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

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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.

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

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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 α with the normal to the core–cladding interface as the incident ray. Moreover, the minimum angle α below which a ray is finally refracted into the water (critical angle α_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

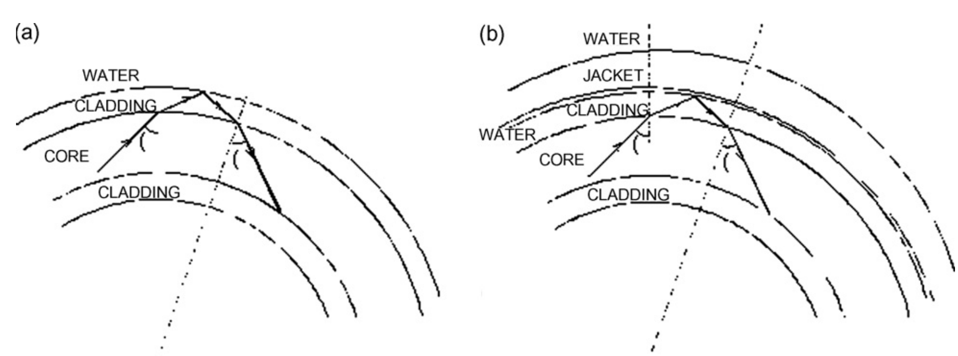

Fig. 1. (a) A ray reflected at the cladding–water interface re-enters the core at the same angle α as the incidence angle at the core–cladding interface; for refraction to occur towards the water: $\alpha \leq \alpha_c = \arcsin(n_{water}/n_{core})$. (b) In jacketed fibres, a hypothetical presence of 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.