Application of Bare, Tapered and Bent Multimode Optical Fibre Refractometer for Measuring the Concentration of Glucose Solution

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Abstract:A bare, bent and tapered multimode optical fibre (BTBMOF) has been used as a sensor probe to find the refractive index of glucose solution. The sensor system consists of a diode Laser source, the sensor probe and a Light dependent resistor (LDR) as detector. The optical fibre sensor has been used for measuring the concentration of glucose solution by using the change in refractive index (RI) of the glucose solution due to change in concentration.

Keywords: Optical fibre sensor, Glucose, Refractive index.

1. Introduction

The determination of glucose concentration is very important in the field of preclinical diagnosis, especially in the diagnosis of diabetic patients. There are various kinds of methods for the determination of glucose concentration based on the enzymatic reaction in which glucose oxidase acts as catalyst [1]

$$D-glucose+O_2 \xrightarrow{GOD} gluconolactone+H_2O_2$$

Glucose can be determined by measuring the production of hydrogen peroxide or the consumption of oxygen. These methods involves redox reactions and sophisticated amperometric instruments. In contrast to these methods, fibre optic sensors are simple, miniaturized, flexible, and lack electrical contact the sensor and the sample. Many optical fibre sensors have been developed for measuring glucose concentration or simply as glucose sensor. Jiang et al., presented a new fiber optic glucose biosensor based on oxygen fluorescence quenching using lock-in technology [1]. The sensor's detecting range (50 mg/dl-500 mg/dl) and responding time (<30 seconds) are acquired. Shah et al., fabricated a new type of optical fibre based oxygen and glucose sensor using the phenomenon of fluorescence quenching [2]. Lu et al., developed a glucose fiber sensor for measuring the glucose concentration in serum with heterodyne interferometry [3]. Hsu et al., also presented a fiber-type glucose sensing system which combined single-mode fiber conjugated with glucose oxidase (GOD) and heterodyne interferometry. The absolute glucose concentration can be obtained by measuring the phase difference coming from the chemical reaction between the glucose and GOD on the fiber sensor [4].

Glucose concentrations can be measured by measuring the refractive indices of different glucose solutions. Optical fibre sensors have been used for the measurement of refractive index (RI) of different types of liquid. The measurement of refractive index is carried out under the loss of intensity method where the modulation of transmitted light takes place either due to emission, absorption or RI change. There are several methods of measurement of refractive index of liquid. A refractometer using a bare and tapered multimode fiber has been used for finding the RI of different liquids [5]. A refractive index sensing system has been used based upon a high sensitivity long period grating Mach-Zehnder refractometer [6]. The applicability of the refractometric measurement system based on an LPG to determine the ethanol concentration in ethanol-gasoline blend has been demonstrated [7]. Measurement of refractive index sensitivity using LPG refractometer has also been demonstrated [8]. The use of two optofluidic configurations to measure refractive index and pressure of liquids have been proposed [9]. A novel demodulation technique based on the monitoring of the polarization-dependent loss in a 1-nm wavelength range to measure the surrounding refractive index by means of weakly tilted fiber Bragg gratings has been proposed [10]. A new and simple liquid refractometer based on multiple total-internal reflections in heterodyne interferometry has already been shown [11]. Fiber-optic refractometers with intensity-type transducer which can operate remotely via long fiber-optic cables have been presented [12].

The concentration of a liquid can be measured by measuring the refractive index of the solution. The refractive index of standard sugar solution has been measured using a bare, tapered and bent optical fibre (BTBMOF) sensor [13]. In this work, a BTBMOF sensor has been fabricated and used for measuring the concentration of standard glucose solution.

In this work, a bare, bent and tapered multimode optical fibre for the measurement of concentration of glucose solution. The sensor probe detects the changes in the refractive index of the solutions in which the probe has been immersed, due to the changes in concentration of the liquid. The loss of optical power due to change in refractive indices is indicated as the change in resistance of the light dependent resistor (LDR) which is a part of a potential divider circuit. The light from the sensor probe is incident on the LDR and so the resistance of the LDR changes. The outputvoltage of the potential divider circuit is read by a digital multimeter.

2. Principle of Bare, Tapered and Bent Multi-Mode Refractometer

The BTBMOF is considered as the sensing element for the proposed measurementsystem tomeasureRI of a liquid. The bare and tapered portion of the optical fiber sensor is given a shape of a semicircular arc of fixed radius of curvature. The geometry of the proposed refractometer is shown in figure-1 [13].

From the geometry of the proposed sensor shown in figure-1, the expression of power associated with laser beam at the output end of the fiber for the BTBMOF portion of the OFSP when the bare tapered and bent portion of the OFSP is exposed to liquid medium has been derived [13] and is as shown.

$$P(L)_l = P_0[K_1 - K_2 n_l^2] \times \left[1 - 0.2304(K_3 - K_4 n_l^2) exp\left\{-K_5(b - K_6 n_l^2 - K_7)^{3/2}\right\}\right] \quad (1)$$

Where,

$$K_1 = \frac{n_1^2}{R^2(n_1^2 - n_{cl}^2)}, \quad K_2 = \frac{1}{R^2(n_1^2 - n_{cl}^2)}, K_3 = \frac{2bn_1^2 k_0 L}{n_1}, K_4 = \frac{2bk_0 L}{n_1}, K_5 = \frac{2}{3} n_1 k_0 R', \quad K_6 = \frac{b}{n_1^2} \text{and} K_7 = \frac{2a_0}{R'}$$

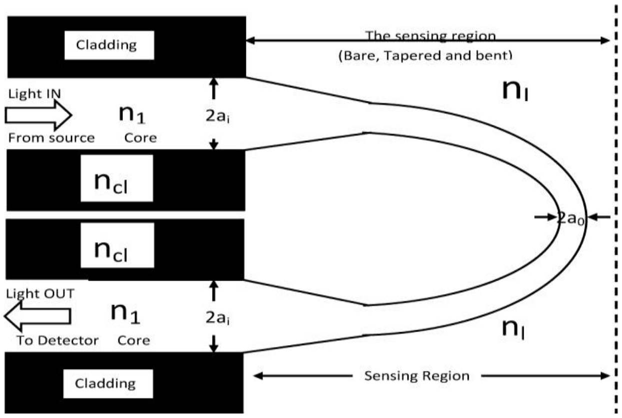

Figure 1: The geometry of the proposed refractometer

α_B is the attenuation coefficient due to macro bending effect, L is the length of the bent portion of the BTBMOF and $P(L)_l$ is the power at the output end of the fiber for the BTBMOF portion of the OFSP and P_0 is the power coupled into the input end of the fiber, n_l is the RI of the medium around the bare, tapered and bent region of the OFSP respectively, R is the taper ratio$\left(= \frac{a_i}{a_0}\right)$, a_i and a_0 are the radius of the core in the untapered and tapered (and bent) region of the BTBMOF, n_1 and n_{cl} are the refractive index of the core and cladding respectively, R' is the radius of curvature of the tapered and bent portion of the BTBMOF, b is a constant (0≤b≤1 for a guided mode) and k_0 represent the wave propagation constant.

When the BTBMOF will be placed in air medium, the term n_l will be replaced by n_{air} (=1.0) and so the value of $P(L)_l$ in air medium will be have a fixed value.

The minimum value of $P(L)_l$ will be when $n_l = n_1$ ($P(L)_l = 0$) i.e. the RI of the core and RI of the medium around the bare, tapered and bent region of the sensor probe are equal. $P(L)_l$ is maximum when $n_l = 0$. Thus the maximum and minimum value of the optical power can be determined from values of n_l and n_1.

3. Description of the Measurement Setup

The multimode optical fibre selected for the preparation of bare, tapered and bent refractometer, has a dimension of 200/230 (core diameter (µm)/cladding diameter (µm)) and with protective coating, overall diameter of the fibre is 500 µm. The RI of the core (n_l) and cladding (n_{cl}) of the fibre are 1.48 and 1.46 respectively. The length of the fibre is 30 cm. At the centre of the fibre, a length measuring 40 mm is made open by removing the plastic jacket. After this, the cladding of this portion is removed mechanically by careful use of a sharp razor. The uncladded portion of the fibre was then heated and pulled very carefully till the length became approximately 42 mm. Thus, a small portion of the bare fibre becomes tapered at its two ends. The diameter of the tapered portion is found to be approximately 0.07 mm and the diameter of the uncladded portion is found to be approximately 0.1 mm. Thus the tapered ratio of the fibre becomes 1.428.

To confirm the proper removal of cladding from the bare and tapered portion of the fibre, a procedure is followed. According to the procedure, the complete removal of cladding from the bare and tapered portion of the fibre is confirmed, if the power of a laser beam is decreased with increase in the RI value of a liquid applied around the bare and tapered portion of the fibre.

Glucose solutions with different RI have been used to confirm the complete removal of the cladding from the bare and tapered portion of the fibre developed for the experimental purpose. The optical fibre is placed inside a plastic tube, by keeping the bare and tapered portion outside the tubes.

The plastic pipe is filled with m-seal (a cementing material normally used for fixing water leakage through roof, water pipe etc.) keeping the fibre at their centres. At one end of the plastic tube, the LDR is placed in such a way that the laser beam emerging out of the fibre is incident perpendicularly on the LDR surface. An extension optical fibre is used for transferring the light from the diode laser source (3mW power) to sensor probe. Similarly, the position of the diode laser source is fixed on the other end of the plastic pipe with proper focusing. An extension multimode optical fibre having the same core/cladding ratio have been used for maintaining the proper focusing of the Diode Laser source to the sensor probe.

The extension optical fibre and the LDR (surface diameter 1.5 mm) are also cemented with m-seal, so that their position remains intact always. The schematic of the experimental setup is shown in figure 2.

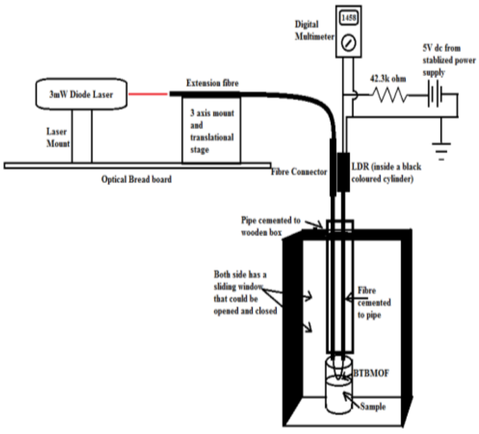

Figure 2: Experimental set-up for measuring the RI of Glucose

The resistance of an LDR has inverse characteristics with the light incident on the LDR surface as shown in figure 3.

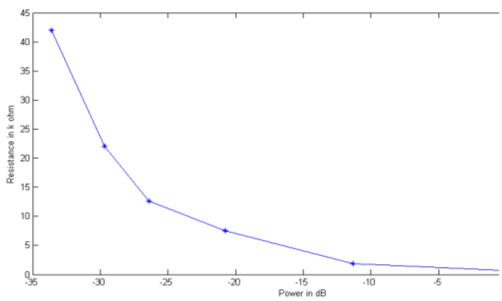

Figure 3: Variation of Resistance (in kΩ) with Optical power (in dB)

A fixed resistance (R_X= 42.3k ohm) is connected across a 5 V DC supply (i.e. V_{CC}= 5V) with the LDR in series to form a potential divider circuit, as shown in figure 4.

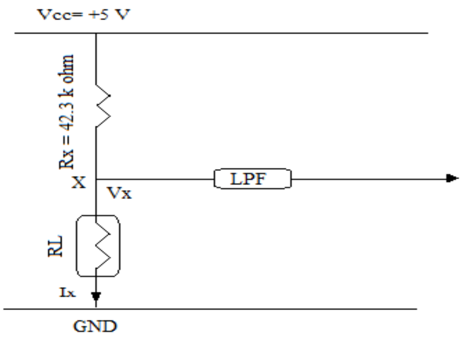

Figure 4: LDR based potential divider circuit

The output voltage of the LDR-based potential divider can be expressed as

$$V_X = I_X R_L = \frac{Vcc}{R_x+R_L} R_L \qquad (2)$$

where $R_L$is the resistance of the LDR. The output voltage of the potential divider circuit $V_X$increases with increase in the value of R_L . Again,R_L increases with increase in the RI of the liquid in which the sensing region of the sensor probe is immersed. The variation of power at the measurement point x can be expressed as-

$$P_X = I_X^2 R_L = \left(\frac{Vcc}{R_x+R_L}\right)^2 R_L = \frac{V_X^2}{R_L} \qquad (3)$$

The value of R_X and V_{CC} remain constant, therefore,$P_X$would be proportional to$\left(\frac{1}{R_x+R_L}\right)^2 R_L$.The voltage at x i.e. V_x is fed to a passive low pass filter (LPF) having a cut-off frequency (f_c) of approximately 2Hz with the values of resistance and capacitance as 10kΩ and 10µF respectively $f_c = \frac{1}{2\times\pi\times10\times10^3\times10\times10^{-6}}$

The LDR used in the potential divider circuit exhibits 450Ω, when it is exposed to the laser beam directly and shows 1 MΩ when the LDR is fully covered (i.e. no light is allowed to be incident on the LDR). It has been found that when the BTBMOF of the sensor probe is exposed to air (i.e. condition for maximum power transfer through the BTBMOF), the resistance of the LDR is found to be 42kΩ approximately.

The electrical power P_X is same as the optical power $P(L)_l$of the laser beam coupled through the bare, bent and tapered portion of the sensor probe. Thus the measure of the electrical power P_X is a measure of the optical power $P(L)_l$ which is dependent on the RI (and ultimately on the concentration) of the liquid in which the BTBMOF of the sensor probe is immersed.

The power $P(L)_l$ associated with the laser beam coupled through the tapered portion of the fibre depends on the focusing arrangement of the laser beam launched from the diode laser source. Thus, depending upon the focusing arrangementof the laser to the input end of the fibre, the valueof $P(L)_l$ may vary from one sensor probe to another sensor probe.

4. Experimental Results and Discussion

To examine the characteristic behaviour of the sensor probe,standard glucose solution (w/v) was prepared by dissolving aknown weight of powdered glucose in 100 ml water to prepare standard glucose solution (e.g. 10 gm of powdered glucose were first dissolved in about 40mL of water and after proper stirring and mixing, the solution was made upto 100mL by adding water) and these solutionswere used as test liquid for the experiment. For immersing the BTBMOF or the sensor probe in the glucose solution, only 4mL of the 100mL glucose solution is taken in a small container and used for testing.

The BTBMOF is first kept in air and then in different glucose solution (with different concentration) and and the measure of voltages V_{air} and V_{liq} are taken in a digital multimeter. To show the repeatability of the measurement system, three sets of measurements, each for V_{air} and V_{liq} has been taken. The value ofV_{air} and V_{liq} as measured by a digital multimeter for bare, tapered and bent refractometer with known percentage of glucose solutions is presented in Table 1. The measure of V_{air} is taken for reference only.

TABLE 1: Variation Of Output Voltage V_{air} And V_{liq} With Different Concentration Of Glucose Solution

For bare, tapered and bent refractometer							
Percentage of glucose	Set1		Set2		Set3		Average of V_{liq} (V)
	V_{air} (V)	V_{liq} (V)	V_{air} (V)	V_{liq} (V)	V_{air} (V)	V_{liq} (V)	
5	2.522	2.990	2.587	3.012	2.519	3.005	3.002
10	2.542	3.042	2.555	3.044	2.522	3.021	3.036
20	2.553	3.095	2.557	3.081	2.548	3.103	3.093
30	2.549	3.150	2.549	3.150	2.560	3.158	3.153

Since $P_X \propto V_x^2$, so at the measurement point (x) of the potential divider circuit, the variation of the values of $V_{liq}{}^2$ withglucose concentration for the three sets of measurement under samecondition is shown in figure 5. The average of the three measurement of $V_{liq}{}^2$ with glucose concentration i.e. 5%, 10%, 20% and 30% is shown in figure 6.

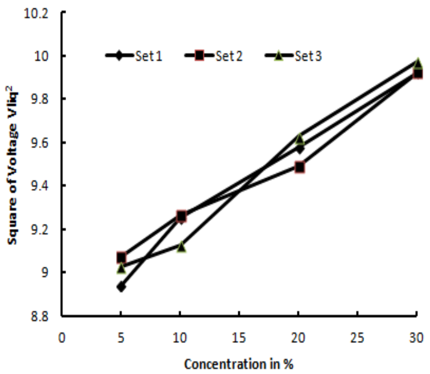

Figure 5: Variation of output voltage of potential divider circuit with concentrarion for three sets of measurement

From figure 5, it is seen that the value of output voltage $V_{liq}{}^2$ at concentration 5%, 10%, 20% and 30% lie very close to each other for the three sets of reading. This shows that the precision of the measurement system is high. The values of $V_{liq}{}^2$ for the three sets of readings are averaged to get the variation of concentration with average $V_{liq}{}^2$.

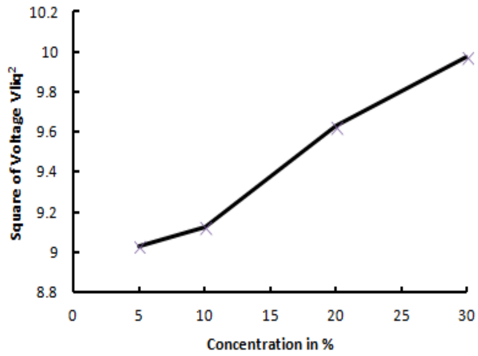

Figure 6: Variation of AverageVoltage of potential divider circuit with concentration

From the graph it can be inferred that the sensor and measurement system can give an average linear response in the given sets of conditions (measurement process) and samples.

Since $V_{liq}{}^2$ is a function of $P(L)_l$, measurement of $V_{liq}{}^2$ will represent the refractive index and concentration of the liquid in which the BTBMOF portion of the sensor probe is immersed. The curve for variation of average value of square of $V_{liq}{}^2$ is interpolated with concentration using 1st, 2nd and 3rd degree interpolation equation. It was found that the 2nd degree interpolation equation gives the least error between the calculated output and the output value obtained from the graph (conc vs. V_{liq}^2) The equation is given as-

$$conc = 2.552\left(V_{liq}^2\right)^2 - 23.5V_{liq}^2 + 10.37 \qquad (4)$$

This equation will be used as the calibration equation for the proposed system. Equation (4) will hold true for finding out unknown values of concentration of glucose within the measurement range for the measurement system. Depending on the focusing arrangement of the laser beam launched from the diode laser source and the type of fibre used, the value of V_{liq}^2 may vary from one sensor probe to another sensor probe. It is seen that the low pass filter (LPF) reduces the fluctuation in the display of the digital multimeter by ±2 value. The measurement system gives a direct measure of concentration of glucose solution as a function of voltage. Compared to works presented by previous researchers, the method and the sensor presented in this work is very simple and involves no sophisticated optical mechanism like fluorescence quenching and heterodyne interferometry. The measurement procedure involves only immersing the sensor probe in a glucosesolution. A look-up table (obtained from calibration process) can be used to compare the output voltage from the measurement to find the concentration of glucose solution. A calibration equation (as shown in equation 4) can also be incorporated in a microcontroller system to directly give the value of concentration. However the calibration equation depends on the value of V_{liq}^2 which in turn is dependent on the focussing arrengement of the sensor probe.

5. Conclusion

A measurement system for measuring the concentration of glusose solution has been constructed using a bare, tapered and bent multimode optical fibre as the sensor. The BTBMOF is used as the sensor probewhich is immersed in standard glucose solution. The output voltage V_{liq} obtained at the output of the LDR based potential divider circuit is measured using a digital multimeter. The values of V_{liq}^2 which is dependent on RI (and also on concentration) of the liquid is a measure of the concentration of the glucose solution. A mathematical relation has been found using 2nd order interpolation equation which can be used as the calibration equation for finding the unknown concentration of glucose solution. The constructed measurement setup can be used for finding the RI or concentration of other liquid samples.

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