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FIBER BRAGG GRATINGS FABRICATION USING FEMTOSECOND LASER

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ABSTRACT

In this paper it is presented a method of fabrication of fiber Bragg Gratings using femtosecond laser.

By using femtosecond laser focused on a small bulk of an optical fiber, it can produce a change of the refractive index of the material. FBG have a wide variety of applications such as sensors and telecommunications.

In this experiment it was used point-by-point writing. By using a frequency of $f = 37{,}3527\ Hz$it was obtained a Bragg wavelength of $\lambda_B = 1552{,}54\ nm$. In this FBG the phenomenon of birefringence was observed.

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1. INTRODUCTION

A fiber Bragg grating (FBG) is a periodic refractive index perturbation along a fiber that is accomplished by exposing the fiber core to a pattern of intense optical interference.
This technique has been studied more extensively because fiber gratings devices have a wide variety of applications such as sensors and telecommunications.
Fiber Bragg gratings have applications on communications, for making good filtration and for the versatility of devices such as wavelength stabilize laser, amplifiers and others. And applications in sensors have been investigated for monitoring of bridges, for example, since these have high sensitivity and resolution spatial resolution, fast response time, and resistance to electromagnetic interference.

The typical way of generating fiber gratings is by exposing an ultraviolet laser beam to a photosensitive core in order to change the refractive index, but this shape has problems associated with long-term thermal stabilization. In this way, the fiber gratings fabricated with femtosecond laser have annealing characteristics and show stability at higher temperatures – this is what is going to be done in this experiment.

1.1. Fiber Bragg Gratings

Consider a mode A(z) and a anti-propagation mode B(z):

$$A^{+}(z) = A(z)e^{i\delta_d z - \varphi/2}$$

$$B^{+}(z) = B(z)e^{i\delta_d z - \varphi/2}$$

The main interaction in FBG is on the wavelength in which the reflection occurs from a mode A(z) to B(z), simplified in the following way:

$$\frac{dA^{+}}{dz} = i\zeta^{+}A^{+}(z) + i\kappa B^{+}(z)$$

$$\frac{dB^{+}}{dz} = -i\zeta^{+}A^{+}(z) - i\kappa A^{+}(z)$$

Where $\zeta^{+} = \delta_d + \zeta - \frac{1}{2}\frac{d\varphi}{dz}$, is the self-coupling coefficient dc; With $\delta_d = \beta - \frac{\pi}{\Lambda} = 2\pi n_{eff}[\frac{1}{\lambda} - \frac{1}{\lambda_d}]$, which is the detuning, z independent; Where $\lambda_d = 2n_{eff}\Lambda$ is th deseign wavelength for Bragg dispersion for an infinitesimal weak grating which condition is $\delta n_{eff} \longrightarrow 0$ with period Λ.

When $\delta_d = 0$, we find:

$$\boldsymbol{\lambda = 2n_{eff}\Lambda} \qquad (1)$$

Which is the **Bragg Condition**. This way, Fiber Bragg Gratings is the periodic modulation of the core's refractive index from a single-mode fiber, in which the guided light in the core will be scattered in each grating plane.

If the Bragg condition is not satisfied, the reflected light in each plane will be out of phase and they will eventually cancel out. When this is satisfied, the reflected light in each plane contributes constructively in the backward direction, to form the back-reflected peak with a centre wavelength defined by the grating parameters.

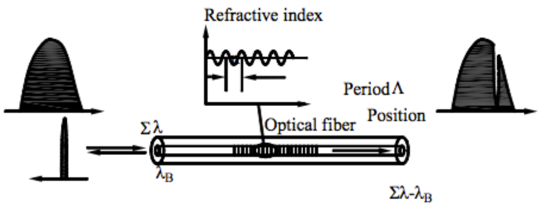

Figure 1 - FBG Schematization.

In fact, the Bragg condition simply satisfies the conservation of momentum and energy. Energy conservation requires that the frequency of the incident radiation be the same as the reflected frequency; the conservation of the moment of the wave vector plus the grating vector is equal to the vector of the scattered radiation.
From these assumptions we arrive at the same condition described above.

By analysing some proprieties, the refractive index profile can be described by:

$$n(x) = n_0 + \Delta n \cos\frac{2\pi x}{\Lambda}$$

Where Δn is the perturbation of the refractive index.

The reflectivity of a grating with constant modulation of amplitude and period is:

$$R(l,\lambda) = \frac{\Omega^2 \sinh^2(sl)}{\Delta k^2 \sinh^2(sl) + s^2 \cosh^2(sl)}$$

Where l is the lenght, Ω is the coupling coefficient for the variation of the refractive index through the fiber, $\Omega = \frac{\pi \Delta n \eta(V)}{\lambda}$, e Δk is the detuning of the wave vector, $\Delta k = k - \pi/\lambda$ and k is the propagation constant, $k = 2\pi n_0/\lambda$, and $s = \sqrt{\Omega^2 - \Delta k^2}$.

As in a wavelength centre of a Bragg grating there is no detuning of the wave vector, $\Delta k = 0$:

$$R(l, \lambda) = \tanh^2(\Omega l)$$

Meaning, the reflectivity raises when the refractive index raise and when the grating length is bigger.

Defining the bandwidth of a uniform Bragg grating as the distance between the 1sts zeros on each side of the maximum reflectivity and assuming that the change in the refractive index is weak,

$$\frac{\Delta\lambda_0}{\lambda} \longrightarrow \frac{\lambda_d}{n_{eff}L} = \frac{2}{N}$$

Which means that the bandwidth of weak gratings is limited due to its length. If the grating is strong, the light does not penetrate the full length and the bandwidth is independent of the length, but is directly proportional to the change in the refractive index.

1.2. Inscribing Bragg Gratings by Femtosecond Laser Irradiation

When femtosecond laser pulses are focused into the bulk of a transparent material, it can produce a permanent change of the refractive index inside a small focal volume. Because the laser intensity is high enough, in this volume happens multiphoton absorption, optical breakdown and microplasma formation. This formation of microplasma causes structural and a refractive index changes, driven by free electrons, in the focal region by leaving a thermomechanical stress, creating local density changes and/or by the formation of colour centres. These mechanisms allow us to perform three dimensional refractive index patterning and to fabricate complicated photonic structures in practically all-transparent materials.

This raises some important parameters that need to be considered:

- Polarization - The absorbed energy is dependent of the incident beam polarization;
- Impulse Energy - The minimum energy necessary for occurring non-linear absorption is the damage threshold energy. For low energy impulses the refractive index varies lightly, for medium energy impulses is possible to occur birefringence, and for high energy impulses occur micro explosions due to the Coulomb repulsion between ions which generates voids;
- Wavelength - The threshold damage linearly varies with the wavelength;
- Numeric Aperture - Determines the volume focal area. Bigger the aperture, then bigger the focus and smaller is the divergence (and vice-versa).

1.3. Writing techniques for FBG fabrication

There are several writing techniques for the manufacture of FBG: Holographic Interferometer, Phase Mask and Point-by-Point Writing.

In the Holographic Interferometer the laser beam is divided in two beams at a beam splitter and then brought together at a mutual angle, by reflections of two mirrors. The main disadvantage is the susceptibility to mechanical vibrations which can be fixed by built the interferometer in a steady base and it is required that the laser source to have a good temporal and spatial coherence.

The Phase Mask is one of the most effective techniques for fabricating FBG. A phase mask is made from a flat high purity silica and a one dimension and periodic surface it etched on the surface. It serves as a precision diffraction grating dividing a monochromatic beam in two beams, creating an interference pattern. Exposure laser radiations on interference patterns cause a periodic modulation of the refraction index in the material's core. The advantage is that the process is simplified which increases the manufacturing, and phase mask technique provides easier optical alignment and requires lower coherence of the laser source.

Point by point writing is a single spot illumination at a time forming a periodic refractive index grating. It requires that the fiber doesn't move along the writing, in the longitudinal axe. Normally, a microscopic lens with high numeric aperture focuses the laser, which causes the imposition of low energy pulses. However, this is only suitable for short gratings, since it is difficult to control translation stage movement accurately enough to make point-by-point writing of a first order grating. This writing is extremely useful for fabricating gratings of long periods. This procedure requires the grating period to be stable (which is extremely important when using short pulses) and that the fiber filling factor is dependent on the size of the spot. The solution is to use a constant speed to move the carriage with the consequence that the grating period is determined by the frequency of the modulation wave:

$$\Lambda = \frac{v}{f} \qquad (2)$$

This is the technique that it will be used in this experiment for fiber Bragg gratings fabrication.

2. EXPERIMENTAL PROCEDURE

2.1. Experimental Setup

The experimental setup was already assembled accordingly to figure 2.

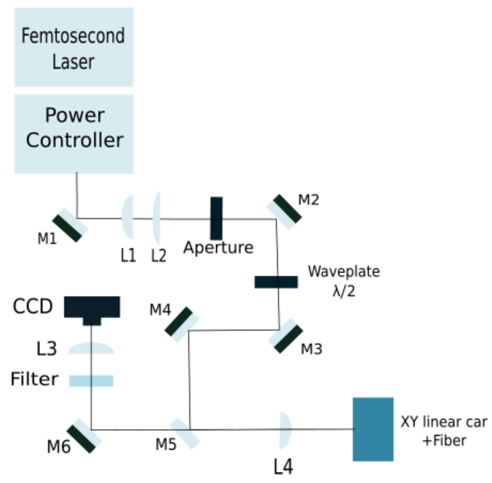

Figure 2 - Experimental Setup.

It was formed by: laser and power controller; Beam conduction system (6 mirrors, 4 lens, aperture and half-wave plate); CCD camera and a motorized XY car where the fiber is. It follows some explanations about the equipment used in this experiment:

- Power Controller: It is formed by a waveplate $\lambda/2$ - that rotates the polarization of the incident beam in 180 degrees, by rotating this plate it is possible to choose the quantity of power that is transmitted; and it's formed by a Brewster angle[1] polarizer (that is computer controlled) which separates the beam in two: one that is going to be used and another that will be guided to a beam dump;

- Kepler Telescope: It's composed by two lens (L1 and L2) and it is used to amplify the beam, which allows obtaining maximum incidence at the lens that focuses the beam at the fiber. The amplifier is used to fill the lens aperture with the consequence of lost of power;
- Aperture: Used to focus the beam;
- Half-wave plate: Change the polarization of the beam into the writing direction;
- CCD camera: used to see the process and do some small alignments. The lens (L4) is used to collimate the beam at the camera. The filter is used to reduce the intensity of the original beam because it could damage the camera; Len 4 was placed over the fiber that was soaked in phase-matching liquid.

2.2. Procedure

Before moving to the procedure itself, it was necessary to align the system. First, using a previously marked, the mirror's alignment was done through the verification that the beam always hit the same spot. It is important that the laser was parallel to the table and that the reflection angle in the mirrors was 45 degrees. The second step was verifying that the beam's inverse way was exactly the same as the direct way – so, the beam was considered aligned when the beam that was leaving the aperture was coincident with the reflected beam. The third step was calibrating the car through he CCD camera – By turning on the laser, it appears a spot on the image of the camera (because the reflective beam is collimated), and there was a mark on the screen that point the spot where the writing was going to be done. During this calibration it was used low power and a filter to not cause damage on the CCD camera. For last, it was done the XY calibration, once it is possible to distinguish the core limits (different shades), and then it was choose the medium point between this limits. For the Z direction, it was found the position where it is not possible to distinguish the core on the transmitted image (no shades).

For the procedure itself, the laser was externally modulated with a square wave generated by a signal generator. The writing was automatized and it was possible to control the writing parameters (speed, frequency, position, duration, period...) in a LabVIEW program. It was possible to observe the transmission spectres on OSA [2].

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1 - Brewster angle (or polarization angle is the incident angle at which the light with a particular polarization is perfectly transmitted with no reflection - $\theta_B = \tan^{-1}\frac{n_2}{n_1}$.

2 - OSA – Optical Spectrum Analyser is an instrument designed to measure and display the power distribution of an optical source over a specified wavelength.

3. RESULTS, OBSERVATIONS AND DISCUSSION

3.1. Problems (and respective possible solutions) found in the experiment

This experiment was performed twice, since in the first one the FBG manufacturing was not successful. This way, in this section will be mentioned the problems found in the first and second experience, as well as some solution ideas to solve them.

1st experiment:

i. The fiber was misaligned in Y and Z- sometimes it was possible picking up the focus;
ii. It was predicted the existence of problems related to the tension of the fiber - mechanical stress;

iii. Problems in power control, which can be neither too much nor too little;

Changes made after the first experience:

• Carriages were included (i.);
• The structures existent in the fiber area were joined in order to increase stability (i.);
• The stress of 1N was changed to 0,2N (ii.);

Even after these changes, the experience continued problematic, however it was already visible the manufacture of gratings in the optical fiber.

2nd experiment:

i. Find out what the position was after entering the core;
ii. Again, problems in power control;
iii. Lens was not well filled;
iv. Again, problems associated with tension - the way the fiber was stretched;

Here are some possible solutions to these problems:

• Instead of using the point-by-point technique, using the technique Phase Mask (i.)
• By changing the power, the distance to the focus is also changed - same power has the same distance, since the numerical aperture is known (ii.);
• Know the power lost through the measurement with two photo detectors positioned in two different places (the last one underneath the fiber) - thus it is discovered which power optimizes the experiment (ii.);
• Filling the lens well to reduce susceptibility to losses (iii.);
• Do the experiment several times but with different stress values and find out which is the most effective (iv.);

3.2. Results of the fabricated gratings

The following parameters were used in the fabrication of gratings:

Table 1 - FBG Parameters.

Power	$P = 30\,mW$
Wavelength	$\lambda = 1550\,nm$
Refractive Index	$n = 1{,}22742$
Period	$T = 535{,}437$
Frequency	$f = 37{,}3527\,Hz$
Speed	$v = 20\mu m.s^{-1}$

Using equations (1) and (2) it was obtained the Bragg wavelength:

$$\lambda_B = 1552{,}54\,nm$$

In the OSA, it is expected that for lower the power, that the reflection peak decrease, that the accuracy of the Bragg wavelength increase and that the grating aspect be more uniform.

The graph obtained in the OSA is shown in figure 3.

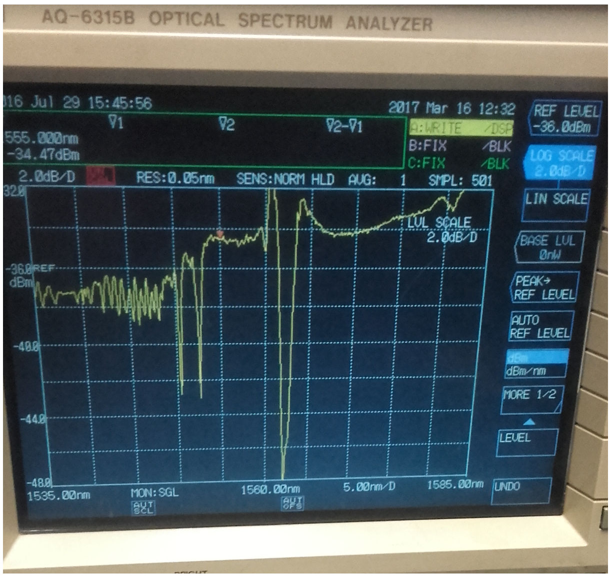

Figure 3 - Spectrum obtained in OSA.

Two smaller power peaks are observed, when only one should be observed. It was predicted that this phenomenon is associated with fiber birefringence. What may have happened is that small disturbances have caused energy coupling from one polarizing component to another. An anisotropic stress in the core can induce high birefringence in the core.

Gratings were rewritten in another position of the fiber. This time with larger power (40mW) obtaining the third peak which is the highest power peak observed in figure 3 (approximately 17dB). Note the appearance of birefringence again; the symmetry is lost, which may be an indicator of fiber misalignment - writing off the fiber.

4. CONCLUSION

In this work it was possible to obtain an idea of the process and the physics involved in the manufacture of fiber Bragg gratings. Once this project was under developed, it was possible to observe the flaws present in the experiment as well as some of the solutions already applied.

A grating of frequency $f = 37{,}3527\ Hz$ was obtained, which corresponds to a Bragg wavelength of $\lambda_B = 1552{,}54\ nm$. In this FBG the phenomenon of birefringence was observed. In the second writing process, from the obtained results it was possible to conclude that the writing was being proceeded outside the optical fiber core.

Although the results obtained were not satisfactory, it was possible to acquire a great deal of knowledge with the experience since different processes such as laser alignment, calibration process and the fiber writing process were observed.

5. REFERENCES

[1] Gattass Rafael R and Mazur Eric. Femtosecond-laser micromachining in transparent materials. Nature photonics, 2(4):219 225, 2008.

[2] Carneiro Alexandre Cascardo and Andrés Pablo López Barbero. Princípio de funcionamento dos sensors ópticos baseados em grades em fibras ópticas e sua importância nas diferentes áreas tecnológicas. ENGEVISTA, V.16, n.4, o.398-403, 2014.

[3] Fernandes Luis Andre. Birefringence and Bragg grating control in femtosecond laser written optical circuits. PhD thesis, Department of Physics and Astronomy of Faculty of Sciences of University of Porto, 2012.

[4] Zhan Chun. Femtosecond laser inscribed Fiber Bragg Gratings Sensors. PhD thesis, The Pennsylvania State University,2007. (also figure 1)

[5] D. Tan, K. Sharafudeen. Y. Yue, J. Qiu, “Femtosecond Laser Induced Phenomena in Transparent Solid Materials: Fundamentals and Applications”, Progress in Materials Science, · September 2015