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A quasi-distributed level sensor based on a bent side-polished plastic optical fibre cable

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Abstract
A flexible quasi-distributed liquid level sensor based on the changes in the light transmittance in a plastic optical fibre (POF) cable is proposed. The measurement points are constituted by small areas created by side-polishing on a curved fibre and the removal of a portion of the core. These points are distributed on each full turn of a coil of fibre built on a cylindrical tube vertically positioned in a tank. The changes between the refractive indices of air and liquid generate a signal power proportional to the position and level of the liquid. The sensor system has been successfully demonstrated in the laboratory, and experimental results of two prototypes with 15 and 18 measurement points in a range of 33 mm and 39 mm respectively and a resolution of 0.08 mm with bend radii of 5 mm and 8 mm are presented.

Keywords: liquid-level measurement, fibre-optical sensor, coil fibre probe, plastic optical fibre

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In many processes, liquid level control plays a major role. A great variety of transducers and instruments based on electrical, acoustic, magnetic and optical methods has been proposed for that measurement. The solutions using optical methods have the advantages of providing high sensibility, immunity to electromagnetic interference and security in explosive or aggressive atmospheres. In the past few years, optical fibre sensors have contributed with different new solutions. When single-mode and multimode glass fibres are used as part of the sensors, the resulting systems are well appreciated in metrology, especially those allowing a cost-effective implementation [1]. New findings in the fabrication of plastic optical fibres (POF) have contributed to expand their application fields; they also represent a low-cost solution [2–4]. In fact, the use of POF offers several advantages such as low weight, flexibility, easy handling, large core diameter and large numerical aperture. POFs with diameters between 0.125 and 3 mm, and typical transmission losses of 120 dB km^{-1} at 650 nm are already commercially available.

Liquid level sensors using optical fibres are divided into two groups: sensors for punctual measurement [5–9] and sensors for continuous measurement [10–13]. In the first group, the optical fibre is used as a transducing device [5, 7], or as a transport element of the light signal [6, 8]. In these cases, a section of the fibre tip is prepared (forming a bend, micro-bends, a side-polished bend or a film deposition) to detect the variations in the light intensity according to the change in the refractive index of the surrounding medium; or the fibre is used with devices (a collimator lens, prism, hemispherical glass) assembled to the extremities, in order to modify the conditions of light propagation when they are in the presence or absence of a liquid. In the second group, an

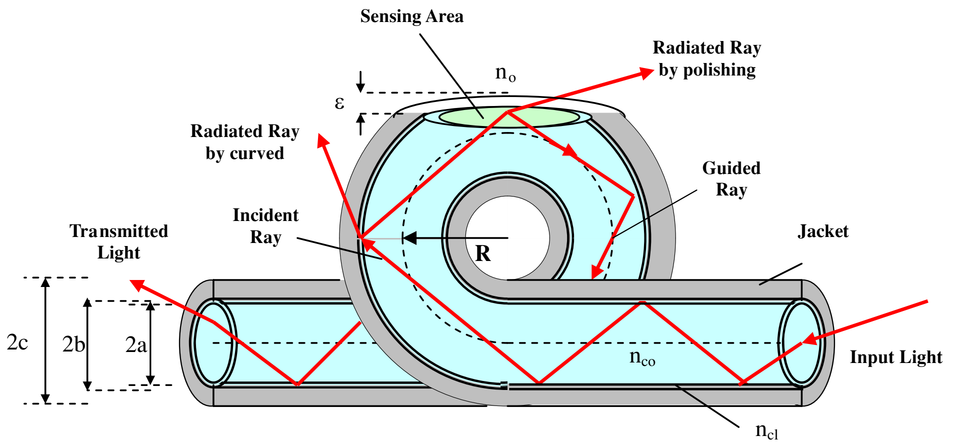

Figure 1. Illustration of a side-polished POF cable loop of the quasi-distributed transducer.

optical fibre is used to illuminate the surface of the fluid, and two fibres are used to collect the reflected light, the intensity of light being proportional to the distance or level of the fluid [10]. An assembly using a lens to collimate and focus the light both with a fibre emitting and a fibre receiving has been proposed for continuous sensing [11]. A solution based on the measurement of the attenuation losses produced by the total internal reflection of light within an optic fibre submerged in a liquid has also been recently reported [12]. The use of the influence of the refractive index of the liquid surrounding a fibre with long-period gratings (LPG) has also been proposed as a liquid-level sensor [13]. All these methods need sophisticated optical arrays and additional optical components, as well as a specific treatment of the signal to deduce the liquid level.

In this document, we present a quasi-distributed invasive liquid-level sensor based on the changes in light transmittance in a POF cable in which the measurement points have been created by side-polishing. The proposed solution is advantageous in the manufacturing of this sensor in comparison to previous sensors. The lateral polishing generates an elliptical surface where part of the core has been removed. The measurement points are laterally distributed along the fibre, placed at each of the N full-turns. A change in the refraction index of the medium in contact with the core produces variations in the transmittance. These changes are detected at the output end of the fibre. The lateral polishing produces moderate losses, thus allowing the measurement even with several points along the entire fibre. In the following sections, a sensor design and experimental results obtained with the developed prototype are presented. Experimental results from two prototypes of 15 and 18 measurement points performed on POF fibre coils with bend radii of 5 mm and 8 mm are also provided.

2. Principles of operation

2.1. Basis of the transducer

The principle of operation of the full-turn sensor is illustrated in figure 1. The fibre-optic liquid level sensor is based on the change of the refraction index between the air and the liquid medium on a bent side-polished POF cable. The side-polishing is accomplished by removing a portion of the jacket, cladding and core of the fibre, bringing a polished elliptical surface out into the open. This polished region of the fibre core is in direct contact with the external medium of index n_o. The polished surface, of several square millimetres, gives rise to optical power variations when the refractive index of the external medium changes (e.g., in the absence or presence of the liquid), which are dependent on the position and level of the liquid. The measurement of the quasi-distributed liquid level is obtained by means of measurement points in each full-turn of an optical fibre spirally wound around a cylindrical rod and vertically arranged in a tank.

2.2. Set-up of the transducer

The proposed transducer consists of a typical multimode step-index POF cable of diameter 2.2 mm (including the jacket) (figure 1). The reason why we chose this cable diameter was only for easier manipulation of the fibre in the laboratory. The diameters of the core ($2a$), cladding ($2b$) and jacket ($2c$) are 0.98 mm, 1.0 mm and 2.0 mm, respectively. The radius of curvature of the fibre, R, is measured from the centre of the curvature to the fibre axis. The section of core removed has a maximum thickness ε. The polished surface (sensing area) is flat and perpendicular to the radial direction of the curvature. Since the radius of the core is large, the conditions of propagation, using the arguments of geometric optics, can be described in a summarized way. The light launched propagates along the POF fibre by means of the total internal reflection effect. Using the paraxial theory, the light confinement in the fibre is governed by the condition

$$\theta \geqslant \theta_c = \sin^{-1}(n_{cl}/n_{co}), \qquad (1)$$

where θ is the angle between the ray path and the axis of the fibre, θ_c is the critical angle, and n_{cl}, n_{co} are the refractive indices of the cladding and the core of the fibre, respectively.

When the rays enter the curved region, the conditions of propagation depend on θ, n_{co}, n_{cl} and a and on the radius of curvature R. The incident rays meeting the outer interface of the curved region are divided into reflected and refracted rays (radiated outside the fibre). The latter represent the bend losses. Those reflected rays that reach the polished interface

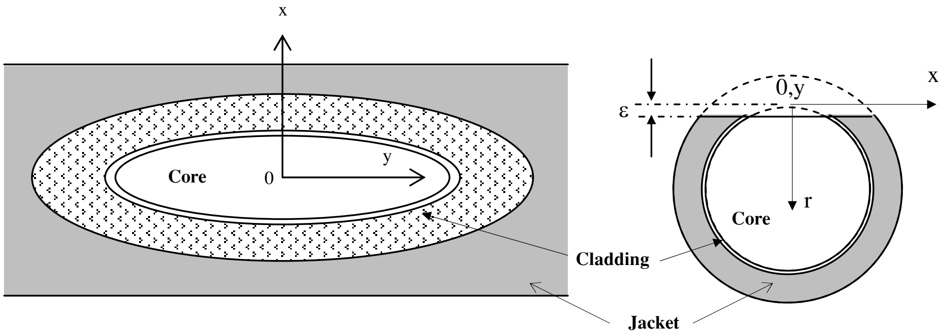

Figure 2. Elliptical shape of the side-polished surface and section of a POF cable.

can also be divided into two rays: reflected and refracted rays. The refracted (radiated) rays represent losses caused by the effect of the polishing and depend, among other parameters, on the refractive index of the outside medium, n_o. The guided rays, after crossing the curved region, are transmitted to a photo-detector. Changes in the refractive index n_o have a strong effect on the intensity of transmitted light, i.e. they cause measurable changes in the transmittance. Consequently, the design of the proposed sensor is based on the simultaneous use of both bending and polishing losses in the POF cable.

Bending losses in fibres with curvatures of 90°, 180° and 360° have been investigated by many researchers and several works have been reported on this subject [14–17]. In the particular case of the typical POF of diameter 1 mm, both theoretical and experimental results show that the bend losses, in terms of R, increase for values of R smaller than 10 mm. These small values of R increase the sensitivity of the outside medium surrounding the bent fibre. Thus, when a U-shaped fibre is submerged in a liquid, weak changes in the intensity of the propagated light are produced, which can be detected at the other end of the fibre [5]. In general, a curved fibre can be used as a simple transducer to measure the presence or absence of liquid. However, if several bends are introduced on the same coil of fibre, more points for level measurement can be obtained. An additional advantage can be found when the measurement of the liquid is confined to a small portion of the curved fibre. This is obtained by means of the lateral polishing of the curved fibre cable. The POF cable has a mechanical protection jacket, which does not have an optical function, but which is very useful in this case. The liquid surrounding the jacket does not affect the measurement.

The position and the level of liquid are measured with precision, and with a resolution corresponding to the diameter of the short axis of the elliptical surface formed by the polishing. If the transducer is composed of N turns for N measurement points vertically arranged in the tank, it will be able to carry out a quasi-distributed liquid level measurement, with the only limitation of bending losses. There is a trade-off between the number of measurement points to be implemented and the radius of curvature.

Finally, it is worth noting that the choice of the fibre diameter is another possible design parameter. However, as we have previously reported, results are scalable according to the ratio ρ/R [18, 19], which means that sensors with a similar ρ/R give similar losses (identical in theory).

3. Side-polishing characterization

When a curved fibre is polished, an elliptical flat surface appears, whose diameters are $2x$ and $2y$, corresponding to the short and long axes, respectively (figure 2). The maximum thickness of the removed core, ε, is calculated in terms of the radius of the fibre, a, and of the radius of curvature R:

$$\varepsilon = (a + R) - \sqrt{(a + R)^2 - y^2}, \qquad (2)$$

where y is the radius of the long axis of the ellipse. The experimental measurement of this value provides the thickness ε. This has been plotted in figure 3 as a function of R for different radii and different values of the long axis of the elliptical surface. For practical applications, a thickness of 0.1 mm is sufficient to be used in the level sensor. This can easily be obtained in the range from $R = 4$ mm to $R = 10$ mm with $y = 1$ mm to $y = 1.4$ mm, respectively. Figure 4 shows an image of the polished surface, which has an elliptical shape. The radiation of the light injected into an end of the fibre can be observed.

4. Manufacture of the transducer

The construction of the quasi-distributed level sensor is obtained by means of a lateral polishing of the coil of fibre. The array and the disposition of the transducer within the tank are illustrated in figure 5. Each full turn of the fibre contains a measurement point and can be adapted to the height of the tank. The minimum range of level measurement between two points corresponds to the total diameter of the fibre. The spiral of the fibre is characterized by the bend radius of a full-turn spiral R', which depends on the pitch P and on the fibre bend radius. It is given by

$$R' = R + (1/R)[P/(2\pi)]^2, \qquad (3)$$

and the fibre length per period is

$$L = [(2\pi R)^2 + P^2]^{1/2}. \qquad (4)$$

Radii R and R' are related to the fibre axis. L represents the fibre length required for the sensor at each measurement point. By using a POF cable of diameter 2 mm, including the jacket, and $R = 5$ mm, the values obtained for R' and L are 5.02 mm and 31.5 mm, respectively.

In figure 6, the characteristics of both bending losses and polishing of a fibre full turn are shown, considering two different radii, $R = 5$ mm and $R = 8$ mm. The fibre used is

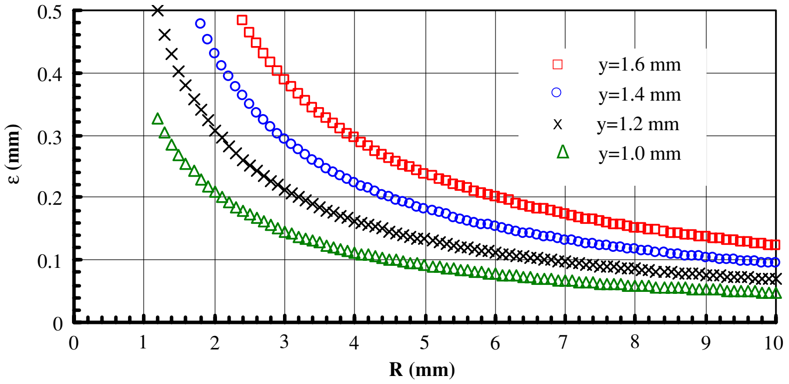

Figure 3. Thickness of the core removed as a function of the bend radius of a POF cable with $a = 0.49$ mm, $b = 0.5$ mm and $c = 1.0$ mm.

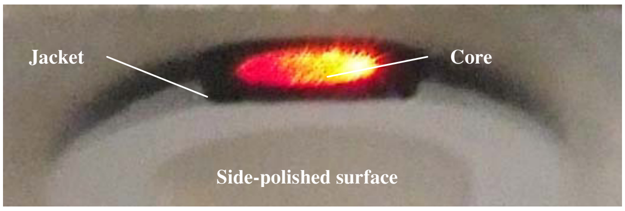

Figure 4. Elliptical surface of bent POF after lateral polishing and light radiated for $R = 5$ mm.

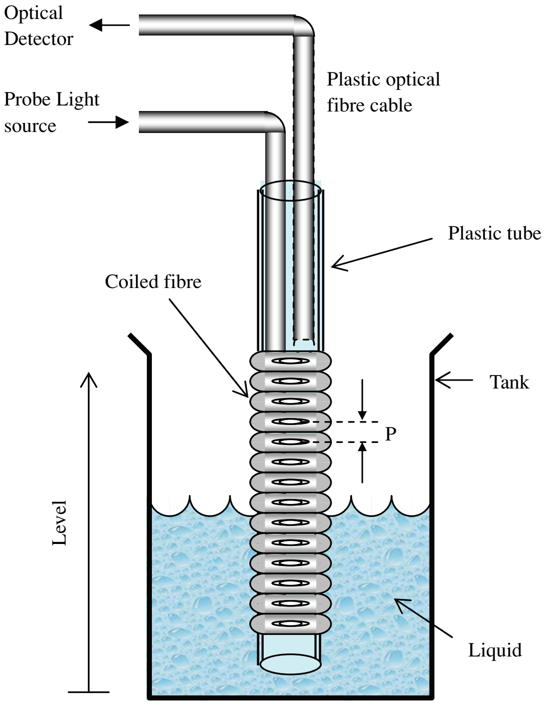

Figure 5. Schematic of the sensor for quasi-distributed level measurement.

a step index PMMA-POF with a diameter of 2 mm including the jacket, where the core and cladding indices are $n_{\mathrm{co}} = 1.492$ and $n_{\mathrm{cl}} = 1.402$, respectively. The medium surrounding the polished surface is air ($n_{\mathrm{o}} = 1$). A He–Ne laser source with a wavelength of 632.8 nm has been used. The direction of polishing goes from the external interface of the jacket to the centre of the fibre axis (figure 2). In the experimental set-up, the polishing depth ε was measured by means of an optical microscope, with an accuracy of ± 10 μm. For both radii of curvature, the polishing has been carried out up to a maximum thickness of 0.4 mm, in order to prevent damage in the fibre.

In the case of $R = 5$ mm, the bending losses are 4.4 dB, which increase according to the thickness of the removed core. For every step of 100 μm the increase is approximately 3.1 dB. For $\varepsilon \approx 400$ μm, the loss is 12.6 dB higher than for $\varepsilon = 0$. In sensing applications, a thickness $\varepsilon = 0.1$ μm can be enough, representing an increment of 0.9 dB of additional losses to those for the bend of $R = 5$ mm. When the transducer is submerged in water ($n_{\mathrm{o}} = 1.33$), an abrupt change of approximately 0.17 dB is measured with respect to air. This demonstrates good sensitivity to perform level measurements.

In the case of $R = 8$ mm, the bending losses of one full turn of fibre are 2.25 dB. The increment of the losses by the effect of polishing reaches 6.6 dB for $\varepsilon = 0.4$ mm. In this case, the increase in the losses in terms of the thickness is smaller compared to $R = 5$ mm. When this transducer is submerged in water, with $\varepsilon = 0.1$ mm, a steep change in the intensity of light of 0.1dB is measured with respect to the air. The selection of the bend radius and the maximum polished thickness of the core depends on the number of sensing points, the sensitivity and the total losses available.

The construction of the level transducer is accomplished by wrapping a POF cable on a cylindrical tube of radius ρ. The radius of curvature of the fibre is given by $R = \rho + c$, where c is the radius of the cable (figure 1); for a typical step-index PMMA-POF of a diameter of 1 mm and a jacket thickness of 0.5 mm, c has a value of 1 mm. A hole made in an end of the cylindrical tube is used to fix the end of the fibre coil. This end is located at the bottom of the tank. Each complete turn of the fibre is successively added until completing the amount required for the level measurement. In this paper, two prototypes, with $N = 15$ and $N = 18$ turns and for radii of curvature $R = 5$ mm and $R = 8$ mm are reported. The side-polishing on the bent fibre can be carried out by several methods, either by direct polishing of all the fibres or by an individual process on each fibre using a U-shaped mechanical support where the fibre is housed. The cut method with a hot knife can also be used to obtain the measurement points. The two ends of the fibre are respectively derived towards the light source and the photo-detector. Images of the sensor set-up and

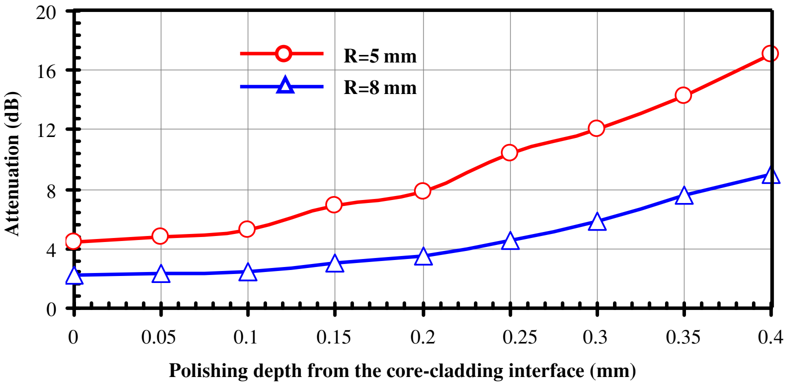

Figure 6. Attenuation for two radii of curvature in a POF stripped of its jacket, which has a U-shaped bend and polished on top of the bend.

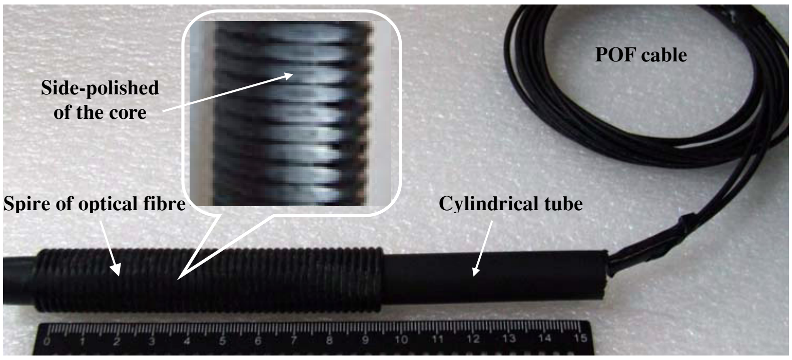

Figure 7. Transducer view with insets to illustrate the optical light radiation of one side polished loop.

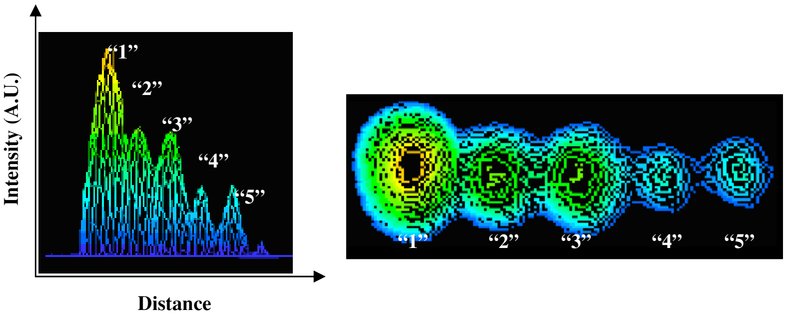

Figure 8. Distribution of the intensity of light in distant field of the first five polished lateral spires.

details are shown in figure 7. If the height of the container is several tens of millimetres, the distance between the points of level measurement (period P) corresponds to the minimum distance, i.e. the diameter of the cable POF. In the particular case of a tank of greater height, from several centimetres to several metres, the distance between the measurement points can be distributed in a periodic way by means of fibres curved with a helical form. In figure 8, the intensity distribution of the light radiated out of the fibre is depicted. This distribution shows how the intensity decreases when the number of turns increases. It also decreases due to the position of the turn depending on the distance or height of the tank.

The main geometrical and optical properties of the two constructed prototypes are summarized in table 1. In both cases, the period of the fibre spire is $P = 2.2$ mm.

5. Experimental results

Measurements of water level in a container have been carried out with the proposed transducer (figure 5). The R parameter is of great importance in the performance of the sensor. For $R < 5$ mm, we have evaluated experimentally both bending losses and increase in sensitivity, but the number of sensing points is limited. Alternatively, for $R > 8$ mm the bending losses and sensitivity decrease but the number of sensing points can increase. We therefore chose for our experimental prototypes two transducers with $R = 5$ mm and 8 mm. A He–Ne laser ($\lambda = 632.8$ nm) has been used as a light source. Light is coupled into the fibre with a modulation frequency of 270 Hz. Thus our modulated signal is above the background noise of the receiver. The signal from the sensor

Table 1. Conditions of use of two level transducers with POF cable of 2 mm diameter, with thickness of removed core $\varepsilon = 0.1$ mm, where $y = 0.9$ mm ($R = 5$ mm) and $y = 1.3$ mm ($R = 8$ mm).

Prototype	Bend radius R (mm)	Full turns (N)	Total bend losses (full turns) (dB)	Total losses by polishing (dB)	Sensibility air–water (dB)
I	5	15	7.5	12	0.17
II	8	18	3.5	4.1	0.10

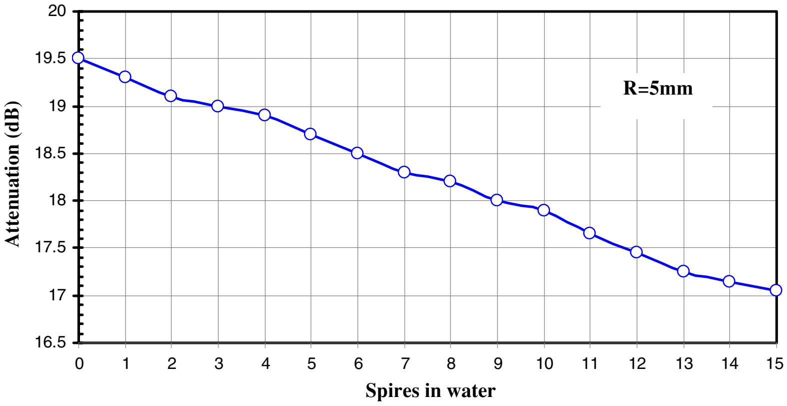

Figure 9. Experimental loss obtained as a function of distance immersed in water for 15 sensing points (period of the fibre spire $P =$ 2.2 mm).

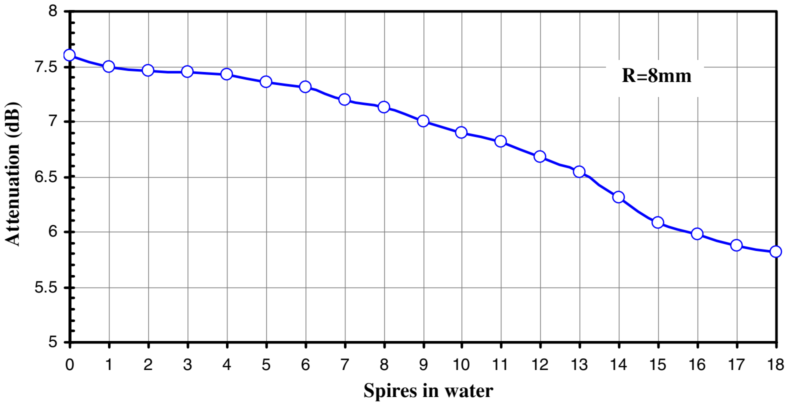

Figure 10. Experimental loss obtained as a function of distance immersed in water for 18 sensing points (period of the fibre spire $P =$ 2.2 mm).

was detected by using an optical power meter (Anritsu Corp.), which allows for the detection at this modulation frequency. The first sensing point is located at the bottom of the water tank. The obtained experimental results in figures 9 and 10 versus the number sensing points immersed in water are plotted.

Figure 9 shows the results of the level measurement with the first prototype ($R = 5$ mm) with 15 sensing points. We observed that the change in the losses in each full turn is 0.16 dB, and it is 2.6 dB for the whole transducer. In the case of the second prototype ($R = 8$ mm), the sensitivity and losses diminish, but there are more sensing points (figure 10).

Data from figures 9 and 10 are neither smooth nor linear. At first sight, this could be interpreted as a problem for practical deployment of the sensor. However, it is the differential jump that is important in this approach, which can easily be resolved by the detector despite the lack of linearity. We are looking for a step-sensor, rather than for a linear one. For the same reason, any small variation in the depth of polishing of the core at the many turns of the fibre has no significant effect on the sensor response.

As can be deduced from figures 9 and 10 the losses decrease when the polished surfaces are in contact with water. Apparently, this result is contradictory with the known theory. However, it can be explained by the existence of a very thin layer of air between the cladding and the jacket. In that case, after crossing the thin transparent cladding, part of the rays would be reflected towards the core again, so the observed attenuation is lower. This lower attenuation when the external medium is water, whose refractive index is more similar to that of the core than to that of air, is rather unexpected at first sight. In addition, simulation and experimental results with the same type of POF, but without a jacket, do not show this small reduction in attenuation. Therefore, it seems reasonable to think that something else in jacketed POFs has a significant influence on the fibre attenuation. We have come to a plausible hypothesis to explain this lower attenuation in water, according to which part of the light propagates along the 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. As a matter of fact, without a jacket, higher attenuation is obtained when the curve is immersed in water instead of being in air, as we have checked experimentally. This has been explained and demonstrated in a previous work [20].

Finally, we would like to remark that, although the sensor prototype seems to be bulky for the measurement range provided, it was intended as an application for high capacity water tanks where the size of this sensor is not a limiting feature. For such applications, the sensor constitutes a low-cost solution with a high resolution.

6. Conclusions

We have presented a quasi-distributed level sensor based on the extra attenuation that appears by bending and polishing plastic optical fibres. By polishing a section of the core in each turn the sensitivity of the device is improved. The feasibility of a quasi-distributed measurement system has been demonstrated along 33 mm and 39 mm long sections with 15 and 18 measurement points, respectively. The precision of the measurement is given by the minor axis of the ellipse formed by the initial polishing ($2x = 0.08$ mm). Due to the flexibility of plastic optical fibres, it is possible to have a wide measurement range if the fibre turns are provided more space, from millimetres to several metres of length. In the latter case, the level of resolution would be maintained, but for heights close to the sensing points. The advantages introduced by the use of POFs make it possible to develop very cost-effective sensing systems.

Acknowledgments

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