

Concepts of fibre optic intensity sensors for liquid level measurement

MICHAŁ BORECKI, JERZY KRUSZEWSKI

Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warszawa, Poland.

KRZYSZTOF KOPCZYŃSKI

Institute of Optoelectronics, Military University of Technology, ul. Kaliskiego 2, 00-908 Warszawa, Poland.

The paper presents an analysis of two new fibre optic liquid level sensors that make use of the reflection phenomenon. The first sensor is of a threshold type. Its head is the knife-edge type fibre tip. The second sensor is of a continuous processing type. Its head has a rubber membrane. These sensors have two major advantages, *i.e.*, simple construction and one fibre used for sending and receiving information.

1. Introduction

There are two major types of liquid level sensors that are currently in use: threshold and continuous processing ones. Threshold processing sensors are used to obtain information about particular level crossing. Continuous processing sensors are applied when information about the level from a predefined range is needed. The commonly known techniques of liquid level measurements take advantage of: the phenomenon that the tested liquid has a higher conductivity than air, the liquid level pressure dependence, time of acoustic signal travel between liquid stage and the bottom. The constructions of the sensors are named: electrical, mechanical-electronic, and acoustic ones, respectively. The acoustic sensors are quite complicated and for constructional reasons are mainly applied to measurements of water level in deep and large reservoirs. The electrical and mechanical-electronic sensors can be simple in construction but their disadvantage lies in the fact that electric circuits have to be located under the liquid level. The disadvantage can be overcome by replacing the electric circuits with optoelectronic ones and electric cables with optic fibres. Currently, widely known is the threshold optoelectronic sensor of water level (that uses two optic fibres and a prism), which according to [1] is presented in Fig. 1. The main drawback of this sensor is the problem with optic fibres bonding to the particular spots on the prism. Usually this is done by gluing. Moreover, when using the sensor these spots are under the risk of breakage, particularly during the head cleaning. Due to this it is practically impossible to measure the level of viscous

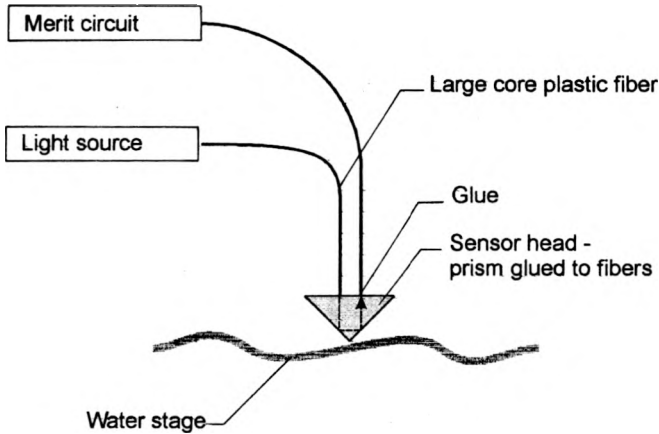


Fig. 1. Standard fibre optic water level sensor.

liquids such as oil in other than laboratory conditions. The research conducted by the authors has led to a proposition of two fibre optic liquid level sensors of simple mechanical construction, and these are presented below.

2. Threshold processing sensor with the needle head type

The idea of a sensor with the needle head type is presented in Fig. 2. This type of head utilises the Fresnel reflection phenomenon on fibre tip. We can define two stable states of fibre tip: submersion and emergence. In submersion radiation reflected from the fibre tip is lower than in emergence due to a decrease in the difference between refraction coefficients of the core and the liquid. The authors investigated three kinds of needle point: flat, knife-edge and one-side sloped. The situation observed when changing the liquid level on a single flat needle is presented in Fig. 3. The reflected signal level of the head submersed in and emerging from water vs. time characteristic is presented in Fig. 4. Water is here used as a sample liquid. Situations marked with "b" and "d" in Fig. 3 and 4 are described in [2] under assumption of non-linear ray tracing. These situations can affect sensor operation. The degree of influence can be analysed using Fresnel reflection coefficients [3] to estimate reflected power distribution. The results assessed for water surface with $n_w = 1.33$, and for the fibre core with $n_c = 1.492$ are presented in the table.

Table. Reflected power distribution received from flat fibre tip.

Situation in Fig. 3	a-d	b		d		
Power [a.u]	S_p	S_{b1}	S_{b2}	S_{d1}	S_{d2}	S_{d3}
	100	3.89	1.93	0.33	2	1.96

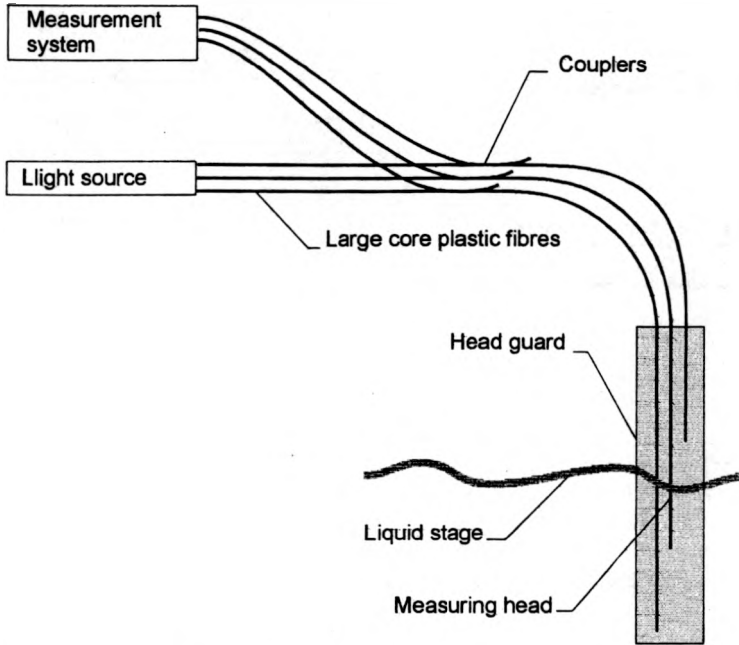


Fig. 2. Concept of multilevel needle head type sensor.

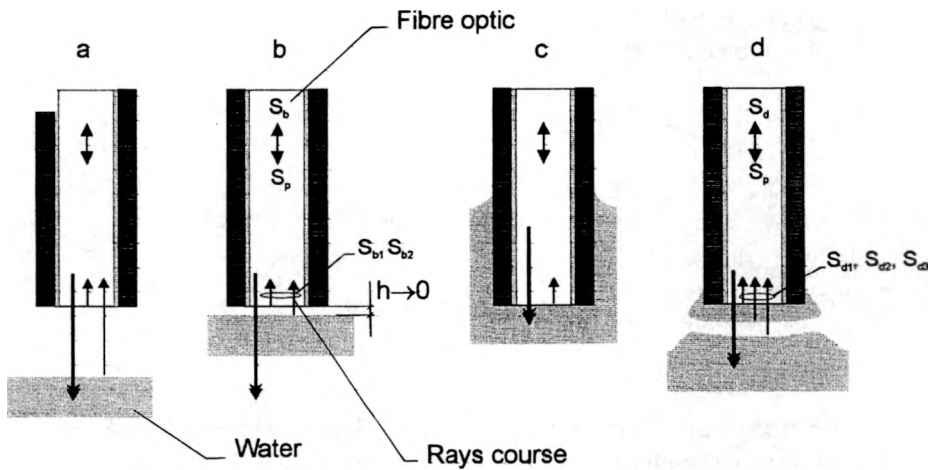


Fig. 3. Situations occurring during liquid level changes on a flat fibre tip.

The data gathered shows that in extreme cases flat tip configuration of the needle may cause wrong level detection. This can occur when the flat liquid surface level rises slowly and stops just under the head at a short distance. To warrant the right level detection in each situation we can use the sharpened needle type heads that are presented in Fig. 5. These heads ensure that smaller portion of radiation is reflected from water in the measured signal and the difference in reflected signal levels is

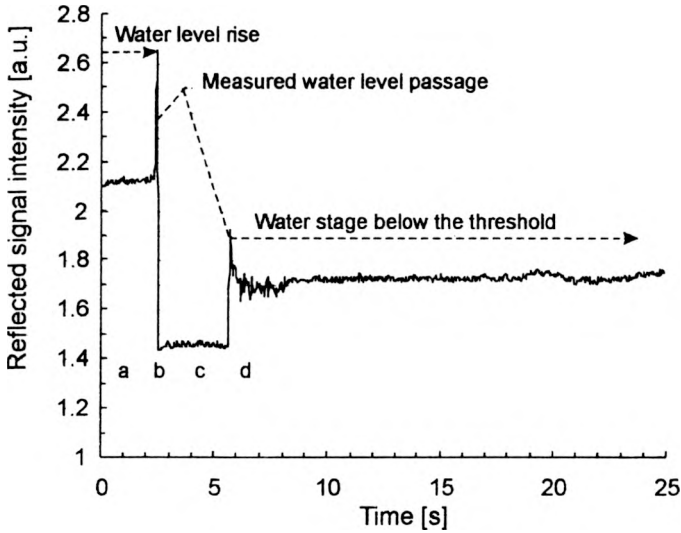


Fig. 4. Reflected signal level vs. time characteristic for situation presented in Fig. 3.

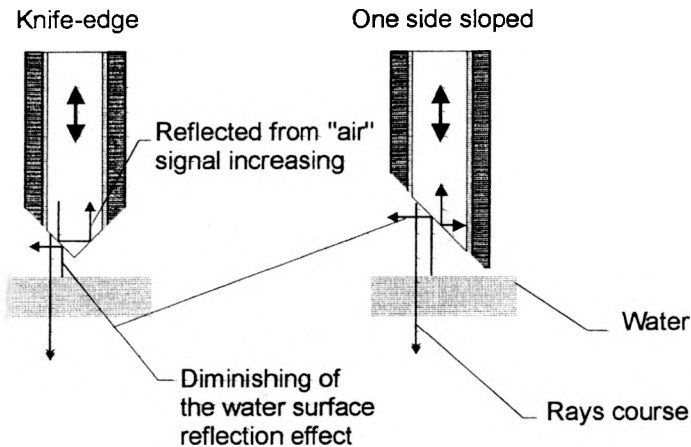


Fig. 5. Sharpened needle-type heads.

bigger than in the case of the head with flat fibre tip. The signal levels of submersion and emergence vs. time characteristics for both needle heads are shown in Fig. 6. The signal received from a knife-edge needle head is much stronger than for a one-side sloped and a flat needle. It is for these reasons that the knife-edge needle should be chosen for the threshold liquid level sensor.

The received signal level vs. time characteristic shows that it is possible to simultaneously detect a few liquid levels using one detection channel. This can be done using optical sum of reflected signals from heads, processed in one opto-electronic interface. To simplify the detection it seems reasonable to use the same radiation power for all optic fibres powering the heads. There are two basic ways

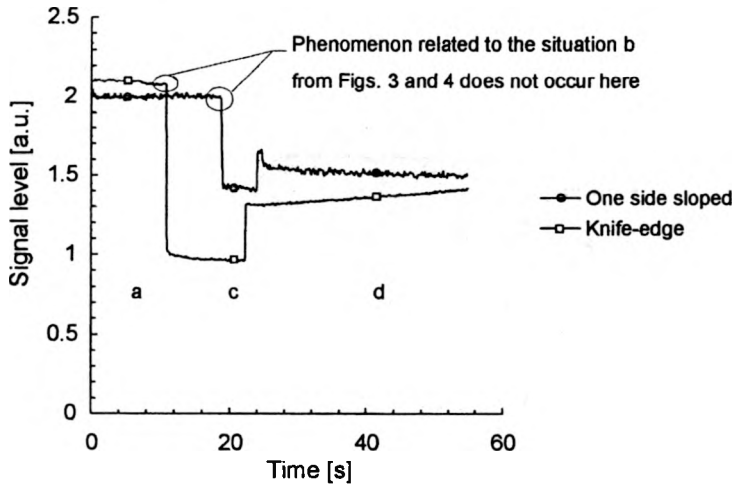


Fig. 6. Signal level characteristic vs. water stage changes for sharpened needle-type heads.

of fulfilling this task: an independent powering of all fibres with stable optic radiation and common powering of the fibres with beam division. This division can be made by means of diffraction grating, planar divider or spacial beam distribution. The powering of fibres by means of special beam distribution seems to be most effective way to be applied in practice as far as a few level sensor is concerned. The number of detected liquid levels being crossed equals the numbers of needle heads and powered fibres. The three or two level crossed sensors are most common due to their usefulness. An example of calculation result for the powering of three optical fibres is described below. The sample realisation of an optic powering system configuration is presented in Fig. 7. Values of the shift of the fibres front were obtained from

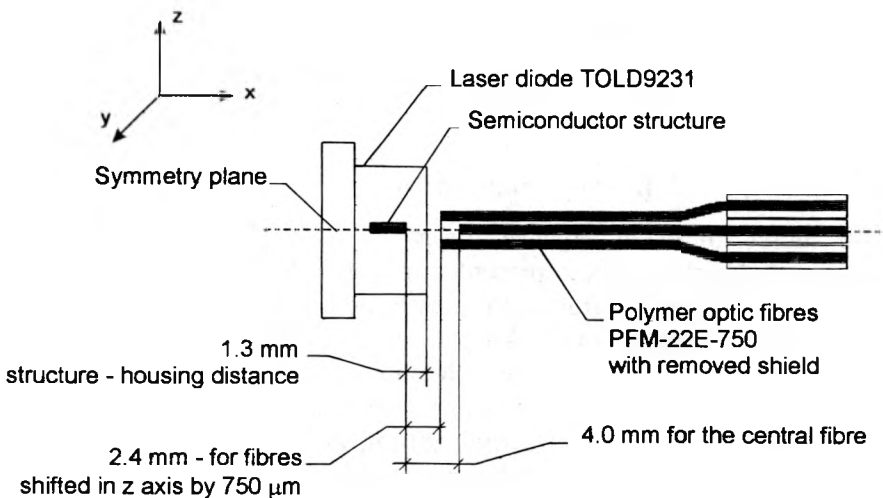


Fig. 7. Idea of the powering of three fibres from one laser diode with equal power.

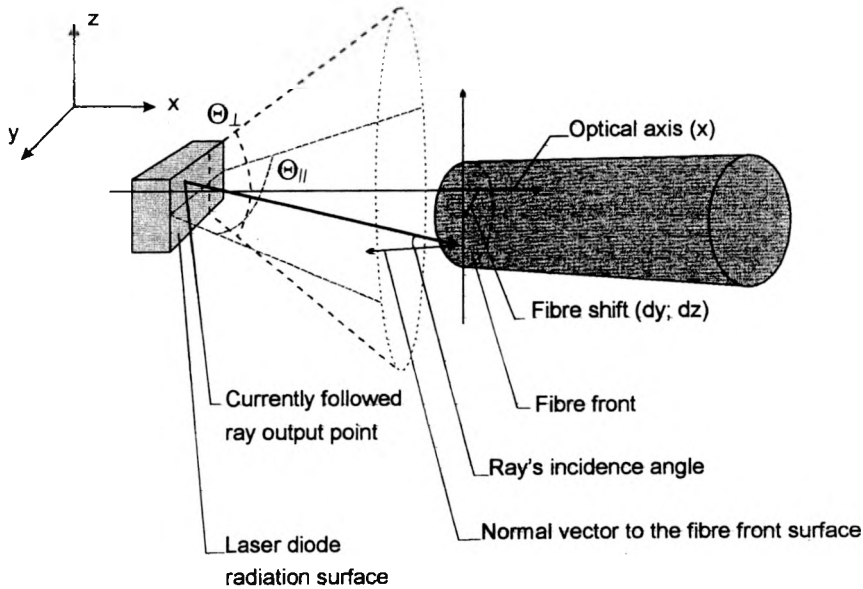


Fig. 8. Simulation of direct fibre coupling with semiconductor laser diode structure.

computer simulation of a direct coupling of laser diode with optic fibre. The idea of this simulation is presented in Fig. 8. For the simulation the following data were assumed:

1. Laser diode TOLD9231: beam divergence $\theta_{\perp} = 10^{\circ}$, $\theta_{\parallel} = 32^{\circ}$, in accordance with Gaussian distribution; the laser radiating area is $100 \mu\text{m} \times 1 \mu\text{m}$ in the coordinates x ; y with the homogeneous radiation density.

2. TORAY PFM 22E-750 optic fibre: coating thickness ≈ 0 (in this fibre the coating was chemically laid on the core), core diameter = $750 \mu\text{m}$, core refraction coefficient = 1.492, coating refraction coefficient = 1.419.

The simulation was based on NRT techniques, taking into account the Fresnel effect. The Box-Muller method was applied to obtain angular normal distribution of the radiation beam

$$\text{Norm}(\mu, \sigma) = \mu + \sigma \sqrt{-2 \ln(\text{rnd}(1))} \cos(2\pi \text{rnd}(1)) \quad (1)$$

where: $\mu = 0$, σ stands for the divergence angles.

The simulation results obtained are presented in Fig. 9. They show that there is a possibility of identical power inserting into three optic fibres at the height of 15% of the total power each, which means making use of 45% total beam power. This solution is comparable to the division of collimated beam power done on the diffraction grating, because power losses in such a system amount to: about 20% for the collimator, about 30% for the diffraction grating and 5% for the fibre front (which means making use of 48% total beam power).

When the proper beam division is made this sensor calibration is quite elementary. It is enough to set threshold values for slope detection. A laboratory

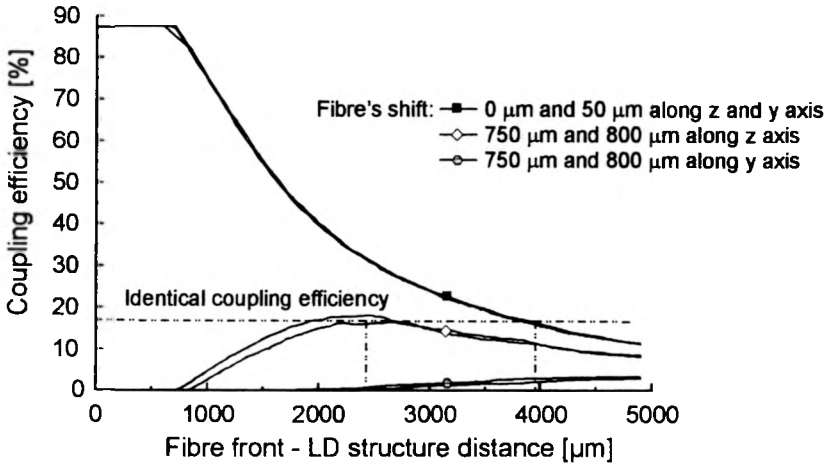


Fig. 9. Simulation results of the direct coupling between optic fibre and laser diode.

version of this sensor was realised on the basis of detection system described in [4]. In this configuration, there were no problems with noise or wrong liquid level detection when 3 mW laser diode was used as a powering device.

3. Continuous processing membrane sensor

The construction of a fibre optic continuous processing membrane sensor is similar to semiconductor pressure sensor based on FET structure introduced in [5]. The idea of the fibre optic membrane sensor is presented in Fig. 10. The sensor utilises the phenomenon of radiation reflection from a membrane. It is known that the received signal level depends on the distance between the head of the fibres (transmitting and receiving) and the reflector [6]. The use of a single fibre as a receiving and transmitting channel defines monotonically growing reflection signal level characteristic vs. hydrostatic pressure. The distance between mambrane and fibre head can be calculated using known dependences that are the subject of the elasticity theory [7]. The deflection of still mounted mambrane as a function of pressure exerted on the membrane can be presented as follows [8]:

$$\Delta W = k \frac{qd^4}{h^3 E} \tag{2}$$

where: ΔW is the central membrane deflection, k – the proportionality coefficient, h – the membrane thickness, E – Young’s modulus, d – the membrane diameter, q – the pressure difference on both sides of the membrane. It results from dependence (2) that deflection of the membrane can be chosen by changing membrane thickness, its diameter and the material that it is made of, therefore the sensor head diameter could be limited by dimension requirements. The maximal deflection of the membrane is limited by the construction of the sensor head and

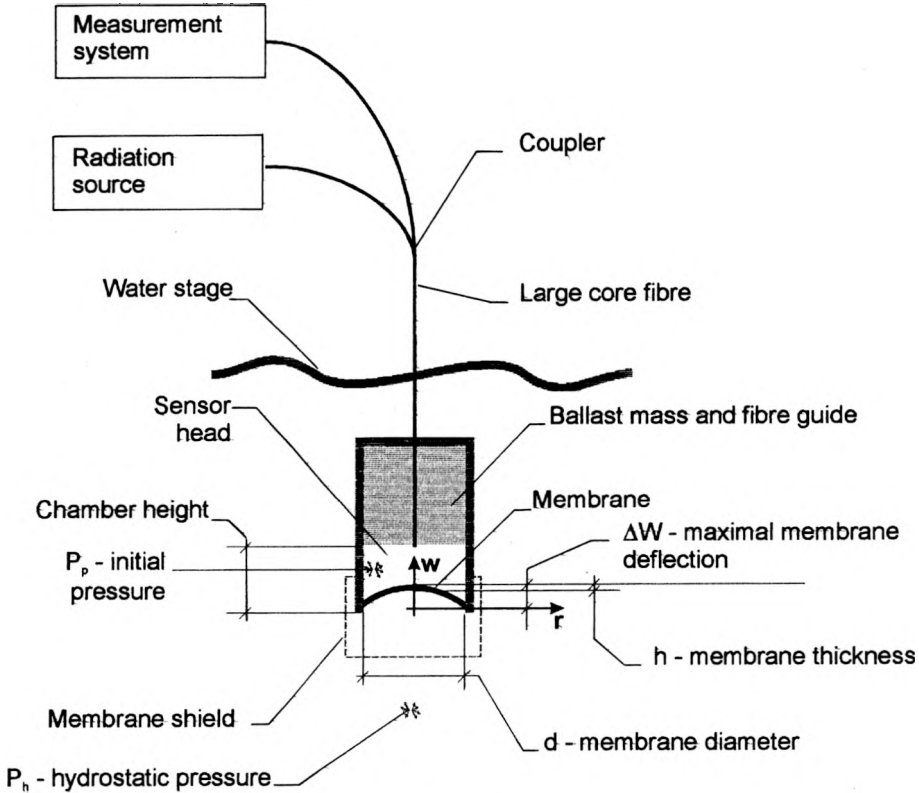


Fig. 10. Idea of fibre optic hydrostatic liquid level sensor.

equals the height of the chamber. It can be diminished by the length of the fibre positioned over its upper wall. On the other hand, the usable range of the membrane deflection is defined by the obtained characteristics of the power reflected from the membrane. To assess this range two border characteristics were calculated. The first was for the mirror surface membrane, the second for the membrane with ideally scattering surface. The data taken in calculations is presented in Fig. 11. The resulting characteristics are shown in Fig. 12. Based on the calculations we propose the height of the measuring chamber equal 4 mm, because the power changes obtained over this figure, as a function of the fibre-membrane distance, become relatively small. In the calculations, a simplification was taken that the membrane was flat. This was done because of the assumption that the membrane diameter is big (about 20 mm) in comparison with the fibre core dimensions (0.75 mm) and the central membrane part is situated on the axis of the fibre (the flattest real membrane area). In other cases the shape of membrane should be taken into account which could be calculated using equations of the elasticity theory presented in [6] or FEM.

The potential range of the sensor implementation as a depth measuring device and its simplicity of construction determines the membrane material. For this application, white rubber with smooth surface can be used. It is characterized by

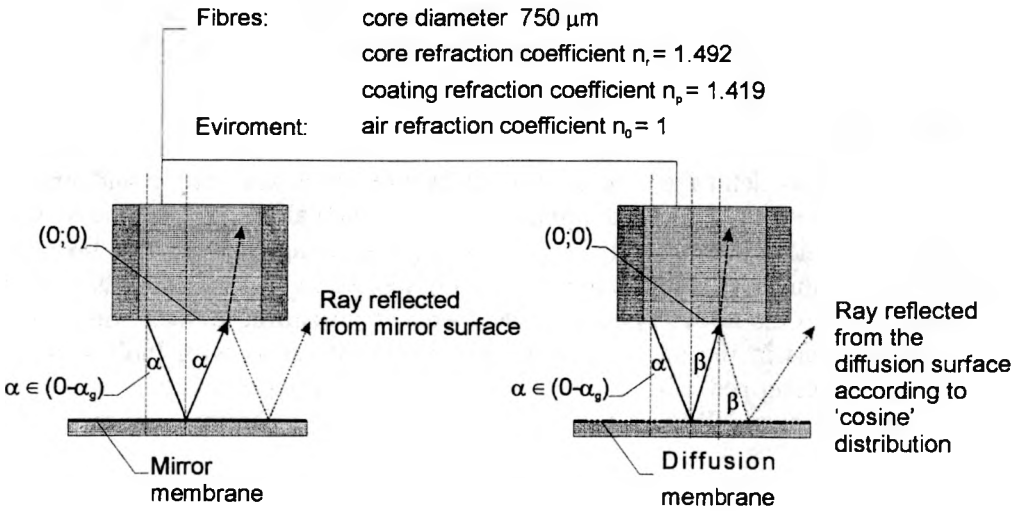


Fig. 11. Beam course for the mirror and diffusion membrane.

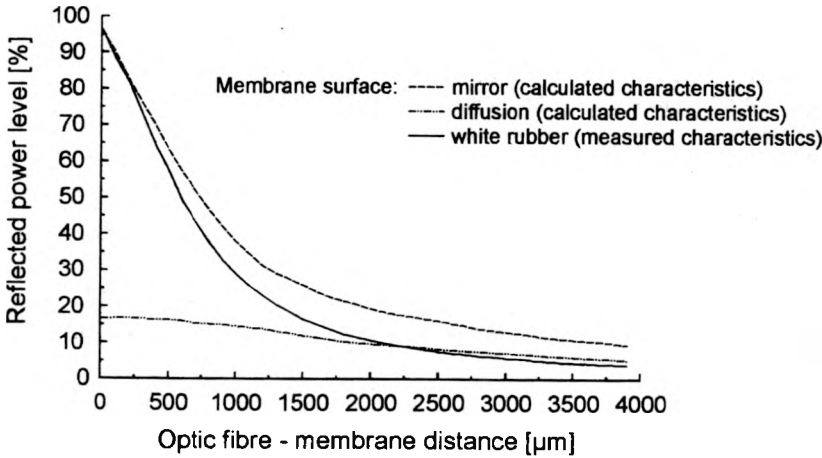


Fig. 12. Characteristics of reflected power from flat membrane.

small Young's modulus and reflects visual rays well. In the defined range of the measurement chamber height, the measured reflected power characteristic from that membrane is presented in Fig. 12.

This type of head used for column of liquid height measurement needs an experimental scaling process. The scaling characteristic, that is liquid height vs. signal level, could be written as a fourth degree polynomial, therefore computer measurement system described in [4] simplifies the detection device construction. The authors made a laboratory version of this sensor using: 3 mW laser diode source with modulation 1 kHz, head with white rubber membrane of 40 mm in diameter, 23 μm in height and optoelectronic interface and computer system. The sensor

worked for 0–50 mm column of water. The sensor accuracy was dependent on measuring time and peak detector noise parameters.

4. Conclusions

The constructional details of the sensor heads presented are simple and ensure relatively high level of measured signal. It is high enough to be processed with standard electronic components. In both cases, the measuring interfaces can be made on the basis of universal measurement unit, as described in paper [4]. It also seems that realisation of the above systems as independent measuring devices should not pose big problems in the age of widely used microprocessors with built-in ac/dc converters and equipped with tools for their effective programming.

The use of a single fibre as transmitting and receiving channel reduces fibre's length.

What is most important about the sensors presented is the fact that they do not induce electric circuits under the surface of the liquid. This enables measurements of flammable and exploding liquids [9].

References

- [1] CULSHAW B., *Optical Fiber Sensors*, Vol. 2, Artech House, Inc., Norwood 1989.
- [2] BORECKI M., KRUSZEWSKI J., BEBŁOWSKA M., *Optoelectron. Rev.* 7 (1999), 203.
- [3] TAMIR T. [Ed.], *Integrated Optics*, Springer-Verlag, Berlin, New York 1979.
- [4] BORECKI M., BEBŁOWSKA M., KRUSZEWSKI J., Proc. 11th European Conf. on Solid-State Transducers, *Eurosensors XI*, Warsaw 1997, p. 1533.
- [5] JACHOWICZ R., ŁYSKO J., *IEEE Trans. Inst. Measurement* 44 (1995), 787.
- [6] HE G., CUOMO F. W., *J. Lightwave Technol.* 9 (1999), 1545.
- [7] NOWACKI W., *Theory of Elasticity* (in Polish), PWN, Warszawa 1970.
- [8] BOCHENEK A., VI Sci. Conf. of Electron Technology, *ELTE '97*, Kraków 1997, Vol. 2, p. 633.
- [9] FRĄCZEK J., III Sci. Conf. of Optoelectronic and Electronic Sensors, *COE '94*, (in Polish), Zegrze k. Warszawy, 1994, p. 161.

*Received September 20, 1999
in revised form December 23, 1999*