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Different Optical Fiber Sensor Designs for Liquid Flow Monitoring

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Abstract: Design and operation of three different optical sensors based on the intensity modulation are reported in this article. These sensors are measuring absence or presence of any liquid and the measurement variable is refractive index and optical absorption. Reported devices can also check the presence of air bubbles in the liquid flow line. Performance of these sensors is tested as a liquid flow monitoring device while using different light sources. Sensor #1 uses a simple cell with the long transmitter and receiver optical fibers. Sensor #2 utilizes a small cell assembly that includes the short transmitter and receiver fibers. Sensor #3 employs a quartz flow cell with the direct light illumination and detection. A voltage difference of about 1.65 V for the case that water flows in the flow cell is measured for sensor #1. For this sensor the wet dry difference is about 32.92 % of the full scale and the bubble effect is about 6.17 % of the full scale, which is a high sensitivity. For sensor #2 using white lamp, there is a voltage difference of about 1.6 V for the case that water flow. There is a voltage difference of 1.1 V for the case of water flow in sensor #3. The reported results are promising and verify the successful operation of all the sensor systems depending on the application condition and requirements.

Key words: Optical sensor, Fiber optics, intensity modulation, liquid, flow testing

INTRODUCTION

Different reports on the design, characterization, operation, and possible applications of optical fiber sensors have been given in literature (Golnabi, 1999; 2000; Krohn, 1998; Bishnu, 1994; Udd, 1991; Emmanuel *et al.,* 1989; Golnabi, 2002; 2006; Golnabi *et al.,* 2007). Physical and chemical effects have been used to develop a variety of optical sensor systems for monitoring different parameters (Chubb and Wolford, 2000; Lau *et al.,* 1992; Goure, 1992; Amud, 2000; Chang *et al.,* 2000; Golnabi, 2000; Golnabi and Azimi, 2008; Golnabi, 2002; Golnabi and Azimi, 2007). Plastic optical fiber (POF) offers some advantages such as component cost, ease of handling and connections, flexibility, visible wavelength operating range, high numerical aperture (0.4), low cost test equipment, and low overall system cost (POF; Weinert, 1999; SANWA). Such advantages over glass optical fiber (GOF) make them attractive for a number of applications including sensor designs. In the reported experiments similar POFs are utilized and based on the light intensity modulation a variety of sensors are designed. Experimental results and theoretical descriptions concerning the performance of such sensors are reported here.

Theory of Operation:

Consider two aligned axial fibers with the air gap that provides two interfaces(core-air and air-core). If a beam of light with the transmission factor of T_1 in the first fiber is incident on the first core-air interface at an angle θ^1, the reflected part is shown by R_1, and the rest is transmitted into air gap. A limited cone of this light is then reflected from the air-core interface of the second fiber with amplitude R_2 before finally transmitted into the second fiber at air-core interface. Using Fresnel relations for R, and absorption/scattering law for A, the expression for transmission of the light emerging at the second air-core interface for the polarized and unpolarized light can be obtained. With some approximations (ignoring axial misalignment loss, index mismatching, etc.) the light transmission factor in the second fiber is

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$$T_{air} = T_1 - R_1(\theta_1, n_c, n_a) - R_2(\theta_1, n_c, n_a) - A(n_a, d) + C(\theta_1, n_c, n_a)\,, \tag{1}$$

where n_c is the refractive index of the fiber core, d is the optical path in the gap medium, and C is the light coupling factor. For air this coupling factor is very small due to beam divergence. For the presence of a liquid, the liquid in the gap forms a wave guide transmission line instead of the regular light propagation in the air gap. Transmission factor for this case is given by

$$T_{liq} = T_1 - R_1(\theta_1, n_c, n_{liq}) - R_2(\theta_1, n_c, n_{liq}) - A(n_{liq}, d) + C(\theta_1, n_c, n_{liq})\,, \tag{2}$$

where n_{liq} is the index of refraction for the filling liquid. In this case the coupling factor C is higher than that of air gap case because of an additional wave guide is formed. This optical waveguide provides condition for the Total Internal Reflection (TIR). Since R_1 and R_2 is usually less for the case of liquid filling, and coupling factor C is larger, thus the transmitted light into the second fiber is increased in the presence of a liquid.

On the other hand for the case that A (absorption and scattering loss) is the dominant factor rather than C, then the emerged intensity of the light into the second fiber is less for the case of liquid path instead of the air path. As a result, a decrease in the transmitted light is obtained for the modulated intensity. The output signal of the sensor defined by T_{liq} and power modulation depends upon any change in n_{liq}. The intensity modulation is highest in the case that the TIR condition is satisfied in the generated wave guide. Then even a small change in RI of the filling medium leads to a large modulation in the intensity of transmitted light.

It is in the nature of the proposed sensors that their responds depends on both refractive index and on optical loss including scattering and absorption. Since the effects of refractive index RI and of absorption are counteracting each other, sensors can respond either with an increase or decrease in signal, depending on which effect is dominant. In the first and second design the effect of RI is considered in which the output signal increases accordingly. In the design of sensor called #3, the absorption effect is dominant and the reduction of the output signal is used as the sensing principle. The effect of RI is a known phenomenon that is used in fiber coupling. Anybody who has ever aligned fiber ends is familiar with the effect of index matching fluid on the coupling efficiency of the fiber.

Sensor Designs and Operation:

The measurement system in general includes a sensor probe, signal conditioning elements, signal processing unit (with related software), and finally a presentation element. The experimental arrangement as shown in Fig.1 consists of a light source, a liquid flow cell, a transmitter and a receiver fiber for the case of optical fibers sensors, a photodetector, a digital voltmeter for output voltage monitoring, and a PC. For the operation of this probe it is possible to use a diode laser, a He-Ne laser, or white lamp as the light source. To test the constructed device a diode laser was used first in our measurements. In our system the input voltage for the diode laser is 5 V DC and operates at wavelength of 650 nm with a nominal power of 5 mW. The visible red light is easier to work with but an infrared source at wavelength of about 850 nm is more efficient source because of the detector higher responsivity at that wavelength range. A power supply provides the required regulated voltages (12 V). A white lamp is also used, which operates at 20 V DC voltage.

A digital multimeter (SANWA, PC-5000) is used for the output voltage reading and data processing (CENTRONIC CO). The general specifications of this instrument (DMM) are such that provides a 0.03% basic accuracy and 0.01 mV DC voltage resolution. This device equips with an optional optical isolated interface port at the meter back for data communication with a PC. The software (PC Link plus) allows one to log measuring data into PC through RS232 port with digital multimeter. By click of save button the transmitted data can be saved as (csv) format file or plot file to a proper storage place. It allows the logging 50000 data points in built-in memory. The operating of this system is possible by using any operation system such as windows 98, NT4.0/2000/ME/XP versions.

In this design as shown in Fig.1, the source light is transmitted through the liquid and collected by means of a photodetector, which is mounted in a proper housing. The photodetector used in this experiment is a planar silicon PIN diode type (Centronic, BPX 65). Typical characteristics of this detector are (CENTRONIC CO): Active area of 1 mm^2, responsivity of 0.2 A/W at 450 nm, 0.55 A/W at 900 nm and 0.4 A/W at 650 nm (diode laser wavelength). The main contribution of the noise to the output signal for such system can be due to the detector noises (the shot noise and Johnson noise), and a term arising from source amplitude noise. The source fluctuation noise (general purpose sources) and amplifier noise are often greater than either of Johnson or shot noise sources. Therefore, shot-noise performance cannot be achieved if a noisy optical source is used and most conventional sources have amplitude noise component in their outputs that usually dominate detection performance.

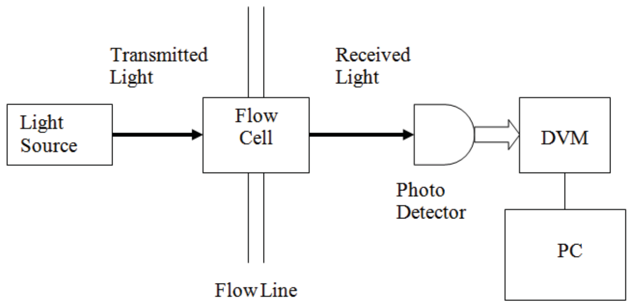

Fig. 1: Experimental arrangement for the sensor operation.

Three different optical designs are tested in this study, which are denoted by Sensor#1, Sensor#2, and Sensor#3, respectively and shown in Fig.2. As can be seen in Fig.2, the sensor#1 and #2 designs utilize plastic optical fibers (POF) for the light transmission while in the sensor#3 light transmission is accomplished directly from the light source to the flow cell and from cell to the photodetector. The fiber arrangement as shown in Fig. 2 forms a transmission line while one end of the first fiber is coupled to the light source and its other end is fixed to the flow cell. The second fiber end is fixed to the flow cell as shown in Fig. 2 while its other end is connected to the photodetector. For sensor #1, the long fibers are used for light delivery. Some general benefits of POFs are simpler and less expensive components, lighter weight, operation in the visible, greater flexibility, immunity to EMI, ease in handing and connecting, and greater safety than GOF. With these advantages one most consider the following disadvantages. High loss, a lack of system provider, a lack of standards, and limited production. However, the high-loss problem is being addressed with the new perfluorinated polymer materials, which have brought losses down to potentially 10dB/km.

Plastic optical fiber sensors, thus can operate successfully at wavelengths from 650 to 1300 nm with the light sources developed for 650-nm POFs and the 850-nm and 1300-nm laser diodes used with GOFs. Because of POFs have larger diameters (about 1mm) than glass fibers (8-100 microns), their connectors are less complex, cost less, and are less likely to suffer damage than connectors for glass fibers. Thus such connector can be made from plastic rather than the precision-machined stainless steel or ceramics that GOF requires. Because of the ease of coupling light from light source, it is possible to embed the source and drive electronics into the connector housing, such as for transceivers used in automotive and consumer products (POF; Weinert, 1999). Finally, because of ease of coupling the POF to a photodetector, the required connector can be made from plastic and at a lower cost.

The flow cell in sensor #1 is made from the Plexiglas material with a dimension of 20 × 20 × 20 mm. A glass tube with the outer diameter of 4 mm as shown in the Fig.2 passes though the cell assembly. The top part is connected to the liquid reservoir and the bottom part is connected to the drain. Two POF with a length of about 40 cm are prepared and the end faces are cleaved and polished. The transmitting fiber delivers the source light, and the transmitted light through the medium is coupled to the receiver fiber and from that to the photodetector. The plastic optical fibers were made of polymethyl methacrylate polymer, which are actually quite resistant to corrosives. In design of sensor#1, and #2 care was taken to align two fibers along the transmission axis in such a way that the transmitted light to be the maximum value. The overall length of the transmission line in Sensor#1 is about 90cm and two fibers are very similar in terms of NA and construction. In reported experiments a multimode plastic optical fiber (core diameter of 800 μm) with the polymer cladding diameter of 900 μm, and overall diameter of 2 mm is used.

For the liquid flow control two stopcocks are used in the inlet and outlet of the flow cell. The assembly of Sensor#1 has the advantage that there is no contact between the liquid and the fiber ends, which can be a problem for the case of corrosive liquids. The choice of long fibers also provides the flexibility for the position of the light source and the photodetector in different applications.

Sensor #2 as shown in Fig.2 consists of a very compact sensor probe, which is suitable for the devices with size limitations. This device is also very appropriate for the flow line checking of liquids such as cerium injections in medical applications. The flow cell is designed in such a way that the plastic tube of the cerium container is directly fitted through the sensor assembly. The cell is made from the Plexiglas with a dimension of 20 20 mm cross section and a total length of 30 mm. Two short lengths of POFs with a length of about 10 mm are used for light transmission as indicated in Fig.2.

In sensor #3 the light transmission is performed with no fibers as shown in Fig.2. A quartz cell with 10 × 10 mm cross section and 40 mm long is used in this sensor design for liquid flow. The light source and photodetector are directly connected to the sample cell, which provides and optical path length of about 10mm in liquid. The quartz cell has two outlet tubes that can be used for the liquid inlet and outlets. Even though glass or other materials can be used for this flow cell, but quartz provides a situation that can be used for more liquid types with a good transmission for the visible and laser diode wavelengths. The cell wall thickness is about 0.5 mm which offers low transmission losses. The advantage of this system is that provides a longer beam path length that can be used for the corrosive absorptive liquids. In sensors # 2 and #3 the light path length in liquid is about 3 mm.

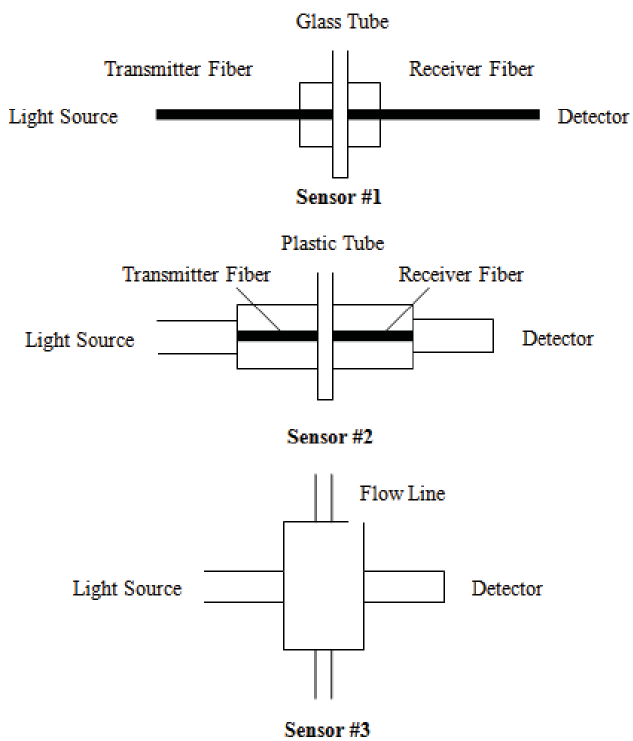

Fig. 2: Design of different optical sensors denoted as Sensor#1, Sensor#2, and Sensor #3.

RESULTS AND DISCUSSIONS

In our analysis when the light path length in flow cell is in a liquid we refer to the output signal as the wet and when there is air we call it the dry signal. For the case of dry signal the refractive index of the transmitting air is one while for the liquid case is generally higher than one. As a result the amount of the light coupling depends on the index of the refraction of the transmitting medium. Such light intensity modulation has been used for the sensing principle of the designed devises. The output signal depends on two factors namely the loss factor and the convergence factor. For Sensor #1and #2 designs the convergence factor dominates the loss factor, thus the wet signal is higher than the dry signal. The reason is that in this case the refracted beam angle in the liquid is less than in air. Therefore more rays of light are coupled to the receiver fiber in comparison with the ray propagation in air medium. Such convergence effect and reduction in the output cone angle is due to the fact that refractive index of liquid is higher than that of air. On the other hand, in Sensor #3 the loss term is the dominating factor and as a result the wet signal is lower than the dry signal. This reasoning is in agreement with the experimental results. However, report of a more complicated theoretical detail of beam propagation is out of scope of this study.

For characterization of a sensor system, some parameters such as the accuracy, full-scale output, linearity, hystresis, repeatability, resolution, measuring range, stability, and sensitivity are important. For the reported sensor factors such as precision, repeatability, response time, and stability are more of concern and hence are reported in this section. Fig. 3 shows the dry and wet output signals for water liquid with the index of refraction of about 1.33. In Fig. 3, the output voltage as a function of the flow time for Sensor#1 using the diode laser is plotted. At the start the cell is empty and as can be seen in Fig.3, the dry signal is about 3.20 V. when there is flow of water in the cell the output signal is increased to about 4.85 V. There is a voltage difference of about 1.65 V for the case that water flows in the flow cell. Another important factor in flow of the liquid is the flow uniformity and the constancy of the flow Debby in the system. To check the potential of the designed sensor for evaluation of the flow uniformity, the effect of air bubble in the line is investigated by this sensor. As can be seen in Fig. 3, at a flow time of about 5 s, there is a voltage drop of about 0.3 V in the output signal, which is due to the presence of air bubble in the water flow line. The wet dry difference is about 32.92 % of the full scale and the effect of a bubble is about 6.17 % of the full scale, which is a high level sensitivity for this type of sensors.

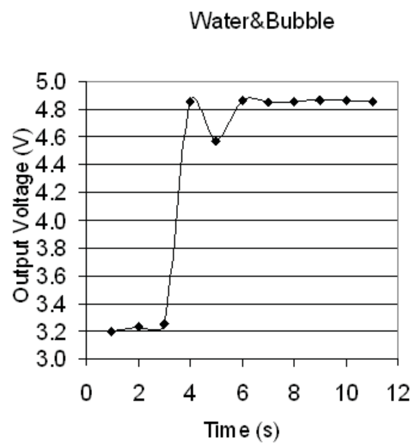

Fig. 3: Output voltage as a function of the water flow time for Sensor#1 using a diode laser.

To show the sensitivity of the reported sensor in Fig.4 the voltage difference is plotted for different water solutions for Sensor #1 operation. As indicated in Fig.4, the dry wet signal difference is highest for the distilled water (1.73 V), next for the mineral drinking water is (1.68 V), and finally for the water and salt mixture is the lowest value of 1.42 V. As can be noticed Sensor #1 offers a high sensitivity that can be used to recognize different liquid types and mixtures that might be very useful for certain applications.

Precision is defined as a measure of the reproducibility of the measurements that is considered as a figure of merit for such a sensing device. Fig. 5 shows the repeatability of the reported sensor. Such parameter indicates the ability of the optical fiber sensor to reproduce output reading when the same measurand is applied to it consequently, under the same condition. To provide such a similar ambient conditions measurements were made for two consecutive runs. Fig.5 shows the reproducibility of output voltage as a function of the flow time for Sensor #1. As can be seen in Fig.5, two series of data are presented for this sensor, which show a very good reproducibility in the obtained results. The output amplitude difference for the dry signal is about 70 mV, while for the wet signal such fluctuation is about 110 mV. Part of such fluctuation is because of the drift in the detector output due to the stray light fluctuations. The output signal corresponding to such a background voltage is about 100 mV for the case that laser source is off and the room light is also off.

Figure 6 shows the output voltage as a function of the flow time for sensor#2 using the white lamp. First, operation cell is empty and as can be seen in Fig.6, the dry signal is about 11.4 V. when there is flow of water in the cell the output signal is increased to about 13.0 V. there is a voltage difference of about 1.6 V for the case that water flows in the flow cell. The background signal for this measurement is about 500 mV, which is due to the detector dark noise and the stray light.

Figure 7 shows the output voltage as a function of the flow time for Sensor#3 using a white lamp. The dominant loss mechanism is found to be the absorption loss in the flowing liquid that can be monitored by output measurement. First, the flow cell is empty and as can be seen in Fig.7, the dry signal is about 16.4 V.

When there is flow of water in the cell the output signal is decreased to about 15.3 V. There is a voltage difference of about 1.1 V for the case that water flows in the quartz cell. Another important parameter here is that when there is a flow of water in the cell the output signal is decreased, which is reverse of results obtained for Sensor#1 and Sensor #2.

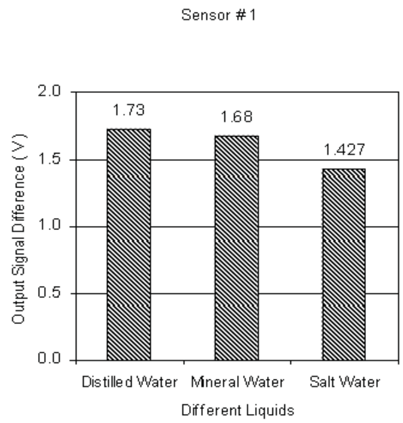

Fig. 4: Dry wet signal difference obtained with Sensor #1 for different water solutions.

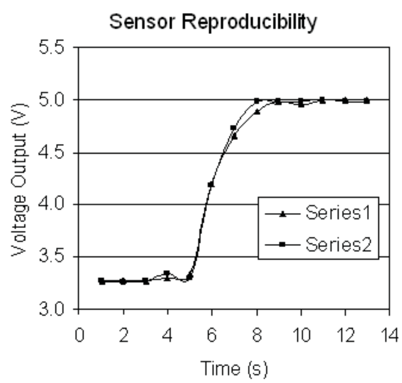

Fig. 5: Shows the reproducibility of the measured output signals for Sensor#1.

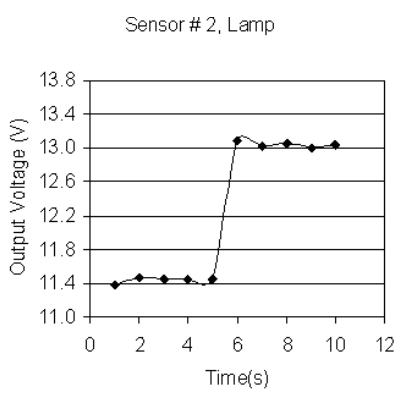

Fig. 6: Output voltage as a function of the flow time for Sensor#2 using a white lamp.

Stability of a sensor is another important parameter, which is described in this study. In general such factor shows the ability of the optical fiber sensor to maintain its performance characteristics for a certain period of time. In this experiment the output signal for the case that the white lamp (Sensor#2) is on is measured for a period of 500 s in 10s increment. In order to monitor the drift in the photodetector due to background light and dark noise the output signal is recorded for the case that the white lamp is turned off for the same period of time. To compare the results both responds are shown together in Fig.8. The result of such study for the dry signal is shown in Fig.8 in which the average signal is about 10.463 V, maximum 10.526 V, minimum 10.371 (difference of 0.155 V), with a standard deviation of order of 0.049. As can be seen, output signal shows a good stability for this period of time (1.47%).

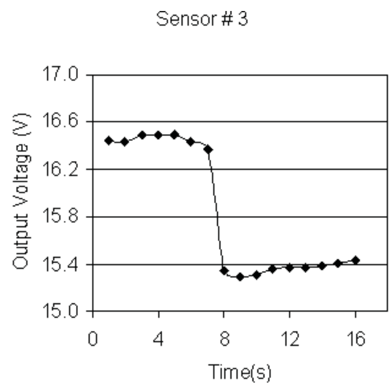

Fig. 7: Output signal as a function of the flow time for Sensor#3 using a white lamp.

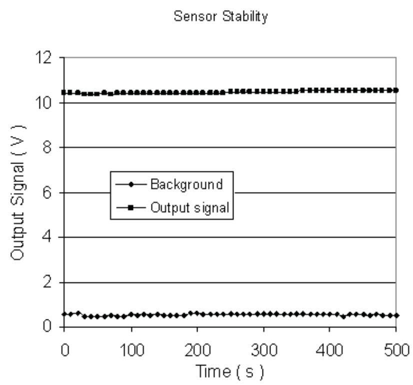

Fig. 8: Shows the stability of the output signals as a function of time for Sensor #2.

The result of such study for the case of no source light shows the average signal of about 0.544 V, maximum 0.6228 V, minimum, 0.4306 V (difference of 0.1922 V) with a standard deviation of order of 0.047. It can be concluded that most of fluctuation in the output voltage is due to drift in the output reading of the photodetector, which is due to dark noise and most likely due to the background variation. A comparable stability in the measurement of the wet signals is noted for Sensor#2. Similar experiment are performed with the other sensors and sensor system with the laser light source offers a better stability and is superior to the ones with the white lamp source. Since the response time or switching time of the sensor is in the order of second, therefore, the output fluctuation is negligible for such a short period of switching time.

As described part of fluctuation is due to the drift in the output of the photodetector. As can be seen in Fig.8, about 1% of the instability is due to such a drift in detector output. To look at the instability during operation, it is noted that at a relatively stable ambient condition, the major source of such fluctuations could be the result of the light source fluctuation. Even though our light sources (laser, and lamp) and photodetector are intensity regulated driven light sources, however, for improving the signal-to-noise ratio, a more stable light source and a very low noise photodetector are recommended.

Conclusions:

In operation of the Sensor#1 and #2, when there is a full flow of the liquid more light is transmitted into the receiver fiber. As described, when a fluid flows in the sample cell since the index of refraction of the fluid is larger than that of air, then the condition for refraction is changed and more light is coupled into the receiver fiber. On the other hand, when the flow line is empty (air) some of the light is lost through the divergence and can not enter the receiver fiber. Such intensity modulation concept is also used to check the air bubble effect in the flow line in Sensor#1. For Sensor#3, the situation is reversed and when there is a flow of liquid the output signal is reduced due to the absorption loss term. Sensor #1 is turned out to be a general purpose device that can be used in most applications for the liquid flow checking and flow uniformity. Sensor #2 is suitable for some particular applications such as in clinical cases for the serum injection. The serum hose can be directly feed through the probe and the liquid flow can be automatically monitored precisely. Sensor #3 is useful for flow checking of liquids that have notable absorption coefficients. Comparing to our previous design (Golnabi, 2004), sensors reported here have the advantage of being a non-contact type sensors, which can be successfully used for corrosive liquids. Since Sensors #2 and #3 are operating with the inexpensive white lamp the overall production cost of these kind of sensors is lower than the Sensor#1. However, for the more precise applications Sensor #1 is recommended, which offers a higher sensitivity and a better stability.

As described, it is in the nature of the proposed sensors that their responds depends on both refractive index and on optical loss (scattering and absorption). Reported sensors can respond either with an increase or decrease in signal, depending on which effect is dominant. The reported results for the tested liquids have been promising and verify the successful operation of all the sensor systems depending on the application condition and requirements. Because of contamination in cloudy or colored liquids these sensor are likely susceptible to aging problem. However, as shown they can be used for clear liquids with no aging problem.

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