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Non-contact refractive index measurement based on fiber optic beam-through technique

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A simple refractive index sensor for various concentrations of sodium chloride (NaCl) in de-ionized water is proposed and demonstrated. The beam-through technique is used to obtain output voltage of liquids with known refractive indices, namely methanol, de-ionized water, acetone and ethanol. Based on the output voltage of these liquids, the sensor characteristic curve is determined and the refractive indices of 2 % to 12 % sodium chloride concentrations are obtained. A sensitivity and detection limit of 23.07 mV/refractive index unit (RIU) and 2.28 x 10^{-3} RIU have been derived from measurements, respectively, with a linearity of more than 97 %. The fiber optic sensor is a promising alternative to other well-established methods for the measurement of liquid refractive index due to its simplicity of design, linearity, non-contact sensing, ruggedness and low fabrication cost.

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1. Introduction

The detection and measurement of small variations of refractive index within solution has recently received considerable amount of attention due to its association with the concentration of molecules. A refractive index sensor with better detection limits is capable in detecting smaller concentrations of molecules. Optical detection methods of refractive index variations enable a label-free detection of liquid molecules which does not require the liquid analyte to be marked with fluorescent dyes. Numerous fiber-based refractive index sensors have been reported based on fiber interferometers [1-2], fiber Bragg gratings [3-4] and tapered fibers [5-7]. These kind of fiber sensors exhibit good performance but some optical setups are complicated and involve tedious fabrication processes. Furthermore, tapering of fibers make them more fragile and difficult to handle.

Recently, many works have been reported on fiber optic displacement sensors based on plastic fiber probe [8]. These type of sensors have been demonstrated to be efficient for different applications [9-12]. They are relatively inexpensive, easy to fabricate and suitable for employment in harsh environments. In this paper, we propose and demonstrate a new choice of refractive index sensor featuring more advantages and potential, which is a simple intensity modulated fiber optic displacement sensor using plastic fibers. In our approach, variations of refractive index are based on different concentration of sodium chloride (NaCl) in de-ionized water. 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 the refractive indices of 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. The transmitting and receiving fibers have an equal core diameter of 960 µm and a length of 0.52 m and 2 m, respectively. A 10 mm path length quartz cell is used to contain the liquids and is fixed between the common ends of the transmitting and receiving fiber. A red 633 nm He-Ne laser is used as the light source with an average output power, beam diameter and divergence of 5.5 mW, 0.80 mm and 1.01 mRads, respectively. The light source is modulated externally by a chopper with a frequency of 113 Hz. The modulated light source is used in conjunction with a lock-in amplifier to reduce the dc drift and interference of ambient stray light. The principle is based on the refraction of the diverging source beam as it enters the liquids with different refractive indices. A silicon detecor detects the portion of light that is collected by the receiving fiber.

Prior to the refractive index measurements the sensor is calibrated by measuring the sensor characteristic curve in methanol, de-ionized water, acetone and ethanol with refractive indices of 1.3284, 1.334, 1.3586 and 1.3776, respectively. The characteristic curve is obtained by plotting the measured output voltage of each of the liquids when placed in the quartz cell with respect to their refractive indices. 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 1, 2, 3, 4, 5 and 6 g per 50 ml of de-ionized water. Based on the characteristic curve, the refractive indices for the 2 % to 12 % sodium chloride concentrations are obtained accordingly. During the experiment, the temperature is kept constant at 25 °C.

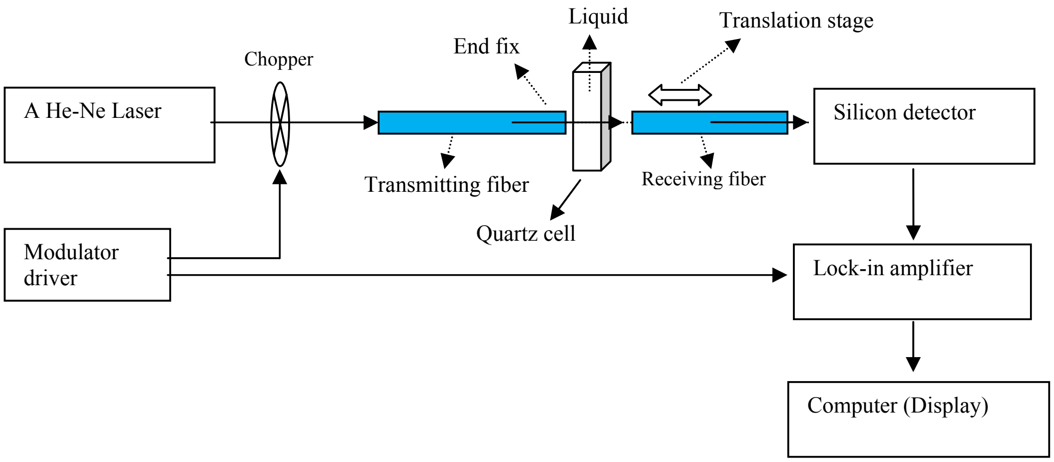

Fig. 1. Experimental setup of sodium chloride solutions refractive index measurement using beam-through technique with a quartz cell path length of 10 mm.

3. Results and discussions

Fig. 2 shows the variation of the transmitted light against the refractive index of methanol, de-ionized water, acetone and ethanol with increasing values of refractive indices accordingly. As shown in the figure, the output voltage from the photodetector, which is proportional to the transmitted light increases linearly from 5.82 mV to 6.92 mV as the refractive index increases from 1.3284 to 1.3776. This can be explained by the reduction of the refraction angle, β as shown in Fig. 3. 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:

$$\beta = sin^{-1}\left(\frac{sin\alpha}{n}\right) \tag{1}$$

where α and n are the divergence angle of the light source and refractive index of the liquid, respectively.

The output voltages of the various concentrations of sodium chloride solutions are tabulated in Table 1. For a concentration change from 2 % to 12 %, the corresponding output voltages vary from 6.23 mV to 6.56 mV which fits within the output range of the proposed refractive index sensor. The unknown refractive index is obtained from the characteristic curve of the sensor (Fig. 2) and a linear relationship between the refractive indices and the concentration is obtained as depicted in Fig. 4. As the concentration increases from 0 % to 12 %, its refractive index increases from 1.334 to 1.3575.

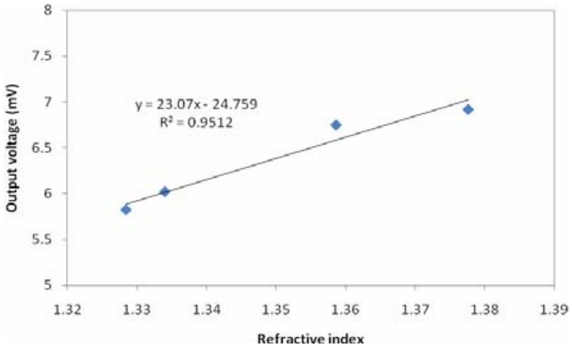

Fig. 2. Output voltage against refractive index of methanol, de-ionized water, acetone and ethanol.

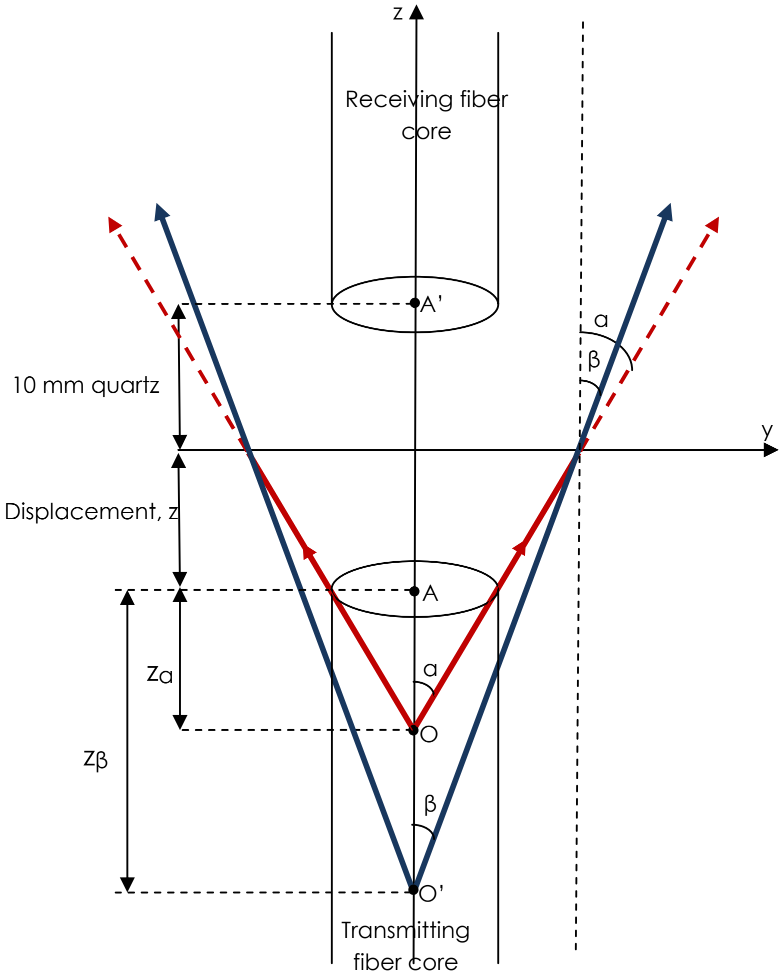

Fig. 3. Cone of light at the transmitting fiber probe.

Table 1. The output voltage of 2 % to 12 % concentration of sodium chloride solutions using the beam-through technique.

Concentration of sodium chloride solution (%)	Output voltage (mV)
2	6.23
4	6.3
6	6.4
8	6.43
10	6.51
12	6.56

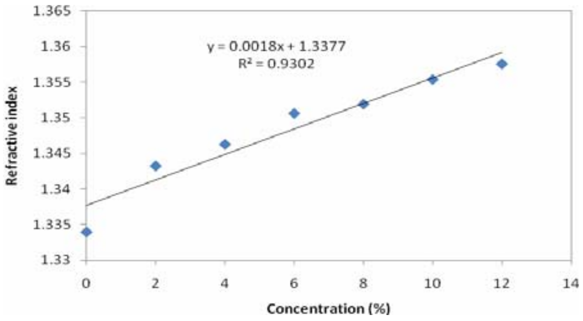

Fig. 4. Refractive index versus various concentration of sodium chloride solution in de-ionized water.

The sensor performance is summarized in Table 2. The sensitivity is obtained at 23.07 mV/RIU with a good linearity of more than 97 % for a refractive index range from 1.3284 to 1.3776 RIU. The limit of detection for the sensor is 2.28 × 10^{-3} RIU and is sufficiently stable with a standard deviation of 0.88 %. Throughout the experiment, a fixed quantity of liquid solution is placed in the quartz cell and the corresponding output voltage is measured by a lock-in amplifier which provides accurate measurements for small signal with large noise sources. Furthermore, the coupling of the lock-in amplifier with a chopper avoids the harmonics from the line frequency and reduces the dc drift and interference of ambient stray light. Moreover, a well-regulated power supply is used for the red He-Ne laser and this minimizes the fluctuation of source intensity.

Table 2. The performance of the sodium chloride refractive index sensor.

Parameter	Value
Sensitivity	23.07 mV/RIU
Linear Range	1.3284 – 1.3776 RIU
Linearity	More than 97 %
Standard Deviation	0.0526 mV (0.88 %)
Limit of detection	2.28×10^{-3} RIU

4. Conclusion

A simple and low cost all-fiber refractive index sensor for sodium chloride solution based on beam-through technique, with adequate performances is presented. Experimental characterization of the sensor response to refractive index changes has been carried out by using liquid with known refractive indices. A detection limit of 2.28×10^{-3} RIU is possible for refractive indices ranging from 1.3284 to 1.3776 with a linearity of more than 97 %. The advantages of simplicity of design, low cost of production and good resolution offer the prospect for development of practical sensors for continuous chemical sensing applications.

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