Refractometric Sensor Based on Induced Losses in the Region of Transition from a Curved Side-Polished POF Fiber

M. Lomer*, C.A. Galindez, M.A. Quintela, A. Quintela, J. Mirapeix, J.M. Lopez-Higuera
Photonics Engineering Group, Universidad de Cantabria, Av. Castros s/n, Santander E39005, Spain

ABSTRACT

A refractometric sensor that uses the transition region of a U-bent Plastic Optical Fiber (POF) when it is polished laterally is presented. By polishing a lateral segment of the fiber, a part of the plastic optical fiber core is removed and an elliptical surface is formed on the bend. It is found that that the polishing with an angle equals to the critical angle of a straight optical fiber the sensitivity of this transducer structure is enhanced. Then, the incident light is totally reflected and the transition losses decrease locally. In addition, the sensitivity increases compared to the polishing in the region of bending losses. The proposed transducer is successfully checked with experimental measurements and different kinds of liquids. Potential applications are suggested.

Keywords: Refractometer, lateral polishing, sensor, polymer optical fiber

1. INTRODUCTION

The bending losses on optical fibers can affect the propagation conditions in optics communication systems, these losses increase when the bending radius is reduced. Although, some works have been carried out in this subject [1,2], this phenomenon can be exploited as a mechanism of transduction in optical fiber sensors. In fact, the bent region of a fiber is more sensible to the refraction index of the environment. Sensors based on bending losses haven been used to measure temperature, humidity, liquid level and some other physical parameters [3-5]. In some cases the cladding is completely removed or the fiber is covered with materials to increase its sensitivity.

In general bending losses in multimode optical fibers have two main components: transition losses and pure bending losses [6]. Transition losses are due to the conversion of the guided modes of the straight fiber in the modes of the bent fiber. The pure bending losses come from the continuous losses in the guided modes in the core associated to the cladding [7]. The most important losses are the transition ones. On the other hand, Plastic Optical Fibers (POF) are easy to handle due to their large diameter and numerical aperture; they are flexible and have a low weight. Hence the POF are attractive to develop sensors at low cost.

This paper shows a refractometric sensor based on bending losses on the transition region of a U-bent POF. Thus, a portion of cladding and core of a fiber have been removed by a lateral polishing on the bent part of the optical fiber. The lateral polishing has an angle equal to the critical angle of the straight fiber. An elliptical surface is formed on the bent region which serves as the sensing region, where the core is in contact with the environment to sense. With a maximum thickness of 0.33mm, the polishing losses have been neutralized and the sensitivity has increased. The prototype and the experimental results are hereafter shown and discussed.

2. THEORETICAL CONCEPT

Propagation conditions can be obtained from the scheme depicted in Fig. 1. Fig. 1(a) shows a U-bent fiber with R as the bending radius, Fig. 1(b) is the same as the previous fiber, but with a lateral polishing that starts at the beginning of the bend. A multimode plastic optical fiber of large diameter, stepped index and large numerical aperture is considered. In order to approach the lateral polishing effect on the U-bent fiber in the transition region only the calculus for the meridian rays are considered.

* lomer@teisa.unican.es, *Phone: +34-942-201495 Fax: +34-942-201873*

19th International Conference on Optical Fibre Sensors, edited by David Sampson, Stephen Collins, Kyunghwan Oh, Ryozo Yamauchi, Proc. of SPIE Vol. 7004, 70045H, (2008) 0277-786X/08/$18 doi: 10.1117/12.786340

In general terms, the propagation directions on a multimode fiber are limited by the critical angle in the total internal reflection between the cladding and the core, this angle is given by $\theta_c = \cos^{-1}(n_2/n_1)$, where θ_c is the complementary critical angle. If all the bound rays are launched at the input end of the straight fiber, the propagation angle of the ray (θ) vary from $\geq\theta_c$ to 90º. In the bent region of the fiber (Fig. 1a), propagation conditions change because now, the critical angle depends on the bending radius and therefore they will be different in the inner and outer interfaces. This new angle of incidence is ϕ, and the changes in the incident rays in the outer interface of the bent region are given by:

$$\phi_1 = \sin^{-1}\left[\left(\frac{R \pm \rho}{R + a}\right)\frac{n_2}{n_1}\right] \text{ and, } \phi_2 = \sin^{-1}\left[\frac{R \pm \rho}{R + a}\right] \qquad (1)$$

For the outer interface, the maximum value of ϕ_1 will correspond to the modes of high order, whilst the minimum value of ϕ_2 will correspond to the modes of lower order. Here R is the bending radius, *a* is the fiber core radius, ρ is the rays entrance height (ρ is measured from the axis of the fiber), and n_1, n_2 are core and cladding refractive indices respectively. The incident angle at the inner interface also changes, but its influence will be lower in this calculation.

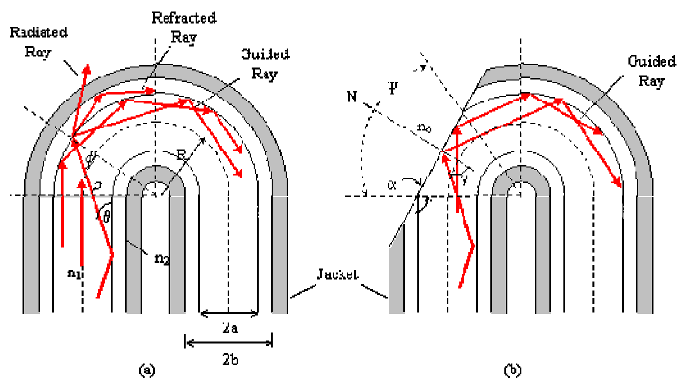


Fig. 1. Structure and operating principle of the U-shape fiber-optic refractometer and lateral polished. a) Illustration of ray guidance in a U-shape optical fiber before polishing. b) Ray guidance after polishing in region of the transition loss.

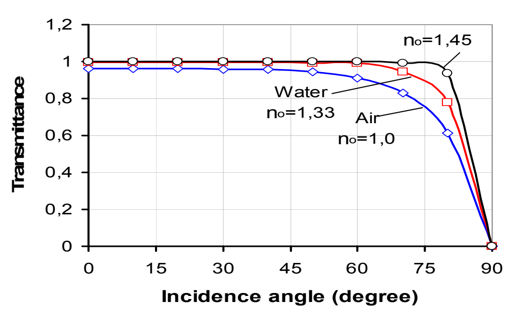


Fig. 2. Normalized Fresnel power transmission at n_o/n_1 interface as a function of the angle with the tangent at the interface in the plane of incidence for several values of n_o and with n_1=1.942.

Then a lateral polishing in the outer interface by reducing a portion of core and cladding, and having a polishing angle (α) – equal to the critical angle of a straight fiber – that coincides with the beginning of the bent region (Fig. 1b), an elliptical surface in contact with the environment can be seen. The refraction index is n_o. The incident rays in this surface n_o/n_1 have an angle γ. If the surrounding area is air (n_o=1), the light propagated by the core of a straight fiber has a smaller critical angle and the light will not depend on the bent radius. In this case the rays will be totally reflected, consequently, transition losses can be reduced. The interface n_o/n_1 is like a mirror that reflects all the incident rays, since γ is greater than the critical angle. When n_0 increases, the system will be more sensible and the losses will be greater. Hence, this interface can be used as a transductor element of a sensor. The influence in the propagation of light in a fiber respect to the outer region (interface n_o/n_1) can be estimated by using the Fresnel's relation in reflection and transmission [8]. In Fig. 2 the Fresnel power transmission is plotted as a function of the angle between the interface n_o/n_1 and the tangent at the perpendicular axis for three types of indices (with n_1=1.492). The transmittance increases when the refraction index of the outer region also increases. In typical POFs, the critical angle is around 70º. When n_o is equal to 1 (air), the interface n_o/n_1 has a lower critical angle in the region of transition. Thus, the rays that should have been refracted out of the fiber are now totally reflected into the core. When n_o increases the transmittances also increase, then the losses are greater and they will be more important when the refraction index of the environment is similar to the index of the core.

3. FABRICATION

The U-bent fibers are prepared according to the procedures cited in reference [5]. Table 1 shows the characteristics of the POF used. U-bent fiber parameters are listed in Table 2. Prototypes of head sensor have been developed by using a bent radius R=5mm. The lateral polishing angle (Fig. 1b), α chosen is equal to the critical angle of the straight fiber, i.e. , α=70º. Due to this angle, the bending angle is Ψ=40º and the maximum polishing thickness of the core is 0.33mm. The lateral polishing creates an elliptical surface of 2.7 mm^2 which is the sensing area. Figure 3 shows the transducer of the refractometer.

Table 1. Parameter of the PMMA-POF Used,

Cable POF diameter	2.00 mm
Cladding diameter (2b)	1.00 mm
Core diameter (2a)	0.98 mm
Refractive index of core	1.492
Numerical aperture	0.5
Transmission loss	0.2 dB/m

Table 2. Bent and polished fiber

Bend radius (R)	5.00 mm
Espesor eliminado de núcleo	0.33 mm
Diameter of ellipse (2y)	1.87 mm
Polished surface	2.7 mm^2
Polished angle (α)	70°
Curvature angle used (Ψ)	40°

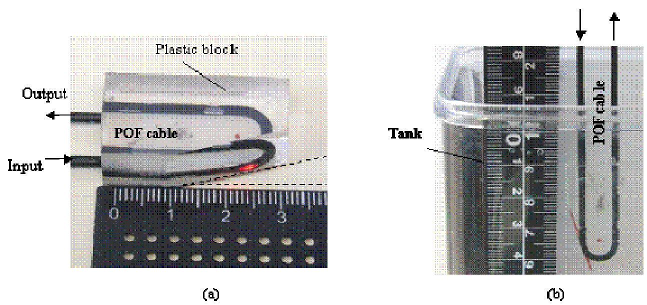


Figure 3. Head sensor base don the lateral polishing of the transition region. a) U-Bent polished with the same critical angle of a straight fiber, b) Transductor measuring liquid level in a tank.

4. EXPERIMENTAL RESULTS AND ITS DISCUSSION

Prototypes of the head sensors developed have been proved experimentally with different kinds of liquids. The experimental set-up is shown in Fig. 4. A He-Ne laser (λ=632.8 nm) has been used as light source. Light is coupled into the fiber with a modulation frequency of 270 Hz. Thus the modulated signal is higher than the background noise of the receiver. The signal from the sensor was detected by using an optical power meter which allows the detection at this modulation frequency.

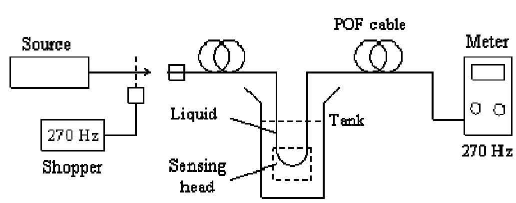
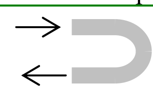
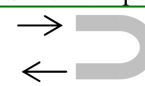
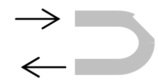


Fig. 4. Experimental setup for the power loss measurement with different liquids

In table 3 the measures of power losses obtain through experimentation can be observed. First, losses have been measured in a POF cable of a length of 2 m, then the bending losses by placing the fiber into a plexiglass cube with a constant bending radius of (R= 5mm) as shown in Fig.3. To compare the power losses in two different regions of the U-bent fiber, a head sensor with a symmetric polish was used (same polishing thickness = 0.33mm). Since the affected region has a bending angle of $\Psi>70^{o}$, then it can be stated that these losses correspond to the pure bending losses region. Therefore, variations of light in relation to the environment will be weaker than those of the region of transition losses which has an exponential variation. When the surrounding area is air, losses in the symmetric polish increase by 2.19 dB, while those in the asymmetric polish are closer to the fiber losses of the non polished fiber.

Table 3.Measurements of power losses obtain through experimentation usign a U-bent fiber with symetric and asymetric polish for different kinds of liquid.

	U-Bent shape	Simetrical polishing	Asymetric Polishing
			
Air (n_o=1.0)	7.80 ±0.02 dB	9.99 ±0.02 dB	7.98 ±0.01 dB
Water (n_o=1.33)		9.82 ±0.02	8.2 ±0.01
Olive Oil (n_o=1.467)		13.06 ±0.02	15.12 ±0.01
Index liquid (n_o=1.476)		17.27 ±0.02	22.99 ±0.01

5. CONCLUSIONS

An enhanced sensitivity refractometric sensor based on the transition losses region of a U-bent POF is presented in this paper. In this region, a portion of the cladding and core have been removed through mechanical polish taking as a reference different angles with respect to the straight fiber. Consequently, transition losses are reduced and the tranductor sensitivity increases when the angle equals to the critical angle. Experimental results show accuracy with those obtained in the theoretical approaches. Preliminary experimental results of several types of liquids and different refraction indices demonstrate high sensitivity when the index of the outer region increases. This transductor can be adapted to multipoint or quasi-distributed liquid level measures to be used in the food and beverage industry or to measure other parameters such as temperature, humidity, pressure, etc. In addition specific layer depositions on the polished surface with this angle can be used for other kind of POF based transducers.

ACKNOWLEDGMENT

The authors acknowledge the Spanish government for supporting this work through the TEC2004-05936-C02 and TEC2007-67987-CO2-01 projects.

REFERENCES

[1] D. Marcuse, "Curvature loss formula for optical fiber" *J. Opt. Soc. Am.* **66**, pp. 216-220, 1976.

[2] J. Arrue, J, Zubia, "Analysis of the decrease in attenuation achived by properly bending plastic optical fibres", IEE. Proc. Optoelectron., **143**, pp. 135-138, 1996.

[3] M. Remouche, R. Mokdad, A. Chakari, P. Meyrueis, "Intrinsic integrated optical temperature sensor based on waveguide bend loss", *Opt., Laser Technol.,* **39**, 1454-1460, 2007.

[4] S.K. Khijwania, K.L. Srinivasan, J.P. Singh, An evanescent-wave optical fiber relative humidity sensor with enhanced sensitivity", *Sen. Actuactor B*, **104**, 217-222, 2005.

[5] M. Lomer, J. Arrue, C. Jauregui, J. Zubia, J.M. Lopez-Higuera , "Lateral polishing of bend in plastic optical fibres applied to a multipoint liquid-level measurement sensor", *Sens. Actuators A,* **137**, 68-73 (2007).

[6] A.H. Badar, T.S.M. Maclean, "Transition and pure bending losses in multimode and single-mode bent optical fibres", IEE Proceeding-J, **138**, 261-268, 1991.

[7] A.W. Snyder and J.D. Love, Optical waveguide theory, (Chapman and Hall, 1983).

[8] M. Born and E. Wolf *Principles of Optics,* Chap. XIV, Cambridge, 1999.