Available online at www.sciencedirect.com
ScienceDirect
Sensors and Actuators A 137 (2007) 68–73
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

# Lateral polishing of bends in plastic optical fibres applied to a multipoint liquid-level measurement sensor

M. Lomer[a,*], J. Arrue[b], C. Jauregui[a], P. Aiestaran[b], J. Zubia[b], J.M. López-Higuera[a]

[a] *Photonics Engineering Group, University of Cantabria, Avda Los Castros s/n, Santander E39005, Spain*
[b] *ETSI of Bilbao, University of the Basque Country, Alda. Urquijo s/n, Bilbao E-48013, Spain*

Received 20 June 2006; received in revised form 15 December 2006; accepted 24 February 2007
Available online 12 March 2007

---

## Abstract

A new liquid-level sensor with a multipoint layout is presented, which is based on power loss arising in laterally polished bent sections prepared along a plastic optical fibre. The polishing is applied to the fibre surface on top of several U-shaped bends until part of the core is also removed. The resultant bare flat area on the core is an elliptic surface in direct contact with the medium surrounding the fibre. Any variation in the optical and geometric parameters characterising our multimode fibre is analysed, since it will cause changes in the propagation of light along the polished bends. Experimental results included in the paper correspond to the prototype for our sensor, which consists of eight sensing probes placed sequentially along the fibre, in combination with an optoelectronic unit working as a liquid-level transducer.
© 2007 Elsevier B.V. All rights reserved.

*Keywords:* Fibre-optical sensor; Polymer optical fibre; Liquid-level; U-shaped probe

---

## 1. Introduction

When an optical fibre is bent, light power is attenuated due to radiation loss along the bend. This loss depends on the characteristics of the fibre, on the curvature radius and on the external medium in contact with the bent section. The resultant increase in attenuation is a problem for optical telecommunications, but it may be useful in fibre-optical sensing technology. In effect, bending losses constitute the basis of many optical sensors, due to the great sensitivity achieved to detect variations in the surrounding medium. Numerous sensors of this type have been carried out for the measurement of acoustic waves [1], breathing [2], liquid refractive index [3,4], angular motion in robot arms [5], humidity [6–8] and displacement [9]. In general, the optical fibre employed is either a glass one or a plastic one (POF). For low-cost sensing systems, POFs are especially advantageous due to their excellent flexibility, easy manipulation, great numerical aperture, large diameter, and the fact that plastic is able to withstand smaller bend radii than glass. Besides, POFs are suitable for short-distance data transmission in any environment such as industrial ones [10].

Measurement of liquid level has traditionally attracted a great interest, giving rise to the development of numerous set-ups based on different principles, such as radiation loss. Accordingly, numerous studies have been carried out to determine power loss caused by bent sections in single-mode [11,12] and in multimode fibres [13–19]. The former fibre type requires application of electromagnetic modal theory and adoption of simplified approaches. In the case of multimode fibres, if the fibre radius is large enough, modal theory can be replaced by geometric optics, obtaining a good approximation to the exact results.

In this paper, we present a multipoint measurement method for the determination of liquid level, on the basis of radiation loss in a laterally polished bent multimode step-index POF. The advantage of using POFs is that the properties of POFs that have increased their popularity and competitiveness for telecommunications are exactly those that are important for optical sensors based on optical fibres [10]. Moreover, optical sensors, such as the liquid-level sensor analysed in this paper, can be employed in dangerous environments, where sparking must be avoided [4]. Because of the advantages of optical sensors, POF sensors

---

* Corresponding author. Tel.: +34 942 201495; fax: +34 942 201873.
*E-mail address:* lomer@teisa.unican.es (M. Lomer).

0924-4247/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2007.02.043

of different types have already been proposed. Although techniques to achieve an enhanced interaction with measurands at the fibre's core–cladding interface, such as tapering [10], have already been proposed, an advantage of our sensor is that it is simpler to manufacture than those using tapers (reductions in the fibre diameter along a short distance). As a matter of fact, we have usually had difficulties for the fibre not to break when trying to make a taper. On the other hand, other liquid-level sensors based on total internal reflection, such as those using a 60°-angled prism, yield low extinction ratios (0.38 dB in the case of a 60°-angled prism to detect the presence of water, the extinction ratio being the difference between the attenuations obtained with and without water [4]). However, the sensor proposed in this paper yields an extinction ratio of about 0.55 dB and it is also easy to manufacture. It is based on polishing the tip of a bent POF, in such a way that part of the core is also removed and the resultant surface is in direct contact with the outer medium (liquid or air). The incidence angles of the rays are reduced due to the polishing, thus facilitating radiation loss in the bend. The chosen bend radius is 5 mm, since with a smaller one the POF could break, and with a slightly larger one there would be smaller dependence of bending losses on the outer refractive index in the presence of a finite cladding thickness [19]. Besides, high losses due to tight bends would reduce the number of sensing sections that could be employed in the same fibre, for a multilevel liquid sensor. In addition, a much larger radius would not yield significant radiation losses. Power loss is experimentally and computationally analysed as a function of the polishing depth in the bent section. In addition, the performance of a set-up with eight sensing probes in the shape of U with similar bend radii is described. Thanks to the flexibility of POFs, the possible range of liquid heights that can be measured is variable, from 1 mm to several meters, with very high accuracy and resolution. A low-cost sensor prototype using an LED and a PIN photodiode, with the corresponding optoelectronic circuit, is presented and discussed.

## 2. Principle of the sensor's performance

The basic principle of the sensor is the variation achieved in the light intensity coming out of a bent multimode optical fibre when the outer medium surrounding the bend changes, the sensitivity being greater if the bend has been previously polished, as will be explained later. Let us first consider the behaviour of a bent POF stripped of its jacket and immersed in water. In such a case, the outer refractive index is 1.333. The total attenuation in the bend can be calculated by means of the ray tracing method [11], by treating light as rays. Each one is assigned a certain amount of power at the entrance of the bend, depending on the input point and direction, in accordance to the characteristics of the light source. To illustrate the effect of the cladding, we will analyse the geometry shown in Fig. 1a. It corresponds to a typical step-index PMMA POF whose core diameter is 980 μm and the cladding thickness is 10 μm (the figure has not been plotted to scale, for the sake of clarity). Since rays refracted into the cladding at the core–cladding interface will find a step in the refractive index at the cladding–water interface, many of them will return to the core again, making the same angle $\alpha$ with the normal to the core–cladding interface as the incident ray. Moreover, the minimum angle $\alpha$ below which a ray is finally refracted into the water (critical angle $\alpha_c$) turns out to be the same as if we only had core and water, without cladding, i.e., $\alpha_c = \arcsin(n_{water}/n_{core})$. Therefore, when calculating attenuation by means of the ray tracing method, the thin transparent cladding can be omitted to a first approach, since the re-entrance point into the cladding is close to the previous exit point and the corresponding perturbation in the attenuation that this approach may cause tends to be statistically compensated when many thousands of rays are launched. On the other hand, in the presence of a jacket (Fig. 1b), any ray entering the cladding would be lost, since it would be absorbed by the black jacket, unless a thin layer of water were present between the cladding and the jacket. This hypothetical case will prove to be of interest later in this paper.

For our sensor, the bend radius is 5 mm, as discussed in the introduction from the points of view of manufacture and of radiation loss. With this radius, the attenuation is high enough for the outer refractive index to have a significant influence on bending loss [19]. Specifically, in Fig. 2 we show the attenuation for different radii of curvature in a POF stripped of its jacket, which has been bent in the shape of a U and polished on top of the bend. Attenuation is plotted as a function of the polishing depth from

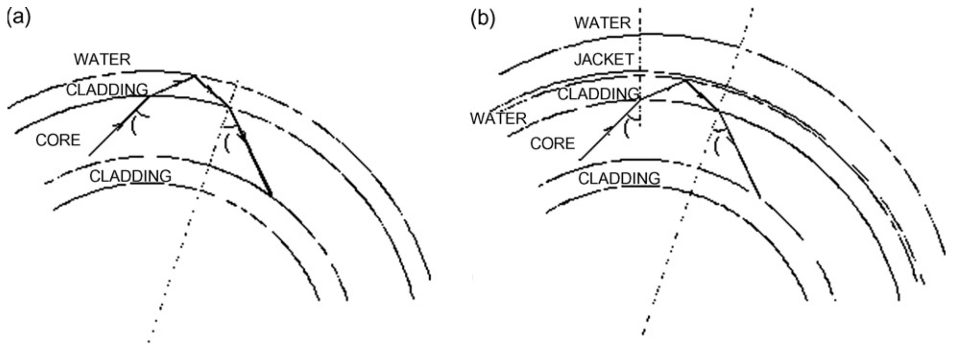

Fig. 1. (a) A ray reflected at the cladding–water interface re-enters the core at the same angle $\alpha$ as the incidence angle at the core–cladding interface; for refraction to occur towards the water: $\alpha \le \alpha_c = \arcsin(n_{water}/n_{core})$. (b) In jacketed fibres, a hypothetical presence of a thin layer of water between the cladding and the jacket would lead to similar radiation losses as in (a), since the black jacket hardly reflects light.

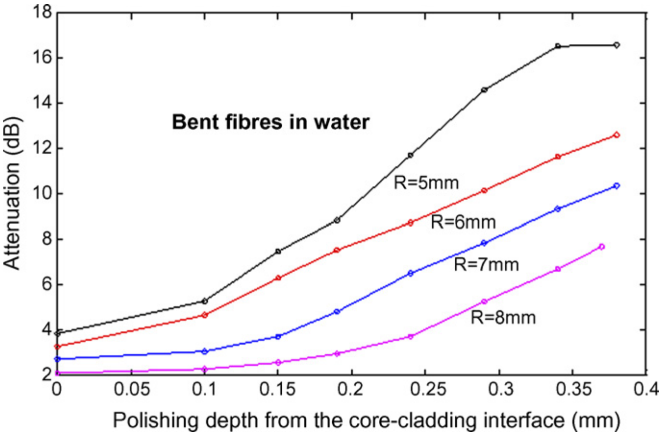

Fig. 2. Attenuation for different radii of curvature in a POF stripped of its jacket and immersed in water. The POF has been bent in the shape of a U and polished on top of the bend.

the core–cladding interface. This figure corresponds to a typical 1 mm diameter 0.5 numerical-aperture step-index PMMA POF, whose core refractive index is 1.492, when immersed in water. It has been computationally calculated by means of the ray tracing method, employing the approach for the cladding described in Fig. 1a, and adopting the approximated values 1 and 0 for the Fresnel transmission coefficient below and above the critical angle respectively. The light source is a collimated beam of rays occupying the whole input surface of the bend. The bend radius $R$ refers to that of the fibre symmetry axis. In jacketed POFs the cladding is isolated from the outer medium (water or air). To a first approach, they will be computationally analysed with only two layers (core and cladding) and without considering reflections outside the cladding, except for the region in which the POF is in contact with the outer medium (water or air), in which case the two layers will be core and water or air.

Fig. 3 illustrates the polished bends that will be used for our sensor. The polishing increases the sensitivity to variations in the outer medium because it removes the jacket, so the critical angle starts to depend on the outer medium, as explained before, and also because the angle between the ray and the normal tends to diminish on the polished zone, so the power loss tends to increase. Such higher sensitivity with polishing will be confirmed experimentally in the following section.

## 3. Experimental and computational analysis

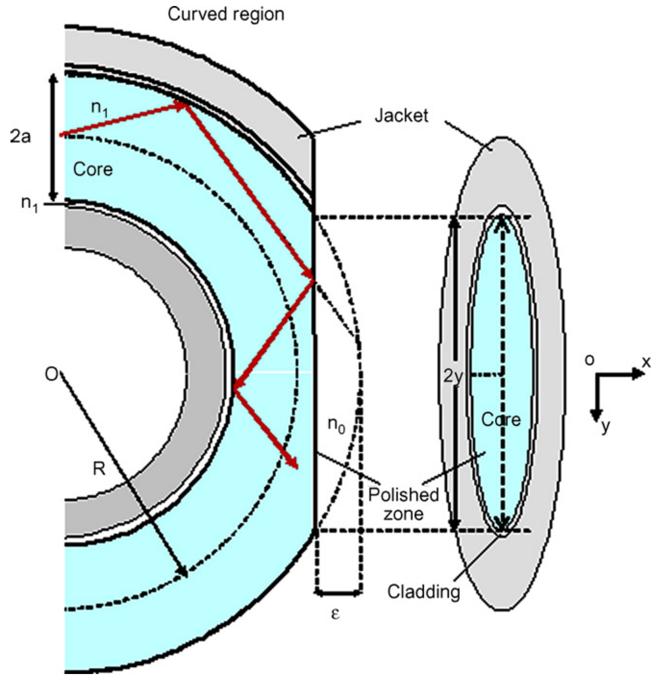

Fig. 3. Polishing of the bent optical fibre and the corresponding elliptical planar interface.

In order to hold the optical fibre with the desired bend radius, 3 mm deep grooves were etched on a Plexiglas block. The jacketed POF, which has a diameter of 2 mm, was attached to the grooves by means of a type of glue suitable for plastic, in a set-up in which the optical fibre adopted the shape of a U. Thanks to the Plexiglas block, the system becomes rigid enough to carry out a polishing process on top of the bend so as to increase the sensitivity of the sensor to changes in the outer medium. The polishing affects the jacket, the cladding and part of the core. When the U-shaped bend is laterally polished, part of the fibre core can be exposed to air, leaving a flat surface of elliptical shape. Fig. 3 shows both the polished fibre with a ray propagating inside and the top view of the elliptical surface. The polishing depth ($\varepsilon$) can be calculated as a function of the long semi-axis $y$, the bend radius $R$ and the core radius $a$, in the following way:

$$\varepsilon = (a + R) - [(a + R)^2 - y^2]^{1/2}$$

The value of $y$ is easily measured. The picture of our device, prepared with the aid of a polishing machine for optical fibres called Kent 3-Engis Ltd., is shown in Fig. 4.

The first task carried out consisted in measuring the power loss obtained for different polishing depths, from zero to the maximum possible one without breaking the fibre. The cor-

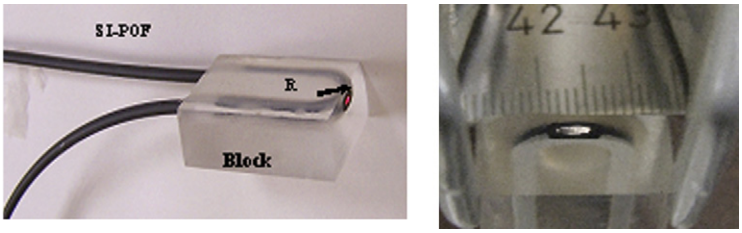

Fig. 4. Sensing head based on laterally polishing a U-shaped optical fibre section. (Left-hand side) Picture of a bend in the shape of U embedded in a Plexiglas block, with a bend radius $R = 5$ mm. (Right-hand side) Picture of the elliptical planar interface after the polishing.

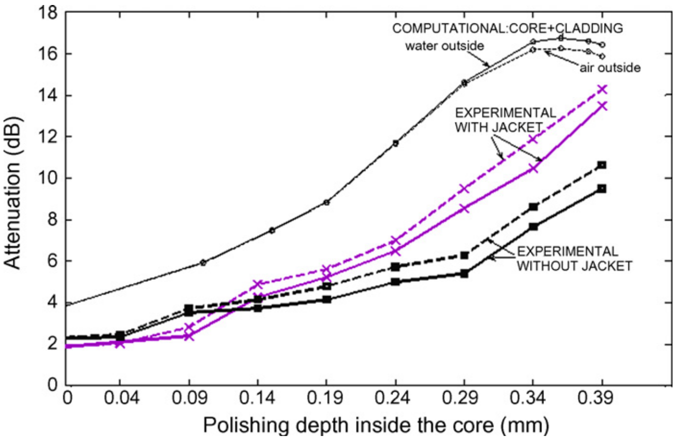

Fig. 5. Attenuation for a bend radius $R = 5$ mm, immersed in water (all solid lines) or in air (all dashed lines). (Uppermost pair of curves) Results obtained computationally considering that reflections only occur either at the core–cladding interface or on the polished surface, i.e., neglecting reflections at the cladding–jacket interface. (Pair of curves in the middle) Experimental results using a jacketed POF. (Bottom pair of curves) Experimental results using a POF without jacket.

responding results, obtained with a 660 nm LED (super-bright LED IF-E97) that includes a lens to collimate light, are shown in Fig. 5 for a 5 mm radius polished bend immersed in air and in water (the two curves labelled as "experimental"). The polishing depth is measured from the jacket–air interface, and it ranges from 0.51 mm (when the core is just reached) to 0.90 mm (a value slightly smaller than the 1 mm distance between the fibre symmetry axis and the jacket–air interface). In the absence of polishing and with a total fibre length of 2 m, the contribution to loss was observed to be 1.6 dB. However, theoretical calculations predict nearly 4 dB of loss without polishing (curves labelled as "computational:core + cladding"). A plausible explanation, which will also serve us to explain the lower attenuation measured when the external medium is water instead of air, would be the existence of a very thin layer of air or water between the cladding and the jacket. In such a case, after crossing the thin transparent cladding, part of the rays would be reflected towards the core again, so the observed attenuation would be lower. The aforementioned lower attenuation when the external medium is water, whose refractive index is more similar to that of the core than air, is rather unexpected at first sight. In addition, simulation and experimental results with the same type of POF, but without jacket or methacrylate outside, do not show this small reduction in attenuation. Therefore, it seems reasonable to think that something else in jacketed POFs, and also in unjacketed POFs embedded in a block of methacrylate, has significant influence on the fibre's attenuation. We have come to a plausible hypothesis to explain this lower attenuation in water, according to which part of the light propagates along an air channel between the cladding and the jacket, in such a way that a fraction of it will enter the core again when it reaches the air–water interface on top of the polished bend. The reason may be explained from the analysis of reflection effects in water, as illustrated in Fig. 6. On the right-hand side of this figure, we have plotted the Fresnel power reflection coefficient as a function of the angle with the tangent at the water-air interface, which serves to illustrate that reflection on the interface can be significant, i.e., that an important fraction of light can be reflected at the air–water interface. This fact can account for the approximately 0.6 dB of difference between the experimental curves of Fig. 5, both with and without jacket. In the absence of jacket, the explanation could be the existence of a layer of air between the cladding and the block of methacrylate used to hold the bent fiber (Fig. 4). As a matter of fact, without methacrylate and without jacket, higher attenuation is obtained when the curve is immersed in water instead of being in air, as we have checked experimentally.

## 4. Results corresponding to the proposed sensor

After having measured the power loss as a function of the polishing depth, the following task carried out consisted in deciding the polishing depth of the U-shaped bend for our sensor, based on experimental results and in order to obtain a good sensitivity.

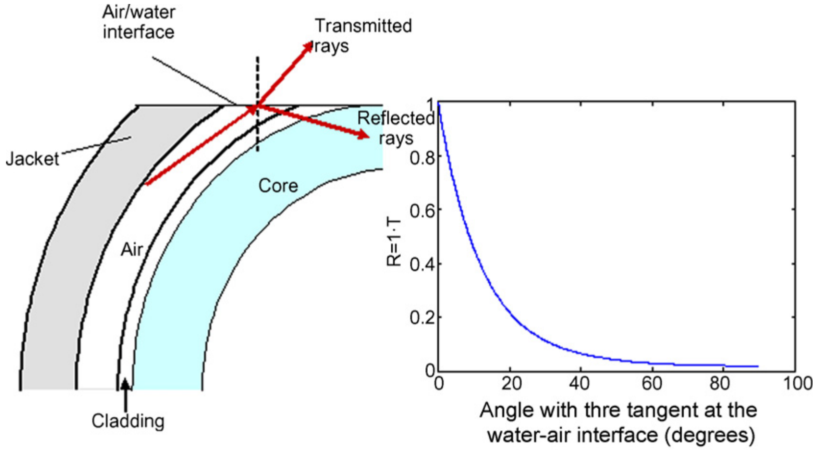

Fig. 6. Analysis of reflection effects in water that could explain the reduction in attenuation when the bend is immersed in water. (Left-hand side) Illustration of the effect of the air–water interface. (Right-hand side) Fresnel reflection coefficient at such interface as a function of the angle with the tangent at the interface in the plane of incidence.

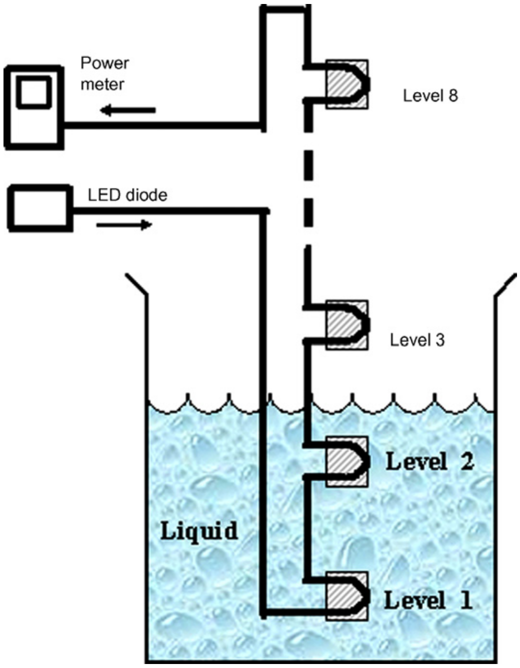

Fig. 7. Set-up of the multipoint measurement sensor for the determination of the liquid level in a water tank.

We finally chose a polishing depth of value $\varepsilon = 150\,\mu\text{m}$ from the core surface. With this depth, a power loss of 5.10 dB is obtained for $R = 5$ mm if the bend is surrounded by air, and of about 4.55 dB (i.e., 0.55 dB lower) if the bend is surrounded by water (Fig. 5, curves titled "experimental with jacket").

Instead of a single U-shaped bend we can use several bends distributed along the fibre to improve the performance of our sensor. Fig. 7 shows the experimental set-up for our multipoint liquid-level measurement sensor, in which a fibre has eight bends acting as sensing heads that will be immersed in water. The separation between measuring points is 34 cm. The first sensing head is at the bottom of the water tank, whereas the others are distributed vertically over the first one. Light is launched into the fibre with a modulation frequency of 1 kHz, which serves to eliminate background noise at the receiver. The photodiode employed is a PIN (IF-D91), whose maximum responsivity is 0.4 A/W at 880 nm. The output of the photodiode is demodulated and amplified, and then the signal is sampled at a rate of 500 samples per second by means of an analog-to-digital converter (A/D). The amplifier provides a variation of 0.5 V per each bend that is immersed in water (Fig. 7). A multipurpose integrated circuit allows us to evaluate the signal variations and determine the liquid level.

Fig. 8 shows the overall system loss in dB as a function of the number of sensing points immersed in water. The reference level was established when the tank is empty (no water). Afterwards, the tank was progressively filled until the eighth sensing head was covered by water, in which case the relative attenuation was 2.11 dB. In other words, the attenuation step per sensing head immersed in water is only 0.26 dB. By this way, the number of liquids whose levels will be measured can be very large, and there will not be any problem to apply our sensor to detect water level in tanks that are many metres deep (e.g., for the multisensor system of ref. [20] the proposed range is in the order of "2 m").

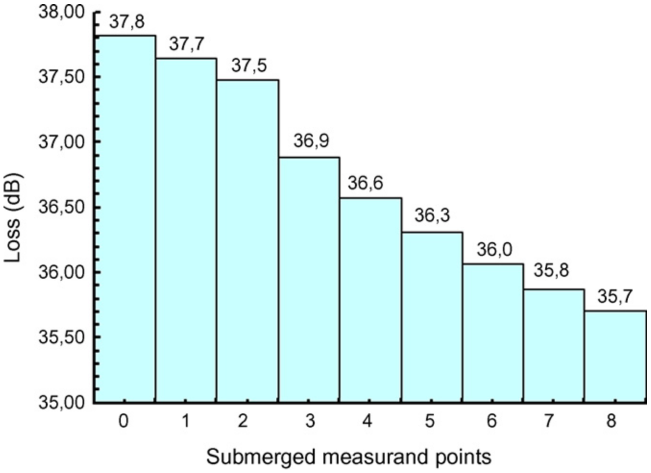

Fig. 8. Experimental loss obtained as a function of the number of immersed sensing heads.

## 5. Conclusions

We have presented a new multipoint liquid-level measurement sensor based on the extra attenuation caused by bending and polishing plastic optical fibres. Polishing part of the core on top of bends improves the sensitivity of the device. Experimental results show a good agreement with theoretical considerations. In the proposed set-up, an opto-electronic unit placed at the output end of the fibre allows us to evaluate the liquid level of the tank. POFs are especially suitable for the sensing heads due to their high flexibility. The sensor can be adapted to measure other physical parameters, such as temperature or humidity, by depositing materials sensible to them on the polished region. In addition, the cost of the sensor is low, thanks to the use of low-cost components, namely a POF, an LED and a PIN photodiode. Its price and adaptability makes the sensor suitable for industrial applications.

## Acknowledgements

This work has been economically supported by the MCYT, through the projects CICYT. TEC2004-05936-CO2-02, EAMOP TIC-2002-01259, TIC2003-08361 and Universidad del País Vasco–Euskal Herriko Unibertsitatea, the Gobierno Vasco–Eusko Jaurlaritza, GIU05/03, UE05/A25, HEGATEK-05, SENSOFIB/SAIOTEK, for which the authors are very thankful.

## References

[1] Y. Uno, Characteristic of a sharply bend optical fiber for sound field measurement, in: K. Nakamura (Ed.), 11th International Conference on Optical Fiber Sensor, OFS-11, Japan, 1996, pp. 658–661.

[2] A. Babechenko, B. Khanokh, Y. Shomer, M. Nitzan, Fiber optic sensor for the measurement of respiratory chest circumference changes, J. Biomed. Opt. 4 (1999) 224–229.

[3] J. Zubia, G. Garitaonaindia, J. Arrue, Pasive device based on plastic optical fibers to determine the indices of refraction of liquids, Appl. Opt. 39 (2000) 941–946.
[4] T. Takeo, H. Hattori, Silica glass fiber photorefractometer, App. Opt. 31 (1992) 44–50.
[5] M. Kamiya, H. Ikeda, S. Shinohara, Analog data transmission through plastic optical fiber in robot with compensation of errors caused by optical fiber bending loss, IEEE Trans. Ind. Electron 48 (2001) 1034–1037.
[6] S. Muto, O. Suzuki, T. Amano, M. Morisawa, A plastic optical fibre sensor for real time–time humidity monitoring, Meas. Sci. Technol. 14 (2003) 746–750.
[7] C.M. Tay, K.M. Tan, S.C. Tjin, H. Rahardjo, Humidity sensing using plastic optical fibers, Microwave Opt. Technol. Lett. 43 (2004) 387–390.
[8] S.K. Khijwania, K.L. Srinivasan, J.P. Singh, Performance optimized optical fiber sensor for humidity measurement, Opt. Eng. 44 (2005) 34401–34407.
[9] A. Babchenko, Noam Itzkovich, J. Maryles, 17th International Conference on Optical Fiber Sensor, OFS-17, Belgium, 2005, pp. 719–722.
[10] R.J. Bartlett, R. Philip-Chandy, P. Eldridge, D.F. Merchand, R. Morgan, P.J. Scully, Plastic optical fibre sensors and devices, Trans. Inst. Meas. Control 22 (2000) 431–457.
[11] D. Marcuse, Curvature loss formula for optical fibers, J. Opt. Soc. Am. 66 (1976) 216–220.
[12] A.W. Snyder, J.D. Love, Optical Waveguide Theory, Chapman & Hall, London, 1996 (Reprinted).
[13] C. Winkler, J.D. Love, A.K. Ghatak, Loss calculations in bent multimode waveguides, Opt. Quantum Electron. 11 (1979) 173–183.
[14] K.S. Kaufman, R. Terras, R.F. Mathis, Curvature loss in multimode optical fiber, J. Opt. Soc. Am. 71 (1981) 1513–1518.
[15] A.H. Badar, T.S.M. Maclean, H. Siraz, B.K. Gazey, Bend slab ray theory for power distribution in core and cladding of bend multimode fibres, IEE Proc. J. 138 (1981) 7–12.
[16] Y.C. Chen, L.-W. Chen, P.C. Chen, Combined effects of bending and elongation on polymer optical fiber losses, Opt. Lett. 30 (2005) 230–232.
[17] J. Arrue, J. Zubia, Analysis of the decrease in attenuation achieved by properly bending plastic optical fibres, IEE Proc. Optoelectron. 143 (1996) 135–138.
[18] A.W. Snyder, J.D. Love, Reflection at a curved dielectric interface—electromagnetic tunneling, IEEE Trans. Microwave Theory Tech. MTT 23 (1975) 134–141.
[19] G. Durana, J. Zubia, J. Arrue, G. Aldabaldetreku, J. Mateo, Dependence of bending losses on cladding thickness in plastic optical fibers, Appl. Opt. 42 (2003) 997–1002.
[20] C. Vazquez, A.B. Gonzalo, S. Vargas, J. Montalvo, Multi-sensor system using plastic optical fibers for intrinsically safe level measurements, Sens. Actuators A 116 (2004) 22–32.

## Biographies

**M. Lomer** was born in Lima, Peru. He received in electronic technique engineering from the Escuela Nacional de Ingeniería Técnica, Lima, Perú, in 1978. He received the degree in telecommunication engineering from the Ecole Nationale de l'Electronique et de ses Applications, Cergy-Pontoise, France, in July 1988. He received his PhD in electronic from the Université de Limoges, France, in July 1992. His doctoral work consist a contribution to the study of whispering gallery modes and making non-linear optical waveguide by diffusion of lead. Since October 1992, he works as associate professor in the University of Cantabria in the Photonic Engineering Group. His current research interests include polymer optical fibers, passive integrated optical devices and fiber optic sensors.

**J. Arrue** received the BS degree in electronic physics in 1990, the MS degree in electronics in 1991 and in telecommunications in 1992, and the PhD degree in optical fibres in 2001, from the University of the Basque Country (Spain) in all cases. He won a special award for his thesis, and an European acknowledgement of the PhD degree. He is a professor at the Telecommunications Engineering School (University of the Basque Country, Bilbao, Spain). He is also involved in international research projects with other universities and companies.

**C. Jauregui** was born in Santander, Spain, in 1975. He received both his telecommunication technical engineering degree and his telecommunication engineering degree at the University of Cantabria. In 1998 he joined the Photonics Engineering Group. In 2003 he received his PhD degree. His primery research concern is the interrogation of Fiber Bragg grating sensor.

**P. Aiestaran** received a degree in Electrical Engineering in 1984 at School of Industrial Engineering (University of the Basque Country, Spain). He was a researcher in the Production Department of Ikerlan (Technological Research Centre). He worked during twelve years as applications engineering in the field of machine tool. Ever since 1998, he is a full professor at the Polytechnical University College of San Sebastian and he is a member of the research group on plastic optical fibres, both works at the University of the Basque Country.

**J. Zubia** received a degree in solid-state physics in 1988 and the PhD degree in physics from the University of the Basque Country, in 1993. His PhD work focused on optical properties of ferroelectric liquid crystals. He is a full professor at the Telecommunications Engineering School (University of the Basque Country, Bilbao, Spain). He has more than 8 years of experience doing basic research in the field of plastic optical fibers. At present, he is involved in research projects in collaboration with universities and companies from Spain and other countries in the field of plastic optical fibers, fiber-optic sensors, and liquid crystals. Prof. Zubia won a special award for best thesis in 1995.

**J.M. López-Higuera** obtained his telecommunication technical engineering degree from the Universidad Laboral de Alcalá de Henares, and his telecommunication engineering degree in the Universidad Politécnica de Madrid (UPM). He achieved his PhD degree in telecommunication engineering from the UPM. He founded and is the read of the Photonics Engineering Group of the TEISA Department in the University of Cantabria. Presently, he works on the development of photonics instrumentation, optical fiber sensor systems for civil engineering, electrical power, environmental and smart structures applications, and in optical diagnostics for industrial applications. He is senior member of the IEEE and member of the IEE, and OSA.