Optical-Fiber Refractometric Sensor with Semi-Cylindrical Optical Detection Element for Measuring the Level of Gasoline

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Abstract

We present a novel optical fiber refractometric sensor with semi-cylindrical optical detection element. A pair of the multimode optical fibers is attached symmetrically to the element's flat plane. The optical coupling of the two fibers due to internal reflection of light from the element's cylindrical surface is sensitive to the refractive index of the surrounding medium. We exploit several internal reflections in series and partial focusing of the optical beam by the element's cylindrical surface to achieve enhanced sensitivity to the refractive index of the surrounding medium and reduced intrinsic optical loss in the transducer. We show theoretically that the transducer, in particular, can discriminate between the air and gasoline. We also present experimental data obtained with plastic detection element, which confirm our theoretical results. A vertical array of such transducers employing a relatively long single semi-cylindrical detection element can access the level of gasoline in automobile tanks.

1. Introduction

Fiber optic sensors offer many advantages over traditional mechanic, electric and other sensors. Previously, it was mainly the silica-based optical fiber that was used in sensors. Recently, the significant advance in quality of plastic optical fibers (POF) opened many new applications for optical transmission and optical sensing. The POFs are attractive for the market because they are multimode devices of a relatively large core diameter, which are easy to handle and install. The POF-based transmission systems use simple and non-expensive components such as visible or near-infrared light-emitting diodes (LEDs), simple plug connectors, branching devices etc., the overall system cost is low and its maintenance is simple. Currently, POFs allow the rates of data transmission of up to 10 Gbit/s over distances of about 300 m [1]. Similarly to silica optical fibers, POFs are immune to electromagnetic interference and noise and have many other advantages common to optical fibers of other types.

POF applications include relatively short-haul local area networks (LANs) in offices, buildings, small campuses. Another emerging application is optical data transmission (analog and digital) on board of cars, trucks, trains etc. A distinctive feature of the transportation vehicles is a need in monitoring of different physical quantities relating to the operation of the vehicle (temperature, pressure, level of different liquids in reservoirs and tanks etc.). Therefore, it is of great practical interest to compliment the optical communications with optical sensing on board a vehicle. For the sake of compatibility, the optical sensors should operate via same POFs as the rest of the on-board optical network.

Some de-facto standards for on-board automotive optical LANs exist already. On particular, the Domestic Digital Bus System (DB2) specifies a ring system which connects different devices, such as radio, TV, CD changers, and navigations systems in vehicles [2]. The Media Oriented Systems Transport Multimedia and Control Networking Technology (MOST) specification is a recommendation for multimedia capable networks in automobiles [3], while the Byteflight system deals with the connection of airbag systems with other control components [4].

Liquid level sensing is important in all automotive applications. There exists a wide range of sensing methods suitable for determining the liquid level. They include mechanical, electrical and optical methods, and their combinations.

Electrical liquid level sensors are employed for accessing the level of fuel in automotive tanks at

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present. In these sensors, the level of the fuel is measured with an electrical signal generated by a variable resistor controlled by floater within the tank. These sensors are simple and cheap, but their resolution is relatively low. Also, electrical wires in a flammable environment present a potential hazard. Optical fiber sensors offer several advantages for these applications, due to the dielectric nature of the optical fibers. The advantages of optical sensors are not limited to the absence of electrical conductivity. They also feature absolute immunity to electromagnetic fields, high resistance to chemical corrosion and absence of a spark hazard. These features make the optical sensors ideal candidates for use in fuel tanks.

There are four principal classes of optical sensors: intensity, phase, polarization, and frequency sensors. The sensors belonging to each of these classes differ significantly in their performance and also cost, which almost directly relates to the complexity of the measurement principle employed. The existing optical sensors for liquid level sensing exploit a wide range of techniques. In the automotive applications, the most important factors in choosing a sensor are sensor simplicity, the ease of processing of signals, a low sensor cost, and simple maintenance. Among the four sensor classes which we mentioned, the intensity-type (amplitude) fiber sensors are the simplest to implement due to easiness of intensity measurement, in contrast to phase and polarization measurements. Also, the intensity-based optical sensors are fully compatible with POFs. Therefore, the intensity optical sensors are the most promising candidates for the automotive applications.

Intensity-type sensors can rely on many principles. One of them is the optical refractometry, which is based on the determination of the refractive index of substances, n. The refractive index n is related to many physical quantities of substances. In the case of liquids, quantities such as temperature, pressure, the concentration of soluble substances (for instance, salt, sugar etc.) can be found indirectly by measuring the refractive index. In addition, refractometry allows one to discriminate between different substances, since each substance or material has a different refractive index.

Some POF sensors suitable for automotive applications are already reported, such as a simple and effective plastic optical sensor for temperature measurement [5], and plastic refractometric sensor which employs a tapered section of graded-index POF [6]. The possibility of refractometric liquid-level measurement with the refractometric evanescent-field sensor composed of multiple sharp bends in an extended single POF or in an array of POFs has been successfully demonstrated in experiments with water [7]. But, the vertical resolution of such a sensor is limited by the finite size of employed fiber loops, and it might be difficult to accommodate many fiber loops in a tank. Here, we present a novel optical fiber refractometric sensor which employs a semi-cylindrical optical detection element. It can be employed as a point sensor, or in a form of vertical array, in which case it can access the level of a liquid, such as gasoline, in a discrete manner in a tank or reservoir. Following is the description of the sensor and its performance characteristics.

2. Optical-fiber refractometric sensor

The sensor that we treat here consists of a semi-cylindrical optical detection element which is connected to a pair of optical fibers as shown in Figure 1. The optical detection element is of transparent dielectric material. In this work, we consider a detection element of polymethyl methacrylate (PMMA) of the refractive index n=1.48 at λ=940 nm. We employ a section of hollow plastic semi-cylinder in order to minimize the mass and cost of the material, but a solid semi-cylinder can be employed as well.

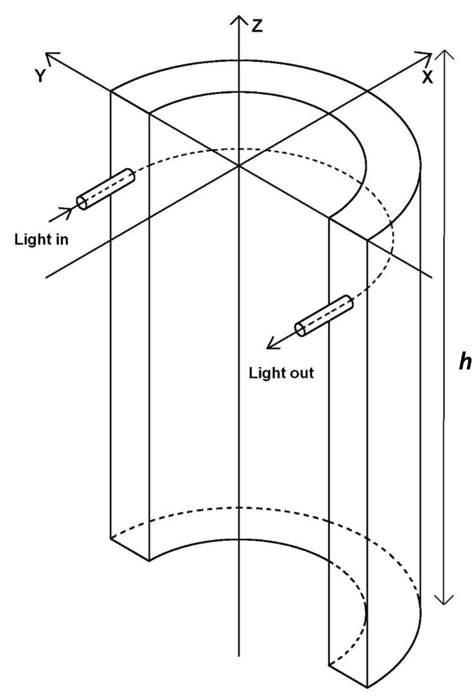

Figure 1. Schematic view of the optical sensor.

The operational principle of the sensor is illustrated in Figure 2, which shows a cross-section of the optical detection element and connecting optical fibers. One of them is a lead-in, and another a lead-out optical fiber. The light from a remote light source (a near-IR light-emitting diode not shown in the figure) is coupled via the lead-in optical fiber (2) to the interior of the detection element (1). The light propagates by means of serial internal reflections at the external cylindrical surface of the element until it reaches the output plane of the detection element. At this plane, some of the light is coupled to the core of the lead-out optical fiber (3) and brought via this fiber to a remote photometer (not shown in the figure).

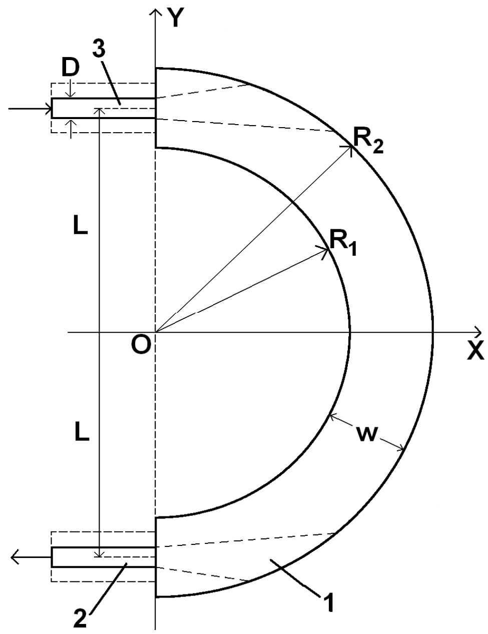

Figure 2. Generic refractometric transducer consisting of semi-cylindrical transparent dielectric element (1) integrated with the lead-in (2) an lead-out (3) optical fibers.

When the element is in the air, the internal reflection is rather strong (under a proper position of the optical fibers relatively to the detection element). When the element is in a liquid, the internal reflection at the external cylindrical surface diminishes or completely vanishes due to a smaller difference in refractive indices of the two media. Therefore, optical transmission of the detection element $T=I_{out}/I_{in}$, I_{out} and I_{in} is the output and input light intensity, respectively, is a measure of the external refractive index n.

The difference in the optical transmission of the detection element in the air and in a liquid, in particular, serves for the discrimination between the two media and is a basis for liquid-level measurement with vertical arrays of such sensors (In such a case, the sensor output is interpreted in a binary manner).

We relate all geometrical parameters of the sensor to the external radius of the detection element R_2 and use the following dimensionless quantities to describe the geometry of the sensor: the dimensionless core diameter of the optical fibers $\Phi=D/R_2$, the dimensionless distance of the optical fibers from the element plane of symmetry $\Lambda=L/R_2$, and the dimensionless internal radius of the detection element $\rho=R_1/R_2$.

The optical transmission T is a function of optical and geometrical parameters of the optical detection element and optical fibers. In view of complex relation between these parameters, we employed an iterative design procedure in order to find the optimum combination of sensor parameters. This procedure included the analysis of sensor transmission against the external refractive index, which was performed by means of numerical ray-tracing algorithm and also experimentally. The analysis provided data for corrections to the initial design. The procedure was repeated until a sufficiently large difference in response of the sensor to the air and the gasoline was achieved.

We performed the numerical ray-tracing by means of the mathematical model, computational algorithm and computer program in Visual Basic programming language described in [8]. The analysis was performed for the rays in the x-y plane only, due to limitations of the existing software. An example of calculated ray trajectories in the x-y plane of the detection element in the case when the external medium is the air is shown in Figure 3.

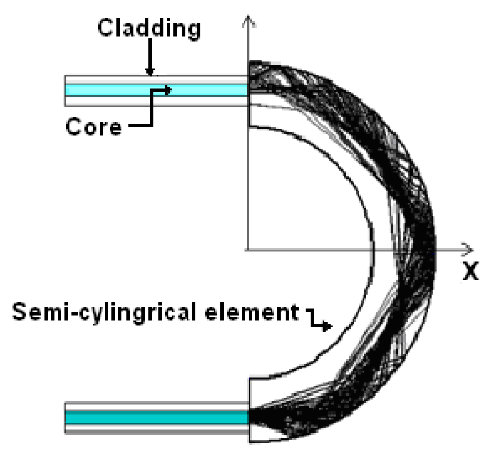

Figure 3. Ray trajectories in the detection element under Φ=0.075, Λ=0.86, NA_{in}=0.485, NA_{out}=0.095.

The numerical analysis yields also the optical transmission T against the external refractive index with sensor geometry and material constants as parameters. In practice, it is convenient to characterize the sensor performance in terms of its relative transmission $T^*= I_{out}(n)/I_{out\ air}$, because this quantity does not include the input light intensity I_{in} which cannot be accessed experimentally [9]. The graphs of the calculated relative transmission T^* vs. the external refractive index n obtained under quasi-optimum combination of sensor parameters for various dimensionless distance Λ are shown in Figure 4.

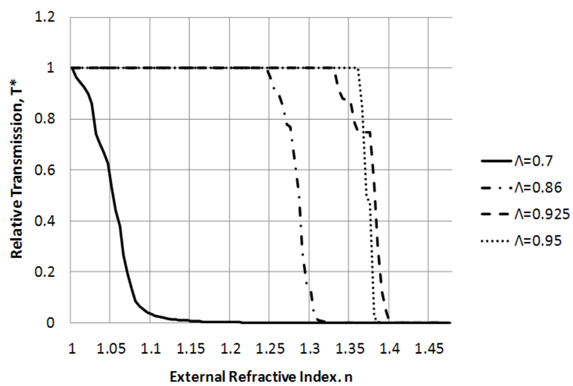

Figure 4. Calculated relative transmission *T vs. the external refractive Index *n* under *Φ*=0.075, *NA*$_{in}$=0.485, *NA*$_{out}$=0.095.**

The data in Figure 4 show the effect of the dimensionless distance Λ on the response of the sensor to different external refractive index. The refractive index of the gasoline is about 1.442 at λ = 940 nm. For the reliable discrimination between the air and gasoline the step-like relative transmission characteristic T^* in the range n=1.3…1.4 is appropriate. Therefore, any of the three dimensionless distances Λ, which yield the relative transmission function in the specified range of external refractive index n: Λ=0.86, 0.925 and 0.95 can be employed in the sensor.

We have also checked the suitability of some commercially available POFs shown in Table 1 for the

Table 1. Some commercial POFs.

Fiber Type	Profile	*NA*	Core Radius [μm]	$\lambda_{opt\ tx}$ [nm]
Standard-POF	SI	0.5	490	650
PCS	SI	0.37	100	850
MC37-POF	SI	0.5	65	650
GI-POF	GI	0.39	450	650

basically the same sensor. The calculated relative transmission T* against the external refractive index under the dimensionless distance Λ=0.95 and identical characteristics of both optical fibers is plotted in Figure 5. From these data, it is possible to draw a conclusion that the standard SI POF is the less suitable fiber for this application, because of the sloping form of the respective relative transmission function T^*.

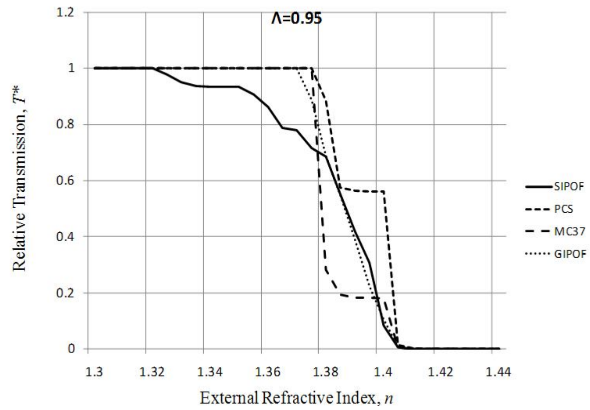

Figure 5. Calculated relative transmission *T vs. the external refractive index *n* for some commercial POF.**

The three other POFs are, generally speaking, suitable for the present application, although the optimum choice between them requires further investigation.

3. Experiment

The experiment was performed with a relatively large physical model of the sensor. The schematic of experiment layout is shown in Figure 6. The light source was a high radiance infrared GaAlAs LED with a peak emission at a wavelength of λ=940 nm, spectral bandwidth of 45 nm and an angular beam full width of 40º. This LED was excited by a triangular current wave generated by a waveform generator, of amplitude of 14 mA at a frequency of 100Hz. The generator was connected in series to the LED and a resistor of 330 Ω. The LED was coupled to the lead-in optical fiber. The triangular wave form was chosen in order to identify a possible saturation of the optical receiver at the sensor output.

The optical fibers were bundle of thousands of optical fibers of very small diameter (about 20 μm each one). The overall diameter of each of two bundles was of 3 mm. We used a diaphragm with circular aperture of various diameters in order to model physically the optical fibers of different core diameter. The effective angular aperture of the lead-in optical fiber (bundle) was controlled when necessary by the excitation angle of the optical fiber at its input. The two optical fibers were in optical contact with the optical detection element at symmetric points on its two side surfaces. An adequate index-matching liquid was employed at the optical contact area in order to avoid an excessive reflection at the contact interface. The fiber terminations that were in contact with the detection element were mounted on two micrometric-precision *x-y-z* translation stages which allowed us to adjust the position of the two fibers in any plane relatively to the detection element. In particular, the translation stages allowed us to change the position of the fiber end faces relatively to the sensor plane of symmetry. The semi-cylindrical detection element had an external radius R_2=20 mm, and internal radius R_1=14 mm (In practical device, the external radius of the optical detection would be reduced many times, and common telecommunications-grade optical fibers would be used instead of optical fiber bundles).

The photo detector was Ge photo diode of a large sensitive area of 25 mm^2, which was coupled to the transimpedance amplifier and then to a photometric unit. The data were stored in a computer via the RS232 interface and finally processed.

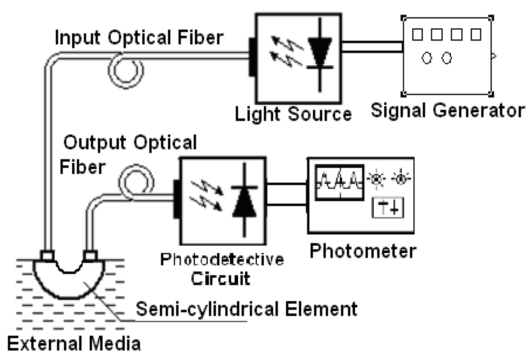

Figure 6. Schematic of experiment layout.

The transducer transmission characteristic was accessed in the following way. The two optical fibers were set initially at the minimum physically possible distance about 0.5*R* (Λ=0.5). Then, the distance of the two fibers from the sensor plane of symmetry was increased in a discrete manner with increments of Λ=0.005 until the edge of the optical detection element was reached at about Λ=0.99. At each discrete position of the optical fibers, the light intensity at the sensor output measured, and respective data stored in the computer. The measurements were performed first in the air and then with the cylindrical working surface of the sensor immersed in various liquids, such as distilled water and gasoline. The relative transmission was calculated, processed statistically, and the respective graphs plotted (we averaged results of ten individual measurements).

Alternatively, the optical transmission of the sensor was measured with various external media (the air and various liquids) under the fixed position of the two optical fibers. This excluded possible errors in optical fiber position when accessing optical transmission under different external media.

4. Results

The experimental data on the sensor transmission in the air against the dimensionless distance Λ is plotted in Figure 7. The peaks observed in the graph are due to the coupling of the two optical fibers by two, three, four or more sequential reflections of light at the cylindrical working surface of the detection element. This corresponds to some discrete dimensionless distances Λ, while intermediate distances do not provide for any optical coupling, or provide for a reduced one.

The transmission in liquids is always less than the transmission in the air, because of smaller reflectivity of the sensor working surface when immersed in a more optically dense medium. Therefore, the zero or near-to-zero transmission regions in the graph in Figure 7 are useless; it is the peak transmission regions which correspond to strong coupling between the two optical fibers that can be exploited for the discrimination between the air and the liquid, and, therefore, for liquid-level measurement.

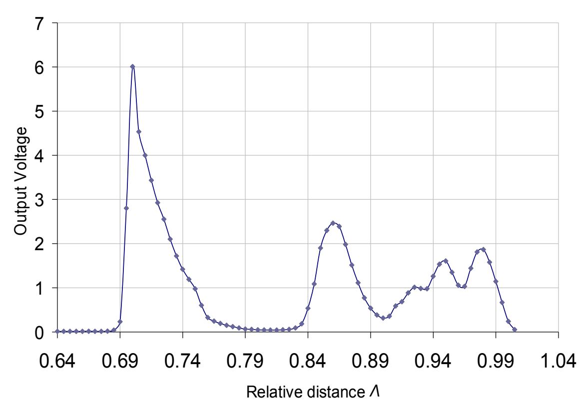

Figure 7. Sensor output voltage vs. optical fiber position Λ when the sensor is in the air.

The dimensionless distances Λ which correspond to the observed peaks in optical transmission in the air are given in Table 2.

The experimental data on the relative transmission of the sensor in distilled water and gasoline are plotted in Figure 8 for two different dimensionless distances Λ and the same optical fiber dimensionless diameter

Φ=0.033. The parameter Λ=0.925 secures more reliable discrimination between the air and gasoline, and, therefore more reliable operation of the respective liquid-level sensor.

Table 2. Transmission peaks in the air.

Transmission Peak no.	Dimensionless Distance, Λ
1 º	0.70
2 º	0.86
3 º	0.925
4 º	0.95
5 º	0.975

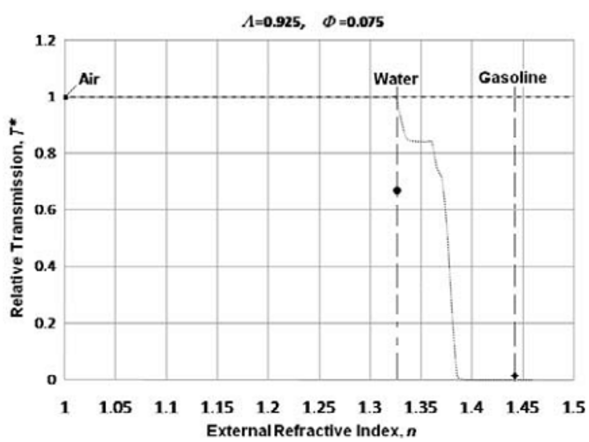

Figure 8. The predicted (······) and observed relative transmission under Φ=0.075, NAin=0.485, NAout=0.095. The experimental points correspond to the distilled water (•) and gasoline (♦).

5. Conclusions

We investigated theoretically and experimentally the response of a novel optical-fiber refractometric sensor with semi-cylindrical optical detection element to the external refractive index. In particular, we investigated the transmission of this sensor in the air and gasoline with the aim to establish the possibility of using this sensor for accessing the level of gasoline in automotive fuel tanks. We investigate the effect of various geometrical and optical parameters of the sensor on its performance characteristics and found the quasi-optimum parameter combination which secures a reliable discrimination between the air and gasoline. The observed response of the sensor is sufficient for practical purposes. A vertical array of such transducers implemented in a single semi-cylindrical detection element of proper length can access the level of gasoline in automobile tanks.

6. Acknowledgment

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