International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 11, November-2015

Two Dimensional Modeling of a Simple Fiber Optic Refractive Index Sensor using Finite Element Method (FEM)

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***Abstract*— Fiber optics are optical devices that are used in different areas in a large range of applications. The aim of this work is to show a model using Comsol Multiphysics® platform of a very simple fiber optic refractive index sensor that can be used as basis for the developing of different fiber optics sensors.**

***Keywords* — Fiber Optics; Fresnel Coeficcients; Refractive Index**

I. INTRODUCTION

Fiber optics [1,2] are optical devices usually made with silica (can be also made using plastic) that are used to guide light between two places. Nowadays these devices are largely used in many different areas. Due to advantages like possibility of remote sensing, low optical losses, immunity to radiofrequencies and low cost, fiber optics is a powerful tool used in telecommunications, industry and sensing (which is the focus of this work) for example. Specifically in the sensing area there are a huge number of applications e.g. to diagnose deseases [3], to monitor pressure [4,5], strain [6] and temperature [7,8] among others. Depending on the application it is necessary to modify one or more characteristic of the fiber optics to make it sensible to a quantity [9].

This work shows a simulation of simple fiber optic refractive index sensor that uses the Fresnel reflectance and transmittance coefficients [10] to measure the refractive index of the medium that is surrounding the fiber endface. This model can be used as basis for the development of other fiber optics based sensors.

The operation of this sensor is based on the change of the values of the Fresnel reflectance and transmittance coefficients caused by the variation of the refractive index of the external medium where the fiber endface is inserted. When light (that is considered here as a plane wave) propagates from a medium with refractive index (RI) equal to n_1 to a medium with RI equal to n_2 the incident wave is partially reflected in the interface between the two media and partially transmitted along the external medium. In according to the Fresnel Equations [8] the s-polarized (i.e. when the electric field is perpendicular to the plane of incidence) coefficients, r_s and t_s, and p-polarized (i.e. when the electric field is parallel to the plane of incidence), r_p and t_p are given by:

$$r_s = (n_1\cos\theta_i - n_2\cos\theta_t)*(n_1\cos\theta_i + n_2\cos\theta_t)^{-1} \quad (1)$$
$$t_s = (2n_1\cos\theta_i)*(n_1\cos\theta_i + n_2\cos\theta_t)^{-1} \quad (2)$$
$$r_p = (n_2\cos\theta_i - n_1\cos\theta_t)*(n_2\cos\theta_i + n_1\cos\theta_t)^{-1} \quad (3)$$
$$t_s = (2n_2\cos\theta_i)*(n_2\cos\theta_i + n_1\cos\theta_t)^{-1} \quad (4)$$

where θ_i and θ_t are the incidence and transmission angles respectively, n_1 is the refractive index of the incident medium (core of the fiber) and n_2 is the refractive index of the transmission medium (external medium). The reflectance R and transmittance T are given by:

$$R = r^2 \quad (5)$$
$$T = t^2 \quad (6)$$

Taking into account that the absorbances of the media are very low one can write that:

$$R+T = 1 \quad (7)$$

In the case of the model shown in this work the change of the values of R and T are due to the change in the RI of the external medium, $n_{2.}$

II. THE MODEL

The physics behind the numerical model shown here is based on the Comsol Multiphysics® solution for the electromagnetic wave problem. The implementation of this model consists in a singlemode (SM) optical fiber with a 5μm core and external diameter equal to 125μm that is inserted in principle in an external medium which refractive index varies between 1.0 and 2.0 (figure 1). The refractive index of the cladding and the core of the fiber are n_{core}=1.4682 and $n_{cladding}$=1.4615 resulting in a numerical aperture NA=0.14. A dense two-dimensional mesh is established over whole system and the problem solved in x and y-axis is wave equation as described below [11]:

$$\nabla\times(\mu_r)^{-1}(\nabla\times\mathbf{E}) - (\kappa_0)^2\varepsilon_r\,\mathbf{E} = 0 \quad (8)$$

where μ_r is the relative permeability, **E** is the electric field, κ_0 is the wavenumber, ε_r is the relative permittivity and ε_0 is the vaccum permittivity.

To solve this problem some boundary conditions shall be adopted: (1) the external medium extends to the infinity in all directions; (2) the field is initially zero in all directions and then it is seted up to be y-axis linear polarized; (3) the size of the mesh shall be a fraction of the wavelength.

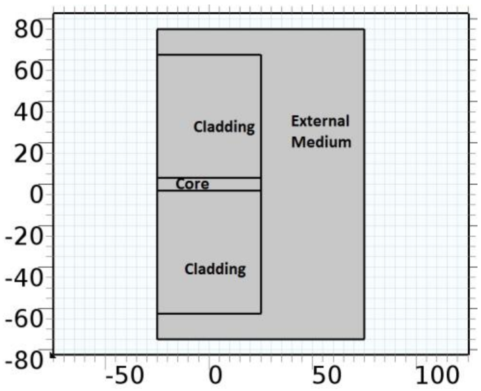

Fig. 1. Geometry of the system used in the simulation.

Here the light will propagate along the core of the fiber, from the left to the right, and until the core-external medium interface. When the light reaches this point it is partially reflected back to the core of the fiber and partially transmitted to the external medium. The incident electric field has the form:

$$\mathbf{E} = \mathbf{E_y}\, e^{-ikx} \tag{9}$$

Furthermore, the model is solved for different external refractive index that varies from 1.0 to 2.0 in steps of 0.05. This is interesting because this is the range that embraces substances like air, water, alcohol and many different gases for instance.

The mesh used here produced 2547688 triangular elements and after all conditions described above are attended, the simulations produced the results shown in the next section.

III. RESULTS AND DISCUSSIONS

The first interesting information that we can take from this model is how the light is transmitted from the core of the fiber to the external medium. If n_2 is smaller than n_1 then the interface acts as a negative lens (θ_i smaller than θ_t), diverging the incident rays as shown in figure 2. If $n_1 = n_2$ then the incident rays are not deflected passing straight through the interface (figure 3). Finally, if n_2 is higher than n_1 then the rays are deflected with θ_t smaller than θ_i i.e. the interface acts as a positive lens converging the rays as one can see in figure 4. The relation between θ_t and θ_i is given by the Snell's Law:

$$n_1 \sin \theta_i = n_2 \sin \theta_t \tag{10}$$

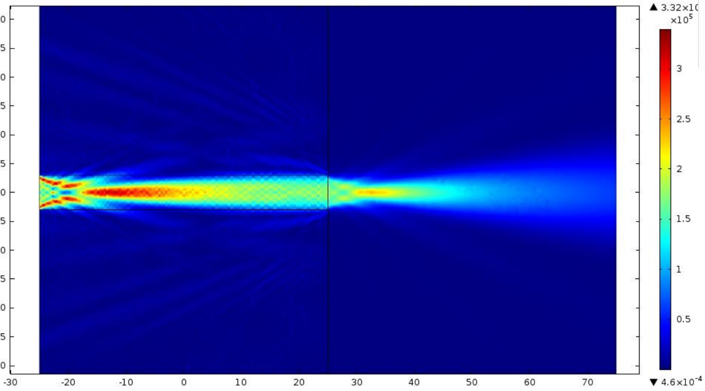

Fig. 2. Intensity of light in the system when $n_1 > n_2$. Here $n_1 = 1.468$ and $n_2 = 1.000$.

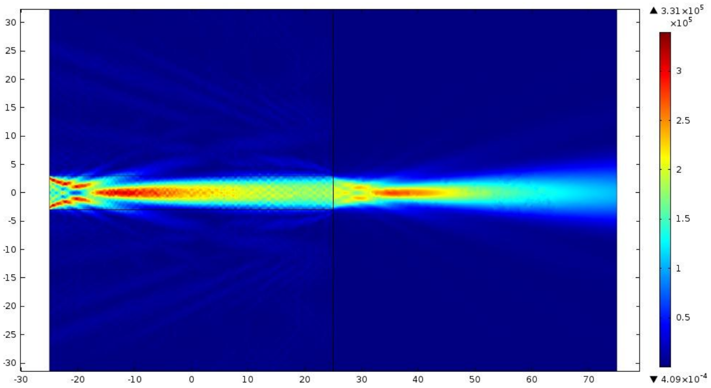

Fig. 3. Intensity of light in the system when $n_1 = n_2$. Here $n_1 = n_2 = 1.468$.

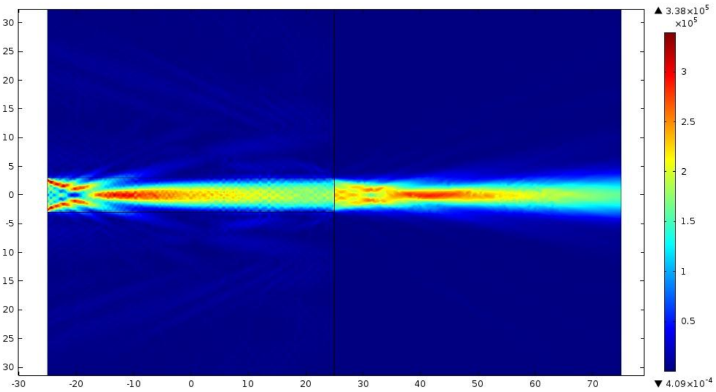

Fig. 4. Intensity of light in the system when $n_1 < n_2$. Here $n_1 = 1.468$ and $n_2 = 2.000$.

However not all incident light is transmitted from the fiber to the external medium. A fraction of the incident light is reflected back to the core of the fiber. The amount of the initial power of the light that is either transmitted or reflected to the fiber depends on the refractive index of the external medium as shown in figures 5 and 6.

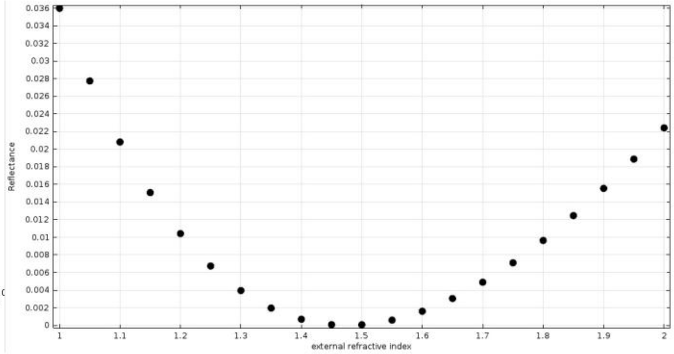

Fig. 5. Variation of the reflectance of the light in the core-external medium interface with the refractive index of external medium.

It is possible to see that both reflectance and transmittance dependence on the external medium show a parabolic-like behavior. Furthermore, one can observe that when the refractive index of external medium has the same value of the refractive index of the core of the fiber no light is reflected. In other words, it means that in the light perspective there is no change of propagation medium. After that the transmittance decreases while the reflectance increases again.

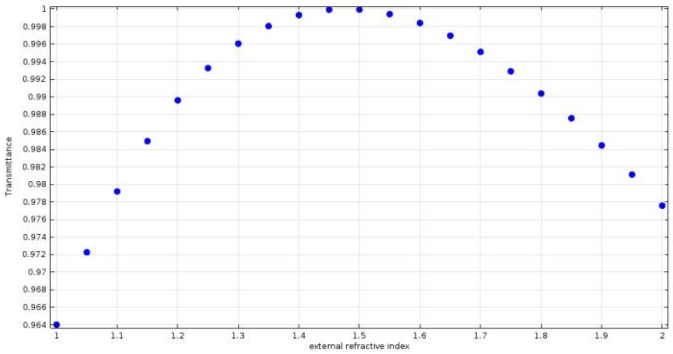

Fig. 6. Variation of the transmittance of the light in the core-external medium interface with the refractive index of external medium.

As an example of specific application of this model one can use it to simulate a sensor to monitor the temperature of water. Bashkatov and Genina [12] studied the dependence of the refractive index of water (n_{WATER}) on the temperature for different wavelengths (λ), i.e. showing that the refractive index of water n_{WATER} is a function of λ and temperature. If λ=632 nm the dependence of n_{WATER} on temperature is shown in the figure 7:

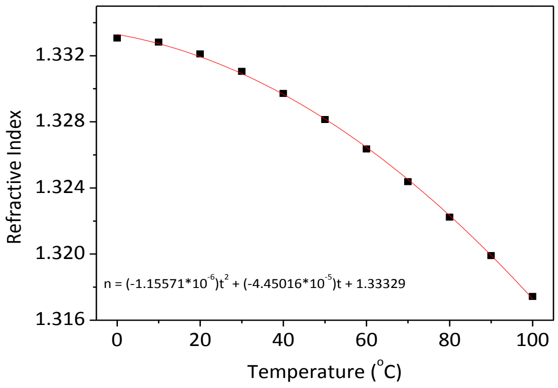

Fig. 7. Dependence on temperature of the refractive index of water[12].

It is possible to observe that the dependence of n_{WATER} on the temperature (t) of water when λ=632 nm (it was chosen because it is the wavelength of He-Ne laser) can be described by a parabola which function is:

$$n_{WATER} = 1.33329 - 4.45016*10^{-5}\, t - 1.15571*10^{-6}\, t^2 \quad (11)$$

To show that the purposed model can be used to simulate a temperature sensor the value of n_2 is made equal to n_{WATER} given by equation 11. Figures 8 and 9 show the reflectance and transmittance of the light in the interface core-water in different temperatures respectively:

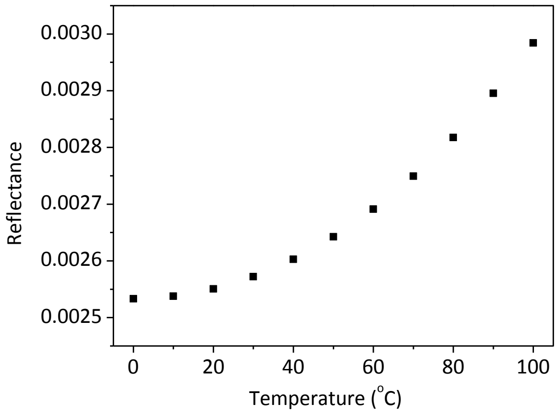

Fig. 8. Reflectance of light in the core of fiber-water interface versus temperature of water.

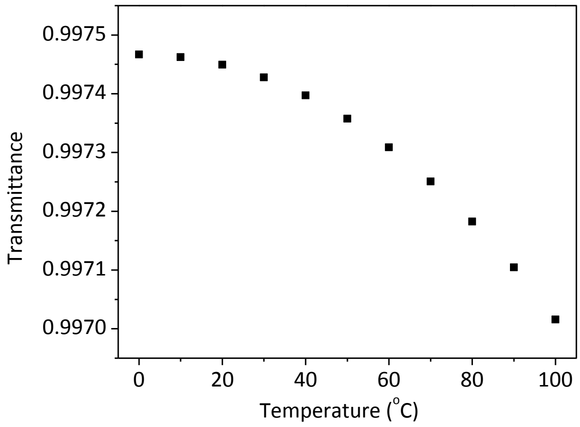

Fig. 9. Transmittance of light in the core of fiber-water interface versus temperature of water.

Figures 8 shows that the amount of light that is reflected back to the fiber in the core-water interface increased 15.12% when the temperature of water grows from 0°C to 100°C (consequently the transmittance of light decreased as shown in figure 9). If the source of light has enough intensity (some tens of miliwatts) 15.12% of increase in the intensity of reflected light is easily measured by a detector e.g. an InGaAs photodetector, a power meter or a spectrum analyzer.

IV. CONCLUSIONS

In this work we purposed a very simple fiber optic refractive index sensor built using the finite elements method (FEM) of Comsol Multiphysics® platform that is based on the difference in the amount of light that is reflected and/or transmitted in the core-external medium interface that can be used as basis to modelling many other fiber optics sensors. Using this model one can sense different substances, once in general different substances have different refractive indices, or perform indirect measurements of an entity (e.g. temperature or concentration of a solute) that causes a variation in the refractive index of a specific substance. This work showed that the purposed model is useful to identify the temperature of water once a variation of 100ºC in the temperature of water produced an increase of 15.12% for light that is reflected back to the fiber in the core-water interface.

ACKNOWLEDGMENT

Alexandre Camara thanks to Luis Pereira from Comsol and João Manoel Pereira from PUC-Rio for the discussions. Virginia Santos thanks to Martin Silva and Diego González for the discussions.

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