PRAMANA © Indian Academy of Sciences Vol. 79, No. 6
— journal of December 2012
physics pp. 1525–1532

Single-mode fibre coupler as refractometer sensor

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MS received 6 March 2012; accepted 10 May 2012

Abstract. We report a simple, non-intrusive fibre-optic refractometer sensor for measuring the refractive index of liquid and optically transparent solid medium. Sensing principle of the proposed sensor is based on monitoring the back-reflected light signal through the second input port of a 2×1 single-mode fibre coupler when light signal from the output port is focussed at the interface of air and a liquid or solid medium and back-reflected exactly along the same path. Depending on the refractive index of the medium, the amount of back-reflected intensity would vary and in the present work we exploit this principle to measure the refractive index of an optically transparent medium. Variation of refractive index as small as 0.001 RIU can be measured with our proposed sensor.

Keywords. Fibre-optic sensor; intensity modulation; back-reflected signal; refractometer.

PACS Nos 89.20.Bb; 89; 89.20.−a

1. Introduction

Measurement of the refractive index of solutions and optically transparent solid medium is important for different laboratory and scientific applications. For instance, in food processing and pharmaceutical industries, refractive indices of various solutions have to be monitored because they convey important information to the manufacturer. From the measurement of refractive index, concentration of important chemicals can be known. Concentrated solution implies high refractive index of the medium. Over the years there has been a great deal of interest in monitoring the refractive index of liquid medium using fibre-optic sensors [1–5]. Compared to the conventional refractometer such as Abbe refractometer, fibre-optic refractometer sensors (FORSs) offer some important advantages such as remote monitoring capability, geometrical flexibility and multiplexing facility. Takeo and Hattori [6] proposed a refractometer which was based on intensity modulation of guided light in an optical fibre as it comes into contact with liquid medium. Most of the FORSs 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 [7]. However, intrusive-type FORSs possess two major disadvantages. First, to measure refractive index 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 be permanently damaged when it is brought into intimate contact with the reactive chemical solutions such as HF, HNO_3, H_2SO_4 etc. Thus, one cannot measure the refractive index of such solutions with intrusive-type sensors.

In the last two decades, there has been an intensive study on design and development of a fibre-optic confocal microscopic system using single-mode optical fibre [8,9]. Single-mode fibre offers several advantages such as geometrical flexibility and Gaussian mode field distribution of the point source from the output port of a single-mode fibre coupler which has largely been exploited for imaging specimen and rejecting the out-of-focus imaging plane. The back-reflected optical signal from the imaging plane depends on two important factors: (i) In-focus position of the imaging plane from collimating and focussing lens arrangement of the optical fibre end [9] and (ii) refractive index of the medium. Although the dependence of back-reflected signal on the refractive index of the medium has not been largely studied [10], the study of such dependence can be a potential tool for measuring refractive index of important chemical solutions which was otherwise not possible with the intrusive-type FORS. In the present paper, we demonstrate a simple non-intrusive refractometer sensor using 2×1 single-mode fibre coupler. Present work is an extension of our earlier work [10] which yields enhanced sensitivity. Variation of refractive index as low as 0.001 RIU can be measured with accuracy using our proposed sensor.

2. Sensing 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 $I_\mathrm{i}A\cos\theta_\mathrm{i}$, $I_\mathrm{r}A\cos\theta_\mathrm{r}$ and $I_\mathrm{t}A\cos\theta_\mathrm{t}$ respectively. Here, I_i, I_r and I_t and θ_i, θ_r and θ_t represent the intensity and the corresponding angle of the respective beams. The reflectance R of the medium is defined as the ratio of the reflected power to the incident power [11].

$$R = \frac{I_\mathrm{r}A\cos\ \theta_\mathrm{r}}{I_\mathrm{i}A\cos\ \theta_\mathrm{i}} = \frac{I_\mathrm{r}}{I_\mathrm{i}}. \tag{1}$$

Again, radiant flux density or irradiance I is defined as

$$I = \langle S\rangle t = \frac{c\varepsilon_0}{2E_0^2}. \tag{2}$$

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

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

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 index of refraction of the incident and the transmitting medium respectively. Likewise, the transmittance is defined as

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

For the non-absorbing medium,

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

In the present sensing investigation, 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, from the above equation it is seen that reflectance of light signal from air–liquid medium interface depends on refractive index of the medium and in the present work, we exploit this principle for measuring the refractive index of a liquid medium.

3. Experimental set-up

Schematic of the experimental arrangement for the present sensing investigation is shown in figure 1. Light signal from a diode laser source (output power = 5 mW, wavelength = 670 nm) splits into two parts by a 50 : 50 beam splitter where transmitted part is coupled to the input port of the single-mode fibre coupler and the reflected part is coupled to a photodiode PD1. Using a pair of collimating and focussing lens arrangement, light signal from the output port of the coupler is focussed on the air–liquid medium interface and the back-reflected signal from the interface is received by another photodiode PD2 through the second input port of the coupler. Signal voltages that are shown by PD1 and PD2 are termed as reference voltage (V_{ref}) and modulating voltage (V_m) respectively. Prior to detect light signals both photodiodes have been reversed-biased at a constant voltage of 5 V. This way we maintain linearity in the response of the detectors and possible sources of noise due to thermal fluctuation and shot noise are eliminated. Voltage signals of V_{ref} and V_m have been fed to an instrumentation amplifier designed with an operational amplifier LM324. Output reading of the amplifier is measured using a digital multimeter (Fluke 179 True RMS). Compared to multimode fibre coupler-based refractometer sensor reported in the earlier work [10], single-mode fibre coupler offers two important advantages. First, output light from the SM fibre tip of the coupler acts as a point source which leads to the formation of a Gaussian source beam distribution. This is useful for the precise collimation and focussing of the input light signal on air–liquid medium interface. Second, mode instability problem present in multimode optical fibre can be avoided in the case of single-mode fibre. The same output fibre tip of the coupler has been used as a point receiver for the back-reflected signal and it is highly sensitive to in-focus and

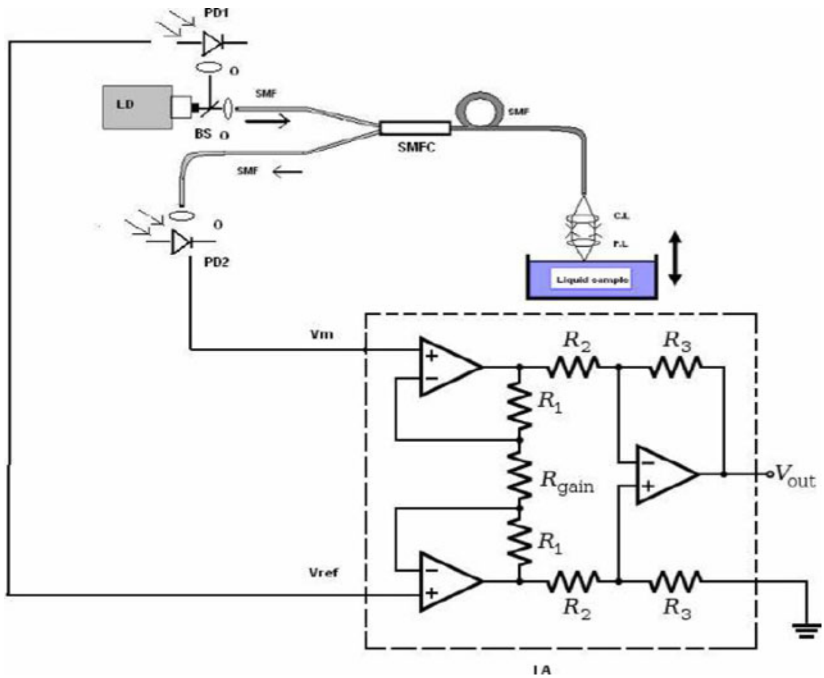

Figure 1. Schematic of the experimental set-up for the proposed refractometer. LD – Laser diode, SMF – single mode fibre, PM – power meter, SMFC – single mode fibre coupler, CL – collimating lens, FL – focussing lens, IA – instrumentation amplifier, PD1 and PD2 – photodiodes, BS – beam splitter, O – objective.

out-of-focus position of the air–medium interface and on the index of refraction of the medium. Focal position of the air–medium interface can be varied by making an axial displacement of the interface along the axis of the optical fibre. In the present sensor, the liquid and the glass sample are mounted on a micrometer scale resolved x-y-z translational stage and it is displaced along the axis of the focussing lens arrangement. For normal incident light signal and in-focus position of air–medium interface, there would be a maximum back-reflected light signal [8]. The horizontal position of the interface can be ensured by placing a spirit level gauge on the translation stage. For measuring the refractive index of unknown medium, we record the maximum back-reflected light signal and the result has been compared with a standard air–medium interface for instance, air–glass plate interface in the present investigation.

4. Results and discussion

To study the characteristics of the proposed FORS, propylene glycol was chosen as a test liquid medium. Refractive index of propylene glycol can be varied by adding pure water into it. Nine samples of different refractive index liquid medium of propylene glycol were prepared by adding pure water into it. To cover wider range refractive medium,

Table 1. List of different media considered with their reflectance values.

First medium (n_i)	Second medium (n_t)	Reflectance (R)
Air = 1.0000	Pure water = 1.331	0.02006
Air	Propylene glycol samples	
	S1 = 1.3401	0.02112
	S2 = 1.3512	0.02231
	S3 = 1.3652	0.02384
	S4 = 1.3712	0.0245
	S5 = 1.3821	0.02572
	S6 = 1.3904	0.02667
	S7 = 1.3982	0.02756
	S8 = 1.4056	0.02842
	S9 = 1.4131	0.0293
Air	Glass plate = 1.5001	0.0401

we took pure water and a thick glass plate and refractive indices of all the samples were measured using Abbe refractometer. Table 1 summarizes the refractive indices for all media considered under present investigation and corresponding reflectance (R) values which have been obtained from eq. (7). At first we investigate the sensor characteristics with air–glass medium interface. A glass plate is mounted on a micrometer translational stage and it is displaced along the axis of the fibre. Figure 2 describes the response of the sensor with axial position of the air–glass medium interface. Gaussian fitted curve of the measured values clearly indicates the confocal behaviour of the sensing system which is sensitive to the in-focus position of the interface as well as the refractive index of the second medium.

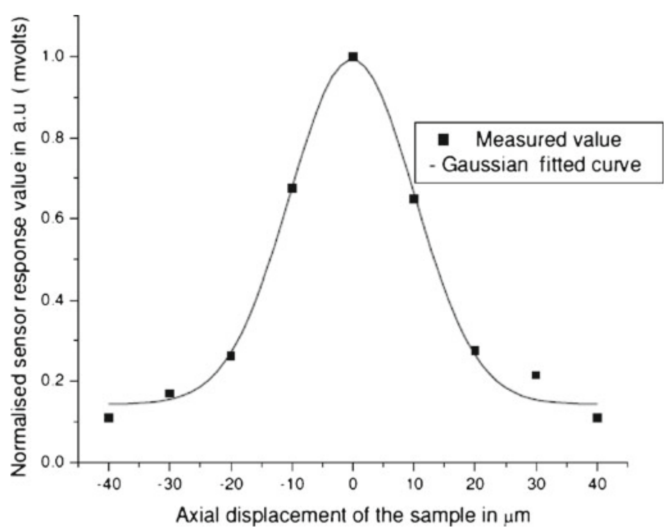

Figure 2. The normalized sensor axial response for the glass plate considered under the proposed sensing.

To measure refractive indices of all the media listed in table 1, only maximum back-reflected light signal, i.e., reflected signal from in-focus position of the air–medium interface was considered. Normalized values of the sensor responses and theoretical values of reflectance for all the listed media are shown in figure 3.

During observation, special care was taken for maintaining constant temperature for the liquid medium, because temperature fluctuation may cause variation in index of refraction of the medium. The sensing investigation was carried out in an air-conditioned room and the temperature of the environment was maintained at 20°C throughout the investigation. To measure refractive indices of acidic solutions, we choose 40% wt. HNO_3 and 20% wt. H_2SO_4 solutions along with glass plate as a reference medium. Initially, refractive indices of these samples were measured using Abbe refractometer and were found to be 1.3866 for 40% wt. HNO_3 solution and 1.3571 for 20% wt. H_2SO_4 solution respectively. Normalized values of axial sensor responses for these three media are shown in figure 4.

To counter-verify the refractive indices of HNO_3 and H_2SO_4 media with the present sensing set-up, the maximum normalized values of the back-reflected signals for all the samples are extrapolated in the graph of figure 3. We observed that for 40% wt. HNO_3 solution, the refractive index value at 20°C is 1.3862 and the corresponding value of 20% wt. of H_2SO_4 is 1.3573. Thus, with the present sensing set-up we can measure refractive indices of reactive acidic solutions whose values matched fairly with the values obtained from the standard refractometer. To check the resolution of the refractometer, two more samples of propylene glycol were prepared by adding pure water. The difference in index of refraction of the samples were maintained at 0.001 RIU. We observed detectable difference in back-reflected signals for these samples. However, for further decrement in the difference in index of refraction of the medium, no significant change in back-reflected signal has been observed. The resolution of the present sensor performance is limited by the low level of light signal coupling from the source to the single-mode fibre-end and the degree of coupling for back-reflected signal to the receiver unit is further lowered due to finite reflections from the air–medium interface. Nonetheless, the present technique

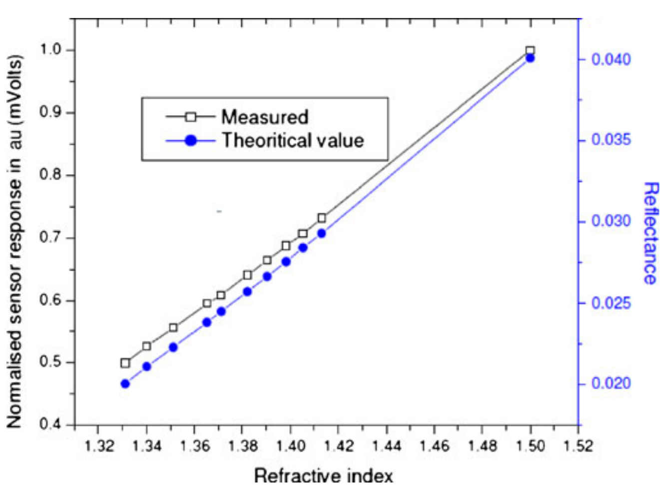

Figure 3. Theoretical and measured reflectance of light signal for different refractive media.

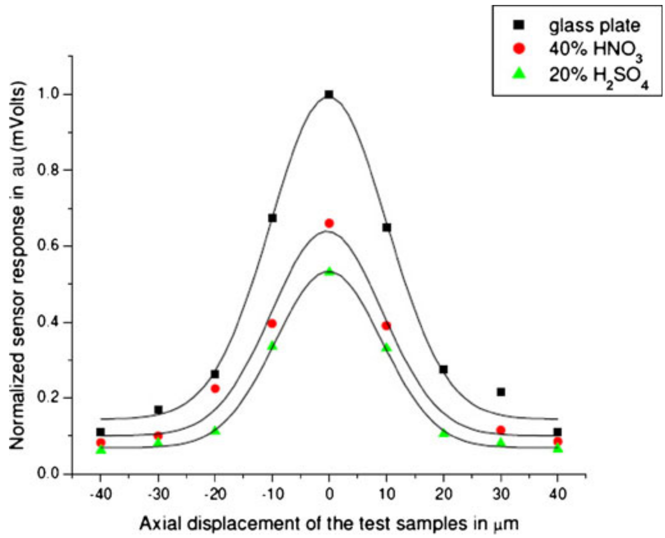

Figure 4. Normalized sensor response for glass plate, 40% wt. HNO_3 solution and 20% wt. of H_2SO_4 solution.

is useful for measuring refractive index and hence, concentration of reactive chemical solutions which were otherwise not possible with the intrusive-type FORSs.

5. Conclusion

In conclusion, we report a simple, non-intrusive FORS with a resolution capacity of 0.001 RIU. The sensing principle is based on light intensity modulation of back-reflected signal from in-focus position of the air–liquid medium interface which occurs due to change in index of refraction of the liquid medium. Use of single-mode fibre coupler for transmitting and receiving light signal to and from the interface offers two significant advantages as stated above. In addition, unlike multimode fibre-based refractometer, the sensing scheme is free from mode instability [9]. The present technique is useful for measuring refractive index of important reactive chemical solutions such as HF, HNO_3, H_2SO_4, methanol etc. which were not possible with the previous intrusive-type FORSs [10].

Acknowledgements

Pabitra Nath acknowledges the support received from University Grants Commission (UGC), India under minor research project letter (UGC letter no. F.No.34/510/2008(SR) 2009).

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