Sensor de Fibra Optica de Anillo Simples

Single-Loop Fiber Optic Sensor

Edmundo A. Soares and Tarcisio M. Dantas

Departamento de Engenharia Telecomunicações,UFF
Rua Passos da Patria,156-24210-Niteroi-RJ-Brasil

## ABSTRACT

In this paper is presented a fiber optic temperature sensor based on the principle of the variation of the index of refraction of a liquid with temperature. The sensor is built by replacing a small region of the clad by a material possessing an index of refraction highly sensitive to temperature. This region will be the sensor probe and the variation of the index of refraction leads to losses that modulate the transmitted optical power bringing information about the temperature.This intensity type sensor can work in several ranges of temperature depending on the particular liquid used.

The experimental results are described and a theoretical model is proposed that explains fairly well the behaviour of the sensor.

## 1. INTRODUCTION

The measurement and the control of temperature play a dominant role in every area of activity of scientific and technological research as well as industrial applications. Depending on the parameters, there are several methods that can be used by taking into account the range to be measured, the desired accuracy, the environment, the transmission of the information to a monitoring point, and other related variables.

Optical fiber sensors are among the most important non conventional methods for temperature measurement due to their immunity to electromagnetic interference, large sensitivity, geometrical versatility, high data transmission capacity and large bandwidth. Most of all, these sensors present a high resolution due to the fact that very small external perturbations lead to pronounced changes in phase, polarization or intensity of the propagating light in the fiber and these changes can be seen as a variation of the optical output power.These characteristics made possible the construction of a large number of sensors using different temperature dependent physical principles [1,2,3] such as absorption and emission, variation of the index of refraction, luminescence, birefringence, etc. The main difficulty relies on the fact that almost every

physical parameter is temperature dependent and so it is necessary to design a system which is capable of separating different effects as well as showing high resolution, linearity, accuracy and high dynamic range.

To measure the temperature continuously, the material replacing the clad must present a large variation of the index of refraction with temperature. Mineral oils are the best suited materials for this application since they have low volatility and low degradation rate as compared to other products. The sensor is built by decladding part of the fiber and substituting an oil for the clad. This region is then encapsulated by using a glass tube and it will constitute the sensor probe. More recently it was used a polymer fiber [4] showing the property of absorbing the oil and then simplifying the task of building the sensor. This kind of fiber also allows a more compact and reliable mounting as compared to the used PCS fiber, since the latter has to be decladded and then becomes fragile requiring a very special care in handling. The former can be twisted very easily to make a loop inside the glass tube.

## 2.DEVELOPMENT OF THE SENSOR AND EXPERIMENTAL RESULTS

It is used a PCS fiber having a nucleus diameter of about 400 micron and the decladded region is about 1 cm long [5]. The choice of the oil depends on the range of temperature to be measured. In this case several kinds of oils were used to cover the range from 20ºC to 100ºC. The sensor probe is built by encapsulating the fiber and the liquid in a glass tube by taking care to lightly heat it in order to prevent the formation of bubbles. The probe is sealed with epoxy glue in both extremities. The geometry is such that the light is detected by transmission which simplifies the system since similar arrangements using reflexion techniques [6] need couplers or beam splitters that introduce instabilities and additional complications, besides turning the sensor more expensive. The experimental arrangement is shown in Fig. 1a.(Please see this figure in the last page).

The optical source is a GaAs LED model TIL 31B and the detector is its matched pair, model TIL 81B. The wavelength of operation is 850 nm. Since this is an intensity sensor, it needs a reference signal that is compared to the reading in the output detector. This usual procedure avoids errors in the calibration originating from the variation of the source power or normal changes due to aging of the components. The electronics is simple, having only drive circuits for the LED and amplification ones for the detector. The simplicity of the electronics comes from the choice of DC detection that can be done in virtue of the large power of light obtained, large enough for the present purposes.

The sensor probe is immersed in a thermal bath and the temperature is changed by means of a resistor placed inside the bath. The temperature is measured independently by means of a thermocouple. The whole system is insulated from the environment by placing it inside a styrofoam box which insures a large thermal constant and good stability of temperature.

In Fig. 1b are shown the results of the reading in the output detector for two kinds of oils. The optimum region of work for oil 1 is between 65ºC and 77ºC and for oil 2 is between 50ºC and 70ºC. The choice of these regions insure good linearity and sensitivity [6].The stability of the system is tested by

repeating the same measurements in different days. For both oils, the maximum variation is 0.5% within intervals of three days showing a very good stability.

## 3. THEORETICAL MODEL

The theoretical model proposes to explain the behaviour of the sensor in the region where the index of refraction of the liquid is smaller than the index of refration of the core which is the region of operation of the sensor.

It is a very simple model assuming a planar dielectric waveguide (slab) with a small region where the index of refraction of the "clad" is different from the remaining "clad" and the index of refraction of the core is constant, as shown in Fig. 2.

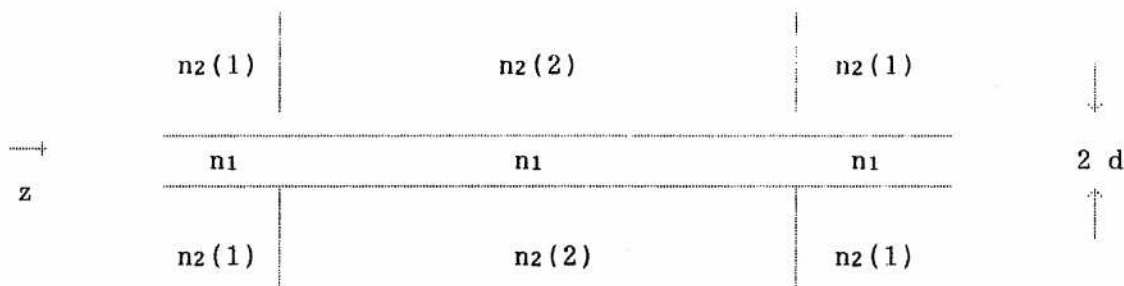|  $n_2(1)$ | $n_2(2)$ | $n_2(1)$ | |
|---|---|---|---|
| $n_1$ | $n_1$ | $n_1$ | 2 d |
| $n_2(1)$ | $n_2(2)$ | $n_2(1)$ | |

z

Figure 2 Ideal slab representing a first approximation of the sensor

It is always possible to choose the geometry and the wavelength in such a way that the structure is monomode as far as guided modes are concerned and this is the initial assumption of the present model. This is justified since it was observed that the shape of the curve is not a pronounced function of the wavelength, but on the other hand the number of guided modes is strongly dependent on the wavelength. If the curve does not change significantly with the wavelength, then it is not a function of the number of modes and the assumption of a monomode structure is reasonable.

One also knows that in a dielectric waveguide the solution of the wave equation leads to guided modes with discrete propagation constants as well as to radiation modes with continuous propagation constants. So, even assuming a monomode structure, there will be radiation modes as soon as the guided mode reaches the boundary and the power will be distributed between the guided and the radiation modes. Taking into account the transmitted and reflected guided and radiation modes it is possible to build a system of integral equations [7,8] after imposing the boundary conditions of the continuity of the tangential components of the fields. The approximate solution of this system leads to the coefficient of transmission of power which describes the response of the sensor. The extension of this model to a real optical fiber is imediate with only an increasing in the mathematical complexity since the fiber is nothing else than a cylindrical dielectric waveguide. The solution of the problem for the fiber leads to reasonable results showing that the proposed model is acceptable allowing a more solid description of the system by

understanding the way the several parameters behave in the final response of the sensor.

The theory for the slab will be shown first and afterwards it will be developped the theory for the fiber and compared to the experimental results.

Assuming only one TE$_0$ mode traveling from left to right, the continuity of the tangential components of the fields in the first boundary leads to the following equations:

$$E_y^{(i)} + a_r E_y^{(r)} = c_t E_y^{(t)} + \int_0^\infty q^{(t)}(p) E_y^{(t)}(p) \, dp \tag{1}$$

$$H_x^{(i)} + a_r H_x^{(r)} = c_t H_x^{(t)} + \int_0^\infty q^{(t)}(p) H_x^{(t)}(p) \, dp \tag{2}$$

In the above equations, the superscripts i, r and t stand for incident, reflected and transmitted respectively. The field components inside the integral are radiation modes and the other ones are guided modes. The parameters $a_r$ and $c_t$ are related to the reflected and transmitted guided mode respectively. Assuming that the incident power is unity, then $[a_r]^2$ and $[c_t]^2$ are the amount of power contained in the reflected and the transmitted guided modes, respectively. $c_t$ and $a_r$ can be calculated by using equations (1) and (2) and the orthogonality of the modes in the same waveguide section leading to the following equations:

$$c_t = [(2 \beta_1 \beta_2)/(\beta_1 + \beta_2)(\omega \mu)] . \int_0^\infty E_y^{(i)} E_y^{*(t)} \, dx \tag{3}$$

$$a_r = (\beta_1 - \beta_2)/(\beta_1 + \beta_2) \tag{4}$$

where $\beta_1$ is the propagation constant for the left and right regions and $\beta_2$ for the central region of the slab.

The reflected guided modes were neglected since it was assumed, in first approximation, that all the radiation occurs in the forward direction. This is justified because the indices of refraction are not much different.

Assuming that the uncladded region is large enough so that all the power carried by the radiation modes does not reach the second boundary, one only needs to calculate the power transmission for the guided mode in the first boundary and this will be given by $[c_t]^2$. This power will reach the second boundary and will give origin to one guided and radiation modes. The power carried by these modes is expressed as $[1-a_r^2]$ where $a_r$ is calculated on the second boundary. The total power $P_s$ reaching the detector can be written as

$$P_s = [c_t]^2 . [1-a_r^2] . \tag{5}$$

The results are shown in Figure 3 (see last page) where it is plotted $P_s$ as

a function of temperature and index of refraction for a given oil with known index of refraction $n_2$ and $dn_2/dT$.

, The above results can be extended for the real optical fiber by using the same method. The integral equations for the boundary are more complicated due to the fact that they are written in cylindrical coordinates:

$$E_r^{(i)} + a_r\, E_r^{(r)} = c_t\, E_r^{(t)} + \int_0^\infty [q^{(t)}(p)\, E_{r1}^{(t)}(p) + m^{(t)}(p)E_{r2}^{(t)}(p)]dp \quad (6)$$

$$E_\varphi^{(i)} + a_r\, E_\varphi^{(r)} = c_t\, E_\varphi^{(t)} + \int_0^\infty [q^{(t)}(p)E_{\varphi1}^{(t)}(p) + m^{(t)}(p)E_{\varphi2}^{(t)}(p)]dp \quad (7)$$

Two more similar equations can be written by replacing E by H in equations (6) and (7). By using the same procedure as for the slab, it can be shown that:

$$c_t = 2\, I_1\, I_2\, /\, (\, I_1 + I_2\, ) \qquad (8)$$

$$a_r = (\, I_1 - I_2\, )/\, (\, I_1 + I_2\, ) \qquad (9)$$

where

$$I_1 = \int_S [E_r^{(i)}\, H_\varphi^{*(t)} - E_\varphi^{(i)}\, H_r^{*(t)}]\, dS \qquad (10)$$

$$I_2 = \int_S [H_\varphi^{(i)}\, E_r^{*(t)} - H_r^{(i)}\, E_\varphi^{*(t)}]\, dS \qquad (11)$$

The total coefficient of transmission of power $P_f$ is also plotted in Figure 3.

## 4. DISCUSSION AND CONCLUSIONS

The results obtained agree very well with the experimental ones moreover if it is taken into account that was used a simple model as compared to more elaborated theories [9,10].

The experiment was made with a multimode PCS fiber, the decladded region is not infinite and there were some unavoidable variations of power and temperature during the measurements.

The approximation of neglecting the reflected radiated power is very good only near the region where the indices of refraction of the clads are nearly equal. Some of the power scattered in the first boundary reaches the second one and this was not taken into account. Besides, the model assumes a monomode structure. These simplifications in the model shall lead to a smaller transmission of power and this can be easily seen in Figure 3, where it is
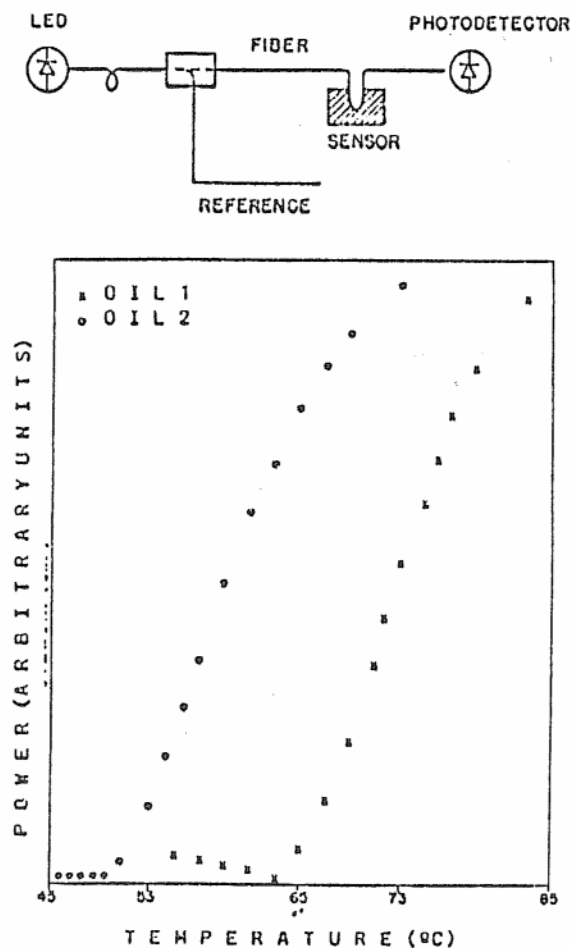
Figure 1 a)Diagram of the experimental
mounting
b)Output power as a function of
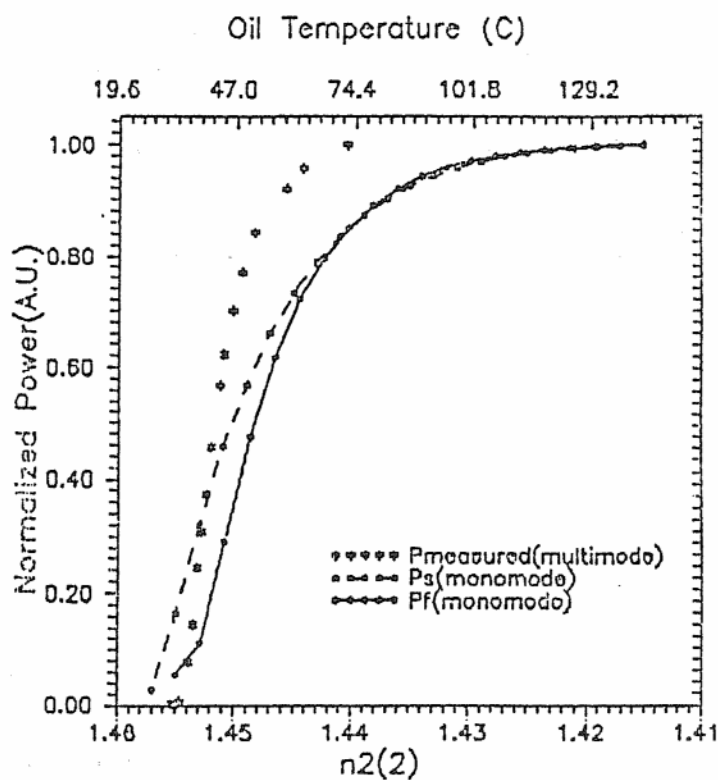temperature for oil1 and oil2



Figure 3
Measured power and results of theory
for the slab (P$_s$) and fiber (P$_f$) as a
function of the index of refraction of
the oil and temperature.The results are
normalized.

shown the normalized experimental result as compared to the results obtained by this model in a slab and in a fiber.

`The theory works to predict the behaviour of the sensor as a function of several parameters and it can be used as a tool in the design of the sensor for different oils, kinds of fiber and ranges of temperature.

## 5. ACKNOWLEDGMENTS

## 6. REFERENCES

1. Giallorenzi, T.G. et al, "Optical Fiber Sensor Technology", IEEE J.Quant.Electr.QE-18, 626, (1982)

2. Giallorenzi, T.G. et al, "Optical Fiber Sensors Challenge the Competition", IEEE Spectrum, September, 44, (1986)

3. Valente, L.C.G. and Soares, E.A., "Temperature Measurement Utilizing Amorphous Hydrogenated Silicon Films", in Fiber Optic and Laser Sensors V, R. P. de Paula and E. Udd, Editors, Proc. SPIE 838, 247, (1987)

4. E.A. Soares and T.M. Dantas, "Simple Theory for a Temperature Sensor", in Fiber Optic and Laser Sensors X, R. P. de Paula and E. Udd, Editors, Proc. SPIE (1992)(In press).

5. E.A. Soares and T.M. Dantas, "Bare Fiber Temperature Sensor", in Fiber Optic and Laser Sensors VIII, R. P. de Paula and E. Udd, Editors, Proc. SPIE 1367, pp. 261-265, 1990.

6. Scheggi, A.M. et al, "Optical Fiber Thermometer for Medical Use", Proc.of the First International Conf.on Optical Fibre Sensors, London, 13, (1983)

7. D. Marcuse, "Radiation Losses of Tapered Dielectric Slab Waveguides", in Bell System Technical Journal, pp. 273-290, 1970.

8. D. Marcuse, "Radiation Losses of the Dominant Mode in Round Dielectric Waveguides", in Bell System Technical Journal, pp. 1665-1693, 1970.

9. B. Rulf, "Discontinuity Radiation in Surface Waveguides", in Journal of the Optical Society of America, pp. 1248-1252, 1975.

10. N. Morita, "A Rigorous Analytical Solution to Abrupt Dielectric Waveguide Discontinuities", in IEEE Trans. on Microwave Theory and Techniques, Vol. 39, no. 8, pp. 1272-1278, 1991.