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Fiber optic salinity sensor using beam-through technique

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ABSTRACT

A fiber optic displacement sensor is proposed to sense salinity based on different concentration of sodium chloride (NaCl) in de-ionized water using the beam-through technique. The performance of a 594 nm and 633 nm He–Ne laser as the light source are compared. For a concentration change of sodium chloride from 0 to 12% in de-ionized water, the output voltage increase linearly and the sensitivity is dependent on the displacement position of the receiving fiber from the quartz cell containing the sodium chloride solutions. Measurements taken at higher displacement positions contribute to lower sensitivity with the highest sensitivity of 0.0237 mV/% and 0.0412 mV/% occurring at the 0 mm displacement position for the 594 nm and 633 nm He–Ne lasers, respectively. Furthermore, a better limit of detection of 1.44% is achieved when the 633 nm He–Ne laser is used compared to the 1.28% limit of detection achieved by using the 594 nm He–Ne laser. The main novelty of this sensor is that it is contactless and non-destructive which are attractive features for applications involving delicate and hazardous processes.

1. Introduction

Salinity measurement is important in many applications such as oceanography, process control in manufacturing industries [1] and desalination of seawater to supplement industrial water use levels as in large coastal cities [2]. Recently, a lot more interest have been shown in the monitoring and measurement of salinity due to the threat that secondary salinization pose to sustainable irrigated agricultural production which are caused by the build up of salts caused by irrigation [3,4]. Traditionally, electrical conductivity due to the presence of chlorine ions in water solution was used to measure the degree of salinity of water [5]. However, this technique is susceptible to electrical interference and does not consider other species that affect seawater density but do not conduct electricity.

Nowadays, fiber optic sensors are preferred for salinity measurement due to their unique advantages such as immunity to electromagnetic interference, compact size, low cost, contactless and non-destructive capability. Several fiber Bragg grating (FBG) based methods have been proposed for salinity measurements [6–8]. However, these methods require a wavelength code demodulator such as an optical spectrum analyzer (OSA) which is expensive. Recently, Zhao et al. [9] demonstrated an optical salinity sensor based on fiber optic array with a mean square deviation of 0.1034% for the measured salinity. This technique requires a Gaussian fit method to compensate for the loss in each fiber array.

In this paper, a simpler fiber optic salinity sensor is proposed and demonstrated based on intensity modulation technique. In our approach, salinity detection are based on different concentration of sodium chloride (NaCl) in de-ionized water, with a higher concentration reflecting a higher degree of salinity. Beam-through technique is used whereby light is transmitted through a transmitting fiber to a receiving fiber and the received light is measured by a silicon detector. This technique offers simplicity, reliability and continuous measurements capability.

2. Experimental setup

The experimental setup for sensing different sodium chloride solution concentrations is shown in Fig. 1. The sensor uses a beam-through technique, which consists of two fibers, one is connected to a light source and is known as the transmitting fiber, and the other is connected to a silicon detector and is termed as the receiving fiber. A 10 mm path length quartz cell is used to contain the sodium chloride solutions and is fixed between the common ends of the transmitting and receiving fiber. In the experiment, the receiving fiber is moved axially as shown in Fig. 1. The diverging source beam is refracted as it enters the different concentrations of sodium chloride solutions and a portion of it is collected by the receiving fiber to transmit into the silicon detector where its intensity

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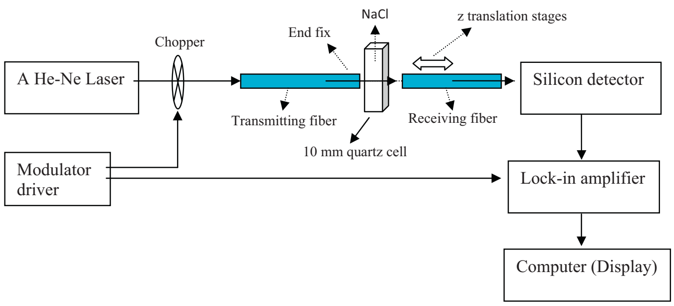

Fig. 1. Schematic diagram for the salinity sensor using beam-through technique with a 10 mm quartz cell path length.

is measured. The intensity of the collected light is a function of the displacement of the fiber. The 594 nm and 633 nm He–Ne laser are used subsequently as the light source with an average output power, beam diameter and divergence of 2.9 mW and 5.5 mW; 0.75 mm 0.80 mm; 0.92 mRads and 1.01 mRads, respectively. The light sources are modulated externally by a chopper with a frequency of 113 Hz as to avoid the harmonics from the line frequency which is about 50–60 Hz. The modulated light sources are used in conjunction with a lock-in amplifier to reduce the dc drift and interference of ambient stray light.

For the displacement, the receiving fiber tip is mounted on a translational stage, which provides movement to the receiving fiber surface in the axial direction. The quartz cell is first filled with de-ionized water; while the output intensity is measured against the change in the position of the fiber optic probe from closest to furthest in a step of 50 μm. The output voltage of the transmitted light is directly recorded by a computer automatically using Delphi software through serial port RS232. The measurements are then carried out for sodium chloride solutions (+80 mesh, ≥98% reagent grade, Sigma–Aldrich, USA) with concentrations of 2, 4, 6, 8, 10 and 12% in de-ionized water. During the experiment, the temperature is kept constant at 25 °C.

3. Results and discussions

Fig. 2 shows the transmitted light intensity versus distance of the beam-through technique at various sodium chloride concentrations. In the experiment, the sodium chloride concentration is varied from 0 to 12%. As expected, the voltage is highest at zero displacement and the displacements of the receiving fiber away from the quartz cell resulted in a reduced output voltage as shown in the figure. The power drop pattern follows the theoretical analysis by Van Etten and Van der Plaats [10] in which the output transmission

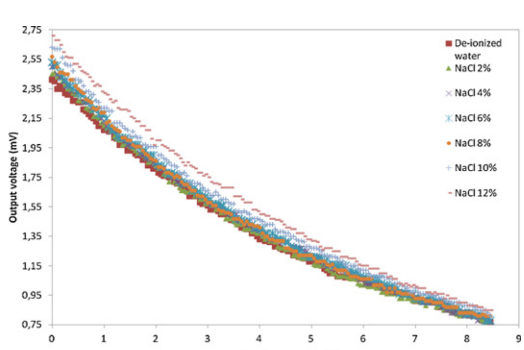

Fig. 2. Output voltage against displacement for various concentrations of sodium chloride in de-ionized water using 594 nm He–Ne laser.

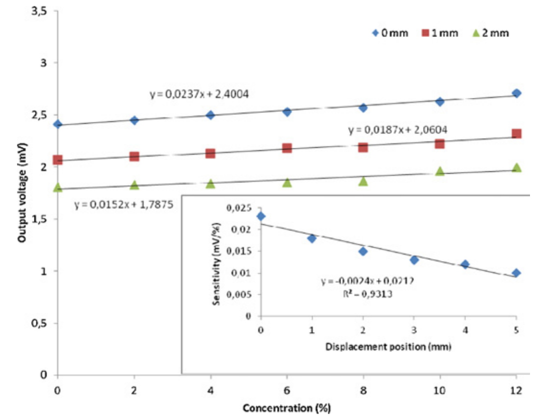

Fig. 3. The output voltage versus concentration of sodium chloride for displacement positions of 0, 1 and 2 mm using the beam-through technique. Inset shows the sensitivity of the salinity sensor versus displacement position.

function is given by:

$$\eta = 1 - \frac{z}{a}\frac{2}{a\pi(\mathrm{NA})^2}\left[\arcsin(\mathrm{NA}) - \mathrm{NA}\sqrt{1-(\mathrm{NA})^2}\right], \quad \text{for } \frac{z}{a} \ll 1 \tag{1}$$

where η, z, a, and NA are coupling efficiency, axial displacement, fiber core radius and numerical aperture, respectively. η is defined as the ratio of output voltage over the maximum voltage. As seen in Fig. 2, for a variation of concentration from 0 to 12%, the sensitivities of slopes for the output voltage versus displacement does not vary much with a range from 0.246 mV/mm to 0.269 mV/mm and a standard deviation of 0.008 mV between the values. The sensitivities are determined by a slope of a straight-line portion in the curves.

Based on Fig. 2, the output voltage is plotted against the concentrations for displacement positions of 0, 1 and 2 mm from the quartz cell as highlighted in Fig. 3. It is observed that the output voltage increases as concentration increases. This can be explained by the reduction of the refraction angle, β as shown in Fig. 4. Fig. 4 illustrates the cone of light at the transmitting fiber probe in which

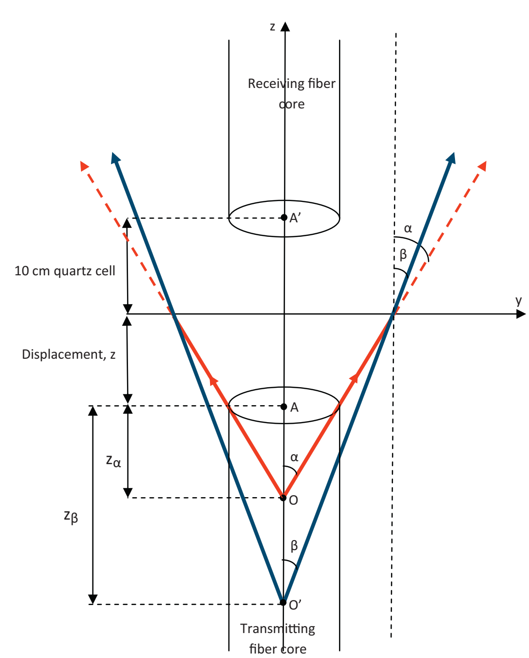

Fig. 4. Cone of light at the transmitting fiber probe.

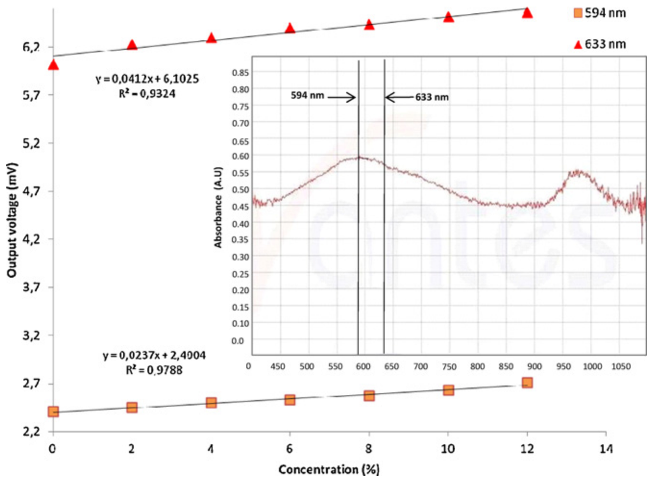

Fig. 5. The output voltage versus concentration of sodium chloride solution using 594 nm and 633 nm He–Ne laser measured at the 0 mm displacement position. Inset shows the absorbance spectrum of a 10% sodium chloride concentration solution.

the central of the transmitting and receiving fiber are denoted as A and A', respectively. The light leaving the transmitting fiber is represented by a perfectly symmetrical cone with divergence angle α and vertex O located at a distance z_α inside the fiber. As the transmitting light enters the air–liquid interface, refraction occurs due to the difference in their refractive indices. By using Snell's law, the refraction angle, β can be obtained by the following equation:

$$\beta = \sin^{-1}\left(\frac{\sin\alpha}{n_2}\right) \quad (2)$$

where α and n_2 are the divergence angle and refractive index of the sodium chloride solution respectively. A higher concentration of sodium chloride solution corresponds to a higher refractive index ranging from 1.3433 to 1.3576 for 2–12% concentrations hence decreasing the refraction angle and subsequently increasing the portion of light to be collected by the receiving fiber. The symmetrical cone of the transmitted light appears to have a reduced divergence angle β and vertex O' located at a distance z_β inside the fiber. Prior to the refractive index measurements the sensor is calibrated by measuring the sensor output in liquids with known refractive indices.

The sensitivity of the sensor which is the slope of the output voltage versus the concentration line decreases as the displacement position increases. At displacement positions of 0, 1 and 2 mm, the sensitivities are 0.0237 mV/%, 0.0187 mV/% and 0.0152 mV/%, respectively. This is because the displacement curves (Fig. 2) follow an almost inverse square law relationship whereby the slope becomes less steep as the displacement increase. The inset of Fig. 3 highlights the linearly inverse relationship between the sensitivity of the sensor and the displacement position.

Fig. 5 shows the relation between the output voltage at the 0 mm displacement position with the concentration of sodium chloride for both sensors configured with 594 nm and 633 nm He–Ne laser. The output voltage varies linearly with the concentration for both sources but the 633 nm light source produces a higher output voltage and is more sensitive than the 594 nm light source. The difference in the output voltage levels is due to the difference in average output power of the light sources whereas the difference in sensitivity is because of the different absorbance of sodium chloride solutions at that particular wavelength as is depicted in the inset of Fig. 4. Sodium chloride solutions absorb more at the 594 nm wavelength than the 633 nm wavelength hence produces higher opposition to the increase in the output voltage.

Table 1
Performance of the salinity sensor using fiber optic beam-through technique.

Parameter	594 nm	633 nm
Sensitivity	0.0237 mV/%	0.0412 mV/%
Linear range	0–12%	0–12%
Linearity	>98%	>96%
Standard deviation	0.034 mV (1.98%)	0.053 mV (0.88%)
Limit of detection	1.44%	1.28%

The performance of the salinity sensor is summarized in Table 1. The sensitivity and limit of detection of the salinity sensor are obtained at 0.0237 mV/% and 1.44%, respectively with the use of 594 nm light source. With 633 nm He–Ne laser, the sensitivity and limit of detection are 0.0412 mV/% and 1.28%, respectively. The limit of detection is defined by the ratio of standard deviation to sensitivity. The results presented show that there is a linear relationship between the signals received at the receiving fiber as a function of the concentration of the sodium chloride solution; or in other words the salinity of the solution. It is observed that an increase in salinity can be detected by an increase in the received output voltage with better results observed at small displacement positions. Since changes in salinity can be converted into changes in electrical voltage, it is apparent that this salinity sensor may be used to record and control salinity of various mixtures continuously. Furthermore, the fibers do not come in contact with the sodium chloride solution hence it is also non-destructive.

4. Conclusions

A simple intensity modulated displacement sensor is demonstrated as a device to detect salinity of sodium chloride solutions varying from 0 to 12% by using beam-through technique. The displacement curves for 594 nm and 633 nm He–Ne laser sources exhibit a similar trend whereby the output voltages form a linear function with the concentration of sodium chloride solution. The results also show that the sensitivity is almost doubled and a smaller limit of detection is attainable when the 633 nm He–Ne laser is used as the light source compared to the 594 nm He–Ne laser. This new salinity monitoring system provides numerous advantages such as simplicity of design, low cost of production, contactless and non-destructive.

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