



Tuneable Optical Filter based on a Fibre Bragg Grating with USB Interface

Final Year Project

July 2006

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621.3(047.3) / CEEC 2006 / F62d

Universidade do Porto
Faculdade de Engenharia
Biblioteca
Nº 105233
CDU
Data 24 / 02 / 2010

Abstract

Optical networks have gradually changed to sustain the growing need for bandwidth in communication networks. Wavelength switched networks using Dense Wavelength Division Multiplexing (DWDM), are a solution to this problem.

Development of these networks demands the research and development of optical devices such as multiplexers / demultiplexers and cross-connects (OXC's), that are able to control the communications channels and route them correctly and transparently. These devices work by routing, switching and selecting signals based on the wavelength, playing a key role in such networks.

The tuning of fiber Bragg gratings are typically used within these devices to allow the selection of the required wavelength.

Therefore, this report describes the design and implementation of an optical tuneable filter, controlled by LabView through an USB connection. The tuneable filter system is based on a piezoelectric actuator which works by compressing the fiber Bragg grating. A high-voltage amplifier was also developed for driving the actuator. The optical filter is suitable for channel demultiplexing within WDM systems.

Acknowledgements

First of all, we would like to thank our advisor, Prof. Henrique Salgado, for his guidance and support throughout the project. We also thank him for being always there with his knowledge and trust, helping us to solve the problems we faced along our work.

We are truly grateful to Eng. Joel Carvalho and Eng. Orlando Frazão, without whom our work would have been certainly harder.

Special thanks to all people from INESC-Porto (UOSE and UTM), specially to João Oliveira, who contributed with very advantageous discussions, opinions and, of course, friendship.

Luís can not forget the permanent support of his family and friends. He would also like to say a special thank to Anabela for always being a constant source of support, encouragement, strength and inspiration.

Daniel would like to thank his family. He is also much indebted to his good friends, for their advice, for their words of encouragement and inspiration at all times.

We would like to thank the financial support given by “Fundação para a Ciência e Tecnologia” (FCT) under the programme “Programa Operacional Ciência Tecnologia e Inovação” POCTI/FEDER with grant REEQ/1272/EEI/2005 - Fibre Optic Supported Broadband Communication Networks.

Finally, we acknowledge financial support from Programa POCI 2010 Acção IV.7.1.

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Chapter 1

Introduction

1.1 Background and Motivation

An unprecedented growth in data traffic has stimulated the telecommunications industry to accept that optical networks are the only solution to build the backbone that will carry global data traffic. Particularly, All-Optical Networks have been considered, from the standpoint of recent advances, the only technology capable of sustaining such growth, satisfying such a tremendous throughput and still providing Quality of Service (QoS).

Therefore, new generation networks are designed as all optical to avoid the electronics bottleneck. That is, information is always carried in the optical domain, avoiding being processed in the electronic domain at the network nodes, where data packets are switched/routed.

The usage of DWDM (Dense Wavelength Division Multiplexing) as a physical layer networking mechanism, especially when signals are routed, switched and selected based on wavelength made optical devices key components in such networks, allowing a more transparent and versatile network management. Moreover, FBGs are typically used within these devices to allow the selection of the required wavelength.

Therefore, the main driving force behind our work, was the implementation of a filter in the optical domain. The filter is to be controlled via PC. Hence, we have built a tuneable filter system based on a piezoelectric actuator which works by compressing the fiber Bragg grating. A high-voltage amplifier was also developed for driving the

actuator. The optical filter is suitable for channel demultiplexing within WDM systems.

1.2 Report Organization

We shall now briefly present the report's structure.

Following this chapter, an entire chapter is dedicated to fiber Bragg gratings and the several switching techniques associated.

In Chapter 3, an overall description of the system is presented. A theoretical introduction to piezoelectric devices is exposed, and finally, a detailed description of mechanical system assemble is given.

Chapter 4 presents a comprehensive explanation of the high-voltage amplifier used to drive the piezoelectric device, as well as it's associated high-voltage power supply.

Chapter 5 is entirely dedicated to all the implications related with the microcontroller, it's associated communication protocol with LabView as well as an exhaustive exposition of the USB related architecture.

In Chapter 6 we present the experimental work which we carried out, namely we present the experimental setup and results gathered concerning wavelength tunability of the device.

Finally, in Chapter 7 we present some concluding remarks, other avenues of research that might be pursued and also what further work is there to be explored concerning the work we have done.

1.3 Contributions

This work brings some insight into the techniques of mechanical switching using fiber Bragg gratings.

The main contribution of this research may be summarized as follows:

- The implementation of a special mechanical system which provides a tuning mechanism of a FBG by the application of compressive stress.

- The practical implementation of a fully based USB communication protocol, between a computer and a microprocessor.

The following publication is a consequence of the work developed and described here:

D. S. Fernandes, L. M. Pessoa and H. M. Salgado, "Tuneable optical filter based on a Fibre Bragg Grating with USB interface", *Digest of SEON 2006 - IV Symposium on Enabling Optical Networks and Sensors*, pp. 53-54, June 2006.

Chapter 2

Switching techniques

2.1 Fiber Bragg gratings theory

Fibre bragg gratings are optical filters that behave just like a pass-band filter. However, they have an intrinsic property which makes them to operate in rejection, thus redirecting the rejected band to another optical path (notch filter behaviour). This characteristic makes fibre Bragg gratings an interesting device for operation within all-optical networks.

A Bragg grating constitutes a high-performance device for accessing individual wavelengths in the closely spaced spectrum of *DWDM* systems. Since this is an all-fiber device, its main advantages are the same as other all-optical devices, namely: low cost, low loss (around 0.1 dB), ease of coupling with other fibers, polarization insensitivity, low temperature coefficient (<0.7 pm/°C), and simple packaging.

A fibre Bragg grating is a periodical modulation of the refractive index in the fibre core and is formed by exposing the core of the fibre to intense 244 nm ultraviolet radiation. The fibre Bragg gratings referred in this project were manufactured in-house employing the phase mask technique. The property connected to the change (increase) of the refractive index with exposure to UV radiation is referred to as photosensitivity. Light propagating along the waveguide is efficiently reflected by the grating, if the reflected portions from all grating planes interfere constructively with each other, giving rise to a backward propagating signal. Figure 2.1 describes the basic principle of a FBG.

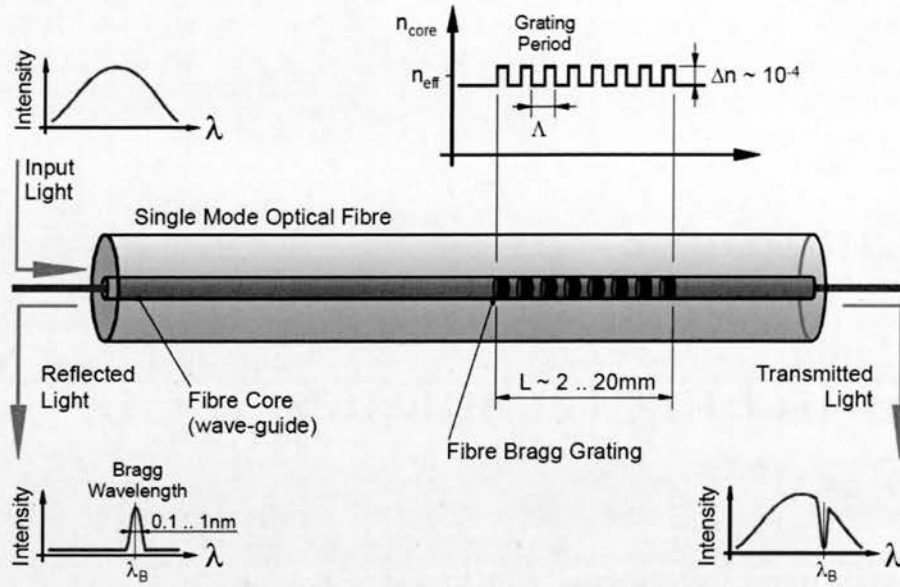


Figure 2.1: Fibre Bragg grating

This condition is known as the so called Bragg condition, i.e. the wavelength in the material, λ_B , has to be twice the grating period times the mode effective refractive index of the core:

$$\lambda_B = 2\Lambda * n_{eff} \quad (2.1)$$

That means that propagation constant of the core guided mode is resonant with the spatial modulation index.

Bragg gratings with a uniform modulation of the refractive index have reflection spectra characterized by a main peak followed by a series of adjacent sidelobes. However, in Dense Wavelength Division Multiplexing (DWDM) applications, a sidelobe reduction is necessary to decrease crosstalk and increase isolation levels between adjacent channels. This sidelobe reduction is attained by tailoring the modulation of the refractive index along the grating length. Gratings with this characteristic are called apodized fiber Bragg gratings [1].

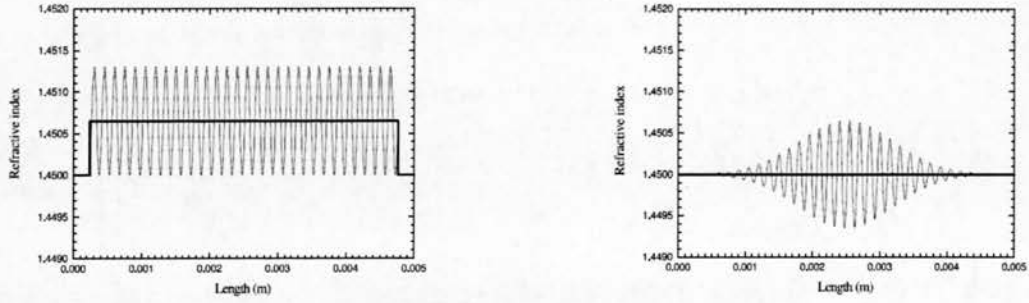


Figure 2.2: Uniform (on the left) and DC-Gaussian (on the right) modulation of the amplitude profile of the refractive index

2.2 Techniques of optical switching

There are essentially two different methods of optical switching being object of research: Tuning of fibre Bragg gratings and the use of non-linear optics. A global idea of fibre Bragg gratings sensitivity to physical variations will now be exposed. If we consider the Bragg Relationship in it's differential form [2]:

$$\Delta\lambda_B = \lambda_B \left(\frac{\Delta n_{efc}}{n_{efc}} + \frac{\Delta\Lambda}{\Lambda} \right) \quad (2.2)$$

we can conclude that any external quantity that changes the effective index or the period, leads to a deviation on the resonant Bragg wavelength. Thus, the spectral response of Bragg gratings is sensitive to temperature variations, mechanical strain, pressure and magnetic fields.

In fibre Bragg gratings, these variations are transformed to a shift of the Bragg wavelength which makes them well suited as tunable filters. This characteristic also offers the possibility to create FBG-based sensor elements.

There are several tuning mechanisms applicable to fibre Bragg gratings, that will be later explained. Among them:

- Thermal switching
 - Induced temperature variations using a Peltier element
 - Thin film coating the fibre Bragg grating
 - Temperature tuning induced through a pump power laser diode

- Mechanical switching
 - Tuning induced by mechanical deformation using a piezoelectric element.
 - Bending
 - Pressure
 - Magnetic Field

Another technique to achieve optical switching, based on non-linear effects, may be obtained by wavelength conversion using the four wave mixing effect (FWM) in a ring fibre laser and dispersion shifted fibre, or by exploring the Kerr effect in a fibre Bragg grating through the use of a high power pump laser.

2.3 Thermal switching

To a given temperature variation ΔT , the corresponding deviation in the resonant Bragg wavelength is given by [2]:

$$\Delta\lambda_B = \lambda_B \left(\frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} + \frac{1}{n} \frac{\partial n}{\partial T} \right) \Delta T = \lambda_B (\alpha + \xi) \Delta T \quad (2.3)$$

where α and ξ are the silica's thermal expansion coefficient and the thermo-optic coefficient, respectively. Substituting those coefficients in the expression we get a theoretical variation of 13.48pm/°C (figure 2.3) which is essentially dominated by the refractive index change, thus the contribution from the modulation period change is almost insignificant.

That result means that, in practice, 60°C of temperature variation are necessary to switch a DWDM channel with a spacing of 0.8nm (100GHz ITU) to the λ_{Bragg} [3].

2.3.1 The Peltier element

The peltier effect was discovered by the French scientist J. Peltier in 1834. It's effect is very weak on metals, becoming impossible to achieve an effective cooling, even with the help of a metallic thermo-element. However, using semiconductor thermo-elements it is possible to achieve a much more effective cooling, which allowed the

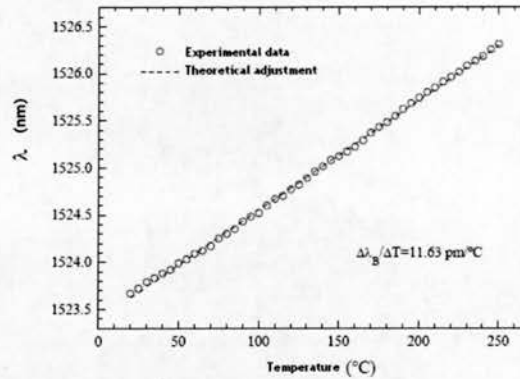


Figure 2.3: λ_{Bragg} variation with the temperature

appearance of several practical applications associated with peltier elements. They are the fundamental part of thermo-electric (TE) coolers, essentially due to their simplicity of construction and reduced size.

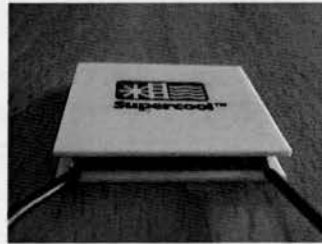


Figure 2.4: Typical Peltier unit

A typical unit is a few millimeters thick by a few millimeters to a few centimeters square (picture 2.4). It is a sandwich formed by two ceramic plates with an array of small Bismuth Telluride cubes ("couples") in between. When a DC current is applied heat is moved from one side of the device to the other - where it must be removed with a heatsink.

They are not very efficient and can draw a few amperes of power. This disadvantage is more than offset by the advantages of no moving parts, no Freon refrigerant, no noise, no vibration, very small size, long life and capability of precision temperature control [4].

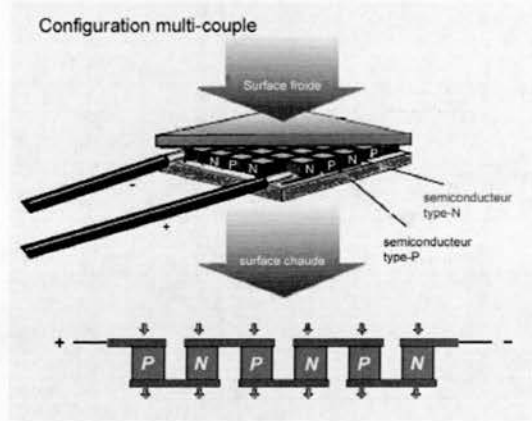


Figure 2.5: General functioning diagram

2.3.2 Induced temperature variations using a Peltier element

In order to easily achieve temperature variations in the FBG, a peltier element may be used. The Bragg grating is placed over the peltier element, and embedded on a thermal paste to allow an uniform temperature distribution along the grating.

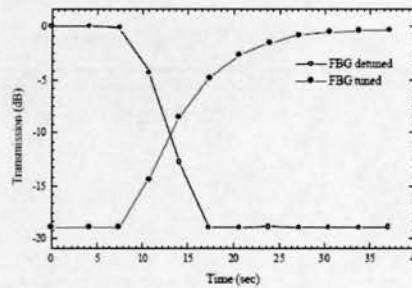


Figure 2.6: Tuning and detuning speed

However there is a performance issue connected to the tuning speed. The temperature control gives stable results but only slow tunability is achieved. This can be seen in the Figure 2.6 where the tuning and detuning speed of the optical filter (FBG) is seen.

When tuning, i.e., reaching a specified wavelength in order to reflect it, the achieved speed is around 10 seconds. But it should be noted that detection of the desired channels begins before the stable wavelength is reached. As the temperature of the grating

increases, the central wavelength reflected by the grating changes until it reaches the desired wavelength. An important point to note is the fact that, once in a specific wavelength, the device maintains stability [5].

2.3.3 Thin film coating the fibre Bragg grating

Optical filters using the technique of thin film coating have been object of research. This kind of tunable filter device uses a resistive coating to directly heat an intracore FBG. The relative wavelength shift of the Bragg grating is due to changes in the length and in the refractive index that are induced by the temperature change in the core.

A tunable FBG with a metallic heater can be modeled as a silica cylinder with thin-film thermal source on its surface and surrounded by air. Thus, the heat generated in the thin-film metal heater will diffuse and radiate into the fibre core as well as to the surrounding air. According to Li *et al* [6], the electric power P is given by:

$$P = IV = I^2 R = I^2 \left[\frac{\rho L}{\pi b(2a + b)} \right] \approx I^2 \frac{\rho L}{2\pi ab} \quad (2.4)$$

where ρ is the resistivity of the thin-film metal, b is its thickness, a is the radius of the fibre, and L is the length between two electrodes.

The single mode optical fibre with the Bragg grating is typically coated with Ti (Titanium) and Pt (Platinum) (or even Nickel) thin films (which can be deposited using the RF magnetron sputtering technique). The Ti and Pt films thickness is generally in the range of a few hundreds of nanometres, resulting in a few ohms of resistance.

To induce a current in the film two electrodes are placed over it and connected to a signal generator that will induce a square-wave current signal with chosen repetition rate and a 50% duty cycle. This current will then heat the film through Joule effect. As the FBG is heated, its reflecting wavelength (λ_B) will increase.

In Figure 2.7, the spectrum of a FBG used in experimental work [7] is shown as well as the resulting spectrum when different current signals are applied. One of the spectrums corresponds to application of a 6mA which induces a shift of 1 nm in the reflected wavelength which was originally 1538.8 nm. And the other spectrum that is presented shows the shift of 10 nm that is caused by application of a 0.31A signal. A switching time of 450 ms has been reported as also as a shift of 10 nm in the reflected

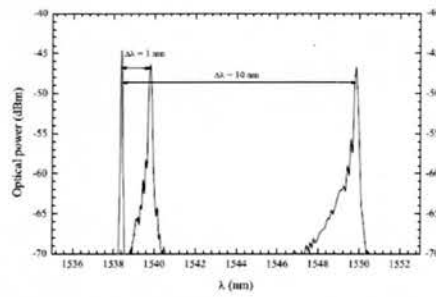


Figure 2.7: Spectrum for the FBG in several situations

Bragg wavelength.

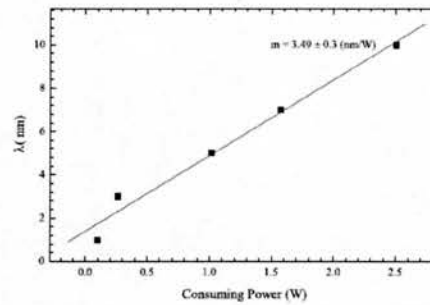


Figure 2.8: Electrical Power consumption versus wavelength shift

A linear power dependence of the wavelength shift is expected when the metal-coated device based on heating effect is in thermal equilibrium. A power efficiency of 3.49 nm/W has been reported. The last value depicted in figure 2.8 corresponds to the maximum tuning range of the device of 10 nm. This technique, compared with the Peltier element technique, seems to give broader tuning ranges and a reduction in the switching time better than 20 times.

2.3.4 Temperature tuning induced through a pump power laser diode

This switching device is a combination of a classical add-drop multiplexer structure, with a high power pumping continuous wave (CW) diode laser. The laser diode allows

the induction of high power density inside the core of a single mode fibre and consequently to achieve thermal switching due to the silica thermal expansion coefficient of 10-11 pm/°C at 1.5 μ m.

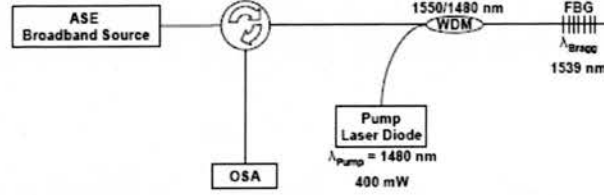


Figure 2.9: Description of the setup

The setup that is used to test this technique is the one on figure 2.9. The ASE broadband source is connected to the OC which is connected to the FBG by means of the WDM coupler, which combines both the broadband signal and the pump laser signal. Typically, the pump wavelength is either 980nm or 1480nm. It has been reported a switching wavelength tuning range of 140 pm showing a grating temperature variation of 14 °C. Switching times around 500ms have been achieved, which corresponds to a maximum tuning speed of 0.28 nm/s and a pumping power of 400mW (Carvalho *et al* [8]). In fact, the wavelength tuning range of this experiment is very short. Although the wavelength change varies linearly with the pumping power, a power of 2.286W would be necessary to switch a single ITU channel (0.8nm). Thus, this technique doesn't seem to be very efficient. However, there is the possibility of using two pumping laser diodes instead of only one.

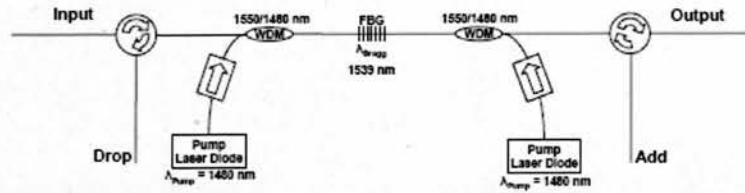


Figure 2.10: OADM with two pumping laser diodes

The above referred possibility is shown in Figure 2.10. It is showed a classical optical add-drop multiplexer, but now with switching enhanced capabilities due to the

use of two pump laser diodes [9].

2.4 Mechanical Switching

2.4.1 Axial strain

Due to the excellent silica behaviour under stress and its low thermal expansion coefficient, 10-11 pm/°C at 1.5μm, mechanical stresses have been preferentially selected to achieve wide tuning ranges. In particular, in 1994, Ball *et al.* [10] realized a compression based tunable fibre laser with 36nm of tuning range, using a stepper motor.

To tune the Bragg grating central wavelength, peak mechanical stresses are usually applied to the optical fibre, preferentially using a piezoelectric actuator. In fact, the tuning range is directly proportional to the fibre Bragg grating strain. So, taking into account that silica's Poisson ratio is somewhere between $\nu = 0.17$ and 0.19, axial strains, ϵ_Z , in comparison with radial, $\epsilon_T = -\nu\epsilon_Z$, are generally applied to fibres. Additionally, due to better resistance properties of silica under compression than under tension (23 times stronger), more and more people are applying compressive stresses, which gives a wider tuning range and a decreased probability of breaking the fibre. The relationship between the stress and the strain for a material in the elastic domain and in the axial direction Z, is given by,

$$\sigma_Z = E \cdot \epsilon_Z \quad (2.5)$$

where $E = 7.25 \cdot 10^{-4} \text{ N/mm}^2$ is the silica Young Modulus and ϵ_Z is the axial strain which is defined by,

$$\epsilon_Z = \frac{\Delta L_Z}{L_Z} \quad (2.6)$$

where ΔL_Z is the axial displacement and L_Z is the stressed length (Figure 2.11).

The shift of the Bragg central wavelength peak, $\Delta\lambda_B$ as a result of stress application is related to the effective refraction index change, n , and the change in the grating period, Λ , by the following differential relationship:

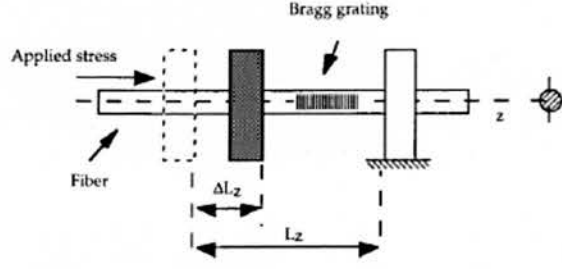


Figure 2.11: Concept of axial compression

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \epsilon} + \frac{1}{n} \frac{\partial n}{\partial \epsilon} \right) \Delta\epsilon \quad (2.7)$$

Solving this equation in terms of transversal (T) and axial (Z) strain we obtain, neglecting thermal effects:

$$\frac{\Delta\lambda_B}{\lambda_B} = \epsilon_Z - \frac{n^2}{2} \cdot [p_{11} \cdot \epsilon_T + p_{12} \cdot (\epsilon_T + \epsilon_Z)] \quad (2.8)$$

where p_{ij} are the photoelastic constants of the strain optic tensor. This equation can be rearranged as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e) \cdot \epsilon_Z \quad (2.9)$$

showing that the sensitivity to stress comes both from the axial strain and the negative contribution of the photoelastic effect. In the above expression, p_e is the silica's photoelastic coefficient, which is given by,

$$p_e = \frac{1}{n} \frac{\partial n}{\partial \epsilon} = \frac{n^2}{2} \cdot [p_{12} - \nu(p_{11} + p_{12})] \quad (2.10)$$

According to Araujo [2], substituting in the above expression the values of $p_{11} = 0.113$ and $p_{12} = 0.252$, and the Poisson coefficient of $\nu = 0.19$, gives a photoelastic coefficient of approximately 0.22. However this value is valid only at a wavelength of $1.55\mu\text{m}$, being higher for smaller wavelengths.

Using the expression given above, with $\lambda_B = 1563\text{nm}$, the theoretical Bragg wavelength shift as a function of the axial strain is found to be $1.22\text{pm}/\mu\epsilon$. In fact, some experimental results found on literature are in accordance as seen on Figure 2.12.

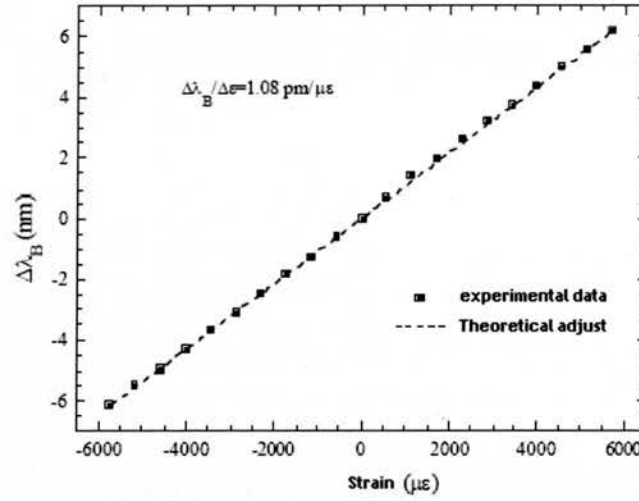


Figure 2.12: Bragg wavelength shift as a function of the axial strain, resulting from both compression and tension

The unit used to refer strain is the *microstrain*($\mu\epsilon$), which represents the relative variation in parts per million. The maximum strain admissible in commercial fibres is about 4% (40000 $\mu\epsilon$), which allows a spectral response tuning of approximately 50nm. However this result is only reproducible in very special conditions, when fibres are fabricated with special coating. Although, through the application of compressive stresses, tuning ranges of 44nm have been reported (with 21nm/ms of tuning speed), using a guiding system with an internal diameter close to the fibre external diameter (125 μm), which avoids the bending and rupture of the fibre [12], [11]. In terms of tuning range the technique referred above seems to give the best potentiality of achieving the broadest tuning range. Furthermore, the power consumption necessary to drive the piezoelectric actuator has to be considered, once it is quite significant. On the other hand, since the Bragg wavelength also depends on temperature, additional circuitry may be necessary to maintain temperature stability, or at least compensate the effect caused by temperature fluctuations.

2.4.2 Bending

In fact, the bending itself is a parameter that can be used to tune fibre Bragg gratings. When a certain curvature is applied to an optical fibre with symmetrical circular cross section, no effect is induced on the center Bragg wavelength, since the core is in the plane of null strain. However, when the fibre cross section has not circular symmetry (type-D fibre), an effective compression or tension is applied to the core, when bending is induced.

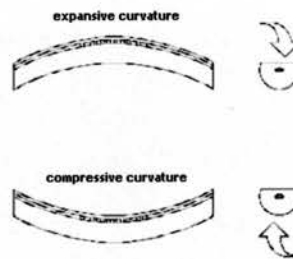


Figure 2.13: *Bragg wavelength shift as a function of expansive and compressive curvature in a FBG fabricated in a type-D fibre*

Total tuning ranges of 7nm have been reported using both compressive and expansive curvatures. Additionally, it should be referred that the dependence of the Bragg wavelength with the inverse of the curvature radius is linear, having different slopes for compressive and expansive curvatures. This linear characteristic can lead to the future development of curvature sensors.

2.4.3 Pressure

The application of pressure can induce a variation in the center Bragg wavelength, once it changes both the axial dimension, as well as the refraction index. Research work on this matter lead to equations that govern the fibre sensitivity to the pressure. A sensitivity of 4.2 pm/MPa ($\lambda_B = 1550nm$) has been found to be the theoretical value. Furthermore, some experiments obtained a practical value of 3.1pm/MPa using maximum pressures values of 70MPa [2] (which gives a tuning range inferior to 1nm). However, some further experiments achieved results as better as 4 times the previous

ones, using a glass vessel to achieve an amplification of the axial strain.

2.4.4 Magnetic field

The Bragg wavelength is also sensitive to the application of magnetic fields, due to the Faraday effect that induces a variation in the refraction index felt by the light that propagates in the fibre with left or right circular polarization. When a magnetic field is applied the refraction index varies differently for each polarization, leading to a spectral response characterized by two different Bragg wavelengths (λ_{B+} and λ_{B-}). This effect is dependant on the silica's *Verdet* constant, whose value is approximately 0.8rad/T/m at 1.3 μ m [2], leading to a difference of indexes between to two polarizations:

$$n^+ - n^- = \frac{V_d H \lambda_B}{2\pi} \quad (2.11)$$

This results in a very reduced sensitivity to the magnetic field (H), which means that very strong magnetic fields would be necessary to achieve effective wavelength shifts.

2.5 Switching based on non-linear effects

The lowest-order nonlinear effects in optical fibres originate from the third-order susceptibility because the second-order nonlinearity is cancelled in a symmetric molecule such as SiO₂. The third order nonlinearity is responsible for optical phenomena such as third-harmonic generation, four-wave mixing and supercontinuum spectrum (SC). In general these effects are related to the nonlinear index of refraction, a phenomenon that refers to the intensity dependence of the refractive index, which leads to a intensity dependant phase shift in optical fibres, which is studied in terms of Self Phase Modulation (SPM) and Cross Phase Modulation (XPM). While the former refers to the self-induced phase shift, the later refers to a nonlinear phase shift of an optical field induced by a copropagating field at a different wavelength.

2.5.1 Optical Switching Based on Kerr nonlinearity

A nonlinear optical-fibre device using the Kerr nonlinearity in a fibre grating coupler has been object of research. In this device, Bragg gratings are formed in the narrow waist of fibre couplers (Figure 2.14). When several wavelengths are launched into the input port (port 1), light at λ_B (Bragg wavelength) emerges from port 2 and the remaining light emerges from the output port (port 4). Generally, a matching oil is placed in port 3 to avoid reflections coming back from that port.

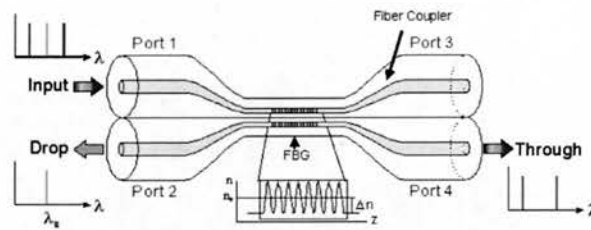


Figure 2.14: Schematic of an OADM using the fibre grating coupler in which FBGs are formed at the tapered waist region

When a high power pump pulse copropagates in the grating region with the signal light, the Bragg wavelength within the coupler is changed due to the optical Kerr nonlinearity, i. e., the pump pulse induces a nonlinear variation of the refractive index that shifts the whole reflection spectra towards a longer wavelength. Therefore, the refractive index experienced by the probe light is then changed due to the XPM, thus, the optical switch is then caused by the XPM induced by the pump signal.

The all-optical switching based on XPM must be separated from temperature effect due to high pump pulse, which also leads to the refractive index changes as seen before. The temperature effect can be avoided by attaching a peltier module to the coupler.

In Figure 2.15, the experimental setup is depicted[14], [15].

The CW probe is coupled at the fused portion of the coupler to a high pump pulse of a mode-locked Erbium-doped fibre (EDF) laser with an amplifier (EDFA) at $1.55\mu\text{m}$. An isolator and circulator are used to prevent back reflection of the signal and to drop the signal from the grating coupler. Additionally, experimental results show that the necessary switching power can be much reduced when non-uniform gratings are used, particularly, a $\lambda/4$ phase-shifted grating needs much less power (10 times) to achieve

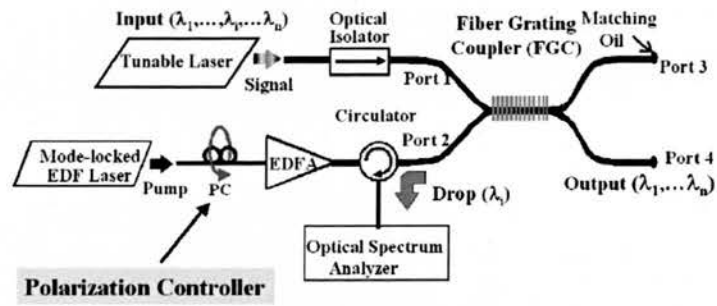


Figure 2.15: Experiment setup for all-optical switching in a fibre-optic grating coupler

the same results, which allows an enhanced immunity to the thermal effect.

Chapter 3

Electronically tunable optical filter

3.1 System Description

Among the optical switching techniques presented in the previous chapter the chosen one was the Mechanical switching based on a PZT element. This technique has several advantages in comparison to the others presented. First of all, the response time of the system can be faster than any other because the limitation factor come from the PZT response time. With a system like this, a response time in the order of milliseconds is expected.

As any other option, this one has also some disadvantages. First of all, these PZT elements require very High Voltages which always difficult the work. The selected model requires voltages around 1000V.

Another challenge was the development of a system capable of interfacing with the PC but using a modern way of communication. Serial Ports are not present in many laptops today. To achieve this purpose the USB interface challenge was accepted.

Figure 3.1 represents a general diagram of the developed system.

3.1.1 PZT actuator

As it was said before, in order to achieve greater tuning range on the FBG, it was selected to compress the FBG instead of stretching it. This action is not simple. It was necessary a lot of precision on the application of the compressive force on the FBG, which physically is a sensible cylinder of silica (glass) with 125 μm of diameter. One

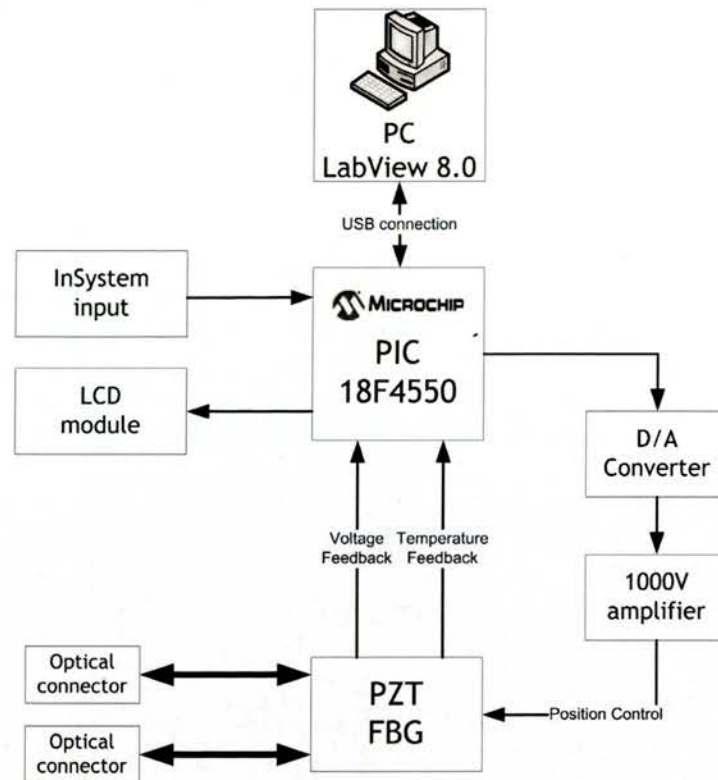


Figure 3.1: Diagram describing the whole functioning mechanism of the system

specific structure was developed in order to effectively attain this goal. Later in the section 3.3, a more precise explanation of the system is given. For now, in the figure 3.2 it is possible to see a photo of the developed structure.



Figure 3.2: steel frame

3.1.2 Amplifier

To drive the PZT a High Power, High Voltage amplifier was developed. This amplifier is a DC amplifier capable to have it's output at 900V. This amplifier needs high power in order to quickly charge and discharge the PZT equivalent capacity. Later on section 4.2 some more explanations are given.

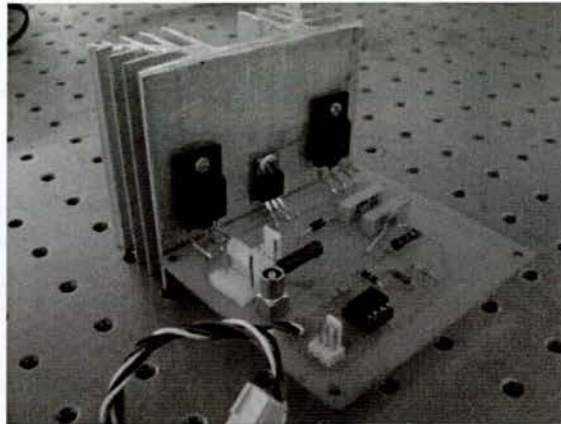


Figure 3.3: *amplifier PCB*

In figure 3.3 a photo of the developed PCB is stated. To supply this amplifier a high-voltage power supply was built. This power supply is able to deliver a maximum of 70W at 1000V. The technical characteristics are presented on section 4.3 and it's photo is depicted on figure 3.4.

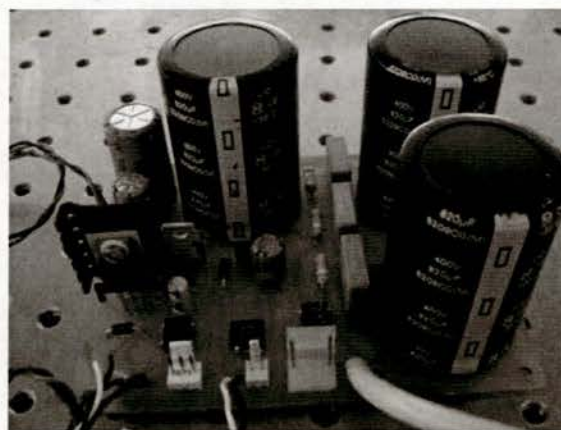


Figure 3.4: *Power Supply PCB*

3.1.3 Microcontroller

At the center there is a microcontroller manufactured by microchip (PIC18F4550). A photo of the developed board is depicted in figure 3.5.

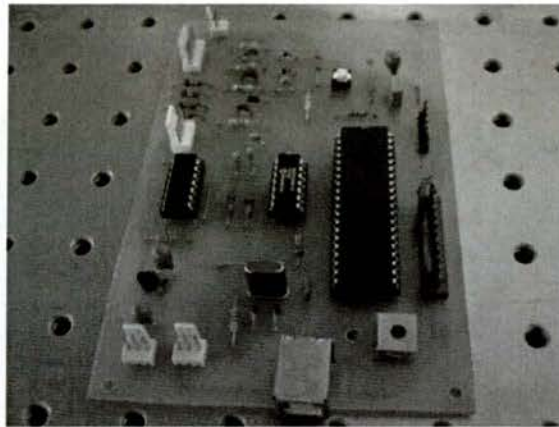


Figure 3.5: *Microcontroller PCB*

This microcontroller PCB is examined in chapter 5. This microcontroller has the aim of controlling the input of the amplifier, monitoring its output and interfacing the system with the user. This microcontroller controls all the electronic components in the front panel.

3.1.4 Front panel

At the front panel there are some input components to control the system and one LCD to give feedback to the user. A photo is presented in figure 3.6. This figure gives a clear perspective of the components position inside the enclosure.

3.1.5 Back panel

The microcontroller is also responsible for the USB communication with the PC. At the back panel, figure 3.7 shows the USB connector, two fusible holders, power connector and the cooling fan.

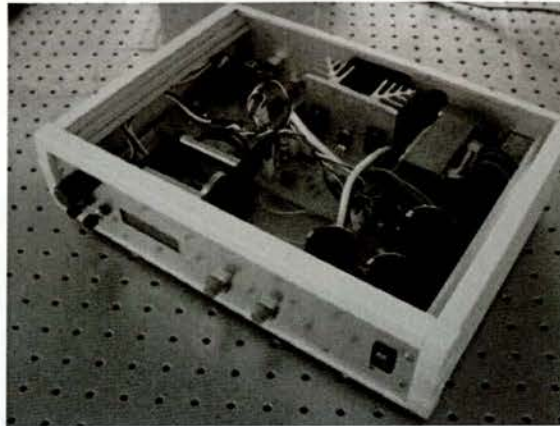


Figure 3.6: *Frontal Photo*

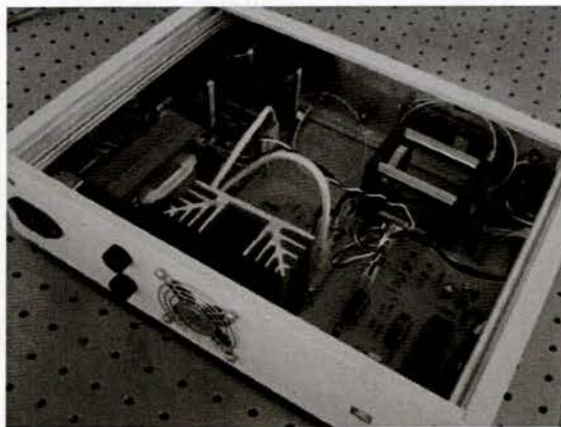


Figure 3.7: *Back Photo*

3.1.6 Complete system

The construction of complete system revealed to be a multi-disciplinary task which enriched the knowledge of both of us. The final results are presented on the figures 3.8 and 3.9. The portable system has 4.5 Kg and dimensions of 85 mm of height, 250 mm of width and 180 mm of depth.

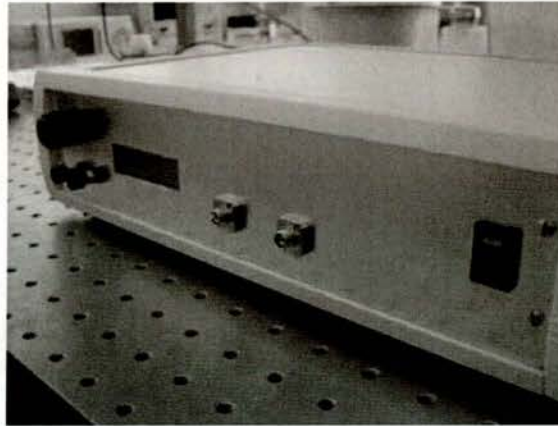


Figure 3.8: *Final front Photo*



Figure 3.9: *Final Back Photo*

3.2 Piezoelectric devices

3.2.1 History

The term "piezo" is derived from the Greek word for pressure or push. In 1880, the brothers Jacques and Pierre Curie discovered the piezoelectricity, discovering that an electric potential could be generated by applying pressure to quartz crystals; they named this phenomenon the "piezo effect". Later they learned that the inverse was also true, that is, when exposed to an electric potential, piezoelectric materials change shape (they deform). This they named the "inverse piezo effect". Crystals that exhibit

these phenomena are said to be piezoelectric. The first commercial applications of the inverse piezo effect were for sonar systems that were used in World War I. However, piezoelectric actuators made their initial entry in medical devices, including surgical tools and ultrasonic testing in the late 1980s.

In today's industrial applications the typical materials employed are polycrystalline ferroelectric ceramics such as barium titanate, lead zirconate and lead titanate (plumbum), since the piezo effect exhibited by natural materials such as quartz, tourmaline and Rochelle salt is very small. Piezoelectric actuators made their initial entry in medical devices, including surgical tools and ultrasonic testing in the late 1980s.

3.2.2 Piezoelectric devices importance

Piezoelectric materials are used to convert electrical energy to mechanical energy and vice-versa. The precise motion that results when an electric potential is applied to a piezoelectric material is of primordial importance for nanopositioning. In the past years, high-speed piezoelectric actuators have become less expensive to manufacture, therefore, they find themselves as a favorite design choice for a growing number of applications. Indeed, piezoelectric actuators are the fastest responding positioning element available with microsecond time constants. They also can produce motions in subnanometer increments. So, it's no surprise to see a dramatic rise in the number of companies designing products that employ these devices.

The piezoelectric effect is often encountered in daily life, for example in lighters, loudspeakers and buzzers. Most electronic alarm clocks do not use electromagnetic buzzers anymore, because piezoelectric ceramics are more compact and more efficient. In addition to such simple applications, piezo technology has recently established itself in the automotive branch. Piezo-driven injection valves in diesel engines require much lower transition times than conventional electromagnetic valves, providing quieter operation and lower emissions.

3.2.3 Principles of functioning

Within the cylindrical piezoelectric actuator illustrated in Figure 6.5,

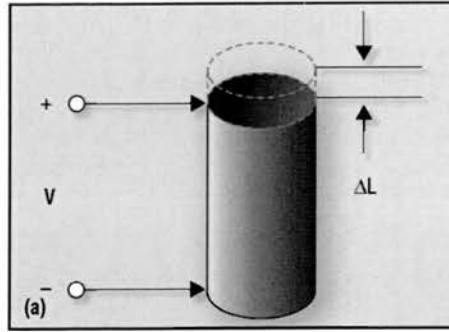


Figure 3.10: A single stack piezoelectric actuator

when a voltage is applied longitudinally, a displacement ΔL occurs along the axis of the device. Typically, a piezoelectric material can withstand a strain, or change in length, of 0.1%. This means an actuator that is 100 mm long that is poled (energized) along its axis can be elongated by 0.1 mm. The displacement, or change in length, of an unloaded single-layer piezoelectric actuator can be closely approximated by:

$$\Delta L = (S)(L_0) \approx \pm E \cdot d_{ij} \cdot L_0 \quad (3.1)$$

where ΔL is the change in length (m), S is the strain per unit length or relative length change ($\Delta L/L$, therefore, dimensionless), E is the electric field strength (V/m) and L_0 is the length of the actuator (ceramic length, m). The term d_{33} is the piezoelectric coefficient of the material (m/V), where the first subscript identifies the axis of the field and the second subscript identifies the axis of the displacement. The coefficient d_{33} describes the strain parallel to the polarization vector of the ceramics (thickness) and is used when calculating the displacement of stack actuators; d_{31} is the strain orthogonal to the polarization vector (width) and is used for calculating tube and strip actuators (Figure 3.11). d_{33} and d_{31} are sometimes referred to as piezo gain.

The maximum electric field that most ceramic piezoelectric actuators can withstand is on the order of 1 kV/mm to 2 kV/mm. To extend travel beyond the approximately 0.1% maximum of a single slice, and to avoid applying a very large field, a multilayer actuator can be fabricated by gluing thin layers of the piezo material together to form a stack. A voltage is then applied to each layer individually (Figure 6.6),

so that each is powered independently. The voltage applied to each slice is still the

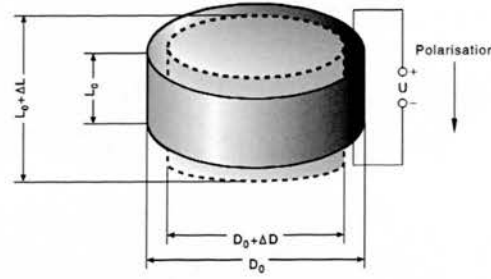


Figure 3.11: Expansion and contraction of a piezoelectric disk in response to an applied voltage

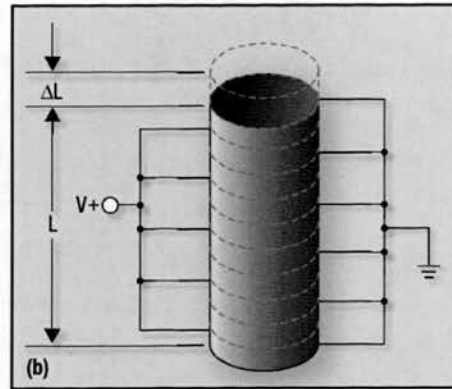


Figure 3.12: A multi-layer piezoelectric actuator in which the displacement is amplified by the number of slices

same, but the total displacement is simply the sum of the individual displacements.

When a piezoelectric actuator is driven by a periodic voltage source whose frequency is below the resonant frequency of the piezoelectric actuator, then the device can be modeled by a single capacitor. Therefore, the impedance presented to the driving source is, to a good approximation, simply:

$$Z_{LOAD} = \frac{1}{2\pi f C_{PA}} \quad (3.2)$$

where f is the frequency of the driving source and C_{PA} is the equivalent capacitance of the piezoelectric actuator.

3.2.4 Piezoelectric Transducer P-289

With the aim of attaining the goal of this project, we bought a piezoelectric transducer from manufacturer "Physik Instrumente". The model is the P-289 (figure 3.13). It is basically a disk translator which has two surfaces that move away from each other as the voltage increases.

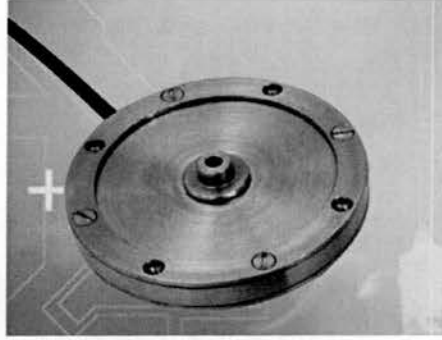


Figure 3.13: Picture of the P-289 model from PI

Characteristic	Units
Open-loop travel @ 0 to -1000 V	200 μm $\pm 20\%$
Open-loop resolution	2.0 nm
Static large-signal stiffness	0.15 N/ μm $\pm 20\%$
Push/pull force capacity	20 / 10 N
Max. operating voltage	-1000 V
Electrical capacitance	130 nF 20%
Dynamic operating current coefficient (DOCC)	0.5 $\mu\text{A}/(\text{Hz} \cdot \mu\text{m})$
Unloaded resonant frequency (f_0)	1.1 kHz $\pm 20\%$
Standard operating temperature range	-40 to +80°C
Weight	56 g $\pm 5\%$

Table 3.1: Technical specifications of the P-289 piezoelectric actuator from Physik Instrumente (PI)

3.3 Developed Structure

A special steel frame has been designed and realised. The piezoelectric actuator is screwed within this frame and connected to a system of ceramic FC ferrules. Two ferrules with $125\ \mu\text{m}$ of internal diameter were used, one mounted to a fixed stage and the other one connected to the PZT. The ferrules were used to accurately compress the fiber along its axis and prevent it from buckling. This is achieved by confining as much of the fiber as possible within the precision ferrules, thus providing a guiding system which is aligned by a ferrule sleeve. Micro and macro bending are so minimized, as well as the probability of breaking the fiber.

Even so, there is always a certain portion of the fiber which will remain unguided. Iocco *et al* [12] found the maximal allowable length without bending of an unguided fiber (L_{cr}) during compression, based on the buckling theory of columns:

$$L_{cr} = \frac{\pi \cdot r}{2 \cdot \alpha} \cdot \sqrt{\frac{L}{\Delta L}} \quad (3.3)$$

where $r = 0.0625\ \text{mm}$ is the fiber radius and α is a constant factor which for a column fixed at both ends is equal to 0.5. For a large value of strain, e.g. 3.2 % ($32000\ \mu\epsilon$), this equation gives $L_{cr} = 1\ \text{mm}$. Since this value is relatively high, the tolerance in the positioning of the gap between the ferrules should not be critical. However it can introduce increased difficulty to the assembly process as we will see later.

The assemble of the device was a very difficult and challenging task. Before this project, our experience with fiber handling was very little. After starting to handle with fibers we discovered how sensitive they are. Specially, when the fiber is uncoated, it requires very delicate handling, otherwise it can easily break with any sudden hand movement that bends or twists the fiber. Furthermore, when we are talking about a fiber Bragg grating, which is essentially an uncoated section of fiber, it is even more fragile, because it's photosensitivity was increased.

Once the internal diameter of the ferrules is equal to the uncoated fiber external diameter, and the fiber is approximately 1 m long with an uncoated section in the middle (of approximately 3 cm), it is imperative to uncoat one of the sides of the fiber (between the end and the FBG). This will allow the introduction of the ferrule system throughout the fiber, up to the FBG section. In fact, we have proceeded in that way

because the device is supposed to have both ends of the fiber accessible to the exterior, so that the user can also obtain the transmitted spectrum.

The first attempts to execute the uncoating process using a plier (fiber optic stripping tool - figure 3.14) were unsuccessful, with the FBG invariably ending broken in the middle.

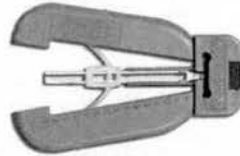


Figure 3.14: *Fiber optic stripping tool used*

At this point several possibilities were considered in order to carry out the uncoating process:

- A special chemical (dichloromethane) was used. This type of chemical was widely used a few years ago (instead of the stripper tool), in the cases where the uncoating had to be perfect, avoiding the micro ruptures caused by the plier friction. This chemical attacks only the plastic (coating) leaving the glass as it is. However, due to the very high toxicity of this chemical, this technique has become of reduced interest. We haven't succeeded with this technique, essentially because the chemical available at our laboratory was old, and consequently very weak. In fact, the fiber broke at the FBG section when we were trying to clean the plastic with a paper, which wasn't as weak as it should.
- We have considered the hypothesis of uncoating the fiber with a special thermic device. This is the same device which is typically used to uncoat the section where FBGs are written. However, as this device uses very high temperatures to melt the plastic, this process could damage the existing grating (which can not withstand very high temperatures without significant and permanent spectral changes). A practical solution could be achieved by using the referred device to uncoat a relatively long length of fiber before effectively write the grating.

Anyhow, since the FBG writing process was not available at the project time, this solution could not be implemented.

- In spite of the first attempts to uncoat the fiber using a stripping plier having failed, this plier tool was not discarded. The FBG section does not withstand the force applied by the stripper, specially because the movement made by the fiber stripper is not perfectly axial with the fiber (due to the human error).

After many attempts, the technique was refined. The fiber is fixed at a end point, instead of being fixed close to the FBG section. Then, the direction of the stripper movement is from the end point to the FBG. This implies that the FBG section is never subjected to the force of the stripper, remaining intact.

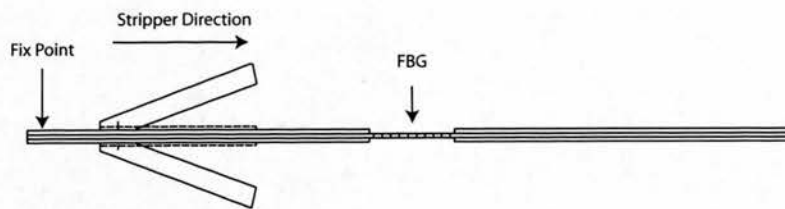


Figure 3.15: *Successful technique of uncoting the fiber*

Once the fiber has one end uncoated, we started planning about introducing the ferrule system into the fiber. This was also a very challenging task, having in account the fact that the ferrules internal diameter is very close to the fiber external diameter (nominally they are the same value), which makes the sliding of the ferrules along the fiber very difficult.

Before all else, it is important to refer that before the uncoating, the FBG was marked in the middle with a special marker pen. Two more marks (equally distant to the center) were made, with 1 cm of spacing each. This added even more difficulties to the uncoating process, essentially because as the uncoating is being executed, there are rests of plastic that must be removed. The removal of these rests is accomplished with a special solvent similar to acetone, which could clean the previously made marks, if not used with extreme caution. These marks are of great importance in the next step, allowing us to precisely confine the FBG (which is 1 cm long) inside the ceramic

ferrules (which cover a total distance of 2 cm). Figure 3.16 shows a schematic of the technique used.

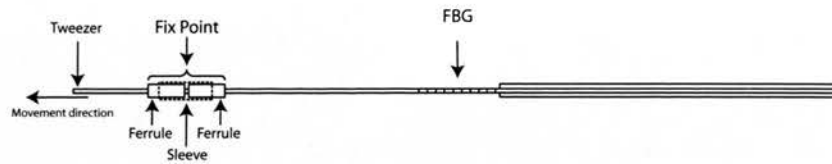


Figure 3.16: Schematic of the technique used to introduce the ferrules over the FBG (not to scale)

In first place, it is necessary to introduce the fiber end into the ferrule hole, by means of applying a precise and slow push movement. Then we verified that the ferrule sleeve does a really great job respecting the ferrule alignment, once the fiber crossed from one ferrule to the other without any friction. After that, we started pulling the fiber with a tweezers, which had in the end a piece of paper embedded in acetone to maximize the adherence. Even so, the force has to be applied always in the end of the fiber, once the pressure made by the tweezers caused the fiber to break a several of times, so we shall minimize the length of the broken piece. Figure 3.17 show the type of tweezers we used to attain our goal.



Figure 3.17: Type of tweezers used

Finally, the ferrule system was glued in both ends (with a total distance of approximately 2 cm), but with a gap left in between the ferrules. Figure 3.18 shows a schematic diagram of the assembled steel frame.

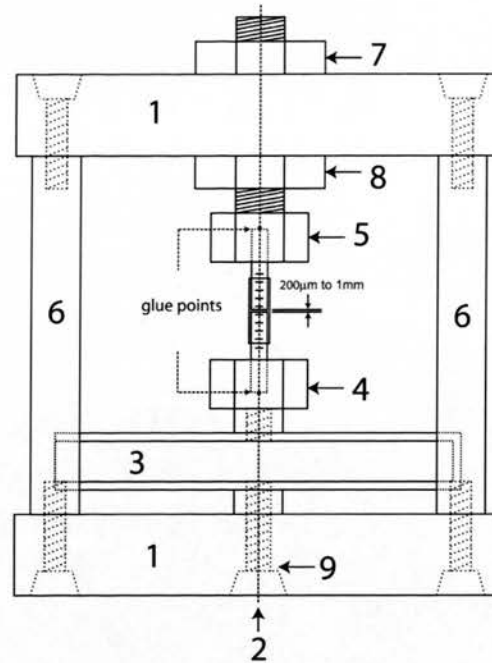


Figure 3.18: Schematic of the assembled steel frame. 1 - steel slabs, which work as base and support of the frame. 2 - The fiber has to cross throughout the frame, from top to bottom. 3 - PZT. 4 - This component screws inside the PZT and has a concentric hole to accommodate the ceramic ferrule. 5 - This part is symmetrical to component 4 but screws to the steel slab instead of the PZT. 6 - These are 4 shafts that connect the steel slabs. 7 and 8 - These screw nuts provide a means of attaining a fine tuning in the frame overall adjustment. 9 - Screw that holds the PZT to the steel slab.

The final part of the assemble consists in introducing the ferrule system into the holes of parts 4 and 5 (Figure 3.18) and give a final adjustment to the rest of the screws within the frame. However, the process of fitting the ferrules into parts 4 and 5 was very difficult. First of all, the ferrule is supposed to suffer pressure from the hole so it gets tightly connected. Besides, when we were pushing the ferrules into the hole, the gap that existed between them suddenly collapsed, and the fiber consequently broke. We had to start it all over again, but now we left a smaller gap between the ferrules. Although we didn't have the means for precisely control the gap distance, we tried to leave the gap as small as possible, having into account that the PZT maximum displacement is $200\text{ }\mu\text{m}$. In fact, when we repeated the process of introducing the ferrules into the holes, the fiber didn't break.

Chapter 4

PZT Drive Amplifier

4.1 Introduction

Piezoelectric actuators are the fastest responding positioning devices available with microsecond time constants. However, they work with very high electrical fields on the order of 20 KV/cm, which generate substantial forces and enables them to achieve small displacements, which are typically in the order of 0.1% of their size. Therefore, piezoelectric actuators require high-voltage drivers that can deliver hundreds of volts, peak-to-peak. In fact, manufactures solved this problem by building piezo-stacks (as mentioned on chapter 3). Although these stacks have larger displacements and need voltages one order of magnitude lower, they are not as stiff as a single piece of ceramic, besides being much more expensive.

Although the manufacturer of the PZT we bought (PI) also sells the corresponding driving amplifier, we have decided to build our own, thus greatly reducing the cost of the whole system.

4.2 High-Voltage Amplifier

The used PZT model, P-289, requires 1000V to produce the maximum translation ($200\mu\text{m}$). The actuator looks virtually like a pure capacitance to the driving amplifier (130 nF for P-289). Moreover, high currents are necessary to charge and discharge it quickly, in order to provide a correspondent high speed position change.

Although the piezoelectric actuator consumes virtually no power, the power dissipating demands upon the power-amplifier circuit employed to drive it are significant indeed.

A quick look through the abundance of high-speed, small-signal op amps will show many amplifiers with bandwidths in the hundreds of megahertz range. But to combine speed with high output voltages, the choices of suitable amplifiers shrink swiftly. Actually, we have even found an high voltage power op-amp that would fit perfectly, but with a very inflated cost. After that, we started thinking about designing an amplifier by our own. We picked a low noise op-amp (OPA227) from Texas Instruments, and started searching for high voltage transistors. In fact, our first thought concerning the design of the amplifier was of a symmetrical design, using a push-pull configuration. However, we found out that the list of available transistors for this voltage is limited, thus only N-type MOSFET or NPN BJT transistors are available. This fact, limits the topology of the amplifier.

4.2.1 Amplifier topology

The first prototype was developed with MOSFET transistors. As only N-type mosfets are available for this voltage, the topology used was single-ended.

In the schematic represented in figure 4.1 it is possible to see the simplicity of this topology. The amp-op provides two inputs to the system, the non-inverted input for the feed-back and the inverted one for the signal input. The total gain may be defined by changing the value of resistors R1 and R2. The gain value is $\frac{R1+R2}{R2}$, but the value of the resistors should be chosen in a way that their sum is at least $1M\Omega$, otherwise the dissipated power would be greater than 1W.

The output of the op-amp drives directly the gate of Q2, which acts as a current sink (controlled by the op-amp). Resistor R4 pulls up the drain of Q2, so that when the transistor cuts, the output voltage will grow up to $R4/(R1+R2+R4)$ of the supply voltage. When the amplifier needs to discharge the PZT, the output of the op-amp goes up, and then Q2 sinks a current only limited by the value of R5. When the amplifier needs to charge the PZT, the charge rate is determined by the value of the pull up resistor.

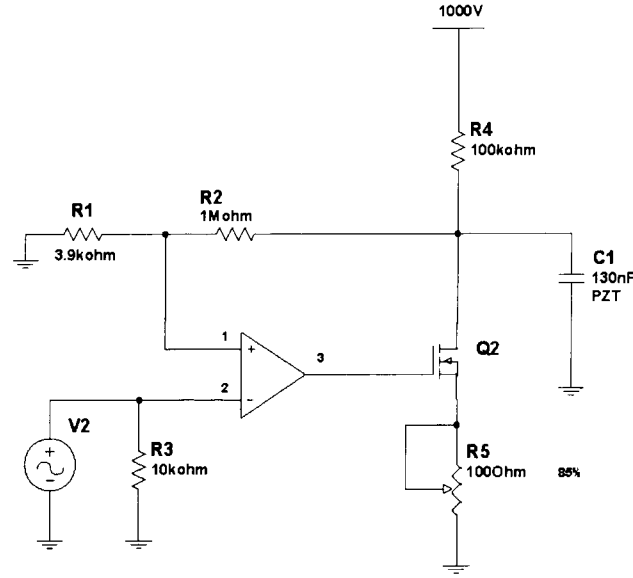


Figure 4.1: Amplifier topology

4.2.2 Active load

The resistor R4 on the previous diagram represented in figure 4.1 needs to be able to dissipate 10W. Thus, to improve the performance of the amplifier we need more than 10W of power dissipation. Moreover, these high power resistors are hard to find, besides having very restricted values. As a solution to this problem, an active load was used instead of the high power resistor. Furthermore, in addition to the advantages related with possibility of achieving a much smaller value of resistance, this solution allows an efficient linking to a heat sink and a much more effective energy dissipation. A schematic of the amplifier featuring the active load is depicted in figure 4.2.

4.2.3 Output Transistor

Analysing the diagram of figure 4.1, it is clear that the slew-rate is defined by the pull up resistor and the capacitor. In fact, when the capacitor is charged, the current flows from the 100KΩ resistor, which gives a rise time (10% to 90%) of $2.2 \cdot RC = 28.6\text{ms}$, without having into account the resistors of the feedback network. In order to reduce

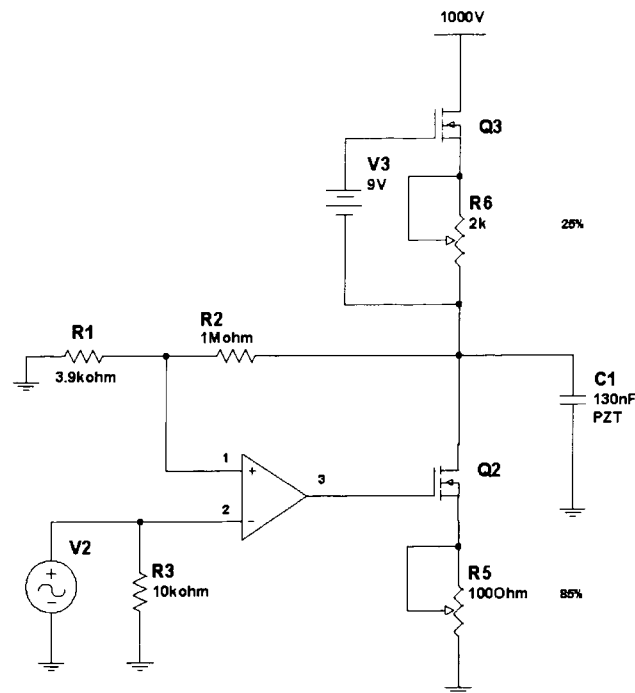


Figure 4.2: Active load

the slew-rate, one output transistor was added (Q1). Figure 4.3 shows the schematic of the final amplifier. The measured slew-rate of this amplifier was approximately 1ms with a 11 nF capacitor, and the active load resistor set to 500 Ω .

The diode D1 becomes of extreme importance now. If only Q3 was added the new problem would be the PZT discharge which would only be possible through the feedback resistors. By adding the diode, the transistor Q1 contributes to discharge quickly the PZT.

The final version of the amplifier was built with BJTs instead of MOSFETs (except for the active load), because the BJTs have a special mold resin in the collector connection to the heatsink, which makes them safer and easier to handle. The performance results were similar in both cases. Another point to focus is the capacitor C2, which is absolutely essential to stabilize the amplifier, and must be selected with caution because it has to support 1KV of voltage drop. The capacitors C3, C4 and C5 are also very important in terms of filtering high frequency noise that may exist in the system.

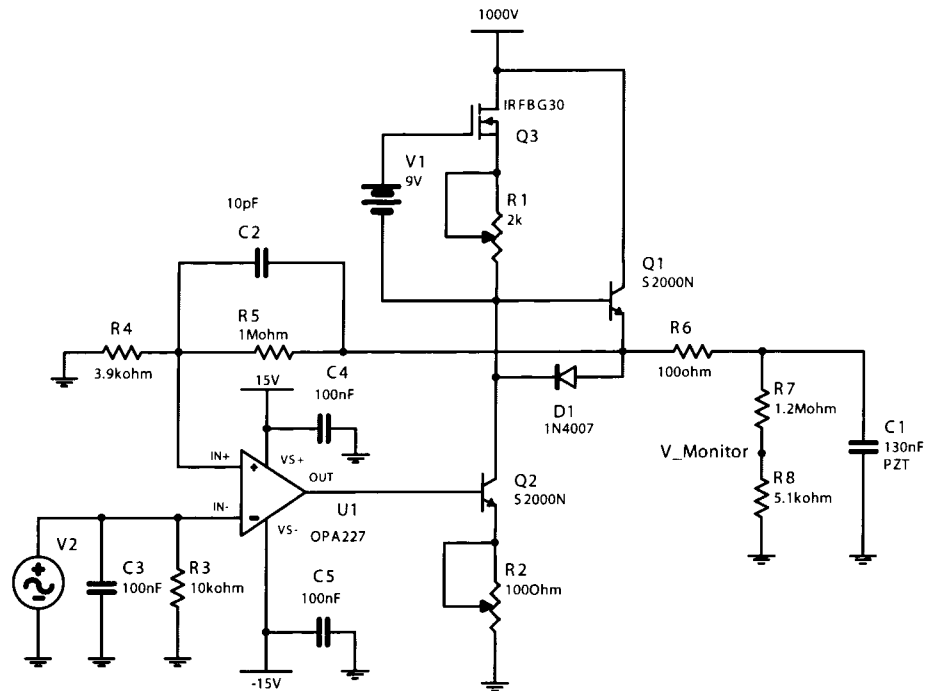


Figure 4.3: *Schematic of the final amplifier*

The resistor R6 has the function of isolating the capacitive load providing improved stability. The presence of the "V_Monitor" signal is of extreme importance, working as a simple solution for the monitoring of the high voltage output.

4.3 High-Voltage Power Supply

We developed a complete power supply, which features an high voltage part, a constant reference of 9V to drive the active load, and a low voltage section, including the supply for the operational amplifier, cooling fan and for the microcontroller board.

First of all, we calculated the specifications of the transformer we needed, and ordered it. The transformer has a 700 V (rms) secondary, which is connected to the diode bridge and to a series of 3 820 μ F 400V capacitors (C4, C5 and C6), paralleled to 3 100 nF capacitors to cut high frequencies and 3 390k Ω 1/2W resistors (R11, R12 and R13) to provide a discharge path when the amplifier is turned off. Figure 4.4 shows the complete schematic diagram of the power supply.

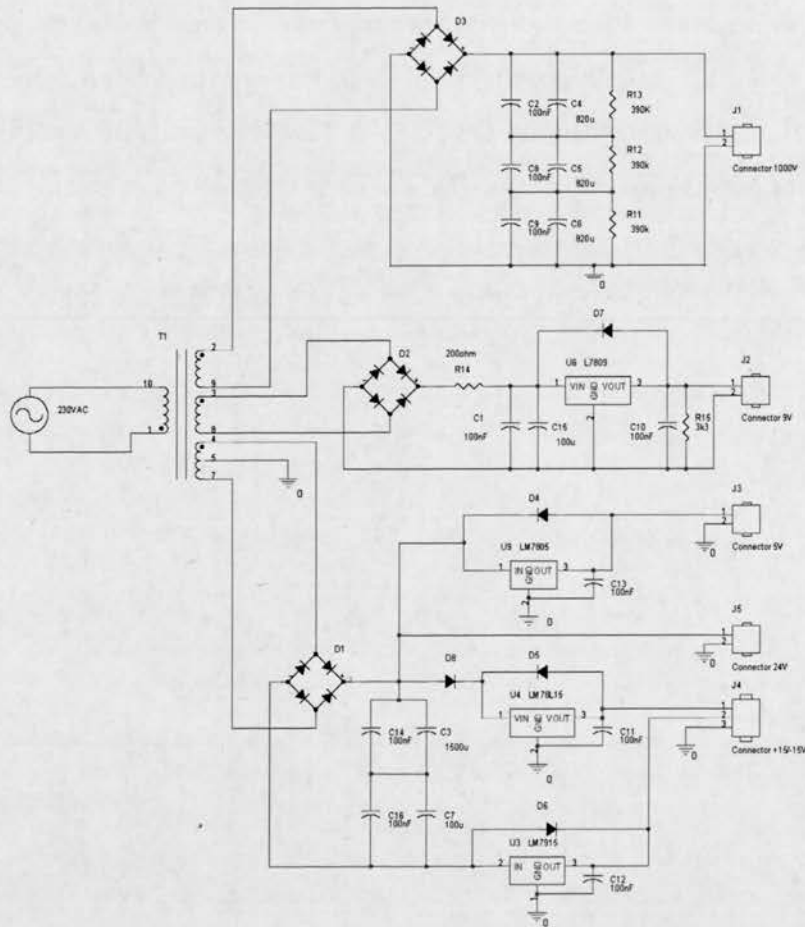


Figure 4.4: Schematic diagram of the power supply

Concerning the low voltage section, there is a 24V connector which is an unregulated output that supplies the amplifier cooling fan, and once it is unregulated, there isn't any active part dissipating heat. All the 100 nF capacitor included in the low voltage power supply function to cut high frequencies. Diodes D4, D5, D6 and D7 are protection diodes, working in the case of an high voltage peak occurs in the following sections. Components R14, R15 and D8 have a special purpose. The first times we turned the amplifier on and off we noticed a strange and unexpected "click" made by the PZT (which could destabilize the system). After some case study, we found the problem. When the amplifier is turned on for the first time no problem occurs, however, when it is turned on for the second time within a short space of time, the high voltage capacitor have retained the the voltage output still very high. Thus, if the 9V output of the power supply grows faster than the 15V output of the op-amp, the amplifier output will be pulled up for a few milliseconds, until de 15V output reaches a value high enough for taking the amp-op to saturate Q2. Indeed, R14 solves this problem by forcing the 9V output to grow slower. Now if we think about the turn off problem, it is clear that the 9V supply has to decay faster than the 15V supply, so, R15 makes the 9V output to decay faster, while D8 compels the 15V output to hold it's voltage a little further.

Chapter 5

Digital control system and communication

5.1 Microcontroller

This board implements the following functions:

- USB communication with the PC
- Amplifier Output read
- Amplifier Input control
- LCD control
- Control panel read
- Temperature read

5.2 Hardware

In the circuit diagram described in figure 5.1, we are able to make an overview of the implementation.

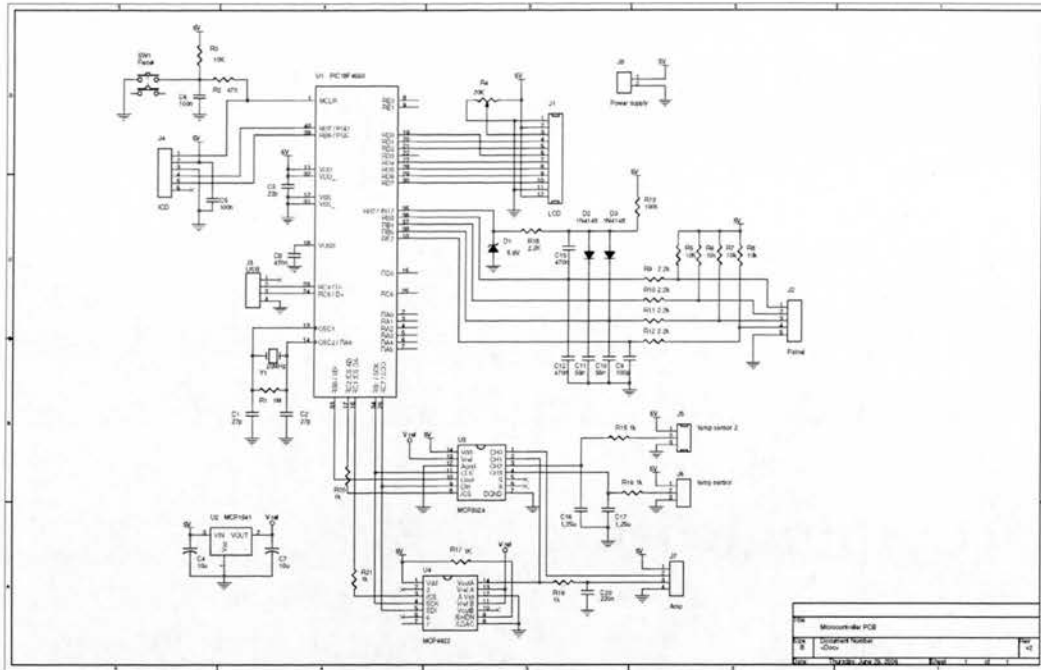


Figure 5.1: Microcontroller PCB diagram

As it was said before, the chosen microcontroller was the PIC18F4550. An USB communication module was built, which is used to interface the system with the PC.

To read the output voltage of the amplifier, one ADC from microchip was used. The chosen ADC was MCP3204, a 12 bits ADC with SPI interface. To control the amplifier input it was used a MCP4922, which is also a 12 bits DAC with SPI interface from microchip. To obtain a precision and fast conversion, a reference voltage of 4.096,V was used. This allows a 1 mV precision in the converted value and the direct relationship of value processed by the microcontroller and the analog voltage in millivolts.

The panel is composed by a 16 step incremental coder and 2 press buttons. The usage of SPI communication is very pin consuming. For that reason, only one external interrupt pin was available. To support these tree devices a circuit was developed to generate interrupts in the microcontroller using one pin only.

The ICD connector (In-Circuit Debugging) was added for allow easy update of the mi-

crocontroller software. The programmer PICKit 2 can be easily plugged-in and all the functionalities supported are available.

This PCB gathers all the digital electronic of the system.

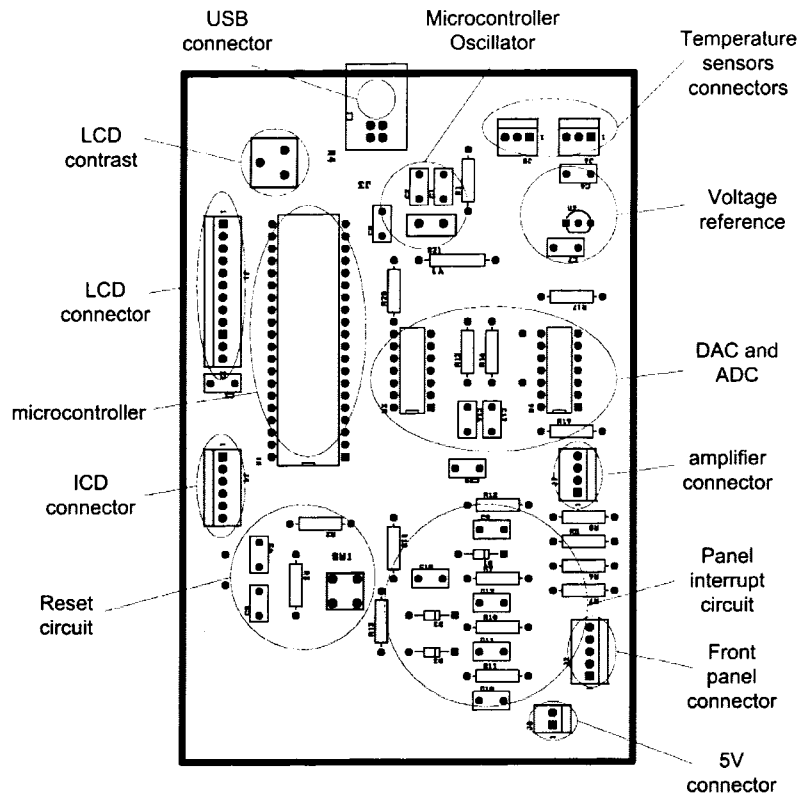


Figure 5.2: PCB components Position

The final board layout is presented in figure 5.2, which allows us to identify the main circuits and corresponding functions.

5.3 Software

The microcontroller software was developed under a C compiler. We also had into account the possibility of picking the Assembly programming language. However, the complexity of the implementation of an USB protocol and the short period of time available did not allow us to implement this solution.

During the development of the code aspects like easy to read, understand or change were had into account. To achieve this goal, the code was divided in small functions with suggestive names.

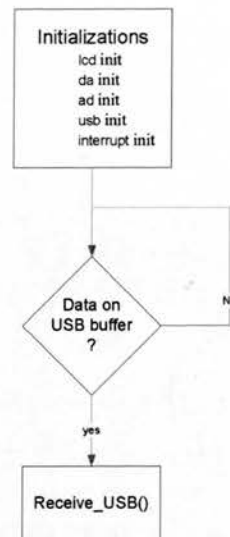


Figure 5.3: Normal execution code

The code can be divided in two main groups. The first is the normal execution code. This is the code that is executed when the reset occurs. In the figure 5.3 the diagram of execution of this part is presented. All the subsystems are initiated and then the microcontroller is hold on an infinite loop waiting for characters in the USB buffer. When any value is received, the Receive_USB function proceeds with the reception. Although this function integrates the microcontroller software, a deepest explanation is in the section 5.4.

The second group of code is the interrupt handlers. The normal execution of code by the microprocessor is stopped in order to execute theses handlers. In the software there are two possible sources of interrupts.

The first possibility is the timer 0 interrupt. This timer is responsible for generating an interrupt approximately twice a second. These moments are used to update the

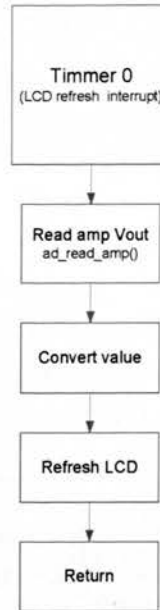


Figure 5.4: *LCD refresh handler*

LCD content. This operation consists in reading the output Voltage of the amplifier, convert this value and than display it on the LCD. The figure 5.4 shows a graphical diagram of the handler.

The other possibility of interrupt is the external interrupt 2. As previously explained in section 5.2, this source of interrupt links all the sources of interrupts in the front panel. In order to easily understand the implementation, figure 5.5 shows the handler functioning. In this case, the software starts by discovering the source of the interrupt. The possible sources are the press of the A or B buttons, or the rotation of the rotary encoder. Because the specific working manner of the rotary encoder, it is necessary to analyse in first place if any button was pressed; if it was, the correct handler is activated. If not, it concludes that the source was the rotary encoder and after analyzing the rotation direction, the correct function is called. The name of each source handler is described in figure 5.5.

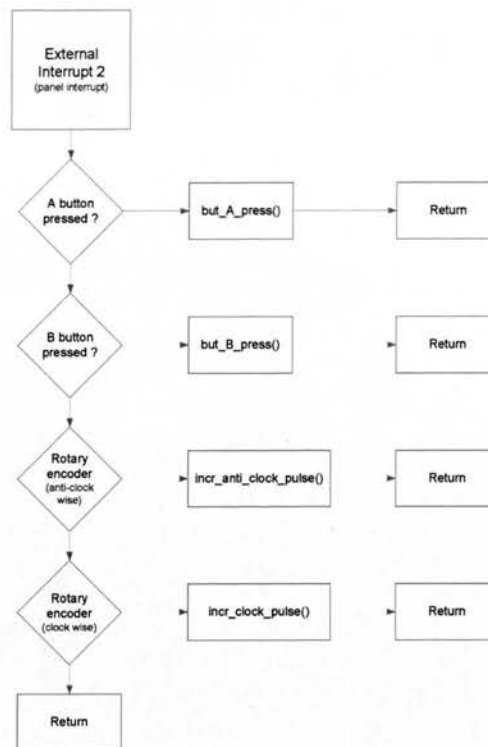


Figure 5.5: Panel interrupt handler

5.3.1 Basic instructions

In order to effectively implement the system, this are the instructions that should be used.

- LCD
 - `lcd_gotoxy(x,y)`- defines the next position to write on the LCD
 - `printf(lcd_putc,"",)` - instruction to write text or variables on the LCD
- DAC
 - `void da_init(void)` - to initialize the DAC
 - `void da_write(int16 valor)` - to write a value on the DAC
- ADC

- void ad_init(void) - to initialize de ADC
- int16 ad_read_amp(void) - to read the output voltage of the amplifier
- USB
 - int usb_cdc_kbhit(void) - returns 1 if data present on the receive buffer
 - printf(usb_cdc_putc,"",) - instruction to send text or variable to the PC via USB
 - char usb_cdc_getc(void) - instruction to read a char from the receive buffer.

5.4 USB communication

At the beginning of the project the only method proposed to control the system was by a PC. Although we have good knowledge of the serial port interface, this port is disappearing from most of the laptops. In order to create an advanced and modern system, and to deepen our knowledge in nowadays PC interfaces, the USB protocol was studied and implemented in the project.

5.4.1 Protocol

This protocol as the goal of ensuring the correct interface between the PC and the PIC18F4550 microcontroller. It enables us to change the system set point, and read some values back, like the temperature. Some more options are reserved for future implementation like calibration. In this communication the host terminal is the PC and the client is the microcontroller. So, all the requests are sent by the PC and answered by the microcontroller.

There are tree types of possible frames in the communication. One is the request send by the PC. The other two are the correct response and the error response generated by the microcontroller. These frames are explained in the following sections.

Request frame format

The frame used to send requests by the PC has always the same format.

Start 2 bytes ;;	Position 1 bytes 0 ...	Action 1 bytes W,R,E,C	Value 7 bytes 0000,00	Checksum 1 bytes	Stop 1 bytes :
-------------------------------	-------------------------------------	-------------------------------------	------------------------------------	----------------------------	-----------------------------

Figure 5.6: frame format

- **Start** This is implemented with two semicolons (;;).

- **Position** This indicates the position where the action will take place. This uses an ASCII symbol and not a numeric value. The available positions can be consulted in the appendix.
- **Action** The available options for this field are R, W, E and C. They represent Read, Write, check Error and Calibrate. Notice that not all positions are writable generating an error in the case of permission to act not being allowed in that position.
- **Value** This field also has a fixed format. It is implemented as four ASCII number characters, a coma and more 2 ASCII number characters. An example is 2738,29. This field can only implement values between 0 and 9999,99 with centesimal precision.
- **Checksum** This field is used for security. This can be calculated by adding all the numeric values of the previous bytes sent.
- **Stop** In the end of the frame a colon must be sent.

One request frame example can be

;;0R0000,00D:

Answer frame format

The answer frames can be divided in two types.

Error Answer frame format

The first type is the error type. In this case the microcontroller produces a frame started by ;E and proceeded by a number that codifies the error occurred. The frame is finalized by new line.

One example of error answer frame is ;E11n

In the appendix is possible to consult the table that explains the meaning of all numeric error codes.

Correct Answer frame format

The other possible answer frame is the correct action answer. In this case the action requested was completed.

Start 1 bytes ;	Position 1 bytes 0 ...	Action 1 bytes W,R,E,C	Value variable	Stop 1 bytes \n
------------------------------	-------------------------------------	-------------------------------------	--------------------------	------------------------------

Figure 5.7: frame format

Now, the Start field is only one semicolon, Position and Action fields are equal to the request frame and the value has no rigid format. The frame is finished with a new line character.

5.4.2 Windows

The USB protocol has some standard implementations. One example is for instance the Human Computer Interface (HCI). This is applied in practical applications, for example in mice. The option selected was the standard Communication Device Class (CDC). With this selection it was possible to develop a windows driver that creates a Virtual Serial Port (VSP) that is available when the system is plugged to the USB port. The advantage of this process, is that it is possible to define the name of the VSP, which is in this case *Tunable Optical Filter*. Therefore it is possible to communicate using the same behavior as it was a serial port. It is also possible to automatically know which serial port we want, by finding it's specific name, and there is no need of configurations of baud rate or data format.

The windows driver is an important point that should be focused. First of all the driver (*driver.inf*) can be edited with a text editor like notepad. One important line is the DriverInstall line. In this line the user can define the vendor ID (VID) and the product ID (PID). Each USB system should have is own VID and PID. In the case that we are developing a system, it is legal to use de microcontroller VID and select one random PID. In our case it was used the VID = 04D8 (hexadecimal number) from microchip and it was selected a random PID = 0088 (also in hexadecimal base). The

other part requiring personalisation is the final part, with 4 lines that add information like the name of the virtual serial port.

5.4.3 Microcontroller

The used microcontroller was selected from a list of processors with built-in USB peripheral. This characteristic simplified the hardware development of the system. Despite this, the initialization of the USB protocol is not a simple software program. For this propose, some software was also adapted. To have an idea of the size of this peace of software, it uses 15% of the ROM and 32% of the RAM of the PIC memory. The memory of the PIC 18F4550 is 32Kbytes of ROM and 2Kbytes of RAM. This represents a large usage of the microcontroller capability.

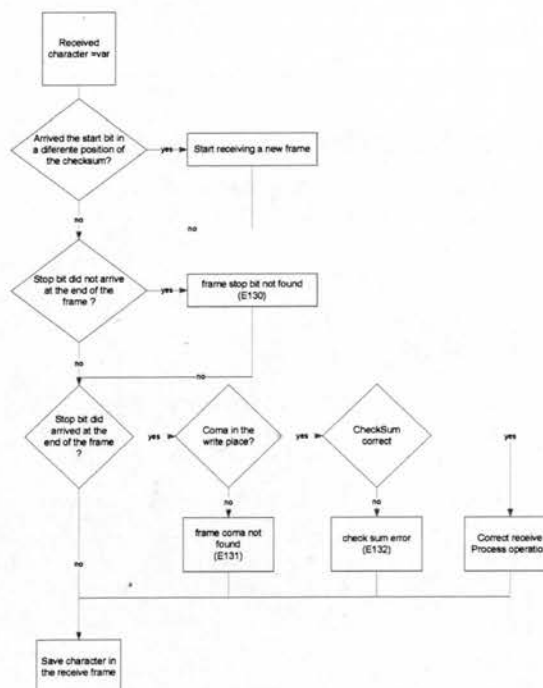


Figure 5.8: USB handler

After this, the microcontroller processes the received character in order to decode the information from the frame or to generate an error code if the reception fails. In the figure 5.8, a simplified functioning diagram of the frame validation process is represented. In between brackets, the error code generated up to that point is represented. A deeper description can be obtained by analyzing the code at the appendix.

5.5 LabView interface

In order to develop a graphical PC application to interface the system, LabView revealed to be a perfect tool. The ease of development of a graphical environment and the possibility to integrate C code (or dll's), have proved to be powerful capacities of this software. Figure 5.9 shows the interface print screen. At this window it is possible to view the current Tuneable Optical Filter working point and the temperature of the system. It is also possible to change the set point value and to detect if the system is connected to the PC. In order ease further upgrades, the basic sub-VI LabView routines will be explained.

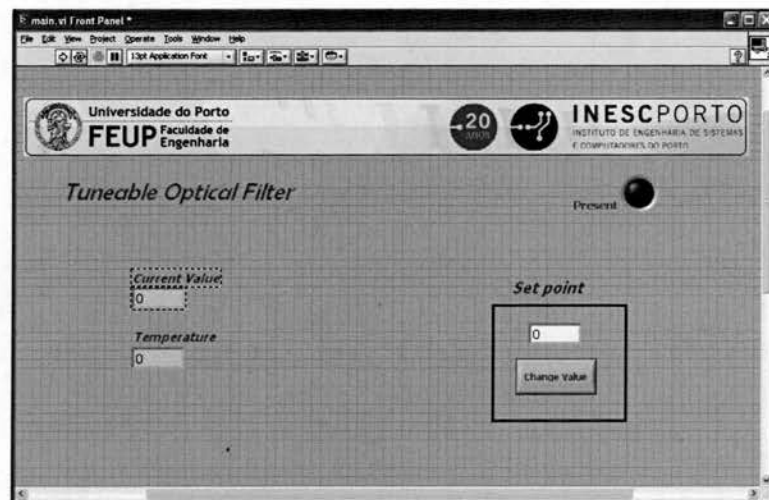


Figure 5.9: LabView print screen

5.5.2 Find Virtual Serial Port SubVI

Other interesting function is the Find Virtual Serial Port. As it was said before, a virtual serial port can be defined with any name by the driver. This function has the goal of finding serial ports with a required name. At the output it becomes available an array with all the matches.

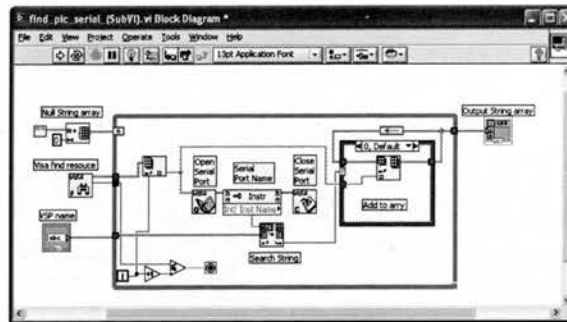


Figure 5.11: LabView find VSP SubVI

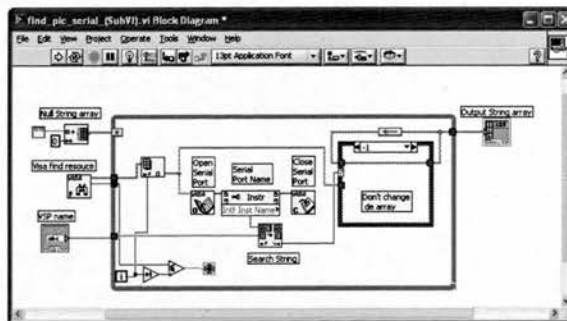


Figure 5.12: LabView find VSP SubVI

On figures 5.11 and 5.12 it is possible to make an analysis of the implementation. This function consists in a *while* loop that analyzes each resource in the system. The figures represent the cases when the analyzed resource matches and does not match the required, respectively. The main difference between them is the case structure, which in one case adds the resource to the array and in the other case, the array remains unchanged.

This function is easy to use:

- input
 - VSP name - this is the string to match on the resources
- output
 - Output String array - array of strings with the match resources names. A null Array is returned if no resources match.

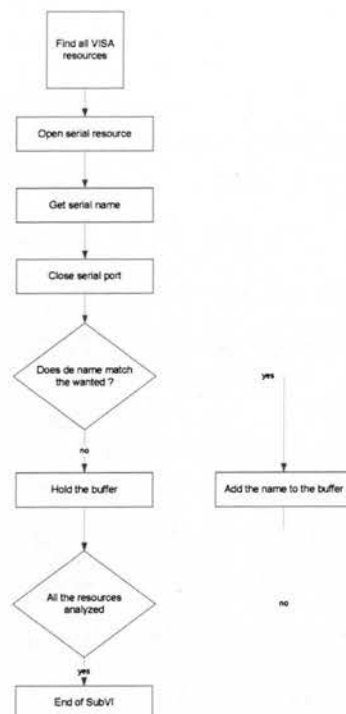


Figure 5.13: LabView find VSP diagram of working

In order to deepen the understanding of this SubVI functioning, a particular attention shall be given to the figure 5.13.

Chapter 6

Experimental results

6.1 Introduction

In this chapter, we will start by presenting the several elements which are used in the experimental setup. Then will describe the experimental setup used for gathering results, as well as the results we obtained. We will also discuss the most relevant parameters related with those results.

6.1.1 Optical Circulator

In order to find the wavelength reflected from the fiber Bragg grating at any given moment, we need a multi-wavelength optical signal and an Optical Circulator (besides the grating itself). In our project, we used a three-port circulator (see Figure 6.1).



Figure 6.1: *3-Port Optical Circulator.*

In figure 6.2 we depict a diagram which illustrates the operating principle of this device. In spite of the fact that the circulator which we used allowed only propagation between the following ports: $1 \rightarrow 2$ and $2 \rightarrow 3$, that was enough for our needs.

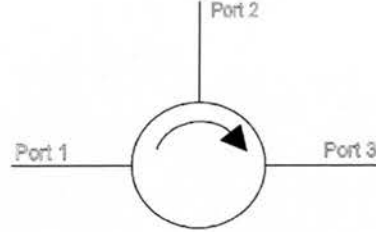


Figure 6.2: *3-Port Optical Circulator Scheme.*

In order to characterize the circulator, we carried out some tests, in which we measured input/output powers, in order to estimate the insertion losses. We used a laser emitting at $\lambda = 1550 \text{ nm}$ with a power $P_{out} = 0 \text{ dBm}$. The measured insertion loss values are presented in Table 6.1.

Table 6.1: *Optical Circulator Insertion Losses*

Ports	Value
$1 \rightarrow 2$	2.65 dB
$2 \rightarrow 3$	1.69 dB

The total loss inserted by the optical circulator in the complete path is 4.34dB. As mentioned previously, there is no power transfer from port 3 to port 1. The losses associated with this blocking path, as well the return losses for the other ports take values of approximately 50 dB.

6.2 Experimental setup

The experimental setup we used to obtain the results is depicted on figure 6.3. The method we used for obtaining the reflection spectrum of the FBG, involves defining the

center wavelength and the span in the optical spectrum analyser (OSA), which commands the tuneable laser for spanning that wavelength region with a desired resolution (2 nm is enough in our case).

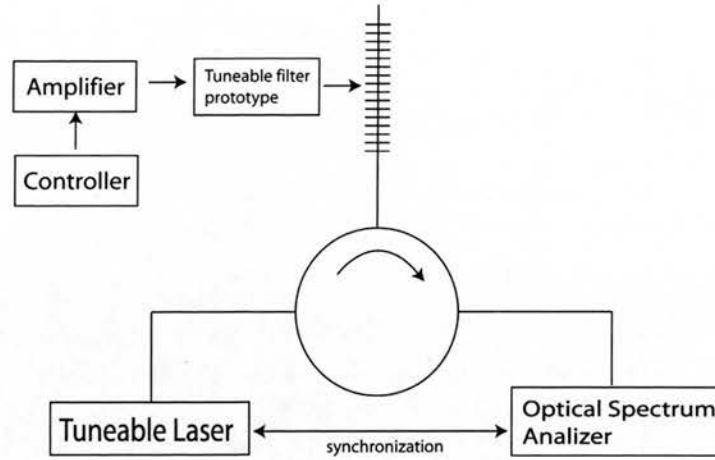


Figure 6.3: *Diagram of the experimental setup.*

The controller referred in previous diagram can be anything that controls the input of the amplifier. Given that the input of the operational amplifier is connected to the output of the digital to analogue controller placed on the microcontroller board, that signal was controlled using an encoder available in the front panel of the device which is also connected to the microcontroller.

Before compression, the central Bragg wavelength was at the wavelength of 1557.9 nm and the grating was 10 mm long. However, the compressed length was approximately 20 mm long.

As can be seen in figure 6.4, considering the original peak (compressed), the power received by the OSA is -5.9dBm. So, given that the laser output power was $P_{out} = 0$ dBm, and having into account the losses of the optical circulator referred previously on this chapter (4.34 dB), and considering a loss of 0.1 dB per connector (with a total of 6 connectors employed), gives a loss (transmissivity) of 0.96 dB for the fiber Bragg grating. This equals to a reflectivity of 80%. The FBG has also a Full Width at Half Maximum (FWHM) of approximately 0.1 nm. The side lobes are within 8 dB of the maximum peak.

Figure 6.4 depicts the result of the application of approximately 200 Volt to the

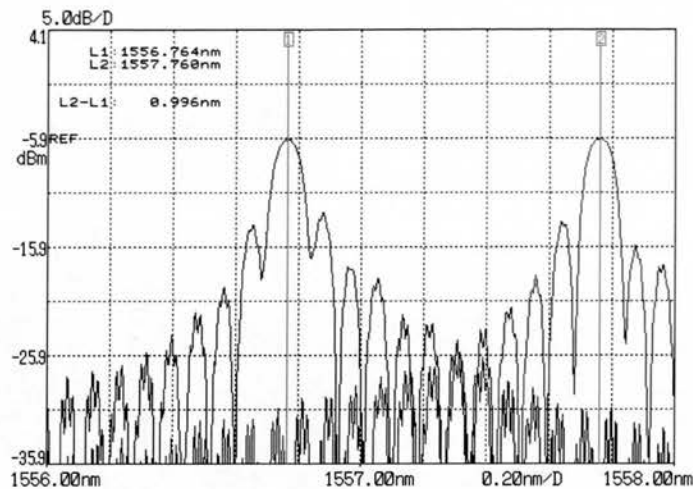


Figure 6.4: Reflection spectra of the compressed FBG (1 nm of shifting).

PZT, which resulted in a wavelength shift of 1 nm.

Figure 6.5 shows that the maximum negative shift achieved was 4.6 nm. Minor spectral changes were also observed, either in the reflectivity of the Bragg wavelength and the side lobes. The difference in the peak of reflectivity between the original (uncompressed) spectrum and the one corresponding to maximum compression was less than 0.6 dB.

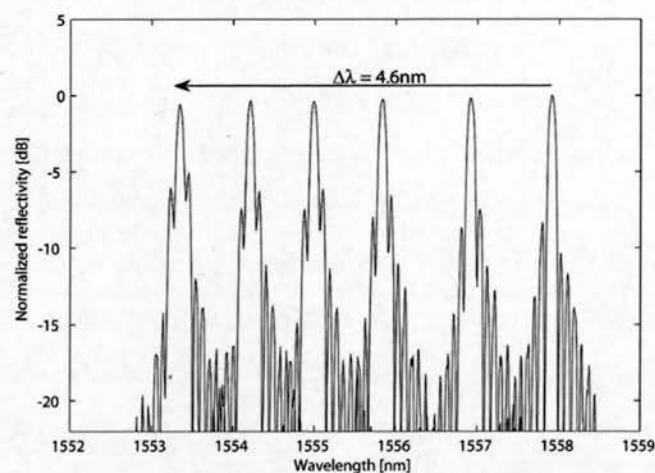


Figure 6.5: Reflection spectra of the compressed FBG.

Figure 6.6 describes the variation of the Bragg wavelength with the applied PZT voltage. The wavelength corresponding to zero voltage was not included in the linear fit because its value clearly does not fit the general behavior of the rest of the experimental data. This is probably explained due to some backlash still existing in the steel frame system which we will try to refine in future improvements.

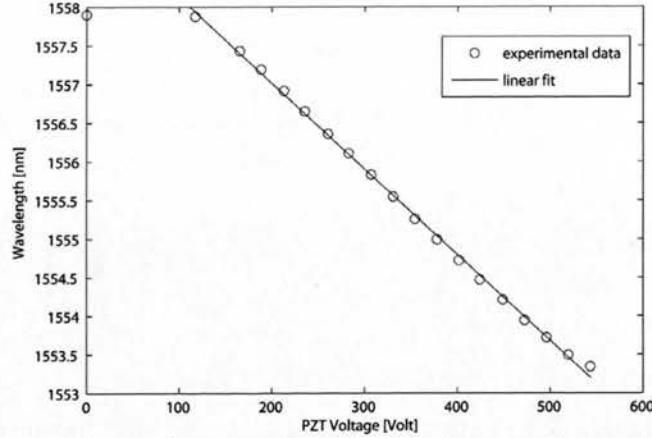


Figure 6.6: *Bragg grating wavelength shift versus piezoelectric actuator voltage.*

The slope of the linear fit is $m = -11.105 \text{ pm/Volt}$. The range of PZT voltage was limited to 550 Volt because at this voltage the ferrules started touching each other, due to the very reduced length of the gap left between them when the steel frame was assembled (topic referred on chapter 3).

Having into account that the characteristic of the wavelength shift is approximately linear with the applied PZT voltage, one can specify the desired wavelength (in the PC or in device front panel), and following that linear relationship, the microcontroller knows the necessary voltage required for the PZT to achieve that switch. However, the descending characteristic is not equal to the ascending one due to the hysteresis of the actuator, in particular, piezoelectric transducers when operated in open-loop have a hysteretic characteristic of the displacement versus applied voltage. This could be troublesome if we wanted to perform an high speed switching between two wavelengths. A few options for this problem can be pointed:

- The use of a sub-nanometer resolution capacitive position sensor. It is a non-

contact, direct-metrology device (for example, the model D-100 from PI), which could give us precise information about the PZT position (and consequently applied strain). As the wavelength depends linearly on the strain, we would attain direct control of the wavelength.

- The use of absorption spectroscopy, by employing an acetylene absorption cell followed by a photodetector, which would give us precise information about the actual wavelength [16].
- Lastly, a fairly reasonable and cheaper option is to obtain a model for the hysteresis of the PZT, and implement it on the microcontroller.

Besides the hysteresis, the other effect needing compensation is the temperature drift. As the wavelength depends linearly on the temperature drift, the microprocessor can compensate it's effect just by monitoring the actual temperature.

Another aspect deserving focus is the response time. Due to the fact that we are using a piezoelectric transducer, the response time is extremely fast. Particulary, for the PZT model we have used, a switching in less than a millisecond is attainable.

Chapter 7

Concluding remarks

One can say that this project was accomplished quite successfully. In the following lines, we will analyze the overall results that we obtained and try to measure the level of accomplishment at each project objective.

We also achieved the main goal of our project with success: the implementation of an optical tuneable filter. We could check that it met all the specified requirements.

In Chapter 2 we studied the state-of-the-art in terms of switching techniques associated with fiber Bragg gratings. We introduced in this chapter the concept of compression based FBGs.

In Chapter 3 we thoroughly discuss important theoretical/practical aspects concerning the process of assembling the FBG within precision ferrules, and hence, within the special steel frame we projected. We have also explained in detail all the characteristics of the final device.

Chapter 4 described all the details related with amplifier circuit designed to drive the PZT. We have also shown the solutions found concerning all the obstacles we faced in the theory to practise transition.

In Chapter 5, we presented the communication protocol developed, and comprehensively characterized the functioning diagrams of the main software routines.

Throughout the project, we came across several difficulties which we were able to overcome. The most significant of them was related to the caution and precision necessary with fiber handling, which, beyond everything else, is really a very sensitive

glass cylinder.

Time is a scarce resource, and unfortunately we were not able to explore deeply all the topics we wanted. Concerning future work that might be done:

- The usage of shorter ferrules to compress a reduced length of fiber would give a broader tuning range, in particular, our system uses a guiding system with 20 mm of length to compress a fiber with a 10 mm long inscribed FBG. Hence, theoretically, the tuning range can be doubled. On the other hand, the usage of a reduced length FBG (e.g. 5 mm) would enable the attainment of the same goal.
- The usage of a sub-nanometer resolution capacitive position sensor would boost the ability to control the device by minimizing the actuator hysteresis.
- The usage of an acetylene absorption cell followed by a photodetector as a feedback mechanism would give precise information to the system on the current wavelength.
- The implementation of a charge control (current feedback) amplifier would also mitigate the effect of hysteresis, because the current-displacement characteristic of piezoelectric transducers is almost linear.

We do sincerely hope that, in the upcoming years, other motivated students will take our work a little bit further, and by refining some of our ideas, or then, by coming up with their own, they will be able to effectively enhance our system's performance.

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