Profile FBG.

As an improvement of the uniform gratings came the apodized ones (figure 3.2), this gratings have special use in WDM systems. Many WDM devices include add&drop filter, and with uniform gratings the reflected spectrum includes side lobes, these are unwanted wavelengths, resulting in crosstalk between channels.

![Apodized FBG](image2)

**Figure 3.2:** Apodized FBG.

Chirped gratings (figure 3.3) are also an evolution of the uniform grating, chirped gratings have the ability of reflect a range of wavelengths introducing a certain time
delay for each wavelength. This type of grating has great use in telecommunications, especially for dispersion compensation. We will focus this ability of chirped gratings along the report.

![Chirped FBG](image)

**Figure 3.3:** Chirped FBG.

### 3.3 Fabrication of Bragg Gratings

The simplest method to alter the effective index of a propagating mode in a fiber is to impose a temperature or a strain profile along the length of the grating. However, pre-straining a fiber during fabrication alters the Bragg grating wavelength in the relaxed state.

The application of the phase mask method as well as the two-beam interferometer method made easier the inscription of fiber gratings. The phase mask method is the process that is currently being used by INESC Porto to fabricate FBG. It uses a phase mask (diffractive element) to generate the fringe pattern, being the fibre positioned just in contact with the phase mask surface.

This method has the advantage of the Bragg wavelength of an FBG is determined by the pitch of phase mask and is independent of wavelength of the UV laser. Also as an advantage, this method offers a high potential for mass production with low cost, as well as, this single beam writing method improves the mechanical stability of the FBG writing apparatus.

### 3.4 Chirped gratings

If the temperature distribution along the length of a uniform grating is a linear function of length, then the Bragg wavelength will vary linearly with length. The grating will demonstrate a linear chirp. This means that the different wavelengths within the bandwidth of the grating will not be reflected from the same physical location of the fiber.

Also, prestraining or forcing a temperature profile along a fiber before writing a grating will also origin in a chirped fiber grating once it is written and the stress/temperature profile is removed. Although, the chirp in a grating fabricated in such way will have the opposite sign of a grating chirped by the application of a temperature or strain profile after it has been manufactured.
This chirped grating reflects different wavelengths (or frequencies) at different points along its length. Effectively, a chirped Bragg grating introduces different delays at different frequencies. Chirped gratings are ideally suited to compensate the dispersion (this subject was object of study in chapter 2) for individual wavelengths than multiple wavelengths. In contrast, dispersion compensating fiber (DCF) is better suited to compensate over a wide range of wavelengths. However, compared to chirped gratings, DCF introduces higher loss and additional penalties because of increased nonlinearities.

In a regular fiber, intramodal dispersion introduces larger delays for lower-frequency components in a pulse. To compensate for this effect, we can design chirped gratings that do exactly the opposite, introducing larger delays for the higher frequency. This is also known as compression the pulse. The delay behaviour as a function of wavelength is displayed in figure 3.4, as an example.

![Figure 3.4: Chirped grating behaviour.](image)

If possible, we want a grating that introduces a large amount of negative dispersion over a wide bandwidth so that it can compensate the fiber dispersion over a wide range of wavelengths. In practise, the total length of the grating is limited by the size of the phase mask. After a web search we found that an example of a phase mask of 15 cm, knowing that we have a delay of 100 ps per centimeter, this length allows the possibility of fabrication of a chirped grating of 1500 ps time delay. Later on, we will see our experimental measurements and check out the time delay of the gratings that was delivered into our hands.
3.5 Summary

Currently, several main applications drive the commercial production of FBGs for telecommunication applications: wavelength stabilizers for pump lasers, narrowband WDM add/drop filters, gain-flattening filters and dispersion compensation.

Chirped gratings can be used for dispersion compensation. The increasing path length introduces a spectrally dependent delay that cancels intramodal dispersion. A 10-cm-long FBG can typically compensate for 80 km of nondispersion-shifted standard fiber over a bandwidth of 100 GHz. In dense WDM systems of 32 channels or more, the single-channel FBG solution is not cost-effective. Network designers for OC-48 (2.5 Gb/s) and OC-192 (10 Gb/s) have instead favored the use of DCF, which is intrinsically broadband.

In today’s networks, fiber Bragg gratings have found applications in which they stand out from all other technologies, in both performance and cost. Grating fabrication is relatively simple and lends itself to mass production and automation. The fabrication technology is still young, however, and there is no doubt that developments in automation will dramatically reduce grating cost, which may open the door to new, more costsensitive applications.
Chapter 4

Fiber Bragg Grating Characterization

4.1 Introduction

Attenuation along a fiber that is frequency dependent results in a dispersed signal. Visually, the effect on a pulse is a broadening of the pulse with respect to time. It is called intramodal dispersion, and it was discussed in chapter 2. Essentially, some modes take longer to travel the fiber than others. Thus, modes that are launched simultaneously do not arrive at the opposite side of the fiber at the same time.

It is normally necessary to measure relative propagation delays as a function of wavelength in order to determine the intramodal dispersion curve of an optical fiber or FBG. The broadening of the pulse is the basic principle underlying most intramodal dispersion measurement instruments used for characterizing fiber gratings or telecom fiber links.

4.2 Identification of the measurement method

Analysis and accurate measurement of the group delay is essential in optimization of the performance of optical systems. We can apply various techniques to measure intramodal dispersion. It can include applications of Kramers-Kronig relations or a Hilbert transformation between the reflectivity and the phase of the components, low-coherence interferometry, and various pulse delay measurements and phase-shift techniques. The parameter that is typically measured is the group delay of the component as a function of the wavelength. Traditionally the group delay of an optical fiber has been an important characteristic to be measured. In practice, it is important to have knowledge of such parameters as the zero-dispersion wavelength, the dispersion slope and uniformity of the group delay of the device under test.
Accurate characterization of the dispersion of FBGs and fiber dispersion requires evaluation of the conventional methods to obtain reliable measurement results of their properties.

It is possible to measure dispersion using Hilbert-transform method, which the amplitude and phase response of an optical filter are related. To assure this relation is valid, the filter must fulfill a so-called minimum phase condition. This condition is fulfilled by optical filters, such as uniform fiber Bragg gratings. For this component, the phase response and then the dispersion can be calculated directly from the measured amplitude response. However, the minimum phase condition does not hold for components as apodized or chirped fiber Bragg gratings. These components have a complex phase response that, in general, the reconstruction of the phase information from the measured amplitude response is not possible.

Measuring dispersion may also be done using interferometric method to obtain the group delay. In the interferometric method, the measurement setups are typically based on Michelson or Mach-Zehnder interferometers. Light from a broadband or a wavelength tunable light source is split in two paths one of which couples light into the component and the other is a reference path. The light transversing the component is combined with the light from the reference path and the resulting interferogram is detected. From this interferogram it is possible to calculate both the amplitude and the phase response of the component by means of a Fourier transform. The group delay of the component can be extracted from the phase of the interferogram. A clear advantage of the interferometric method is its resolution. Very small dispersion values can be measured accurately. However, interferometers often use freespace optics, which make them sensitive to variations in the environment. Also long components are difficult to be measured since the length of the reference arm needs to be approximately equal to the optical length of the device under measurement.

An other method is the conventional phase-shift technique which includes pulse-delay measurements and various phase-shift techniques. A basic measurement setup for the phase-shift technique is outlined in figure 4.1. The light from a tunable laser is modulated with a sinusoidal signal. The modulation generates sidebands on the optical carrier. The sidebands will experience a phase shift when the modulated light passes through the device under test. The phase shift of the detected signal allows the group delay of the component to be determined. The basic setup and variations of it using different light sources have been utilized for measurements of the dispersion of an optical fiber for years. Several commercially available dispersion measurement systems rely on this measurement principle.
4.3 Measurement setup

The most commonly used and standardized technique is referred as the phase shift method, in which light is sinusoidal-intensity modulated. Phase variations related to wavelength are measured at a given high frequency. The reference signal, with respect to which phase shifts are measured, can come directly from an electronic oscillator or optical signal. The phase shift method can also be modified to measure much smaller relative delays typical of most fiber-optic components when used with a tunable laser, an electric network analyzer, as well as modulation frequencies of up to many GHz.

![Diagram of measurement setup](image)

**Figure 4.1:** Setup to measure group delay using the phase-shift method.

4.3.1 Laser Source

In order to measure the phase shift it necessary a continuous wave (CW) laser source, to work as carrier of the modulation signal. Due to the fact we wish to characterize the grating over a wide wavelength range, the laser must be tuneable and with high resolution.

The New Focus model 6427, has two control options, local and remote. Our main criterium for selecting this laser was his capability of being controlled remotely through a GPIB interface, making this model unique from all that INESC owns. This system provides high resolution between wavelengths. Although the standard resolution is 0.01 nm, the laser allows a resolution of 0.001 nm. This higher resolution will be the standard step resolution for our characterizing system.
CHAPTER 4. FIBER BRAGG GRATING CHARACTERIZATION

<table>
<thead>
<tr>
<th>Laser Characteristics</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range (nm)</td>
<td>1520</td>
<td>-</td>
</tr>
<tr>
<td>Wavelength step resolution</td>
<td>-</td>
<td>1570</td>
</tr>
<tr>
<td>Power (dBm)</td>
<td>-3</td>
<td>-</td>
</tr>
<tr>
<td>Time to warm up</td>
<td>45 min</td>
<td>6.9</td>
</tr>
</tbody>
</table>

**Table 4.1:** Laser main characteristics [14].

4.3.2 Polarization Controller

To maximize the modulated signal, the carrier signal must maintain its polarization. This fact makes essential to pay attention to the polarization, so that the signal after modulation stays as big as possible.

![Figure 4.2: Agilent 11896A polarization controller block diagram.](image)

The Agilent 11896A motorized polarization controller adjusts polarization and not power. Its optical fiber loop design provides all states of polarization with extremely small optical insertion loss variations (±0.002 dB) over a wide spectral range (980 nm and 1250 to 1640 nm.) This performance combination maximizes measurement accuracy for power sensitive applications, such as polarization dependent loss and gain, because the measurement uncertainty contributed by the polarization controller is minimized.

The transmitted signal enters the polarization controller and passes through the internal four-fiber-loop assembly. The dimensions of each loop are optimized to approximate a quarter-wave retarder response over the polarization controller’s specified wavelength range. Complete and continuous polarization adjustability is achieved by independently adjusting each loop over an angular range of 180°. This range is divided into 1000 equal steps (000;999), providing an adjustment resolution of 0.18°. The adjustment can be made manually, using the front-panel knobs, or automatically, using remote GPIB commands or the built-in autoscanning control.

Also as an alternative for the polarization controller, it is possible to use a Polarization Maintaining (PM) Fiber. As the name means, it maintains the light’s polarization...
from laser source, through the fiber, to the modulator.

### 4.3.3 Modulator

The LiNbO3 based device is a optical modulator which uses high performance travelling-wave electrodes. It has the following features:

- Low insertion loss
- Low driving voltage
- Wide-band
- Polarization Maintaining input port
- the structure of the electrode is optimized to reduce unwanted electrical reflection

To input the modulator signal in the optical modulator we have two possible SMA connectors. Each one are associated to an individual electrode.

In order to optimize optical output wave-form it is necessary to adjust the Bias voltage. From our experimental analysis of the modulator it was possible to find out that the modulated optical output was minimum at 0.4 V and 4.5 V, this confirms the last inspection sheet [19] about the driving voltage, table 4.2. The central value would be 2.45 V, this is the Bias voltage that we will set. Knowing this last value we can say that the NA peak-to-peak voltage can be half of the driving voltage, to ensure that it is working in a linear zone of the modulator. But we decided to use an even more strict gap, not $V_{ppNA} = 2.05V$ but $V_{ppNA} = 1V$. Having these parameters set, it is just necessary to calculate the NA output power:

$$V_{rmsNA} = \frac{V_{ppNA}}{2\sqrt{2}}$$

$$P_{NA} = \frac{V_{rmsNA}^2}{R} = 2.5mW \approx 4dBm$$

<table>
<thead>
<tr>
<th>Modulator Characteristics</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving voltage $V_\pi$ (V)</td>
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</tr>
<tr>
<td>Insertion loss (dB)</td>
<td>-</td>
<td>5.5</td>
</tr>
<tr>
<td>Maximum input optical power (dBm)</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Bias DC voltage (V)</td>
<td>-</td>
<td>2.45</td>
</tr>
</tbody>
</table>

| Table 4.2: Modulator main characteristics. |
4.3.4 Network Analyzer

Network analyzers measure the reflection and transmission characteristics of devices and networks by applying a known swept signal and measuring the responses of the test device. The signal transmitted through the device or reflected from its input is compared with the incident signal generated by a swept RF source. The signals are applied to a receiver for measurement, signal processing, and display. A network analyzer system consists of a source, signal separation devices, a receiver, and a display.

The HP8753A produces a sept RF signal in the range of 300 kHz to 3.0 GHz. A portion of the transmitted signal is routed to the R (reference) input of the receiver, and transmitted and reflected signals are applied to the A and/ot B inputs. The HP85046A S-parameter test set contains the hardware required to make simultaneous transmission and reflection measurements in both the forward and reverse directions. The reflectivity of the FBG corresponds to the forward gain of the NA. In figure 4.1 the block that is identified as the network analyzer in reality it is the combination of the HP8753A and HP85046A, being RF\textsubscript{out} the Port 1, and RF\textsubscript{in} the Port 2 of the HP85046A.

S-parameters (scattering parameters) are a convention used to characterize the way a device modifies signal flow. S-parameters are always a ratio of two complex (magnitude and phase) quantities, its notation uses the numbering convention where the first number refers to the port where the signal is emerging and the second number is the port where the signal is incident. For example, the S-parameter S21 identifies the measurement as the complex ratio of the signal emerging at Port 2 to the signal incident at Port 1, forward direction. The complete S-parameter test set is fully described in appendix A.

\[ \begin{align*}
S_{11} & \quad S_{12} \\
S_{21} & \quad S_{22}
\end{align*} \]

\[ \begin{align*}
a_1 & \quad S_{21} \\
S_{11} & \quad S_{22} \\
b_1 & \quad S_{12} \\
a_2 &
\end{align*} \]

\textbf{Figure 4.3:} \textit{S-parameters of a two-port device.}

In the table 4.3 it is possible to consult all possible minimum values for the sweep time. When preset is done, in the Network Analyzer, the default value for the IF Bandwidth is 3000 Hz, and the developed software does not allow modifications. This means that the only values of the minimum sweep time we must take into consideration are the ones associated to the IF of 3000 Hz.
Table 4.3: Network Analyzer minimum sweep time [9].

This instrument has limited resolution for the phase measurement, being its minimum phase resolution $0.1^\circ$. In the table 4.4 it is possible to see the time resolution of the phase method, for all different modulation frequencies given.

Recalling the group delay equation for a given phase shift:

$$\tau = \frac{\theta}{360f_{mod}}$$  \hspace{1cm} (4.3)

Table 4.4: Group delay resolution.

As it is possible to see, the increase of the modulation frequency improves the delay resolution. But this increase of the frequency has a con: it makes the optical signal spectrum larger. This enlargement of the optical signal is due to the modulator characteristics. Normal modulators output signal has the carrier, and two sidebands. The spectral resolution is given directly by the width of the signal, the distance between the two sidebands, as it is possible to imagine based on figure 4.4.

With Equation 4.6 is possible to calculate the distance from one sideband to the carrier $\Delta \lambda$, according to the laser wavelength $\lambda$, refractive index $n$ and frequency of modulation $f_m$:

$$\lambda = \frac{v}{\nu}$$ \hspace{1cm} (4.4)

$$\Delta \lambda = -\frac{v}{\nu^2} \Delta \nu = -\frac{\lambda^2}{v} \Delta \nu$$ \hspace{1cm} (4.5)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4_4_modulated_signal.png}
\caption{Modulated signal.}
\end{figure}

\[ |\Delta \lambda| = \frac{\lambda^2}{c} |\Delta \nu| \] (4.6)

For 1GHz modulation frequency (\(\Delta \nu\)), and the laser set to 1550 nm, the spectral resolution on this optical system is given by \(2 \times \Delta \lambda = 16 \text{pm}\).

Thus, we have lower spectral resolution for higher frequencies. So, it is clear that the group delay resolution resolution is improved with the increase of the modulation frequency, but in the other hand, the increase in frequency will increase the spectral width of the optical signal, decreasing spectral resolution. Therefore it is necessary to settle a frequency considering a compromise between this two factors. A good value is 1 GHz, allowing a group delay resolution of 0.28 ps and a spectral resolution of 16 pm.

\section{4.4 System Control}

In this section we will briefly explain the control of the whole setup. But first we will emphasize the function of each individual machine in the process of characterizing an FBG.

The laser source has an important function in the setup. His beam is modulated and travels all the setup including the device under test (DUT), suffering the dispersive effect and attenuation that we wish to characterize. Since we want to characterize the DUT under a wide wavelength bandwidth, this laser source must be variable, that is the reason we used the New Focus model 6427. With this laser it is possible to have a wavelength resolution of 1 pm, which is a generous step size for characterize a FBG. It is possible to remotely control the laser source by two different ways. One possibility is to define the start and stop wavelength and the step size. With this option, as the measurement is running we send the command to increase one more step to the actual wavelength. The other possibility is, for each step of measurement, we send a
command defining the following wavelength. We choose to control the laser by this last process, mainly because with this way we have full control of the laser wavelength. Case something unexpected changed the laser wavelength, for instance if we are controlling the laser remotely and the user changes it manually, the step control wouldn’t be any useful. For this important reason we choose to set individually all wavelength.

After the laser, it is plugged the polarization controller, as it was mentioned in section 4.3.2, his function is to maximize the modulated signal. It was also told that it can be replaced by a PM fiber. Even so, we will explain how to work with it. In order to operate the polarization controller it is necessary with the NA to read the output after the modulator. So that we can see if, when we change the paddle, there is any change of the modulated signal. In section 5.3.2 the process of moving the paddle will be explained more precisely.

In order to further understand the control and operation of the NA we will explain step by step all possible ways to obtain the desired measurement.

In System Engineering, to develop a system its necessary to present not only a single solution, but three solutions. You may ask ”why three?” and the answer is quite simple ”because it is a good number”[10]. This criterium was a constant in our software development. We can say that the only exception in the whole project was for the phase-shift method that was a certainty since the beginning of the project.

The first approach is based in sampling one point in n sweeps. This process has the following configuration:

- We set a center frequency and a span of 0 Hz, this way the phase shift can be related to a single frequency.

- The number of points was set to the minimum value possible, 3 points. So that a single sweep can be as fast as possible. Also, for the 3 points, we just need one point, being all others ignored.

- The number of sweeps allows to characterize the DUT more precisely. Doing an averaging it is possible to reduce glitch noise of the signal.

The averaging of the samples can be processed by the NA. This solution showed it self not very good, due to the really low performance. To have an idea, for 3 points and the sweep time of 100 ms, the theoretical time for an 128 samples is $128 \times 0.1 = 12.8$ seconds, but experimental results showed that the NA takes around 25 seconds to run all 128 samples and simultaneously average it. This means that the NA is not reliable for fast processing. A possible solution is to reduce all computation from the NA.

The other solution is to keep the averaging of the samples, but with no processing from the NA. It is possible to send all data to the PC and at the end average all
samples. This solution is still not a good solution because all data transfer makes the characterization of the DUT even slower than the previous solution.

The final solution is the usual approach for a single frequency sweep. The CW (continuous wave) mode is a quite different approach than the ones before. The number of samples is not directly related to the number of sweeps like before, but from now on the number of samples is the number of points of the NA. This number can not be a random value. It is pre-defined by the NA. Most of the values for the number of points are indicated in table 4.3. Thus, with this solution we need only to do a single sweep for each wavelength, but we have a significant increase of data flow. A good value to the number of points is 201. In our experimental measurements it was possible to verify that the data flow for 201 points to the PC takes around 1 second (table 4.5).

As we could see, the less processing the NA has, the better time performance we will have. Since all control is done from the PC, the need for the NA physical display is none. So, by turning off the display, the NA does not waste time in sending data to the display. Thus, a great time performance of the NA was achieved. Later on we will see how big our latest improvements are for the overall performance of the system.

<table>
<thead>
<tr>
<th>Number of points</th>
<th>Data flow timings (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>≈ 0</td>
</tr>
<tr>
<td>201</td>
<td>1</td>
</tr>
<tr>
<td>401</td>
<td>3</td>
</tr>
<tr>
<td>801</td>
<td>8</td>
</tr>
<tr>
<td>1601</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4.5: Time for the data flow from NA to PC.

4.5 Summary

In order to measure the relative propagation delay we will use the most standardized method, the phase-shift method. This method has a great advantage for improving resolution. It is possible to increase group delay resolution while decreasing spectral resolution, or the other way around, just by adjusting the modulating frequency.

The brain of this setup, besides the computer with our software, is the NA. This machine control is critical. Our goal is to reach the best performance possible with the most reliable data. Later on, we will present all performance/reliability results based on the possible approaches mentioned in section 4.4.
Chapter 5

Software Implementation

5.1 Introduction

In this project it is developed a software application that allows to characterize fiber Bragg gratings. This application is developed in LabVIEW graphical language and it pretends to be an useful utility that acquires transmissivity, and reflectivity and respectively group delay of the fiber Bragg grating under test, under previous defined parameters.

This application has as main principle the integration of all hardware resources in order to turn the characterization autonomous, so this chapter may be seen as a continuation from the previous chapter where physical setup is discussed. Besides that, this software is not dependent of if the hardware setup is connected to computer, to allow opening previous saved logs of old measurements to further analysis or even to print data at home, for instance.

As good rules indicate, initially there are defined the software requirements: applications targets and input and output required data. Next it is demonstrated the general workings of the program, and at last it is presented the detailed software implementation, commenting implemented algorithms, taken options in the software developments, and followed methodologies.

5.2 Specifications

Has already referred, the Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto) has the ability to produce fiber Bragg gratings, and therefore one of main areas of research of Optoelectronics and Electronics Unit (UOSE) is related to fiber Bragg gratings. This focus area has brought the necessity to characterize them and to test their performance at the several possible applications of fiber Bragg gratings.

Fiber Bragg gratings may be used as dispersion compensators (as discussed in
Thus, one important characteristic to know is the group delay associated to range of reflection of determined fiber Bragg grating. Until now, to characterize these devices, they would have to be sent to Instituto de Telecomunicações of Universidade de Aveiro, the nearest location with this kind of ability. But in fact, UOSE has all necessary hardware, missing only the will to develop the setup. And this will has come with the following main motivations:

- to strengthen UOSE’s qualification in fiber Bragg gratings characterization
- to save money shipping devices under test to and from Aveiro
- to save time in travels

Besides that, the fact of being owner of this setup opens a new door in fiber Bragg gratings’ investigation. The setup’s owner has more freedom to do all experiments that could be repressed by the fact of not being at home with foreign material and human resources.

These were the motivations for the project, whose main incentive was also to improve upon work already done at Aveiro. One main objective consisted in to increase accuracy measurements. Another important task consisted in to minimize the time measurement. Measurements, depending of wavelength range and accuracy, may take hours to produce final results, therefore the time optimization was also a mainly task. Knowing that application would get results for each measurement using a cycle, therefore the motivation was high knowing that suppressing a small amount of time at each measurement (iteration) it would result in an considerable amount of saved time at the overall cycle.

### 5.2.1 Objectives

Before starting with the software development, it was necessary to define a list of objectives in order to improve program conception planing. These targets were specified after documentation research (including fiber Bragg gratings datasheets), discussions with Professor Henrique Salgado and other INESC researchers, and a fruitful visit to Instituto de Telecomunicações of Universidade de Aveiro.

The software application may:

1. be independent of Operative System, although the laboratory PC is working actually with Windows

2. operate with all hardware through GPIB protocol (the development platform may support this hardware interface)
3. allow to dismiss Network Analyzer calibration step if it is already calibrated

4. show a continuous evolution of the acquired results along the measurement process

5. sustain all acquired results even if the measurement process is aborted

6. show the results in a user-friendly interface, giving the chance to save or print them

7. allow to open saved data

8. allow to quantify grating quality, calculating ripple, and also allowing to save or print this data

5.2.2 General Workings

Having set all targets, now it is defined the general program flow. The block diagram of the program general working is:

As it can be observed, figure 5.1 suggests a state machine based implementation, therefore, the program core is conceived as a state machine of six states:

- **Get Measurement**: Computer communicates with hardware to prepare it and to acquire results under conditions defined by user
- **Open File**: A defined file is opened and data is parsed
- **Save Data**: Saves current data in a specified file name optionally adding comments
- **Print File**: Print file to computer default printer
- **Ripple Calculus**: Calculates ripple of a selected characteristic
- **Exit**: Closes program

![Figure 5.1: Software general workings.](image-url)
5.2.3 Input and Output Data

From the six previous described states, four are usually seen in software as support to the two main states. The two main states, Measurement and Ripple, are those where data is processed. For each of these two states it would be better to define input and output data.

Starting with the process of characterizing the fiber Bragg grating, this state may allow the following input data:

- Start wavelength of measurement range, in nm
- Stop wavelength of measurement range, in nm
- Step size between wavelengths, in pm
- Frequency of modulation of laser source, in GHz
- Number of samples for each measurement of a parameter at a determined wavelength (the final result at each wavelength is an average of these samples, increasing accuracy)
- Sweep time, in seconds (samples are acquired during this time)
- Laser Source Power, in dBm
- Laser Source GPIB Address
- Polarization Controller GPIB Address
- Network Analyzer GPIB Address
- Polarization Controller enabler
- Network Analyzer calibration enabler
- Which characteristics may be measured (Group Delay, Reflectivity, Transmissivity)

This state may produce the following output data:

- List of wavelengths, in nm
- List of measured values of each selected characteristic at the corresponding wavelength

This output data may be shown in a graphical mode, with group delay expressed in picoseconds, and reflectivity and transmissivity expressed in decibels. The ripple calculus allows:
• List of wavelengths, in nm

• List of measured values of each selected characteristic at the corresponding wavelength

• Selected characteristic to calculate ripple

After calculus, these are the results:

• Selected characteristic (maintained from input data)

• List of wavelengths, in nm (maintained from input data)

• List of calculated ripple values of the selected characteristic at the corresponding wavelength

• Average ripple

5.3 Implementation Description

After specifying the program, the development phase can initiate. At first, development environment was defined. There were two suitable program development applications which fit specifications: Matlab and LabView. Both are available at INESC and FEUP, both have versions at Linux and Windows operation systems, both are often professionally used, and both support GPIB interface. We chose LabView environment because only recently the Matlab Instrument Control Toolbox supports GPIB, and also due to have already some experience with Matlab, and therefore learning a new program language would be a good challenge, giving opportunity to expand our knowledge.

At first, front panel is described. This main idle stage is the gate from where the program can go to other states and to which automatically returns at the end. Next are described other states of operation, including measurements acquirement.

5.3.1 Front Panel

This is the main state program. From this point it may be defined some measurement parameters, or to observe measurement results or even to select options at left control panel. The front panel overview is shown at figure 5.2:

When ”Start Measurement” button is pushed, it starts a process that uses all parameters defined at front panel. At bottom, two dials and their respective numeric controls define wavelength range, and a third numeric control defines the step size.

At their right, in a tab control, it may be defined the power of laser source and frequency which modulates it. Therefore, wavelength by wavelength, the laser source
emits at a specified power, which is modulated in order to define a reference phase. During each wavelength, Network Analyzer gets a number of samples during a sweep time. The number of samples and sweep time are also defined in the "Parameters" tab. The number of samples may be chosen from a list (3, 11, 26, 51, 101, 201, 401 or 801) which are allowed by Network Analyzer. Because Network Analyzer physical limitations, obviously there is an inferior limit to sweep time, referring to required number of samples, exposed in table 4.3. We chose not to obligate final user to know correspondent time limit for each number of points. In fact, when measurement process initiates, firstly a number of required samples is set into the Network Analyzer, and then the sweep time is set. If sweep time is below the requirable minimum time, network analyzer is automatically adjusted to that minimum, without any information to the user.

At "GPIB Addresses" tab are defined addresses of all hardware, that the software can communicate by GPIB protocol. In fact, VISA is the effective used protocol. This protocol is in an higher layer than GPIB protocol. Hardware address list is shown in figure 5.3.

Each addressable hardware has a defined GPIB address that can be changed to avoid conflicts at GPIB data bus with other hardware. Therefore, although the software, by
default specifies the actual GPIB addresses, it has an option to scan addresses of all hardware connected to the computer.

![Fields to input hardware addresses.](image)

**Figure 5.3:** Fields to input hardware addresses.

As seen in figure 5.4, a table shows all hardware addresses and respectively response to command "*IDN?" (by default, when receiving this command, the device returns its description).

![List of connected hardware.](image)

**Figure 5.4:** List of connected hardware.

After finishing fiber Bragg grating characterization, all data is displayed at the main graphic display. Because of LabView implementation style, this idle state is continuous called, while no other state is called, by pressing one left buttons. This leads that at every 100 milliseconds (a defined cycle time, to not overload the PC with lots of bulk cycles per second), front panel is called, buttons state are watched, but the graphic is not refreshed. This option saves processing. Only after characterizing a FBG or opening a file, the graphic is refreshed with all available data and autosized. At rest
of time user may zoom and/or select (and unselect) measurement parameters under already existing data.

### 5.3.2 Get Measurement

The process of characterizing the fiber Bragg grating under test includes, not only the act of acquiring measurements, but also the previous system preparation and calibration. Next it can be seen the functional decomposition of this process:

![Measurement state block diagram](image)

**Figure 5.5:** *Measurement state block diagram.*

Before starting, if there is any data on the system which would be lost, it is asked what to do with it. Next a window pops up asking to select the grating characteristics to measure, and also to enable polarization control and Network Analyzer calibration.

Network Analyzer calibration may be disable if the Network Analyzer is already
calibrated. In same way, polarization control may be disable if polarization is already maximized, or even if setup does not requires a polarization controller, as explained in section 4.3.2.

After that, hardware connections though GPIB are tested, matching each asked device description with the previewed answer. This is done to laser source and Network Analyzer, and to polarization controller, if polarization control is enabled. If anyone of these matches gives a negative answer, the measured is aborted.

If polarization control was set to on, the process of adjusting polarization begins. The main principle consists in adjusting polarization in order to maximize the received signal value in the Network Analyzer. Therefore it is first necessary to calibrate the Network Analyzer to read S21 parameter, before the polarization adjustment.

After that, polarization control starts. It is not strictly necessary to achieve the global maximum value, but only a local maximum value of the received signal. The most important is that the signal that arrives to the modulator should not be perpendicular to the modulation orientation, to avoid a null modulated signal in modulator output. Therefore, to reach a local maximum, laser source is turned on, and the polarization controller is reseted, setting all four paddles to the middle position, 500 (each paddle has a range between 000 and 999). Starting with first paddle and maintaining other paddles, the received value at position 500 is saved, and compared with values measured in positions 600 and 400. Between these three values, if the value referred to the position 500 is the highest, a local maximum was found. If not, the algorithm

Figure 5.6: Selection of characteristics to measure, and other options.
searches a local maximum in direction of the higher value between the values at 400 and 600. The algorithm steps 100 by 100, and stops when a local maximum is found or when one of boundaries is reached (000 or 999). After that, the same process is done but jumping 10 by 10, and at last, 1 by 1, improving the method resolution. So at this point a maximum is founded moving the first paddle and with all the other paddles locked in position 500. This process is repeated to the second paddle (maintaining the first at position registered its maximum value, and the third and forth in position 500), third and fourth paddles, having in the end a local maximum value and avoiding a null modulation.

If Network Analyzer calibration was set to off, then it is time to confirm if it is already calibrated with the critical parameters, defined in the front panel. Therefore, it is verified if the Network Analyzer has S21 parameter set (see figure 4.3), if the power emitted is 4 dBm (see equation 4.2), and if the sweep time, number of points and modulation frequency match with same values specified at front panel. If one of these parameters failed, measurement is cancelled. We did not choose to calibrate the Network Analyzer in case of failure because, to do that, it was necessary to have the setup correctly connected, as it will be discussed next.

In the other hand, if Network Analyzer calibration was set to on, the calibration starts at this moment. The calibration is important to create a reference value to the received power and to phase shift. Therefore, the setup may be disposed as the following scheme:

![Diagram](image)

**Figure 5.7**: *Recommended calibration setup.*

Using this procedure, Network Analyzer sets gain and phase to zero, so that when the device under test is connected, what is actually measured is only the gain and phase shift introduced by the FBG, and not gain and phase introduced by cables, circulator, etc. As it can be observed at (figure 5.7), that calibration does not count with the
insertion loss and phase shift introduced between two terminals of circulator, because it only passes one time trough circulator, while it can be seen in figure 5.8 that the modulated signal passes two times trough it:

![Figure 5.8: Setup to measure group delay using the phase-shift method.](image)

In fact, while the phase shift introduced may be despised, the insertion loss influences not. To overcome this situation, when a window pops asking to connect a "thru" instead of the grating, it also asks the insertion loss between two ports (it is usually indicated in circulator datasheet or it may be previously measured), having by default 0.4 dB. This value is the usually insertion loss between two ports of an ordinary circulator, and it is in fact the value measured in our setup circulator. This value will be used to adjust the results received from the Network Analyzer.

![Figure 5.9: Calibration details.](image)

Observing figure 5.9, the Network Analyzer calibration includes paths 1 and 5, excluding paths 2, 3 and 4. As said before, path 4 is manually included by user. We opted to consider that the branch between connector and grating that corresponds to paths 2 and 3 belongs to the device under test. We took this option because that fibre segment and connector also influence when the fiber Bragg grating is used in
compensation. Therefore, the results given by the setup are the characterization of the grating plus the fiber and connector.

Having the right setup, laser source is set on, and it is ordered do Network Analyzer the modulation frequency, number of points, sweep time (these three are defined in front panel by user), 4 dBm at output and to read the S21 parameter (already explained). Having these main parameters defined, finally the Network Analyzer is calibrated. It is also defined how Network Analyzer will return the values (in polar mode). At the end, laser source is turned off and a message pops asking to insert the fiber Bragg grating in the measurement setup.

![Figure 5.10: Screenshot while measuring.](image)

When user enables or not the Network Analyzer calibration and polarization control (figure 5.6), it is necessary to explain that when Network Analyzer calibration is enabled, polarization control may be enabled or not, but when polarization control is enabled Network Analyzer calibration must be also enabled. This is mandatory because polarization control changes the amplitude reference value. Therefore it is necessary to calibrate the Network Analyzer in order to set to zero the amplitude and phase reference values. The software already predicts these options.

Having the setup ready (like figure 5.8), laser source is turned on, Network Analyzer
display is turned off (it increases its processing velocity) and measured process starts:

The figure 5.10 shows a measurement process. From top to bottom, it is displayed the characteristic which it is measuring, the current wavelength in that characteristic measurement, the elapsed time between the measurement start and current time, the time to finish current measurement, the time to finish all measurements, and at bottom a graphic which shows measured data in real time. These informations are useful to user in order to know in what point of the measurement process is, and to analyze measurements that have already been done.

User may select three characteristics: reflectivity, the respective group delay and/or transmissivity. If reflectivity or group delay is selected, the Network Analyzer will measure reflectivity. So, for each iteration, wavelength is calculated and ordered to the laser source, and a sweep is ordered to Network Analyzer. Network Analyzer returns the sweep samples as complex values, and the software calculates logarithmic module and phase in grades. Recalling the group delay equation for a given phase shift:

\[ \tau = \frac{\theta}{360 f_{mod}} \]  \hspace{1cm} (5.1)

Reflectivity must be corrected with the addition of insertion loss indicated in path 4, already observed in figure 5.9.

Next, if transmissivity characterization is selected, the laser is turned off, and asked to display the setup.

The process is the same as described to reflectivity measured, except that insertion loss is not added (because that branch is not used) and also phase shift is discarded (not necessary to characterize).

In all this process a main principle was to suppress all the possible time. Therefore all cycles were carefully defined, minimizing processing inside cycles. Also all hardware features are used in order to minimize processing in hardware and minimizing software waiting time to the hardware answer after a question. When this process ends, data is sent to front panel to be displayed.

\[ \text{Figure 5.11: } \text{End of measurement.} \]

### 5.3.3 Save Data

After the characterization of the FBG, all data flows into the front panel. This data not only is available for graphical presentation, but also for printing as well for backing
Saving data is a very important procedure in all kinds of system software. In our particular system, the basic visual presentation may be not enough. All data is necessary for post analysis. Thus, we needed to be aware of the format of the file, the plain text format (.txt) was our choice. There is an example of saved data in appendix B.

The post analysis of the data can be done by 3rd party programs, as a well known program Microsoft Excel or Origin. With these programs if the data is properly organized, its treatment can be easily done. To accomplish the necessary compatibility the data is organized in columns, wavelength is one column, reflectivity is another, and so on.

![Extra information field](image)

**Figure 5.12:** *Extra information field.*

To further improve data storage we included a field to save extra information in the file, figure 5.12. This field is particularly important to log certain parameters of the characterization, like modulation frequency, laser power, and so on. Improving once more the logging of the experiment, at the end of the file, there is a time stamp.

### 5.3.4 Open File

Post analysis of acquired data can be done not only by 3rd party programs, but also by our own system. For this purpose it is also relevant to be able to open files. Post analysis such as ripple or visual analysis, can be done directly by our software. We had the will of giving a solution that is more independent, and that minimizes time spent with setting other programs to properly present the data.

After opening a file, for our system is like when it receives data after characterizing an fiber Bragg grating. This means that graphical display is available, as well as printing, ripple analysis or even saving data.

When opening a file all extra information, regarding the measurement setup or
DUT, are ignored. So, when the data is saved again all extra information must be re-written.

### 5.3.5 Print Data

Printing is also a very important ability of our program. It allows quick and easy visual log of the fiber Bragg grating characteristics.

![Figure 5.13: Printing selection.](image)

It is possible to select which parameters we need to print, can be either the group delay, reflectivity or transmissivity, all together or independently, figure 5.13. Each one has its graphical representation and the corresponding label.

![Figure 5.14: Sample of a print, printed to pdf.](image)
All printing command goes to the default printer, that prints the graphic display of the measurement. This graphical representation of the measured characteristics are black and white, but it is possible to distinguish each other from its corresponding label due to the different type of line. Therefore it can be readable from any kind of printer. As it is possible to see in figure 5.14, a time stamp is also present.

5.3.6 Ripple Calculus

The software allows to analyze fiber Bragg gratings quality, calculating the ripple of a given measurement. This functionality state is be summarized in figure 5.15

![Ripple state block diagram](image.png)

Figure 5.15: Ripple state block diagram.

Entering the ripple state, window pops up with a graphic having the same data that front panel has. At top a selection list shows all characteristics that are presented at the graphic allows to select the characteristic that the user wishes to analyze. As the ripple calculus may be effectuated only from an approximate linear segment of the function of the chosen characteristic, in each bottom corner a dial and its respective numeric defines of the inferior and superior boundaries. As this limits change may be a visual process, the graphic reflects these changes, zooming to the selected area, in order to give an user-friendly interface to user. Under the graphic, a blue slide shows the actual zoom level that user is selecting.

Pressing “Calculate Ripple” button, there is formed a array with all wavelength points which belongs to the user defined boundaries, and other array constituted by each selected characteristic values to the defined wavelength points. This function is approximated by a straight line which best represents the function, using the least-squares solution. At each wavelength, of the measured value is subtracted the correspondent
point of the calculated straight line. This new array is the ripple and it is shown as result, as it can be seen:

At the top is indicated the characteristic which the ripple is calculated. At bottom right is shown the average ripple. At bottom, besides closing the window, the user may save data into a log file or print the graphic, as explained in previous sections.
5.4 Summary

The developed software has as main function to control all the equipment in the data acquisition. The software coordinates the complete setup, acquires data and computes the amplitude and delay parameters of FBGs. This process uses all equipment features in order to minimize the processing time.

The application has an user-friendly interface where user may save and comment acquired data, print graphics or open old measurements. User may also order the ripple calculus of each characteristic. This is a extremely useful information to analyze FBG quality.
Chapter 6

Measurements

6.1 Introduction

It is important to say that all measurements were not done after the software development. The process was quite interactive, with many changes in the system code. This procedure was adopted in order to improve the program efficiency and to improve its implementation. This process had a consequent, the first measurements were not very accurate.

6.2 First Measurements

The first measurements had a very big problem, the signal not was stable. Manually doing continuous sweeps for a single optical wavelength, we could see that the signal had big oscillations, up to 5dB. After some time searching for the faulty device, we came across that a single movement of the input cable of the polarization controller made the signal to oscillate. Thus, either the cable was faulty or it was not made of PM fiber. The solution was to replace the polarization controller by a PM fiber. From now on the oscillation was still present but much more negligible. It is possible to see the measurement before (figure 6.1) and after (figure 6.2), for 1GHz and step of 10 pm.

This physical problem of our system is now identified and solved. Still the fiber used to connect the laser to the modulator is not PM all the way, because there were not in INESC Norte a PM fiber with APC and FC-PC connectors. It was used a PM fiber with a APC connector with a splice to a normal fiber with a FC-PC connector. In measurements it is necessary to be aware of this sensibility of the measurement setup. The fiber before modulator must be stable, it can not move, as well as the DUT. Vibrations lead to a less accurate measurements.
6.3 Two different approaches

As it was mentioned in chapter 4.4, the development of the software took two main different approaches. One was the "n sweeps" for a single wavelength, and the other was the "CW" mode. After the main structure of the program has been done, both approaches were put under test. Our main concern was the reliability of the data, and
its time to perform all data measurements. For these reasons we made the following measurement for each method.

**Figure 6.3:** "n sweeps" method.

**Figure 6.4:** "CW" method.

The measurement conditions for the "n sweeps" were:
- Start wavelength 1552 nm thill 1561 nm, with a step size of 0.1 nm;
- Modulation frequency of 1 GHz;
- Sweep time of 100 ms;
- 128 samples;
- 2dBm laser power.

The measurement conditions for the "CW" were:
- Laser source start wavelength 1552 nm thill 1561 nm, with a step size of 0.1 nm;
- Modulation frequency of 1 GHz;
- Sweep time of 15 seconds;
- 201 points;
- 2dBm laser power.

In figures 6.3 and 6.4, there are the measurements for "n sweeps" and "CW" respectively. Both measurements have the same parameters apart from the sweep time and number of samples. Despite the low step resolution, it is possible to see that visually they are quite similar. To confirm this visual feeling, we measured the ripple in the
band from 1555 nm to 1559.8 nm. Both methods showed and average ripple almost identical, as it is possible to see in Figure 6.5

On the other hand, the time performance difference is significant, the "n sweeps" took 40 minutes for 128 samples, while the "CW" took 29 minutes using more samples (201). Looking at these times at first it does not seem that big the time difference, but we need to take notice of the step resolution. This measurement was done with 100 pm step, and the system allows up to 1 pm step, thus for a lower step the time difference will increase a lot.

The time difference from both methods became the main criterium for choosing the "CW" method. Still its the time to characterize the DUT for 100 pm step was too high, but later on, we manage to see that a 15-second sweep is excessive, it is enough 2 or 3 seconds to obtain relative accurate samples. Another point in favor of "CW" is the ability to control the sweep time. In "n sweeps" the sweep is always a constant, it is used the preset value of the NA. So, in "CW" we have another parameter, which we can specify in order to accurate measurements, or save time.

6.4 CW method, further measurements

From now on, all further measurements will be directly compared. We will compared

![Figure 6.6: 1552-0.05-1561nm, 2dBm, 1GHz, 15s, 201 points, 55 minutes.](image)
its performance, as well its accuracy. The accuracy will be always relative, and we can not say for sure which is the best. We will mainly express our opinion. The first measurement series was done purely to compare the effects on the measurement by changing the sweep time.

In the measurement on figure 6.6 the laser was set for a bandwidth from 1552 nm to 1561 nm with a step size of 50 pm and power of 2dBm. The NA was set for a sweep time of 15 seconds and in each sweep the NA reads 201 points. For the measurement on figure 6.7 all parameters are equal except for the sweep time, it has been decreased to 5 seconds.

![Figure 6.7: 1552-0.05-1561nm, 2dBm, 1GHz, 5s, 201 points, 20 minutes.](image)

As it is possible to see, both measurements have very similar results. For 5 seconds sweep time the group delay ripple is slightly lower than the 15 seconds sweep, this can be explained by the oscillation in the signal between two consecutive samples. For the same number of points, the points which are sampled for 15 seconds are more apart from each other than the 5 seconds measurement. This can cause that for the 15 seconds measure, the signal has more time to change. The increase of points for higher sweep times, may soften the group delay ripple, lowering average. Comparing the time performance, the time relation from each measurement is the same as the relation for the sweep time. As expected the measurement on figure 6.6 took three times longer than the one on figure 6.7.
In the following measurements we will change the number of points, with all others parameters equal to the one of figure 6.6.

![Graph showing group delay and reflectivity](image)

**Figure 6.8:** 1552-0.05-1561nm, 2dBm, 1GHz, 15s, 401 points, 59 minutes.

![Graph showing group delay and reflectivity](image)

**Figure 6.9:** 10 1552-0.05-1561nm, 2dBm, 1GHz, 15s, 801 points, 63 minutes.

As it is possible to see, comparing figures 6.8 and 6.9, for an higher number of points, the group delay ripple gets slightly improved. This confirms what it was said
before, for figures 6.6 and 6.7. But this increase of the number of points reflects on the time performance of the system.

Figure 6.10: 1552-0.05-1561 nm, 2dBm, 1.5GHz, 15s, 801 points, 63 minutes.

Figure 6.11: 1552-0.05-1561 nm, 2dBm, 0.5GHz, 15s, 801 points, 63 minutes.

For the next measurements the laser is set as before (from 1552 to 1561 with 50
pm step), but the NA is set for 801 points with a sweep of 15 seconds and we will change the modulation frequency. The first measurement (figure 6.10) was done for higher group delay resolution, with 1.5GHz modulation frequency. The measurement of figure 6.11 was done with a modulation frequency of 0.5GHz.

Directly comparing both measurements, it is possible to see that for the higher modulation frequency (higher group delay resolution) we have lower average of the group delay ripple. If we compare directly the average 6.10 with the one of figure 6.9 the average group delay ripple increased a little bit, this means that the increase of the group delay resolution has a direct consequence on its ripple, it is more sensitive for signal fluctuations.

By equation 4.3, $f_{mod}$ influences the range of the group delay that can be correctly measured. The phase $\theta$ varies between $-180^\circ$ and $+180^\circ$, therefore, for example modulating at 1GHz, the group delay range will between -500 ps and +500 ps. If the FBG has a greater group delay range, it will not fit in the measurement band and consequently it shifts when reaches one of the boundaries.

![Figure 6.12: 1552-0.01-1561nm, 2dBm, 1GHz 2.5s, 201 points, 63 minutes.](image)

Most of the measurements until now were done with 15 seconds sweep time. Now we will try lower sweeps for even lower step time. We decreased the sweep time significantly so that we have reasonable timings for characterizing a chirped FBG. Now the laser
step size is 10 pm, with the NA sweep time of 2.5 seconds (figure 6.12), and on figure 6.13, the step size is the same, but with an even lower sweep time, 0.2 seconds.

If we look directly to the average of the ripple we notice that its value is higher than all previous measurements for 1GHz modulation frequency with 50 pm step size. Specially for 0.2 seconds sweep (figure 6.13) it is significantly higher. Still we must take into consideration that for lower step size it might be “normal” to see sudden changes of the group delay.

An other measurement was done for 10pm step size, but this time with 3 seconds sweep (figure 6.14). This measurement can be directly compared with the ones from figure 6.12 and figure 6.13. Even so the average group delay ripple is similar to the previous references.

To directly compare with the previous measurement, it was done an other measurement but this time with 1 second sweep (figure 6.15). As it has been seen many times before, when comparing identical measurements with different sweep, the one with lower sweep time has lower average group delay ripple.

Although the low time for acquiring a measurement, we believe that setting the sweep time to around one second should be enough to characterize a chirped FBG. When higher sweeps are needed we also recommend the increase of the number of points, as already discussed.
Finally, we can compare some results with a reference. Reflectivity was characterized with a white light source, a circulator and an Optical Spectrum Analyzer, as seen
in figure 6.16.

Figure 6.16: FGB’s reflectivity in an Optical Spectrum Analyzer.

Figure 6.17: Same reflectivity amplitude that figure 6.15, in linear scale.

In figure 6.17 it can be observed reflectivity characteristic in linear scale. The two scale values differ because, in figure 6.16, that values correspond to the power that is reflected from the chirped FBG, emitted from a white light source with an unknown power value. In other hand, our values show the relation between the power reflected from chirped FBG and the power measured without the chirped FBG (calibration). Therefore, these absolute values must not be compared.
The shape of the two figures may be compared. Between 1552 and 1556 nanometers, it can be seen that the shapes are very similar. Before that value the shapes differ. In figure 6.16 the amplitude value increases, while in figure 6.17 it decreases. This
can be explained by the fact that the white light source bandwidth is limited, and its amplitude starts decreasing and consequently decreasing the reflected power. Another consequence is that the amplitude ripple that the chirped FBG has between 1556 and 1557 nanometers is attenuated in figure 6.16 due to the same reason. If it was due to noise in the setup system, this noise should be over all entire measurement, what it does not happen.

We also characterized a normal FBG, the fiber that we characterized had two gratings written into it. On figure 6.18 we can see both gratings over a wide bandwidth, but with a step size of 0.5nm.

On figure 6.19 it is possible to see with high detail the second grating of the fiber.

6.5 Summary

Measurements demonstrate the good setup performance. All parameters that may be changed allow a good flexibility between measurements accuracy and time processing, giving the chance to use the best group of parameters that better results produce according to specific necessities. Time processing is also dependent, obviously, from the wavelength width of the FBG that will be characterized.

The number of points and sweep time are parameters that demonstrates that flexibility. These two values must be defined taking a compromise between accuracy and time processing. When increasing the sweep time, number of points should be also increased, in order to improve results accuracy.

Frequency of modulation represents another compromise, this time between spectral and group delay resolution. A middle value should be chose in order to achieve good results.

In this chapter it is also compared some results with measurements obtained with the same FBG. It can be observed the good system performance.

The chirped fiber Bragg grating which is being characterized does not have the opposite extremity completely adapted with index matching gel or oil. Therefore all the reflected amplitude that is measured effectively is the sum of the FBG’s reflection and 4% of the power which reached the opposite extremity. This Fresnel reflection is not automatical deleted by the software because we hope that index matching gel or oil will belong to the measured setup in the future.
Chapter 7

Conclusion

This project has great importance for the optical communications department of INESC Norte. From now on INESC Norte is able to characterize all fibers that are fabricated within the company. If a FBG can be easily characterized in order to its reflectivity and transmissivity with a white light source, a circulator and a Optical Spectrum Analyzer, the group delay can not be measured this way. For the group delay there is the phase-shift setup, and, with our system, the measurement of the group delay is automated. Besides that, we believe that this method has greater accuracy in the calculus of the reflectivity and transmissivity, because there is no risk of losing linearity due the white light source. Also, the method used by the setup that we developed is useful not only to characterize the group delay of FBG, but as well as the group delay of others optical devices.

Working in this project, we acquired greater sensibility in matters as optical transmission in single-mode fibers, in the subject of attenuation and dispersion, and methods to compensate these problems. More precisely, the use of chirped FBG for dispersion compensation, allowed us to further understand this method and all effects produced, and above all, the importance of the characterization of these devices.

With our system accomplishing most of requested tasks, it was possible, in early stages of development, to test it with other projects in development. This interaction allowed us to be more sensitive to the actual/future user requests to further improve our system for an higher satisfaction level. It also allowed us to invest all knowledge already acquired in the process of development of this project.

As this setup allows modification of several parameters that condition the measurement, it gives to user full control of the method application. With a user-friendly interface user may define wavelength range, frequency of modulation, number of samples, sweep time and laser source power. These parameters directly influences measurement accuracy, processing time, spectral resolution and group delay resolution. A compromise between all these factors should be achieve.
This high performance was achieved due to how Network Analyzer is remotely operated. Using it in Continuous Wave mode and controlling sweep time and number of points, an efficient control was achieved. Characterization of fiber Bragg gratings is carried out with high-resolution and fast processing.

To characterize the used chirped FBG in the system performance analysis, we recommend the following values:

**Wavelength range:** 1552 to 1561 nanometers.

**Wavelength step:** 10 picometers.

**Number of samples:** 201.

**Sweep time:** 1 second.

**Modulation frequency:** 1 GHz.

**Laser source power:** 2 dBm.

With these defined parameters it can be achieved a group delay resolution of 0.28 ps and a spectral resolution of 16 pm, having a processing time of 40 minutes.

A critical factor to improve measurements accuracy is the stability of all hardware setup. Any perturbation implies attenuation and dispersion variations in the fiber, which will be noted in results, due to this setup high sensibility. Another critical parameter is that the extremity of the FBG must be completely adapted, so that extremity must be perfectly cut, and an index matching gel or oil must be used.

Finishing a project like this, after five months of work, there is always space to implement other features in order to improve the characterization setup in future work. This project may grow and, for example, a web interface may be developed. Labview language supports this feature. This portal may be hosted in an already existing web server owned by INESC. Measurements may be effectuated remotely. The setup may be calibrated locally, but all measurements which not need new calibration may be ordered remotely. Allowing a file upload, several measurements may be ordered at the same time, and the software may coordinate all measurements and send results to an also specified e-mail address, for example. This new feature should be welcomed by INESC but also by foreign researches.

This web interface may be a new impulse to future work that will complement the project here described. Like this idea, others related to this subject should be useful in order to make this setup even more robust and functional.
Bibliography


[23] METER MANUAL DO LABVIEW.
Appendix A

Network Analyzer

A.1 S-parameter Test Set

The HP 85046A S-parameter test set contains the hardware required to make simultaneous transmission and reflection measurements section 4.3.4.

![Diagram of HP 85046A S-parameter test set]

Figure A.1: HP 85046A S-parameter test set.

Reflection: FWD S11 (A/R) configures the S-parameter test set for a measurement of S11, the complex reflection coefficient of the test device input.

Transmission: FWD S21 (B/R) configures the S-parameter test set for a measurement of S21, the complex forward transmission coefficient of the device under test.

Transmission: REV S21 (A/R) configures the S-parameter test set for a measurement of S12, the complex reverse transmission coefficient of the device under test.

Reflection: REV S21 (B/R) defines the measurement as S22, the complex reflection coefficient of the device under test.
A.2 GPIB Addresses

The GPIB is a general purpose digital interface system that simplifies the integration of the IEEE Standard 488-1978. The GPIB uses a party-line bus structure in which up to 15 devices can be connected to one contiguous bus. With this cabling system, many different types of devices including instruments, computers, plotters and printers can be connected in parallel.

For the Network Analyzer HP 8753A it is possible to set the GPIB address. This NA, has two addresses for control through GPIB. One of the addresses is to control the device, and the other is for the display. The display address is always dependent of the device address. If the device address is even, the display address is that number plus one. If it is odd, the display address is that number minus one. For instance, the NA has the factory set address of 16, making the display address 17.

A.3 NA Technical Problems

If the NA does not turn on, please go to the rear panel of the NA and look to the "Power supply diagnostics LEDs". The instructions in the rear panel are quite clear, if the bottom LED is off the problem might be the fuse. During the project development, for several times, the fuse burned. These burns might be caused by the age of the NA. Maybe its components, with the age, have started to consume more power.

For information on replacing the fuse, refer to the NA manual.
Appendix B

Example of a Data Log

B.1 Save Data

1552 - 0,1 - 1561
1 GHz
3 amostras
2dBm

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### APPENDIX B. EXAMPLE OF A DATA LOG

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Appendix C

Additional work

C.1 Generic Data Acquisition from the Network Analyzer

While developing the system for characterization of FBG we acquired the knowledge and experience of controlling the NA. To do a program that acquires all data presented in the display of the NA was a simple application of our already acquired knowledge.

The application developed allows not only pure data acquisition, but also its graphical presentation. For graphical presentation, the software needs to identify the actual type of measurement presentation. When user orders a new data acquisition, the software asks the NA for the type of measurement:

- **LOG MAG**  log magnitude format
- **PHASE**  Cartesian format of the phase portion of the data, measured in degrees
- **DELAY**  group delay format, with values given in seconds
- **SMITH CHART**  Smith chart format
- **POLAR**  polar format
- **LIN MAG**  linear magnitude format
- **REAL**  just the real part of the measured data on a Cartesian format
- **SWR**  reformats a reflection measurement into its equivalent SWR (standing wave ratio) value

As the main purpose of this small application was to acquire data and save it, the operating sequence was simplified. This software was therefore developed in order to
KISS ("keep it simple and stupid" [10], great principle of Extreme Programming). So the program does not control the NA, but just asking information to the NA.

After the "Update" button has been pushed, but before the data acquisition, the software consults the main NA set parameters. Those parameters are, the S-parameter, the number of points, the parameter format (for the graphical presentation), as well as the NA power.

After that, the NA is order to return a single sweep measurement. With the sweep acquired, it is possible to save data to a file or print it. When data is saved, it is generated a file that besides the measurement, it includes all parameters read before. As in the main software of this project, the saving procedure allows to write additional information about the measurement.

![Software for acquisition of data from the NA.](image)

**Figure C.1:** *Software for acquisition of data from the NA.*
Appendix D

Presentation Poster

Characterization of Fiber Bragg Gratings for Dispersion Compensation

http://paginas.fe.up.pt/~ee99113/

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OBJECTIVES:
• Characterization of Fiber Bragg Gratings
• Implementation of measurement setup
• Software for control and data acquisition
• Data analysis: delay, bandwidth, ripple

DELAY MEASUREMENT:

FIBER BRAGG GRATING:
http://paginas.fe.up.pt/~ee99113/

SPECIFICATIONS:
• Wavelength Bandwidth: 1520 nm – 1570 nm
• Wavelength Resolution: 1 pm
• Modulation Frequency: 300 kHz – 3 GHz
• Spectral Resolution: 16 pm (1 GHz)
• Group Delay Resolution: 0.28 ps (1 GHz)

DEVELOPED SOFTWARE:

CONCLUSIONS:
A measurement setup was implemented for characterization of the amplitude and group delay parameters of Fiber Bragg Gratings. Efficient control of the setup and a user-friendly interface was achieved. Characterization of Fiber Bragg Gratings is carried out with high-resolution and fast processing.

ACKNOWLEDGEMENTS
L. M. Ramos and R. P. Ramos would like to acknowledge Prof. A. Teixeira for his collaboration and are thankful for the grant conceded by the Program PRODEP III - Medida 3.

ADDITIONAL WORK:
Fig. 8: Generic software for data acquisition from the Network Analyzer.