Detection of glucose concentration in distilled water using fiber coupler and concave mirror

SAMIAN*, A. H. ZAIDAN, M. FAIDA, M. YASIN
Physics Department, Faculty of Science and Technology, Universitas Airlangga, 60115 Surabaya, Indonesia

Detection of glucose concentration in distilled water with volumes of 70 μl has been successfully demonstrated. The working principle of the sensor is based on displacement sensor using fiber coupler and concave mirrors as reflector which also acts as sample container. The glucose concentration is detected through peak voltage value due to the shift of the sensing port fiber coupler against the concave mirror. Peak voltage value will change depends on glucose concentration. The developed sensor can detect changes in glucose concentration with a range of 0-50% and 1% resolution without contact with the sample.

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1. Introduction

Several optical methods can be used to detect substance concentrations in an aqueous solution such as absorption, refraction, or a combination of both absorption and refraction of light by the solution. Although the detection of substance concentrations in the solution using the principle of absorption is usually more sensitive than using the principles of refraction, the availability of light sources that has wavelength match with solution absorption spectrum often becomes an obstacle. Therefore, the principle of refraction is still often used to detect substance concentrations.

Fiber optic sensor detection of substance concentration was conducted utilize changes of the substance concentration in solution which will change the refractive index of the solution resulted in the change of refraction direction. This principle has been used to detect refractive index of chlorinated water and the concentration of the uric acid utilizing side micro bend fiber optic [1] and tapered fiber coated ZnO [2]. Based on the displacement sensor, detection of liquid refractive index [3], the concentration of glucose [4], and calcium [5] successfully carried out using the bundled fiber probe. In this method, the detection of the substance concentration in solution is done through values of the peak voltage that occurs due to the probe sensor displacement against the reflector. The same method is also used to detect the concentration of sodium chloride (NaCl) using principles of absorption [6]. Fiber coupler, as beam splitter, has been applied as a displacement sensor [7]. Based on the displacement sensor, fiber coupler can also be applied to detect the substance concentration in a solution using the principles of refraction [8, 9] and absorption [10].

The substance concentration sensor detection method that has been mentioned requires direct contact between the sensor probe (fiber optic) and the sample. It is a drawback in term of sensor maintenance. Detection without direct contact between sensor probes and sample (non-contact detection) was successfully performed using a fiber coupler with a concave mirror as a sample container to detect rhodamine B concentration [11]. The principle used is the absorption of rhodamine B solution against green light (543 nm) that is converted into signal. The Non-contact method is beneficial in terms of sensor maintenance costs. In this paper, based on displacement sensor, the performance of fiber coupler as a sensor of glucose concentration in distilled water was demonstrated by applying a non-contact detection method and refraction principle. A concave mirror with a diameter of 9 mm is used as a reflector as well as a sample container so that the sample is required only in a relatively small volume. This is an advantage when a small sample is owned.

2. Sensor work mechanism

The design of glucose concentration sensor in distilled water using fiber coupler based on displacement sensor with a concave mirror as the reflector is shown in Fig. 1(a). The detection mechanism is based on the connection between the peak voltage value and the displacement of the sensing port against the sample surface (*d*). The displacement of the sensing port against the sample surface produces a change in the output voltage. In the range of a particular displacement, there is a peak voltage which is located around the radius of curvature (concave mirror) [10]. Peak voltage value changes due to changes in glucose concentration which is occurred due to the refraction of light. Changes of peak voltage value due to changes in glucose concentration are illustrated by Fig. 1(b). Fig. 1(b) illustrates the propagation of light from sensing port to the concave mirror and back to sensing ports. Sensing ports position in Fig. 1(b) is located at a curvature radius of concave mirror. In the process, light passing through glucose solution and reflected by the concave mirror. The light coming into the sample (black ray), partly reflected by the surface of the sample which is shaped like a convex lens and partly refracted (red ray) towards the surface of the concave mirror. The shape of the convex lens-like samples occurs because the cohesion force of glucose solution is greater than adhesion force between glucose solution and concave mirror surface (aluminum). A part of reflected light from concave mirror will be refracted by the glucose solution towards sensing ports. If the refractive index (concentration) of glucose solution is higher, then the light would be refracted (blue ray) closer to the line of normal (*n*). Refraction of light by glucose solution with higher concentration, causing the reflected light from concave mirror did not return to the sensing port, so the intensity of light (in this case the value of the output voltage detectors) will be reduced. Thus, an increase in glucose concentration will lead to a decrease in the value of the peak voltage. Large sample volumes require a concave mirror with larger radius of curvature. As a result, the curved sample surface is reduced (flatter) and the incident angle of light becomes smaller. Based on the principle of refraction, more light is coming back into the sensing port (blue ray). Thus, changes in light intensity due to changes in the sample refractive index are not too large so the sensor becomes less sensitive.

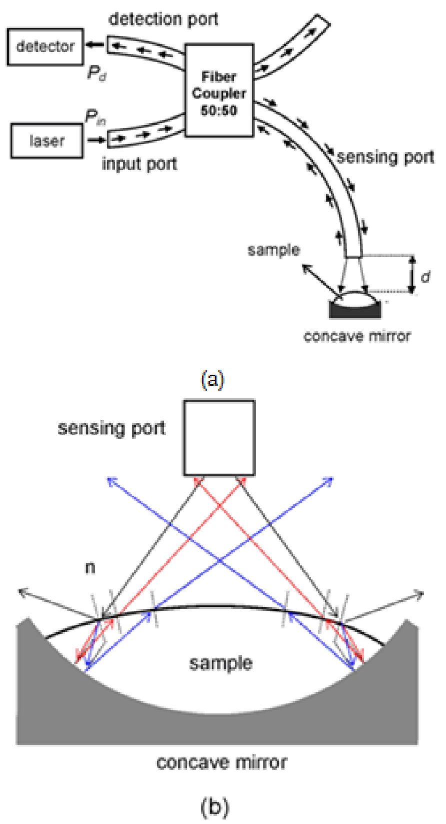

Fig. 1. (a) Design of glucose concentration sensor using fiber coupler using concave mirror as reflector and (b) illustration of light propagation due to refraction (color online)

Besides the non-direct contact with the sample, the use of concave mirrors makes it easy to detect glucose concentrations because observations are made through changes in peak voltage values. This is different if the detection is conducted using a flat mirror, where peak voltage is not generated. The determination of glucose concentration is conducted through changing the value of the output voltage detector when the sensor probe coincides with a flat mirror (a distance of almost zero) [8]. This requires caution when pouring the sample in the container or sliding the sensor probe, bubbles can occur in the small space between the sensor probe and the mirror. If so, the accuracy of the detection results is questionable.

3. Experiment and discussion

The justification that the working principle of the sensor is indeed based on the refraction of light was done by measure the absorption spectra of glucose solution using UV-Vis spectrophotometer. The glucose absorption spectra with a concentration of 40% are shown in Fig. 2 with absorption peaks occur at wavelengths of 197 nm and 263.5 nm. The laser used in this experiment has a wavelength of 632.8 nm. At the wavelength of 632.5, the absorption of the glucose solution is 0.03 ABS which is small and negligible in this case.

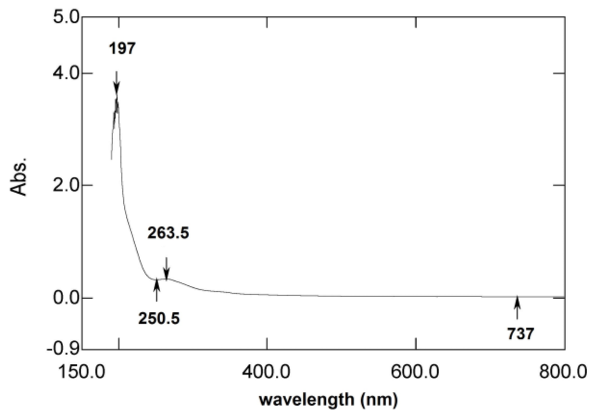

Fig. 2. The absorption spectra of glucose solution with a concentration of 40%

The first experiment was to identify the profile of the detector's output voltage against the displacement of the sensing port in the various volume of solvent (distilled water). The experimental set-up is shown in Figure 3. The experimental set-up consists of a He-Ne laser (with 632.8 nm wavelength and 10 mW power output) as a source, a silicon photo detector as an optical detector with a multimeter (Fluke) to read the detector output voltage. Fiber coupler used multimode structured 2x2 made of plastic (1 mm diameter, 1 m length, 50/50 split ratio, 3.7 5.6 dB insertion loss, and 1.6 dB excess loss). Concave mirrors with focal length 4.5 mm and 9 mm diameter (protected aluminum) serves as reflectors as well as sample containers. XYZ stage with a displacement resolution of 10 μm and range of 25 mm is used to shift the port sensing. The identified solvent volume is 10-70 μl with a variation of 10 μl. The largest solvent volume that the concave mirror can accommodate as sample in container is 70 μl which is almost twice the volume of a concave mirror (40 μl). As explained before, due to adhesion and cohesion force the solvent in the concave mirror will shape like a convex lens. Data retrieval was conducted by putting the sample (solvent) from the smallest volume (10 μl) in the concave mirror using a micropipette. The next step is to place the sensing port of the fiber coupler that acts as the sensor probe close to the sample surface (approximately 50 μm). Detector's output voltage was recorded each sensing port is shifted 100 μm away from the sample surface. The shift of sensing port is stopped when the value of the detector's output voltage was in steady state. The data collection process is carried out for volume variation with the addition of 10 μl to the largest volume (70 μl).

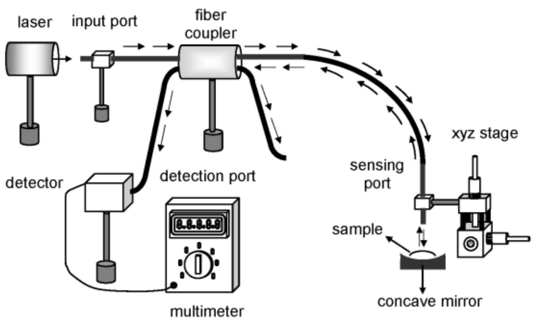

Fig. 3. Experimental set-up of glucose concentration sensor in distilled water

The profile of change in the detector's output voltage against the displacement of sensing port for distilled water with a volume of 10-70 μl is shown in Fig. 4. The results show that for distilled water with volume of 10-60 μl, two peak voltages are formed with the second peak voltage decreasing as the sample volume increases. When reaching the largest volume (70 μl), the second peak voltage has disappeared. From profile data that is obtained, a solution with volume of 20 μl was used to represent the volume of solution with two peak voltages.

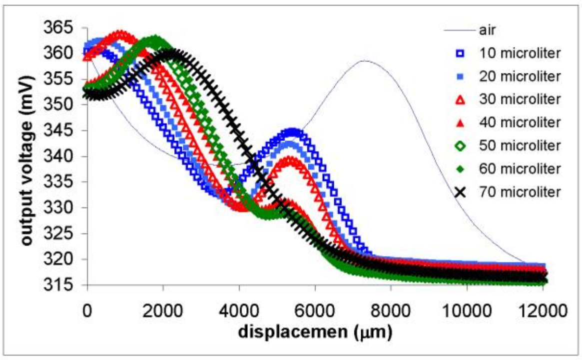

Fig. 4. Profile of change in the detector's output voltage against the shift of sensing port (color online)

The second experiment was to detect changes in glucose concentration in solution. The samples are glucose solution with concentration of 0-20% with a variation of 2%. The experimental procedure is the same as first experiment. Data retrieval of each sample was conducted three times. The result of the second experiment is shown in Fig. 5 with the largest measurement error of 3.1 mV. The relationship between peak voltage value and peak voltage position against glucose concentration is shown in Fig. 6. From data, we conclude that the result is irregular and inconsistent. We suspect that the cause is inconsistent sample position. It was difficult to place glucose solution on the concave mirror in the same position. We do not have devices which can put samples precisely in the middle of the concave mirror. Thus, from the second experimental data, it can be concluded that detection of glucose concentration with a volume of 20 μl was failed.

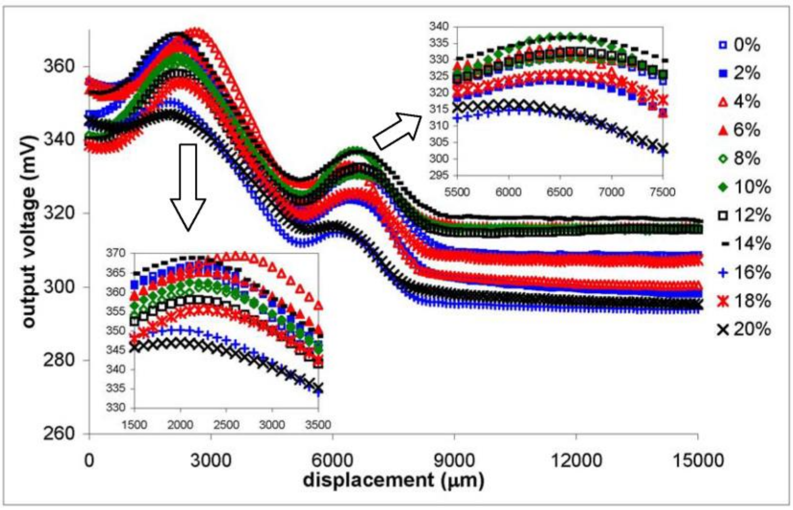

Fig. 5. Graphs of changes in glucose concentration in solution with volume of 20 μl (color online)

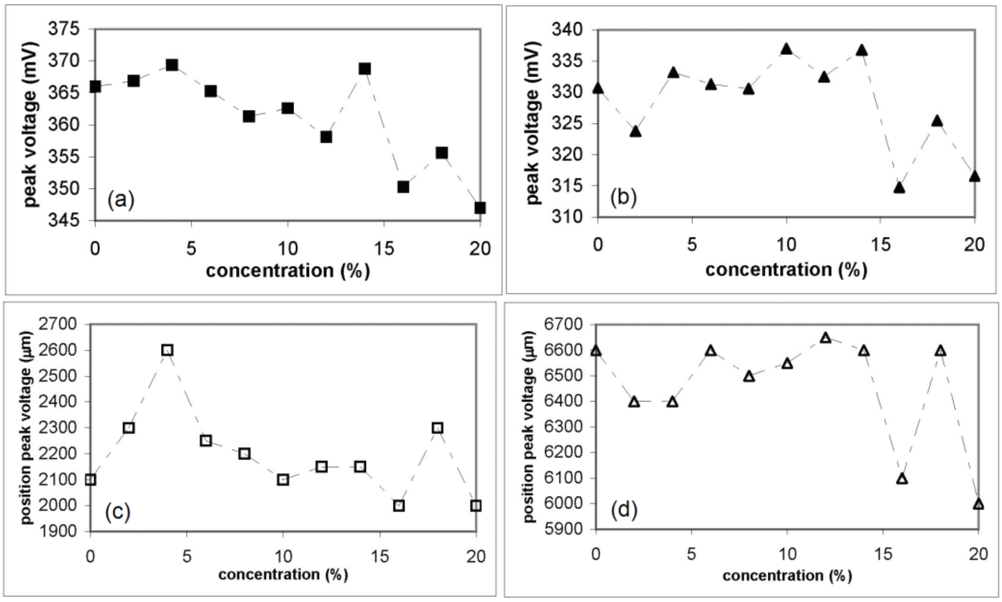

Fig. 6. Relationship between (a) first and (b) second peak voltage value, (c) first and (d) second peak voltage position against glucose concentration

From the second experiment, it is known that the detection of glucose concentration in solution with a volume of 20 μl was constrained by the difficulty of putting the sample to the center of the concave mirror. The third experiment was conducted by selecting a larger sample volume of 70 μl which fills the entire surface of the concave mirror. After the sample was placed in the concave mirror, it resembles a convex lens with radii of the concave mirror. This experiment was conducted to minimize the change of sample shape in the experiment. The third experimental procedure is the same as the second experiment. The samples are glucose solution with a concentration of 0-50% with a variation of 5%. The measurements of each sample were also repeated three times. The third experimental results are shown in Fig. 7 with the largest measurement error is 0.3 mV. The third experiment results are much better than the second experiment which can be seen from small measurement error obtained. The relationship between the peak voltage value and position against the detected glucose concentration is shown in Fig. 8.

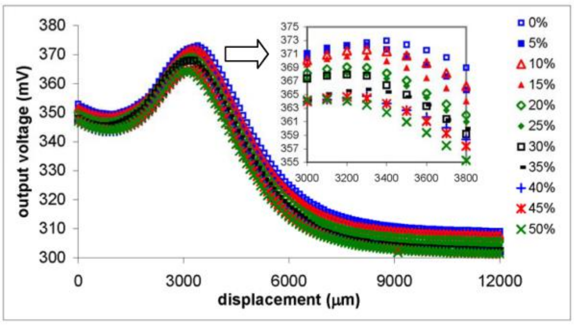

Fig. 7. Detector's output voltage as function of displacement due to changes in glucose concentration in solution with volume of 70 μl (color online)

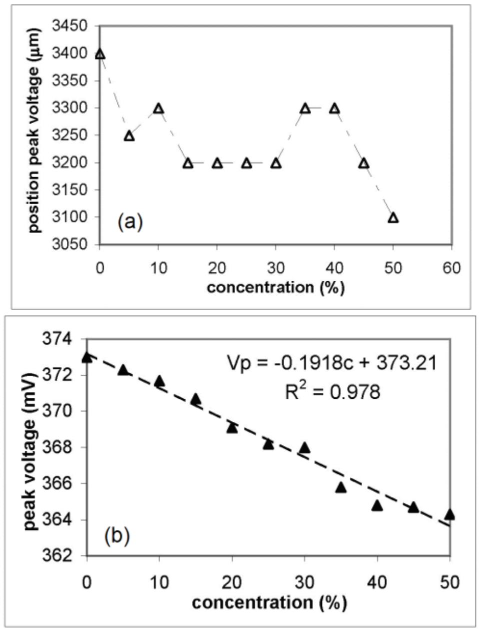

Fig. 8. Relationship between (a) peak voltage position and (b) peak voltage value against glucose concentration in solution with a volume of 70 μl

The result in Fig. 8 (a), indicates that the relationship between the peak voltage positions against the glucose concentration is random. It means that the concentration of glucose in solution with a volume of 70 μl can't be detected through its peak voltage position. However, the relation between peak voltage values to glucose concentration is linear for all glucose concentration tested with the linearity more than 98%. The slope of linearity test results is the sensitivity of the sensor. From these results, we conclude that the concentration of glucose in distilled water can be detected in solution with volume of

70 μl. By comparison, the refractive index of each experimental sample was tested using the Abbe Refractometer and the results are shown in Fig. 9. It appears that the relationship between the refractive index against the glucose concentration is also linear.

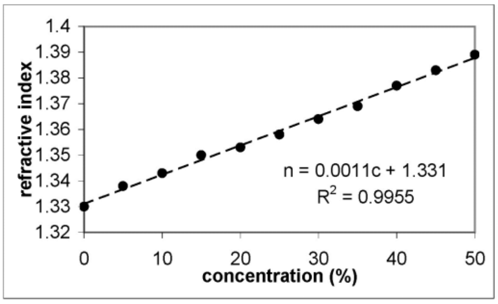

Fig. 9. Refractive index of each experimental sample from Abbe Refractometer measurement

The fourth experiment was conducted to find out the sensor stability for the sample volume of 70 μl. The stability test was carried out by placing the sensing port in a position that produced a peak voltage for each glucose concentration. The detector's output voltage was recorded every 30 s for 14.5 minutes. The results are shown in Fig. 10. The largest standard deviation from the sensor stability test is 0.1 mV. The ratio between standard deviation with the sensitivity of the sensor is the resolution of the sensor.

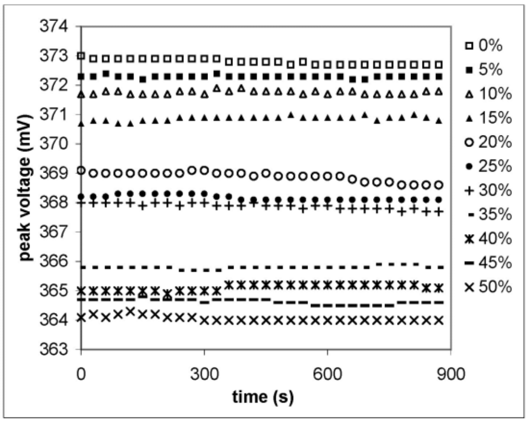

Fig. 10. Sensor stability for solution with volume of 70 μl

Overall, our experiments in a room with a fixed temperature of 24 ^{0}C resulted in a sensor with characteristics as shown in Table 1. The sensor has a linear region of 0-50% and a resolution of 1%. The sensor resolution is no better than the resolution of some concentration sensors that have been developed such as the calcium concentration sensor with a resolution of 0.05% [5], magnesium ion with a resolution of 0.2% [9], but our sensor offers a small volume detection and non-contact system. Based on the light propagation scheme as shown by Fig. 1 (b), the sensitivity or resolution of the sensor is expected to increase in value if the dimensions (radius and diameter) of the concave mirror are larger due to the sample volume Detected larger.

Table 1. Characteristic of glucose concentration sensor in distilled water using fiber coupler and concave mirror

Parameters	**Value**
Sensor range (%)	0 - 50
Linear region (%)	0 - 50
Sensitivity (mV/%)	0.2
Resolution (%)	1

4. Conclusion

Glucose concentration in solution with a volume of 70 μl can be detected using a fiber coupler with a concave mirror as a reflector without direct contact with the solution. The mechanism of sensor is based on the displacement sensor using the principle of light refraction. Detection is performed through peak voltage values that occur due to fiber coupler sensing port displacement against the sample surface that is shaped like a convex lens. The sensor can detect glucose concentration in the range of 0-50% with 1% resolution.

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* Corresponding author: samian@fst.unair.ac.id