

# Fiber Optic Pressure Sensor

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**Abstract:** The purpose of this paper is to analyze the inherent and induced effects of the perturbations that result in losses of the optical power on the fiber measuring element of pressure/force detectors. Inherent or induced perturbations result in losses of the polarization state and optical power on the fiber. The presence of outer mechanical stress (pressure or tensile force) on the fiber results in the microbending loss phenomenon embedded in the optical fiber. The paper deals with both modeling and simulating the sensor behavior and with measurements on a physical sensor.

**Keywords:** Fiber optics, birefringence, polarization state, fiber optic sensor, microbending.

## I. INTRODUCTION

The purpose of this paper is to analyze a fiber optic pressure sensor for detecting and monitoring the level of pressure on civil and industrial structures. An optical fiber incorporated into a structure deforms together with the structure and the light transmitted through the fiber is modulated as a result of the changes in the physical parameters of the surrounding environment.

In making the fiber optic pressure sensor we took in consideration two phenomena:

- the birefringence phenomenon: is an inherent or induced phenomenon and the main cause which affects the maintaining of the polarization state. When losing the polarization state, the performances and power of the fiber optics diminish.

- the microbending phenomenon: is an induced phenomenon on the fiber by an external force which results in microscopic deformations at the surface between the core and the cladding. These microscopic deformations increase the attenuation in the optical fiber. The attenuation due to the microbending increase with

the wavelength (higher attenuation at the wavelength of 1550 nm than at 1310 nm).

The application is approached from two points of view: First, modeling and simulating the fiber optic sensor in the program Comsol Multiphysics® and second, using an experimental set-up we apply several weights on the fiber optic sensors. The active length of applying pressure was established at  $\Lambda = 20$  mm.

The program Comsol Multiphysics® is used to simulate a transmission of light with a wide spectrum range, from ultraviolet to infrared, on a plastic type (PMMA) optical fiber with the core diameter of 486  $\mu\text{m}$  and 800  $\mu\text{m}$  the cladding.

On an experimental set-up, we applied force by placing weights on a plastic type (PMMA) optical fiber with the core diameter of 486  $\mu\text{m}$  and 800  $\mu\text{m}$  the cladding. The weight limit was established at 1kg as to not destroy the optical fiber and compromising the experiment. The experiments are made using a light source in the visible spectrum.

## II. THEORETICAL BACKGROUND

A fiber optic sensor is a sensor that uses optical fiber as the sensing element itself or using fiber optic as a means of transmission from a sensor at a distance to the electronic system that processes the signals. Depending on the application, optical fibers are used due to the advantages of being small, do not require electrical power, and multiple sensors may be multiplexed over the optical fiber by changing the wavelength of the light beam. Fiber optic sensors are used in chemical, biological, medical, aeronautical and civil engineering [1].

Light is characterized by the electric field vector and the magnetic field vector. The polarization state of the fiber is described by the electric field vector. A ray of

light in optical fibers can be treated as an electromagnetic wave transverse [2].

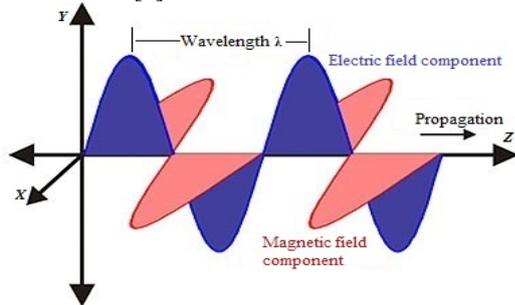


Fig. 1 –Light vectors propagated on optical fiber [3]

An electromagnetic wave is described by an electric field intensity vector  $E$ , which propagates in the direction of the  $z$  axis of the orthogonal coordinate system. The wave is a superposition of two partial waves with mutually orthogonal linear polarization and identical frequency [4].

The birefringence represents the difference between the propagation waves and is the significant factor which affects the performance of the fiber optic. The birefringence is inherent or induced in non-circular cores, caused by applying stress, twisting or bending the fiber, in the presence of a longitudinal magnetic field or the presence of a metal in the vicinity of the fiber core.

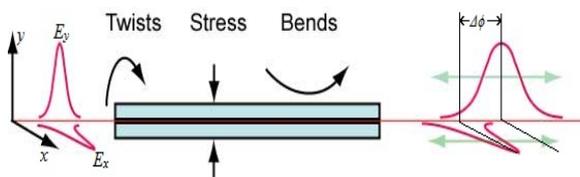


Fig. 2 – The phase shift between the electric field vectors [6]

Microbending, is an induced phenomenon on the optical fiber by an external force. Applying a force on the fiber results in compression and deformation of the fibers core due to the opto-elastic effect. Considering  $F_m$  the force which acts on the length unit, the phase shift  $\Delta\phi$  between the fibers modules is [7]:

$$\Delta\phi = \frac{2\pi}{\lambda} C_f \frac{4F_m}{\pi d_{cl}^2}, \quad (1)$$

where:

$\lambda$  is the wavelength,  $C_f$  is the characteristic coefficient of the optical fiber, and  $d_{cl}$  is the fibers diameter.

The light ray transmitted on the fiber, in contact with the cores strain, modifies the critical angle, enters the cladding and is lost. In the case of a multimode optical fiber not all rays of light exceed the critical angle in contact with the strain, which they will continue to propagate along the fiber.

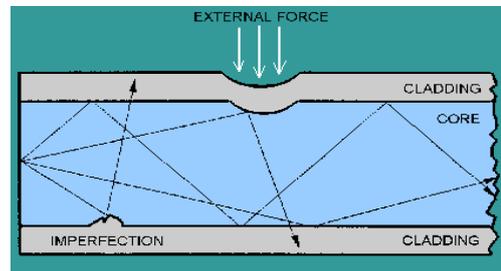


Fig. 3 –Microbending loss [8]

- The advantages of using fiber optic sensors are several:
- they are not affected by electromagnetic interference;
  - they do not conduct electricity, being able to be placed in places with high voltage or places with high levels of danger;
  - they can be designed to withstand high levels of temperature;
  - the possibility of using one optical fiber for a simultaneous measurement of several parameters;
  - they are immune to static interference, such as those caused by lighting, electric motors or gas discharge lamps.

### III. SIMULATIONS RESULTS

The first step of the simulations was computation of the optical power transmission in ideal conditions without inducing any phenomenon mentioned earlier to obtain a reference and comparison point.

The second step was computing the optical power loss transmitted after inducing the birefringence phenomenon by making a microbend on the optical fibers core.

The wavelength chosen for the simulations was 1330nm. The attenuation value is minimum, 0.33 dB/km. The type of fiber used was multimode with the refractive index of 1.42 for the cladding and 1.49 for the core.

The boundary conditions established in Comsol Multiphysics® are: the type of material used for the fibers cladding and core is plastic (PMMA), Young module  $E=73.1e9$  [Pa], length of the fiber 10cm, the microbends length 50 $\mu$ m, 100  $\mu$ m and 150 $\mu$ m. In figure 4 is a representation of the mesh established for the simulations, analyzing on the entire length of fiber the wave propagation and its properties.

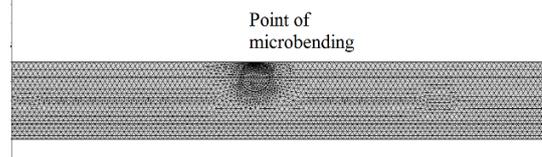


Fig. 4 – Mesh model for simulations

The mesh used for the simulations is calibrated for general physics, the triangular type elements are predefined as extremely fine with the maximum element size of  $100\ \mu\text{m}$  and minimum element size of  $0.2\ \mu\text{m}$ . At the point of microbending the mesh is finer than for the rest of the fibers length.

The wavelength chosen for the simulations is set at  $1310\text{nm}$  due to the low optical loss, for this wavelength the value attenuation is minimum,  $0.33\ \text{dB/km}$ .

Figure 5 represents the polarization state of the light transmitted on the fiber optic in ideal conditions, without external influences. In ideal conditions the polarization state is constant on the fibers entire length.

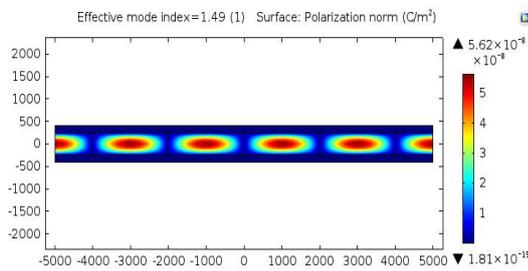


Fig. 5 – Polarization state in ideal conditions

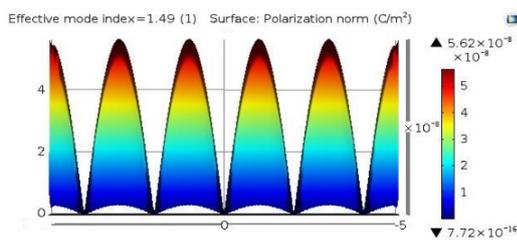


Fig. 6 – Polarization state in ideal conditions

In figure 7 is represented the electric field, one of the components which define an electromagnetic wave. It can be observed that in ideal conditions the light is constant, it maintains its optical power on the entire length of the fiber without any losses.

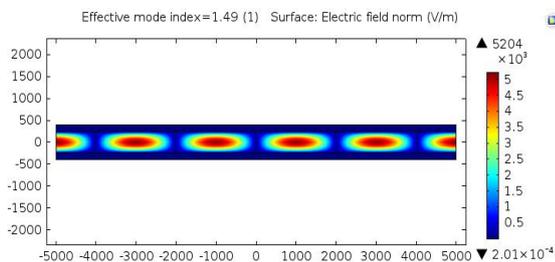


Fig. 7 – The electric field in ideal conditions

The next step is inducing the birefringence phenomenon by creating a microbend of  $50\ \mu\text{m}$  on the fibers core. The microbend will have the refractive index

of 1.42, the same as the cladding and we will analyze the resulting effects it has on the wave propagation on the optical fiber.

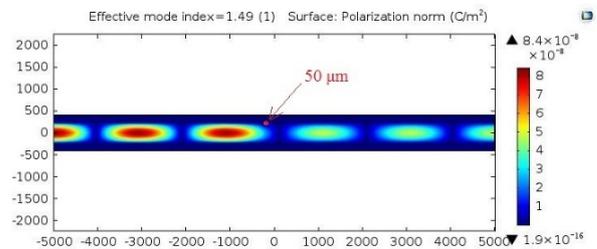


Fig. 8 – The polarization state with a  $50\ \mu\text{m}$  microbend

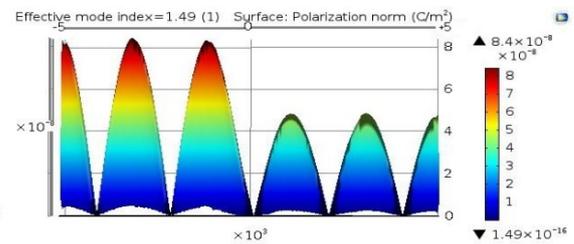


Fig. 9 – The polarization state with a  $50\ \mu\text{m}$  microbend

In figures 8 and 9 it is represented the polarization state after creating a microbend of  $50\ \mu\text{m}$  on the fibers core. It can be observed after the point of the microbend the optical power decreases to approximately half its value that of the value from before reaching the microbend.

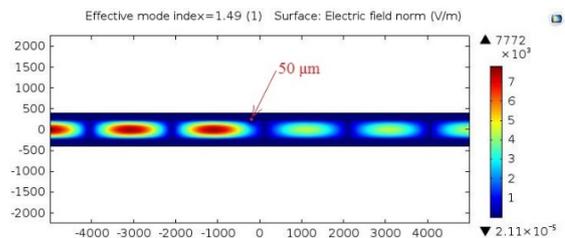


Fig. 11 – The electric field with a  $50\ \mu\text{m}$  microbend

The electric field represented in figure 11, decrease as same as the optical power on the optical fiber due to the microbend present in the fibers core.

Next, we will simulate a  $100\ \mu\text{m}$  microbend on the fiber optic core and analyze the results.

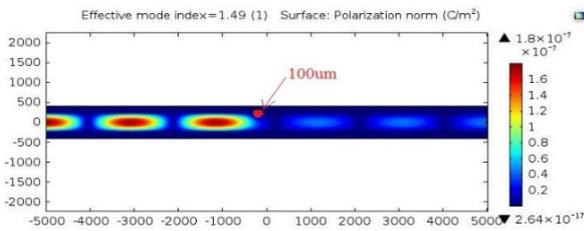


Fig. 12 – The polarization state with a 100 μm microbend

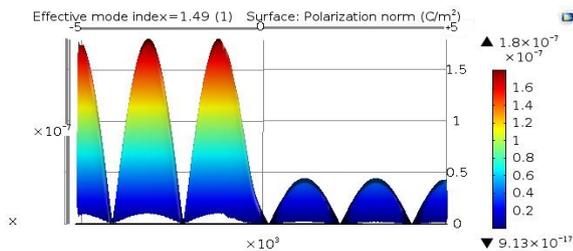


Fig. 13 – The polarization state with a 100 μm microbend

Figures 12 and 13 representing the polarization state on the optical fiber for a microbend of 100 μm we can observe a significant loss in the polarization state. The optical power is constant and presents no losses to the point of the microbend on the fibers core. Beyond the point of the microbend the optical power has decreased significantly.

Figure 14 representing the electric field of the electromagnetic wave on the optical fiber with a microbend of 100 μm shows us that a wider microbend the loss grows proportional than in the case of a 50 μm microbend.

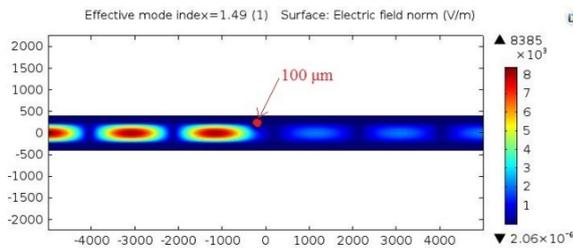


Fig. 14 – The electric field with a 100 μm microbend

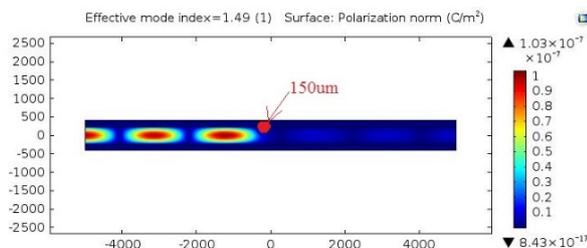


Fig. 15 – The polarization state with a 150 μm microbend

The last step of the simulations is creating a microbend of 150 μm on the fibers core. Considering the previous simulations, we can presume the loss of the optical power on the fiber to be far greater with a 150 μm microbend on the core. As presumed, the polarization state of the fiber has decreased far greater with 150 μm microbend on the fibers core than the previous microbends (Fig.17).

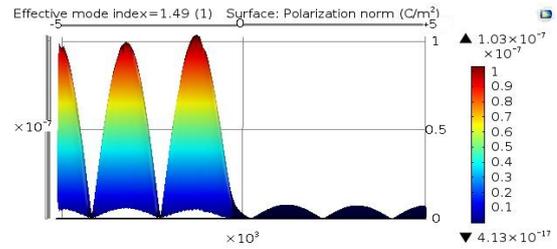


Fig. 16 – The polarization state with a 150 μm microbend

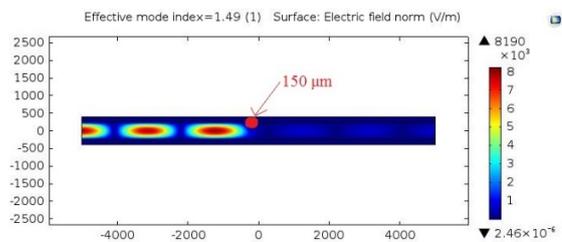


Fig. 17 – The electric field with a 150 μm microbend

The electric field after the point of the microbend decrease greatly compared with the other simulations. The microbend of 150 μm occupies 1<sup>st</sup> of the fibers core resulting in the highest loss of optical in these simulations.

#### IV. EXPERIMENTAL RESULTS

Using an experimental set up we analyzed the effects of the microbends on the optical fiber by applying different weights on a section of 20 mm of the length of the fiber. The type of fiber used is plastic (PMMA) with the same parameters as in the simulations. The size of the core is 486 μm with the refractive index of 1.49 and 1.42 for the cladding. The weights chosen are: 100 g, 200 g, 500 g and 1kg. The weight limit was established at 1kg as to not destroy the optical fiber and compromising the experiment. As a light source, a common white bulb was used to send light in the visible spectrum. The spectrophotometer used to measure the light transmitted on the optical fiber is an Ocean Optics USB4000-UV-VIS spectrophotometer with the software of measurement, Spectral Suite. The USB4000-UV-VIS is a miniature spectrometer preconfigured for general UV-Vis measurements from 200-850 nm including absorption, transmission, reflectance and emission.

The first measurements are made with the fiber optic in ideal conditions to achieve a reference point. We measured both the optical power and the light intensity on the optical fiber. In figure 20 it is represented the method used to induce microbends on the fibers core. The experimental device is 20 mm in length.



Fig. 20 – Experimental set up for inducing microbends



Fig. 21 - Reference measurement of light transmission

Figure 21 represents the reference measurement of light transmission on the optical fiber in ideal conditions. The peak value of transmission has stabilized at 98 % at the wavelength of 530 nm. We will use this point as the reference for the next measurements.

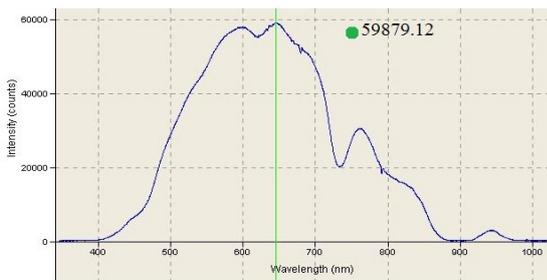


Fig. 22 – Reference measurement of light intensity

Figure 22 represents the reference measurement of light intensity on the optical fiber in ideal conditions. The intensity of light is measured in photons or counts as Spectral Suite is programed. The peak value of intensity has stabilized at 59879.12 counts at the wavelength of 640 nm. We will use this point as the reference for the next intensity measurement

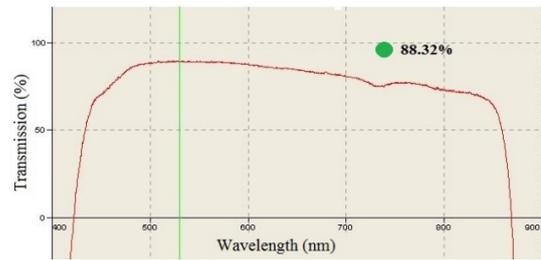


Fig. 23 –Transmission for a 100 g weight

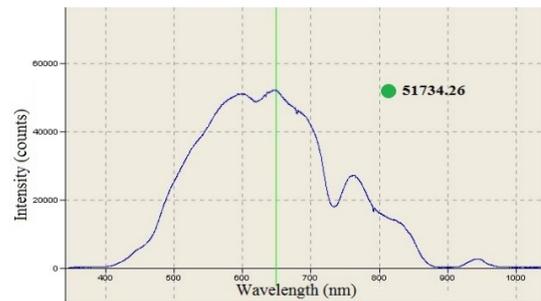


Fig. 24 – Intensity for a 100 g weight

Comparing the reference graph of the transmission with the one for applying 100 g weight on the fiber we can observe a 10 % loss. The same can be observed in the intensity graphs, we have a loss in the photon count. Next step we will apply a 200 g weight on the set up and proceed in measuring the same parameters.

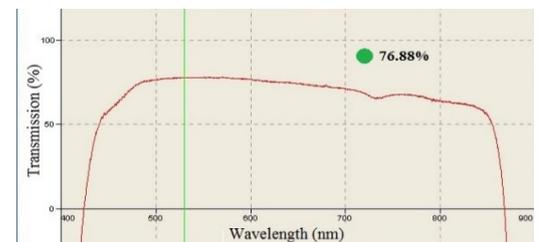


Fig. 25 – Transmission for a 200 g weight

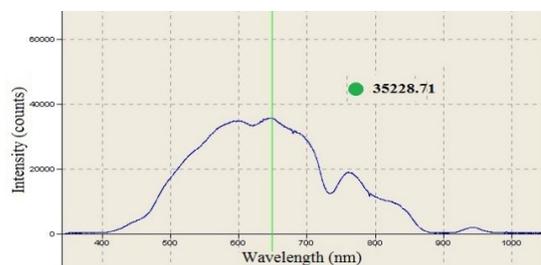


Fig. 26 – Intensity for a 200 g weight

In figures 25 and 26 we can observe a loss of 76 % in transmission and over 10 thousand photons count loss in intensity compared with the reference measurements.

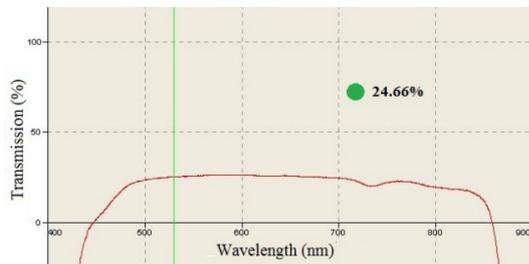


Fig. 27 – Transmission for a 500 g weight

The next step will be applying a 500 g weight on the set up and measure the transmission and intensity loss.

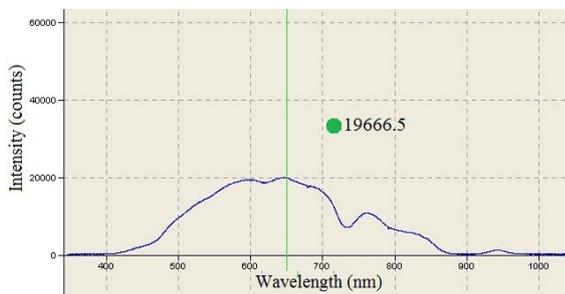


Fig. 28 – Intensity for a 500 g weight

When applying a 500 g weight on the set up the transmission on the fiber optic drops at 24 % and the intensity loss is less than half that of the reference value. The last step is applying a 1 kg weight on the set up.



Fig. 29 – Transmission for a 1 kg weight

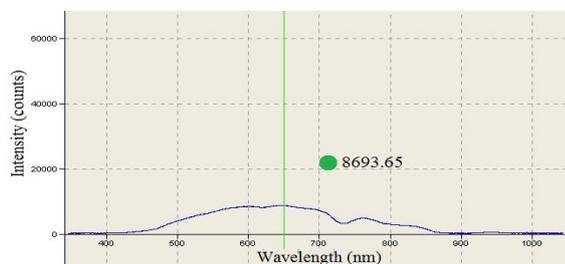


Fig. 30 – Intensity for a 1kg weight

Final results for applying a weight of 1 kg on the set up shows how much the performance of the optical fiber can

be influenced by the microbending phenomenon. The transmission loss when applying 1 kg has dropped to 12 % and the intensity under 10 thousand counts. We can conclude from these experiments how sensitive the optical fibers are when applying pressure on them and also their high performance.

## V. CONCLUSION

In this paper, we demonstrated how much the optical power on the optical fiber is affected when applying a pressure on its core but also, we demonstrated the high sensitivity of the fiber optic based measuring devices.

Analyzing the results of the simulations, the occurrence of a microbend on the fibers core will result in loss of optical power proportional with the size of the microbend. Also we have shown the modifications of the polarization state.

Analyzing the experimental results, we observed how the intensity and optical power transmission on the fiber optic decreases with the different weights applied.

Both the results from the simulations and the experiments show us the performance capability of the optical fibers. The high sensitivity of the fiber optics is ideal for realizing a pressure type sensor and many more.

The applicability of such a pressure sensor is rather wide, for example, but not limited to, in the civil engineering field to monitor the outer or inner pressure on structures (building) integrity.

## VI. ACKNOWLEDGMENT

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