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Detection of Rhodamine B levels in distilled water based on displacement sensor using fiber coupler and concave mirror

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Detection of Rhodamine B levels in distilled water based on displacement sensor can be done using fiber coupler and concave mirrors as reflector. The mechanism of detection is done through changes in the value of the voltage peaks due to absorption of Rhodamine B solution against the green light with a wavelength of 532 nm. This sensor system capable of detecting Rhodamine B levels in distilled water with a range of 0 – 8 ppm and a resolution of 0.02 ppm.

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Keywords: Fiber coupler, Displacement sensor, Rhodamine B levels, Absorption spectrum

1. Introduction

Optical fiber as a waveguide has been widely applied as sensors, such as displacement sensor based on modulation of intensity. Displacement sensor using fiber coupler and fiber bundle as a probe capable of detecting a shift in the flat mirror target [1,2] and concave mirror target [3] with the reflection technique. Displacement sensor using fiber coupler with a flat mirror as target has a characteristic that output voltage detector decreases exponentially with when target displacement increase. Meanwhile, displacement sensor using fiber bundle and concave mirror generate output voltage peaks at certain position between targets with the probe.

The medium between target and probe on fiber-optic displacement sensor is liquid. As the result, a change in voltage peaks or shift of voltage peaks will occur. This principle has been used to detect changes in refractive index of liquid [4], salinity levels [5] and glucose levels [6]. Change in the value or voltage peak position occurs due to changes in the level of measured substance which causes changes in refractive index of liquid. Another method to detect liquid levels is the technique of side-emitting and surface plasmon resonance (SPR) on the optical fiber. The method of side-emitting is done by replacing part of the cladding with polymer material (novolac) and used to detect alcohol levels [7]. SPR method is accomplished by coating the tip of optical fiber with silver so that the change of resonance wavelength of the optical fiber is occurred when the tip interacts with glycerol solution which experience changes in its level [8]. The latter two methods require a rather complicated technique in making the probe sensor (sensor head).

This paper report Rhodamine B (a dye substance widely used in the paper industry and the textile side) level detection system in distilled water using a displacement sensor based on fiber coupler and the concave mirror as a reflector. The mechanism of detection is based on light absorption of Rhodamine B solution. Green laser with a wavelength of 532 nm was used as a light source. The sensor system proposed in this paper is a preliminary study to develop a simple sensor to detect the presence of Rhodamine B which is widely abused as food and beverages coloring in Indonesia.

2. Sensors design and operating principle

The design of Rhodamine B levels sensor in distilled water using fiber coupler and concave mirror is shown in Fig. 1. The mechanism of detection is as follow, the light from the green laser (P_{in}) is coupled to the input port of fiber coupler and partly toward the sensing ports. Light output of the sensing port (P_e) is then forwarded to the concave mirror through the sample. Part of reflected light from concave mirror will go back to the sensing port (P_b) and forwarded to the detector through the detection port (P_d). Optical power of light received by detector is read as output voltage of detector.

Shift in the position of sensing port against concave mirror will produce a change in output voltage detector. The relationship between the optical powers of light that goes back to the port against the shifting of sensing port (d) is presented in Fig. 2.

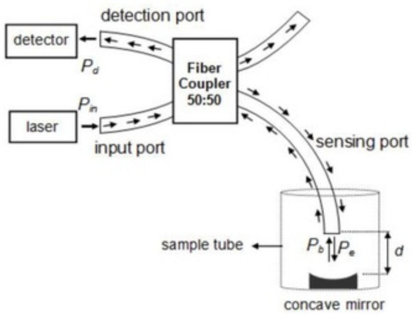

Fig. 1. The design of Rhodamine B level sensors in distilled water using fiber coupler and the concave mirror as reflector.

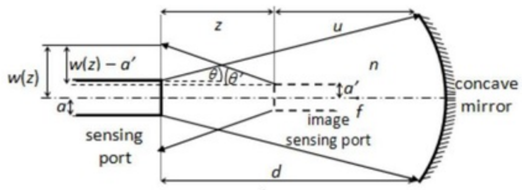

Fig. 2. Geometry of sensing port position against concave mirror

Fig. 2 shows the formation of sensing port image by a concave mirror produces an image with distance (u) in accordance with the equation:

$$u = \frac{df}{d-f}, \tag{1}$$

with d and f are distance of sensing port to the concave mirror and the focal length of a concave mirror respectively. from image magnification, the image radius of sensing port (a') and refraction angle of the light produced by image of sensing port (θ') can be written in the following forms:

$$a' = \frac{u}{d}a \tag{2}$$

and

$$\tan\theta' = \frac{u}{d}\tan\theta, \tag{3}$$

with a and θ are the radius and refraction angle of the light formed by sensing ports. If it is assumed that the light output of the sensing port is Gaussian beam, then the optical power that goes into sensing port (P_b) can be written as:

$$P_b = P_e\left[1-exp\left(-\frac{2a^2}{w^2(z)}\right)\right], \tag{4}$$

with P_e is the total power of light that does not depend on the position of z and $w(z)$ is the radius of the light which depend on the position of sensing port against concave mirror (d). From geometry in Figure 2, the radius of the beam of light can be written as:

$$w(z) = z\tan\theta' + a'. \tag{5}$$

Using equations (1), (2), and (3), then equation (5) can be rewritten in the following form:

$$w(z) = \frac{fa}{d-f}\left(\frac{d^2-2df}{(d-f)a}\tan\sin^{-1}\left(\frac{NA}{n}\right)+1\right) \tag{6}$$

Angle θ that should be in the equation (6) has been replaced with a numerical aperture of optical fiber i.e. $NA = n\sin\theta$ with n is the refractive index of medium between the sensing ports with concave mirror. Substituting equation (6) into the equation (4) will give the relation between optical power of light which enters the sensing port against displacement of the sensing port and can be written as:

$$P_b = P_e\left(1-\exp\left(-\frac{2(d-f)^2/f^2}{\left(\frac{d^2-2df}{(d-f)a}\tan\sin^{-1}\left(\frac{NA}{n}\right)+1\right)^2}\right)\right). \tag{7}$$

Travel light from the input port – concave mirror – detection port can be written in the form of the following equation:

$$P_d = P_0\left(1-\exp\left(-\frac{2(d-f)^2/f^2}{\left(\frac{d^2-2df}{(d-f)a}\tan\sin^{-1}\left(\frac{NA}{n}\right)+1\right)^2}\right)\right) \tag{8}$$

with:

$$P_0 = 1.15cr(1-cr)\left(10^{-0.1Le}-2\times10^{-0.1D}\right)^2 P_{in}, \tag{9}$$

where cr, Le, and D are coupling ratio, excess loss, and directivity of fiber coupler respectively, while the P_{in} is the optical power of the light from laser coupled to the input port [1].

Plot of relation between P_b with d for four values of refractive index of the medium (n) using the equation (7) exclude value of $d = f$ is shown in Figure 3. An increase in the value of refractive index of the medium between the sensing port and concave mirror causes an increase in the value of the voltage peaks. It is due to the properties of medium to refract the light.

On the other hands, if medium has properties to absorb the light that passed through it, then the beer's Law will apply to this situation. The application of Beer's Law is shown through the following equation:

$$P = P_0 \exp(-2dec) \qquad (10)$$

with P and P_0 are optical power of the light before and after passing through the material. While e and c are absorption coefficient of the material and concentration of the medium respectively. In the sensor detection mechanism as shown in Figure 1, $2d$ is the optical path length traveled by light. Optical power that goes back to the sensing port based on equation (7) opposite when compared to the equation (8).

In this paper, because Rhodamine B solution absorbs green laser light, then the mechanism of detection is based on absorption principle. This mechanism requires that the changes of level in Rhodamine B is not too large so that the light refraction effects can be minimized.

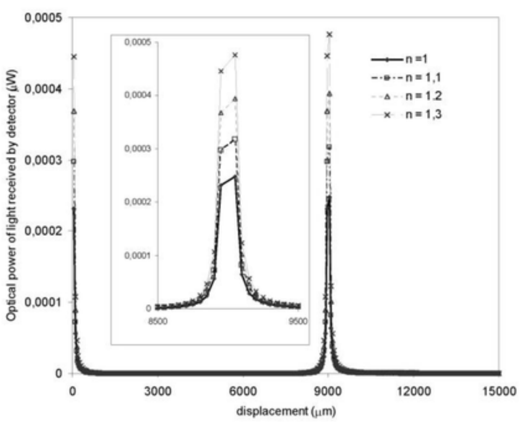

Fig. 3. Graphic simulation of the relationship between the optical powers of the light coming into the sensing port against displacement with the value of the refractive index of the medium.

3. Experiment

Schematic diagram of Rhodamine B level sensors experiment is shown in Fig. 4. The experimental set-up consists of green lasers with wavelength of 532 nm and output power of 10 mW as the light source, PDA 100A as optical detectors with a multimeter (Fluke) to read the output voltage.

Fiber coupler used in this experiment is multimode with structured 2 x 2 made of plastic (2.2 mm diameter fiber with jacket, 1 m length, 50/50 split ratio, 3.7 – 5.6 dB insertion loss, and 1.6 dB excess for loss). Focal length and diameter of concave mirror are 4.5 mm and 9 mm (protected aluminum) respectively as a reflector which is placed at the base of the sample container with shape of cuboid that has dimension 5 cm x 5 cm x 5 cm. Micrometers translator was used to adjust the sensing port.

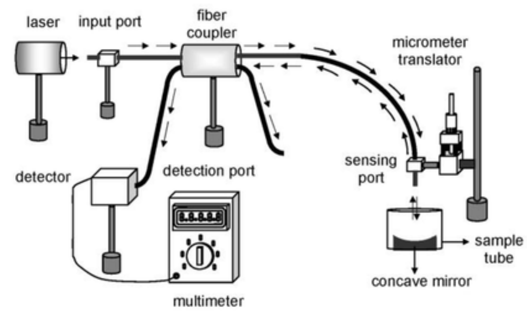

Fig. 4. Experimental set-up of Rhodamine B level in distilled water sensors.

Experimental procedure is performed with the following steps: first, the sensing port placed nearly coincide with concave mirrors in air medium (displacement 0 mm). Sensing ports are not placed coincide with the concave mirror because it could damage protected aluminum of concave mirror. Furthermore, the sensing port shifted away from concave mirror. Each shift of 100 mm, output voltage detector is recorded. Displacement is done until the output voltage detector is unchanged significantly. These steps are repeated for distilled water medium and Rhodamine B solution with the change of 2 ppm in the concentration. The next step is to test the stability of the sensor. The stability test is done by measuring the peak voltage of each sample in time range of 30 s to 900 s. The final step is to measure the refractive index of Rhodamine B solution for each concentration using Abbe Refractometer.

4. Result and discussion

Absorption spectrum of Rhodamine B solution in distilled water with concentration of 1 ppm obtained using a UV-Vis spectrophotometer is shown in Fig. 5. It appears that solution of Rhodamine B can absorb light with wavelength of 532 nm (wavelength of the laser used in the experiment) although the absorption peak is at wavelength of 553.60 nm.

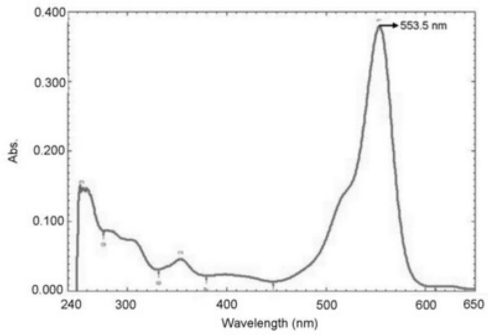

Fig. 5. Absorption spectrum of Rhodamine B solution at concentration of 1 ppm

Fig. 6 shows experimental results of sensing port displacement against concave mirror with medium of air, distilled water and Rhodamine B 2ppm solution. All voltage peaks are not located at a distance radius of curvature of the mirror, i.e. 9 mm. It is due to the position of sensing port which is not coincided with concave mirror at displacement 0. The increase in the value of the voltage peak occurs when the medium was changed from air to distilled water. This increase occurred due to the refraction of the medium. The increasing value of the refractive index of the medium (refractive index of distilled water from measurement using Abbe refractometer is 1.333) that causes angle θ in Fig. 2 become smaller. As a result, the optical power coming into port sensing increases. Equations (8) can explain the changes in refractive index medium.

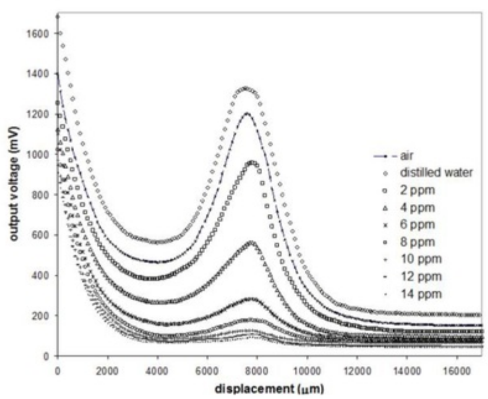

Fig. 6. Output voltage detectors against displacement of sensing port for air medium and various concentration of Rhodamine B solution

In case of solution of Rhodamine B was used as medium, the peak voltage decreases when concentrations of Rhodamine B increases. The concentration limit detectable (generate peak voltage) was 14 ppm. For concentrations larger than 14 ppm, peak voltage no longer appears. Measurement results of refractive index of Rhodamin B solution at concentration 2-14 is constant at 1.338. Thus the working principle of the sensor is based on absorption (absorption solution of Rhodamine B against a green laser) and not based on the principle of refraction. Fig. 7 shows the relationship between the positions of peak voltage against the concentration in range of 0 – 14 ppm. It appears that the trend is not constant therefore detection of Rhodamine B levels through peak voltage position is not reliable.

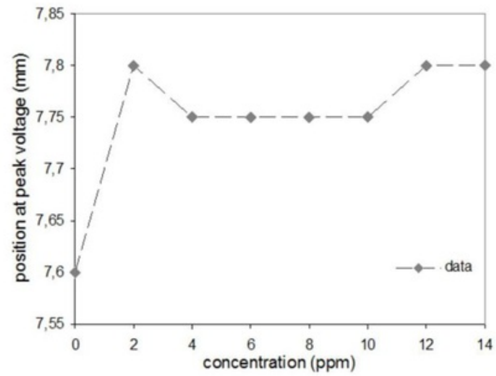

Fig. 7. The position of the peak voltage as a function of concentration of Rhodamine B solution.

The relationship between the peak voltage against concentration of Rhodamine B solution is shown in Fig. 8. The fitting results of data using equation (10) produces a very good suitability (values R = 0.979). Fitting equation justified that detection mechanisms of Rhodamine B levels using fiber coupler as the sensor follows beer's Law. If it is assumed that the optical path length is twice the average value of peak voltage position ($2d$ = 15.5 mm), then it can be determined that absorption coefficient of Rhodamine B solution to light with wavelength of 532 nm is 0.0133/ppm·mm.

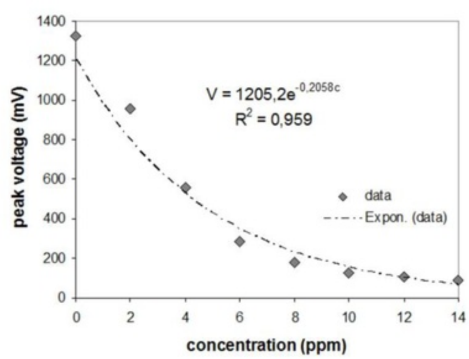

Fig. 8. Peak voltage as a function of concentration of Rhodamine B with data fitting results.

The linear relationship between voltage peak against concentration of Rhodamine B solution is shown in Fig. 9. It occurs that linear region is at range of 0 ppm – 8 ppm and linear slope, i.e. the sensitivity sensor, is equal to 148.6 mV/ppm with linearity greater than 95 %.

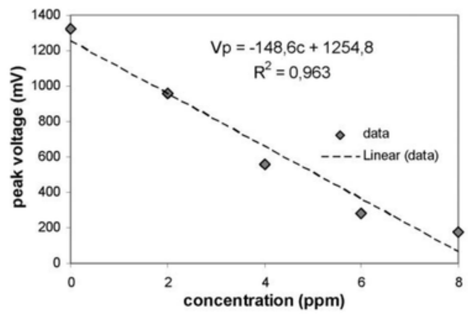

Fig. 9. Linear region of voltage peak against concentration of Rhodamine B solution

The sensor stability test was done by measuring voltage peak for 900 s with 30 s intervals at concentrations of 0 ppm – 8 ppm. The results are shown in Fig. 10. The standard deviation for concentration of 0 ppm, 2 ppm, 4 ppm, 6 ppm, and 8 ppm are 7.7, 4.2 mV, 1.7 mV, 1.3 mV, and 1.3 mV respectively with average 3.2 mV. If resolution of the sensor is average of standard deviation of sensor stability of sensor with sensor sensitivity, then the resolution of sensor is 0.02 ppm.

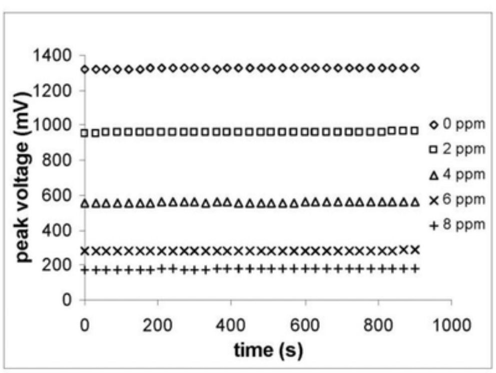

Fig. 10. Stability test results

Overall, the performance of Rhodamine B level sensor in distilled water is shown in Table 1. The working area of the sensors (linear region) for this sensor is small but the resolution is high, i.e. 0.02 ppm. This means that the presence of Rhodamine B in distilled water in very small quantity (0.02 ppm) was able to be detected by the sensor. The results of this initial study can be used for development of sensors with a simple working principle in detecting the presence of Rhodamine B in a food or beverage or as an environmental pollutant waste.

Table 1. Characteristics of Rhodamine B levels sensor in distilled water

Parameters	Value
Dynamic range (ppm)	0 – 14
Linier region (ppm)	0 – 8
Sensitivity (mV/ppm)	148.6
Resolution (ppm)	0.02

5. Conclusion

Detection of Rhodamine B levels in distilled water can be done using fiber coupler-based displacement sensor with concave mirrors as reflector. The detection is done through changes in peak voltage generated from displacement of sensing port against the concave mirror with Rhodamine B solution as medium. The decrease in the peak voltage occurs due to absorption of Rhodamine B solution to green light (wavelength of 532 nm). Results show that sensor system capable of detecting Rhodamine B levels in distilled water with concentration of 0 – 8 ppm and resolution of 0.02 ppm.

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