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Non-intrusive refractometer sensor

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Abstract. An experimental realization of a simple non-intrusive refractometer sensor is demonstrated in this communication. The working principle of the sensor is based on intensity modulation of the back-reflected light when output light from an optical fibre end focusses onto air–medium interface. The change in the refractive index of the medium affects the reflectance of the incident light signal and thus modulates the back-reflected signal. Refractive index variation as small as 0.002 RIU can be measured using the present technique. The advantages of the technique are its simplicity, cost efficiency and usefulness in monitoring refractive indices of acidic solutions.

Keywords. Fibre-optic sensor; back-reflection; refractometer; non-intrusive refractometer.

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1. Introduction

Measurement of the refractive indices of liquids is critical for various industrial and laboratory applications. For instance, in sugar industries it is often necessary to monitor the concentration of sugar solution and this can be done by checking the refractive index of the solution during preparation. Highly concentrated solution implies high refractive index of the medium. Similarly, in food processing and pharmaceutical industries it is often required to monitor refractive indices of various solutions as it conveys important information to the manufacturer. Over the years there has been a great deal of interest in monitoring liquid refractive index using fibre-optic (FO) sensors [1–5]. Compared to conventional refractometers such as Abbe refractometer, fibre-optic refractometer offers three major advantages. First, remote monitoring is possible using fibre-optic sensor, secondly, it is geometrically flexible and thirdly it offers multiplexing facility. Thus, refractive indices of several liquids can be monitored using single sensing set-up. Takeo and Hattori [6] proposed a refractometer which was based on intensity modulation of the guided light of an optical fibre as it comes into contact with liquid. Again, Asseh *et al* [7] had proposed a fibre Bragg grating refractometer using evanescent field refractive index fibre sensor that comprises of a 42 mm Bragg grating in an etch fibre. Most of the fibre-optic refractometer sensors reported are intrusive type, i.e. the sensing region of the fibre is in intimate contact with the liquid medium, and modulation of the evanescent field absorption due to change in refractive index of the medium is exploited for measurement. However, intrusive-type FO refractometers possess two major disadvantages. First, to measure refractive indices of different liquids, e.g. propylene glycol and polyvinyl alcohol solutions, the sensing region has to be cleaned properly. This makes the measurement process lengthy and difficult. Secondly, the sensing region of the fibre may permanently be damaged when it is brought into contact with some reactive chemical solutions such as hydrofluoric acid (HF), nitric acid (HNO_3) etc. Thus, one cannot measure refractive index of such solutions. In this communication, I report a simple, cost-efficient non-intrusive fibre-optic refractometer sensor which is based on the intensity modulation of the back-reflected light signal due to change in index of refraction of the liquid medium [8]. Refractive index variation as small as 0.002 RIU can be measured using the present technique. The present technique may be useful for monitoring refractive indices of active chemical solutions which was not possible with intrusive-type FO sensors.

2. Sensor principle

For a circular beam of light with cross-sectional area A, incident at an angle θ_i on the surface of a second medium, the power associated with the incident, reflected and transmitted beams are $I_i A\cos\theta_i$, $I_r A\cos\theta_r$ and $I_t A\cos\theta_t$ respectively [8]. Here, I_i, I_r and I_t and θ_i, θ_r and θ_t represent the intensity and the corresponding angle for the respective beams. The reflectance R of the medium is defined as the ratio of the reflected power to the incident power.

$$R = \frac{I_r A\cos\theta_r}{I_i A\cos\theta_i} = \frac{I_r}{I_i}. \tag{1}$$

Again, radiant flux density or irradiance I is defined as

$$I = \langle S\rangle_t = \frac{c\varepsilon_o}{2E_o^2}. \tag{2}$$

Here $\langle S\rangle_t$ is the Poynting vector. From (1) we can write

$$R = \frac{E_{or}^2}{E_{oi}^2} = r^2, \tag{3}$$

where, r represents the amplitude of reflection coefficient and is given by

$$r = \frac{(n_t - n_i)}{(n_t + n_i)} \tag{4}$$

n_i and n_t are the refractive indices of the incident and the transmitting mediums respectively. Likewise, the transmittance is defined as

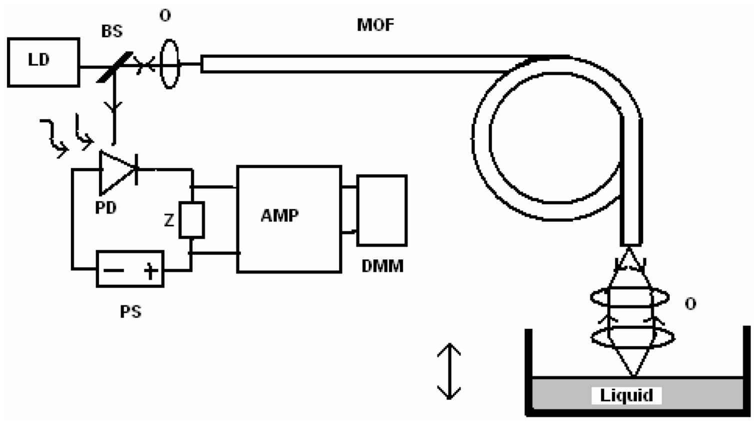

Figure 1. Schematic configuration of the experimental set-up. LD – Laser diode, BS – beam splitter, O – objective, MOF – multimode optical fibre, PD – photodiode, PS – power supply, Z – impedance, AMP – amplifier, DMM – digital multimeter.

$$T = \frac{I_t \cos\theta_t}{I_i \cos\theta_i}. \tag{5}$$

For non-absorbing medium

$$R + T = 1. \tag{6}$$

For the present case, we are interested only in the reflectance of the medium, and for incident angle $\theta_i = 0$, we can write from eq. (4)

$$R = \frac{(n_t - n_i)^2}{(n_t + n_i)^2}. \tag{7}$$

Thus, it is seen that reflectance of a medium depends on its refractive index and in the present investigation, we exploit this principle for measuring the refractive index of a liquid medium.

3. Experimental set-up

The experimental arrangement for the present sensing investigation is shown in figure 1. The optical fibre used here is a plastic clad silica (PCS), step-index multimode optical fibre (MMOF) with a core diameter of 200 μm and a numerical aperture (NA) of 0.37. Light from a laser diode operating at a wavelength of 670 nm with an output power of 5 mW is coupled with one end of the fibre. Light signal from the output port of the fibre is focussed onto the air–medium interface by using a pair of collimating and focussing lens arrangement. The useful back-reflected light signal from the medium is received by a detector using a beam splitter and after amplification is finally read by a digital multimeter (Fluke make: 179 true

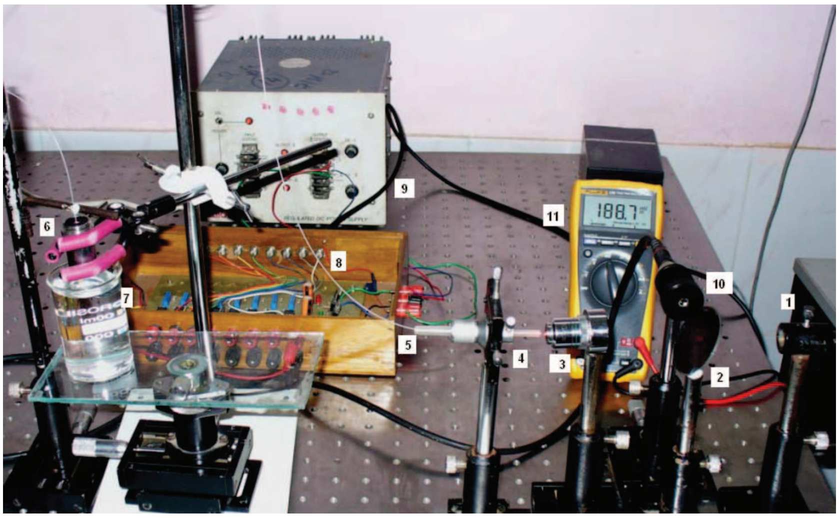

Figure 2. Photograph of the experimental set-up for a non-intrusive refractometer. 1 – diode laser, 2 – beam splitter, 3 – objective, 4 – fibre holder, 5 – optical fibre, 6 – objective, 7 – liquid sample, 8 – amplifier, 9 – power supply, 10 – photodiode, 11 – digital multimeter.

RMS). The level of the medium can be varied by placing it on a three-dimensional translational stage with a vertical axial resolution of 0.5 mm. Thus, for the present sensing arrangement the in-focus incident light onto the medium would yield maximum back-reflected light signal when compared to the out-of-focus incident beam. The experimental arrangement for the present sensing investigation is shown in figure 2.

4. Results and discussion

To study the response of the present FO refractometer, propylene glycol has been chosen as a test liquid medium. Refractive index of propylene glycol can be varied by adding pure water into it. Several samples have been prepared by adding pure water into it. To increase the range, we also take pure water and a glass slide and values of all the samples were initially measured by Abbe's refractometer. Table 1 summarizes the refractive indices of different mediums for our investigation and the corresponding reflectance (R) of light signal for air–medium interface which has been derived from eq. (7).

Figure 3 shows the sensor response for three different mediums, namely, water ($n_{\mathrm{w}} = 1.331$), propylene glycol (S_5) ($n_{\mathrm{s}_5} = 1.4052$) and glass plate ($n_{\mathrm{g}} = 1.5001$). These responses clearly show that with increasing index of refraction of the medium, the reflectance of the incident light increases and thus, larger back-reflected signal would be observed for the medium with higher refractive index.

The observation was then repeated for all the samples listed in table 1 and normalized values of the sensor responses and theoretical values of reflectances for

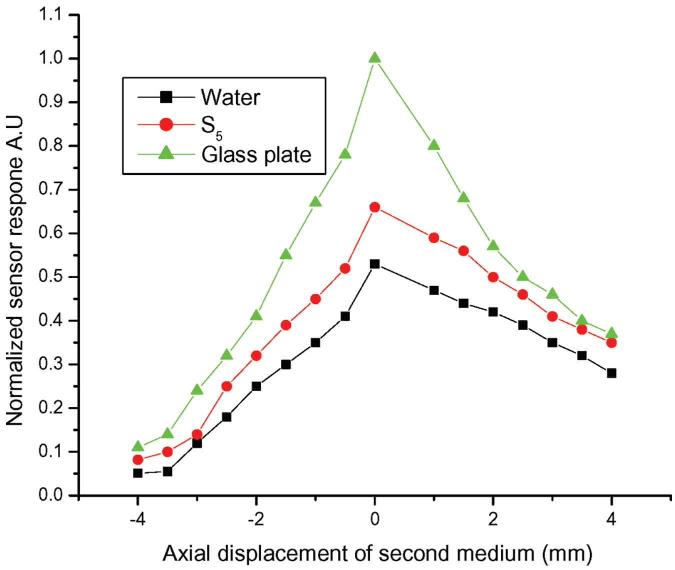

Figure 3. Representation of the sensor response with axial displacement for three different mediums.

Table 1. List of different mediums with their reflectance values from air–medium interface.

First medium (n_i)	Second medium (n_t)	Reflectance (R)
Air=1.0000	Water=1.331	0.020059
Air	Propylene glycol sample	
	S_1=1.3401	0.02118
	S_2=1.3652	0.023818
	S_3=1.3811	0.025492
	S_4=1.3901	0.026627
	S_5=1.4052	0.02835
	S_6=1.4131	0.02929
Air	Glass plate = 1.5001	0.0401

all the samples have been presented in figure 4. For all mediums, only the maximum back-reflected light signal from the air–medium interface was recorded during investigation. This implies that the second medium is in-focus for the sensing arrangement. This way one can keep the distance fixed for all mediums from the fibre-end tip.

During observation, special care was taken on thickness and temperature of the medium. For all samples, the medium thickness was taken as ≈1.5 cm. This ensures that only negligible back-reflected light signal from the back plane of the medium would reach the detector section thus improving the signal-to-noise ratio

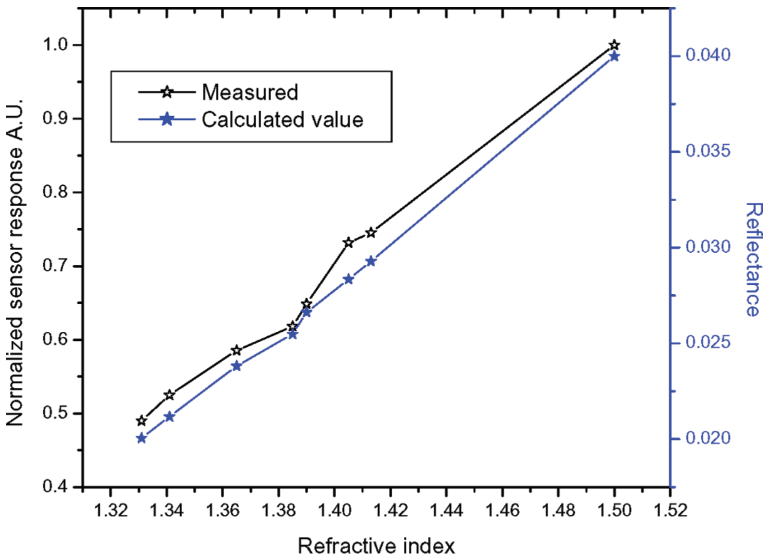

Figure 4. Theoretical and measured reflectances of light signal for different refractive mediums.

for the present sensor. Also the temperature was kept constant at 25°C during investigation of all samples. The investigation was carried out in an air-conditioned room and the temperature of the environment was maintained at 25°C throughout the investigation.

To measure the index of refraction of an acidic solution, 48% wt. hydrofluoric (HF) acid solution was taken and the investigation was carried out with the same sensing set-up. For referencing, we also took water and the sensor responses for these two mediums are described in figure 5.

If we extrapolate the sensor response value for HF in figure 3 it would be nearly 1.155 for diode laser operating at a wavelength of 670 nm. This value is nearly the same as obtained in [9] for anhydrous HF with 656.26 nm light source.

To check the resolution of the refractometer, two more samples of propylene glycol were prepared by adding pure water. The differences in index of refraction of the samples are found to be 0.002 RIU. For these samples the sensing arrangement shows different modulated back-reflected signals. However, for further decrement of the difference in index of refraction of the medium no significant change in back-reflected signal is observed by the detector. Thus, the resolution of the present sensor can be taken as 0.002. The resolution can, however, be increased with single mode fibre sensing arrangement [10] where the MMOF is replaced by single mode fibre coupler. In such a scheme, the signal-to-noise ratio improves dramatically and higher sensitivity can be expected [11]. The present sensor performance is limited by the noise which is developed due to mode instability in MMOF and multi-reflection which occurs in the space between the focussing lens and the liquid medium. This can be avoided by increasing the length of the in-focus position for air–medium interface. However, this leads to the decrease in irradiance for back-reflected signal and thus there is a trade-off between these two.

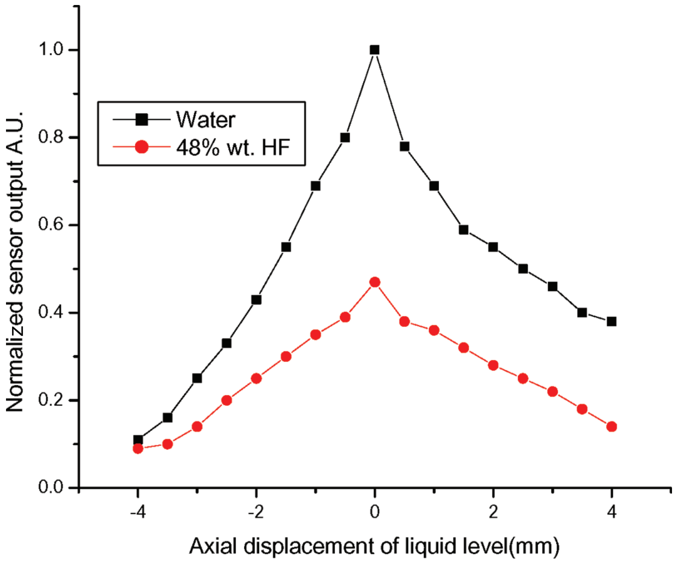

Figure 5. Normalized sensor response for water and 48% wt. HF solution.

5. Conclusion

In conclusion, a simple non-intrusive fibre-optic refractometer sensor with a resolution capacity of 0.002 RIU is presented. The sensing principle is based on irradiance modulation of the back-reflected light signal from a medium when the output light from an optical fibre end is focussed onto the medium. The present technique is useful for the measurement of refractive index of important chemical solutions such as HF, HNO_3, methanol etc. which was not possible with the previous intrusive-type FOS. Better sensitivity of refractometer can be achieved with single mode optical fibre arrangement.

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