Plastic optical fiber multipoint liquid-level sensor with single semi-cylindrical detection element

Sergei Khotiaintsev, Selene Pérez-García, Alfredo Beltrán-Hernández, Enrique Llanito-Caudillo
Dept. of Telecommunications Engineering, Faculty of Engineering, National Autonomous University of Mexico, Av. Universidad 3000, Mexico, D. F., C. P. 04510, Mexico

ABSTRACT

We present an optical fiber liquid-level sensor which employs an array of plastic optical fibers coupled to a single semi-cylindrical refractometric detection element of plastic. The sensor measures the level of liquids in a discrete way and also is capable of discriminating between different liquids (such as gasoline and water) in a tank or reservoir.

Keywords: Specialty optical fibers, plastic optical fibers, optical fiber sensors, liquid-level measurement

1. INTRODUCTION

Plastic optical fibers (POF) has become an important transmission medium for robust short-distance data communications in a variety of applications such as Fiber To The Home (FTTH) systems, Multimedia Communications in Cars (MOST) and Industrial automation Networks (PROFINET).[1] The biggest advantages of POF are their large core, simplicity of handling and a low system cost.[2] Therefore, it is attractive to complement POF-based communication systems with a variety of POF-based sensors of different physical quantities.[3-5] Here we present an optical fiber discrete-type liquid-level sensor which employs an array of POFs and a single relatively long detection element. We investigate the characteristics of this sensor under different parameters of optical fibers and sensor geometry. In addition, we investigate the possibility of discriminating between different liquids (such as gasoline and water) in a tank or reservoir.

2. CONCEPTUAL DESIGN OF THE SENSOR

The present optical discrete-type liquid-level sensor consists of a long semi-cylindrical transparent detection element of plastic, which is connected to M symmetrically placed pairs of POFs as shown in Fig. 1. We use a hollow segment of semi-cylinder for detection element in order to reduce its mass and volume, but a solid semi-cylinder can be used for the same purpose

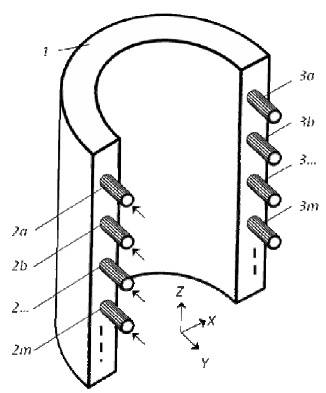

Figure 1. Conceptual design of the sensor: (1) - detection element of plastic, (2) and (3) - transmitting and receiving POFs, respectively.

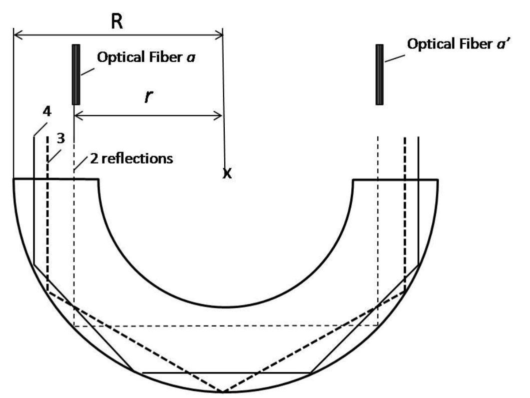

Figure 2. Light propagation in *xy* plane of the detection element for different parameter *r*.

as well. Each pair of POFs (2*a*-3*a*, 2*b*-3*b*, …, 2*m*-3*m*) together with the section of the semi-cylinder which lies between them constitutes an elementary refractometric transducer. The POFs of each pair are optically coupled via the internal reflection of light at the cylindrical interface between the element´s material and external medium. The internal reflection at the interface is a function of the refractive index of the two media. The optical transmission is high when the elementary transducer is in the air and it is low when the elementary transducer is in a liquid. The difference in optical transmission is exploited for the discrimination between the two external media: the air and liquid. The individual transducers of the array are interrogated in sequence (via the respective POFs) using the remote optical transmitters and receivers (not shown in Fig. 1). The liquid level is associated with the lowest transducer of the array which exhibits high optical transmission.

It is possible to see in Fig. 2 that the optical coupling of the two optical fibers takes place under certain distance of the optical fibers from the cylinder axis, *r*. Therefore, the optical transmission varies with *r* and there are several transmission zones which correspond to different parameter *r*. In different transmission zones, the optical rays have significantly different angles of incidence ϑ_i at the cylindrical surface of the element. This property can be exploited for the discrimination between two different liquids of different refractive index (which results in different critical angle θ_c). It requires two pairs of transmitting-receiving POFs in the same elementary transducer for the discrimination of the liquids. The fibers of each pair have to be placed at different dimensionless distance from the element's axis $\Lambda=r/R$, *R* is the external radius of the detection element. Table 1 presents the considerations for the choice of the angle of incidence θ_i and dimensionless distance Λ for some particular cases.

Table 1. Considerations for the choice of angle of incidence θ_i and dimensionless distance Λ.

	Function	Angle of incidence θ_i	Distance Λ
1.	Discrimination between the air and water	$\theta_{c\ air} < \theta_i < \theta_{c\ water}$ (42.6° < θ_i < 64.0°)	0.71 or 0.87 *(2 or 3 serial internal reflections)*
2.	Discrimination between the air and/or water, and gasoline	$\theta_{c\ water} < \theta_i < \theta_{c\ gasoline}$ (64.0° < θ_i < 76.5°)	0.92 or 0.95 or 0.97 *(4, 5 or 6 serial internal reflections)*
3.	Discrimination between the air and gasoline - Not necessary, because condition 2 is more strict	$\theta_{c\ air} < \theta_i < \theta_{c\ gasoline}$ (42.6° < θ_i < 76.5°)	

The number of elementary transducers in the array *M* is depends on the height of particular tank or reservoir and the required resolution in accessing the level of liquid. The total number of optical fibers in the sensor is 2*M* in the liquid-level measurement mode and 4*M* when the discrimination between two different liquids is implemented in addition to the liquid level measurement. As some applications require hundreds of elementary transducers, the total number of optical fibers in the sensor may be very large. The operation of the detection element in the reflection mode requires only a half of the optical fibers necessary in the transmission mode, but instead directional optical couplers are necessary for the separation of the input and output optical radiation. We envision that with the advance of new types of optical fibers, such as muli-core POFs with dozens or hundreds of cores in the same cladding and POFs of small bending radius, the size of the optical fiber bundles would be reasonably small even in large arrays.

3. RESULTS OF THEORETICAL AND EXPERIMENTAL STUDY

We found the properties of the elementary transducer by numerical ray-tracing of light propagation in the detection element, using the concepts of the geometrical optics. The mathematical model, ray-tracing algorithm and respective computer program were reported previously.[6-8] Following are results obtained for the detection element and optical fibers of polymethylmethacrylate (PMMA) of the refractive index n=1.4828 @ λ=920 nm in the case of symmetric position of optical fibers of a dimensionless core diameter $\Phi=2a/R$, *a* is the radius of the optical fiber core.

The propagation of light in the semi-cylindrical detection element is illustrated in Fig. 3, which shows two orthogonal projections of the element and light trajectories in it. Due to the curvature of surface in one direction, the element has focusing properties in *xy* plane but no focusing properties in *z* direction. Therefore, the optical beam spreads in *z* direction and only small part of it is collected by the receiving optical fiber at the element´s output. However, the respective optical loss is generally acceptable because other losses are not too large and the optical power budget of the sensor can be significantly superior to these and other losses.

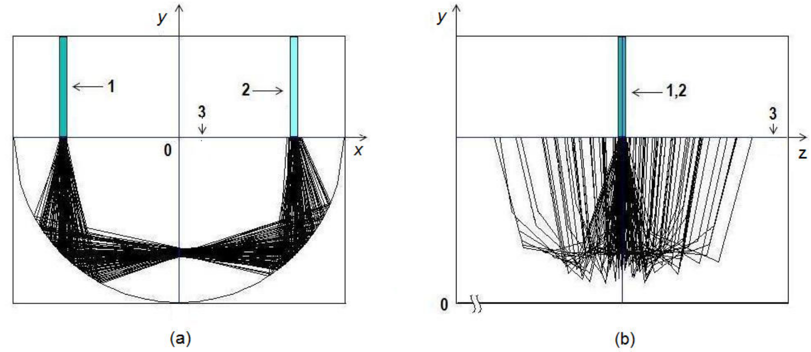

Figure 3. Simulated light trajectories in the semi-cylindrical element under Φ=0.049, Λ=0.7 and NA_1=NA_2=0.5: (a) – *xy* projection, (b) – *yz* projection. (1) and (2) are the transmitting and receiving POF, respectively, and (3) is the detection element.

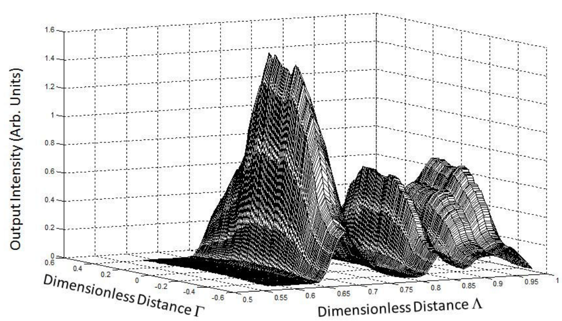

Figure 4. Measured light intensity distribution over the output facet of the detection element for Φ_1=Φ_2=0.049 , NA_1=NA_2=0.5 and a symmetric variation of the parameter Λ_1=Λ_2.

The existence of a series of transmission zones in the element and the spread of the optical beam in *z*-direction was verified experimentally by scanning the output facet of the detection element with the optical fiber tip and measuring the received light intensity. The respective data are shown in Fig. 4.

The established zone nature of optical transmission in the element confirms the possibility of discriminating between different liquids with optical fiber pairs placed at different dimensionless distance Λ in the transducer.

The theoretical data showing the relative optical transmission $T^*=I_{out}(n)/I_{out\ air}$, $I_{out}(n)$, $I_{out\ air}$ is the output light intensity when the sensor is in the air and liquid, respectively, vs. the external refractive index *n* for various dimensionless distances Λ and Φ=0.049, NA_1=NA_2=0.5 are plotted in Fig. 5. The graphs in Fig. 5 show that there is a sharp step in optical transmission *T** which can be exploited for the discrimination between the air and a liquid. In addition, the step position on *n*-axis can be selected in such a way as to discriminate between the liquids of different refractive index. For example, for the discrimination between the gasoline (*n*=1.442) and water (*n*=1.333) which can be beneath the gasoline in a tank, a step in optical transmission at about *n*=1.4 is necessary. The graphs for *Λ*=0.925 and *Λ*=0.95 show the required behavior.

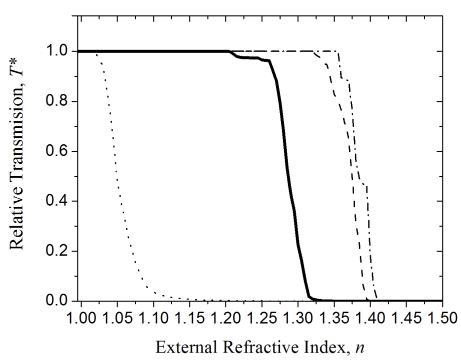

Figure 5. Theoretical relative transmission *T** vs. external refractive index *n* for Φ=0.049, NA_1=NA_2=0.5 and different dimensionless distance: Λ=0.7 (···), 0.855 (-), 0.925 (- - -), 0.96 (- . -)

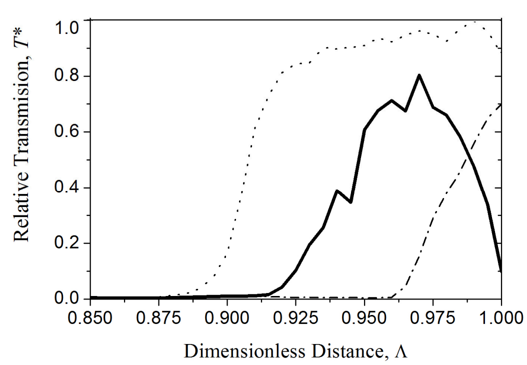

Figure 6. Experimental relative transmission *T** vs. dimensionless distance Λ for Φ=0.049, NA_1=NA_2=0.5 and different external media: air (- - -), water (···), gasoline (-) and diesel fuel (- . -).

The experimental relative transmission T^* against the dimensionless distance Λ for different external media is shown in Fig. 6. These data correlate well with the predicted behavior and can be used for selecting the parameter Λ for particular application of the transducer.

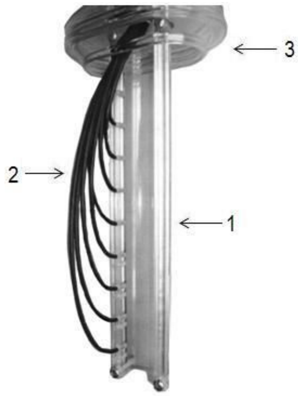

Figure 7. The prototype plastic optical fiber liquid-level sensor operating in the reflection mode. (1) – detection element, (2) – POFs, (3) - flange.

The prototype liquid-level sensor was implemented in the reflection operational mode (Fig. 7). It successfully measured the level of various liquids during numerous cycles of filling and emptying the tank where it was installed.

4. CONCLUSIONS

The sensor described in this work can measure the level of liquids and, simultaneously, discriminate between different liquids in a tank or reservoir. It is a discrete-type sensor which employs an array of elementary refractometric transducers which are implemented in a single detection element of plastic in a form of a relatively long semi-cylinder. The transducers of the array are coupled to the remote optical transmitters and receivers via the plastic optical fibers. The use of a single detection element of plastic makes the sensor significantly simpler and cheaper than the existing arrays of point transducers of silica glass. New types of plastic optical fibers such as multi-core fibers would allow the designers to reduce the total amount of the optical fibers in this sensor. This would contribute to its competitive advantages over the existing sensors.

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REFERENCES

[1] Breyer, F., Lee, S. C. J., Randel, S. and Hani, N., "PAM-4 signaling for gigabit transmission over standard step-index plastic optical fibre using light emitting diodes," 34th European Conf. on Optical Communication 1-2 (2008).

[2] Ziemann, O. and Poisel, H., "Short distance optical connections for home networks, sensing and mobile systems," in Optical Fiber Communication Conf. 1-3 (2007).

[3] Jiménez, F., Arrue, J., Aldabaldetreku, G., Duran, G., Zubia, J., Ziemann, O. and Bunge, C. A., "Analysis of a plastic optical fiber-based displacement sensor," Appl. Opt. 46, 6256-6262 (2007).

[4] Fukumoto, T., Nakamura, K. and Ueha, S., "A POF-based distributed strain sensor with intrinsic memory effect", Proc. SPIE 6770, 67700P (2007).

[5] Montero, D. S., Vazquez, C., Möllers, I., Arrúe, J. and Jäger, D., "A self-referencing intensity based polymer optical fiber sensor for liquid detection," Sensors 9, 6446-6455 (2009).

[6] Svyryd, V., Khotiaintsev, S. and Swart, P., "Linear and steplike characteristics in an optical fiber refractometric transducer with hemispherical detection element" Optical Eng. 42(5), 1383-1389 (2003).

[7] Svyryd, V., Khotiaintsev, S. and Swart, P., "Novel optical fiber refractometric transducer employing hemispherical detection element" Optical Eng. 41(4), 779-787 (2002).

[8] Khotiaintsev, K., Undergraduate thesis, Universidad Autónoma de Puebla, México (2005).