Design of reflective optical fiber sensor for determining refractive index and sugar concentration of aqueous solutions

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Abstract. A reflective optical fiber sensor designed for measuring refractive index and sugar concentration of aqueous solutions is described. Two strains of parallel polymer optical fibers (POF) were wrapped in a bundle such that one of their fiber's end cross-sections had the same distance to the mirror surface. The light coming out from one strain of the fiber was reflected by the mirror to the second fiber. Sugar concentration of the aqueous solution filling the space between the fiber ends and the mirror was varied (1.0 M, 1.5 M, 2.0 M, 2.5 M, 3.0 M, 4.0 M, and 5.0 M). It was shown from the experiment that light intensity detected by photo-detector is linearly related to the percentage of the dissolved sugar in the solution as well as the variation of the sugar solution refractive index ($R^2 = 0.987$).

1. Introduction
In the last few decades, fiber optic sensors have emerged as the one of the main class of modern sensors. Now, these sensors are available for measuring almost all physical properties at which the already established sensors such as the electronic based sensors have long been used, i.e. mechanical sensor [1,2], temperature sensor [3], biochemical sensors [4]. The fast growing interest in this relatively new class of sensor is mainly driven by the fact that fiber optic has some unique physical properties related to their small size, high flexibility, immunity to electromagnetic and radio interference, and high resistance level to harsh environments. Having these properties, fiber sensors have found widespread applications which comprise the use of the sensors in physical, chemical and biological sensors.

Fiber sensors used for chemical substance monitoring have been developed by employing varies types of light-material interactions, i.e., reflection, refraction, absorption, emission, and polarization. Among them, fiber sensors work based on absorption and emission are mostly used. Examples of fiber sensors developed under these working principles are fiber sensors used for detecting CO$_2$ [5, 6] and glucose [7, 8]. Due to the nature of the absorption and emission processes, these types of the fiber sensors work only at a particular wavelength corresponding to the energy difference between the ground electronic state and an excited electronics state of a substance under investigation. Using these sensors, a chemical substance contained in any mixtures can be theoretically determined. In a process involving different flows of different single solution, employing these types of sensors mean that many different chemical sensors must be available at any time.

In this paper, a reflective optical fiber sensor which has the ability to determine the refractive index and sugar concentration in aqueous solution is reported. This type of sensor works based on the fact that solution with different sugar concentration will result in the different refractive index.
2. Experiment

Figure 1 is the experimental setup used to determine the optimum configuration of the fiber sensor for measuring refractive index and concentration of sugar solution. Light from the light source is split into two paths: modulation path and reference path. Light in modulation path is directed to a reflector through fiber transmitter such that reflection occurs. Part of the reflected light will then go to the fiber receiver adhered to the fiber transmitter. Light from these two paths are captured by photodetector detectors (PD1 and PD2) for further processing in the oscilloscope.

![Figure 1. Schematic arrangement for refractive index fiber sensor (1. Solution, 2. Mirror, 3. micrometer, 4. Modulated path optical fiber, 5. Reference path optical fiber, 6. The light source, 7. Oscilloscope)](image)

Light transmittance \( T \) is then defined based on the ratio between the intensity of light coming from modulation path \( (I_m) \) and reference path \( (I_r) \) as given by equation (1).

\[
T = \frac{I_m}{I_r} \times 100\%
\]  

(1)

\( T \) is set to 100% if the fiber sensor is in the air. As the fiber sensor is dipped into sugar solution the range of angles over which the fiber transmitter emits the light (numerical aperture) is decreasing. The numerical aperture (NA) of a fiber whose core and cladding refractive indices are \( n_{co} \) and \( n_{cl} \) is given by equation (2).

\[
NA = \sin \alpha = \frac{1}{n_m} \sqrt{n_{co}^2 - n_{cl}^2}
\]  

(2)

Where \( \alpha \) is the acceptance angle and \( n_m \) is the refractive index of sugar solution. Variation of refractive were made by making a solution with a different concentration of sugar (1.0 M, 1.5 M, 2.0 M, 2.5 M, 3.0 M, 4.0 M, and 5.0 M). LED of 632 nm is used.

3. Results and Discussion

As shown in figure 1, the intensity of light transmitted through receiver fiber as well as reference fiber is measured by oscilloscope as voltage. Figure 2 shows how light transmittance change as the distance of fiber ends facing to the mirror changes. Due to the simplicity of the experiment, measurement repetition produced the type of curve but different in their path. Interestingly, the peaks of all curves for each sugar concentration are located at the same mirror-fiber ends distance.

Looking back to Figure 2, it can be seen that the peak of the curve obtained for 5.0M of sugar solution is located at higher value of displacement (distance between fiber ends and the mirror) compared to that of 1.0 M. The way the peak positions change as function of sugar concentration is
shown in figure 3. It is seen that peak position shift is linearly related to the sugar concentration ($R^2 = 0.987$).

**Figure 2.** Normalized voltage change measured as a function of the distance between the mirror and the fiber ends for (a) 1 molar solution, (b) 5 molar solution.

**Figure 3.** The peak position of the curve as a function of sugar concentration.

**Figure 4.** Reflection model explaining the position of mirror relative to the fiber ends giving maximum transmittance.
The above results can be understood by applying equation (2) and figure 4. For a given sugar concentration and thus at the solution refractive index is fixed, a light path for a given light guide mode will leave the fiber transmitter at the same acceptance angle (α). All the reflected light will enter into the receiver fiber only at a certain distance. As the mirror is positioned very close to the fiber ends, only small fraction of light comes into the receiver. This fraction gets higher as the distance from the mirror to the fiber ends bigger. After a maximum value is reached, this faction will decrease. Furthermore, fiber Numerical aperture decreases as the sugar refractive index (sugar concentration) increases. This leads to decreasing the same acceptance angle (α). Consequently, the mirror has to be displaced further down to a position at which the far left of the reflected light as shown in Figure 4 falls into the left wall of the fiber receiver.

4. Conclusions
An experimental setup used to configure a sugar refractive index fiber sensor working based on reflectively modulated fiber sensor have been shown. Analysis has been given to see the unique character of the reflected light by the mirror dipped into the sugar solution. For a given solution, it is found that the maximum transmission is obtained at a particular distance. This distance is displaced farther as the sugar concentration and thus the refractive index of solution increases.

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