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Short communication

All-fiber optic sensor for measurement of liquid refractive index

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ABSTRACT

A novel intensity modulated fiber optic sensor (FOS) for liquid refractive index measurement is presented in this communication. The sensor principle is based on frustrated total internal reflection effect caused by refractive index change of a medium surrounding an optical fiber tip. Experimental results obtained for liquids of different refractive index confirm the sensor potential to act as a sensitive refractometer.

1. Introduction

Measurement of liquid refractive index is critical for various industrial 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 other food processing industries it is required to monitor refractive index of various solutions as it conveys important information to the manufacturer.

Over the years there has been a great deal of interest to monitor refractive index of liquid solutions using fiber optic sensors [1–5]. Compared to conventional refractometer such as Abbe refractometer, fiber-optic refractometer offers two major advantages. First, remote monitoring is possible using fiber optic sensor and second, it offers multiplexing facility. Thus, refractive index of several liquids can be monitored using single sensing set-up. Takeo and Hattori [6] proposed a refractometer which was based on the intensity modulation of the guided light of an optical fiber as it comes into contact with liquid. Again, Asseh et al. [7] had proposed a fiber Bragg grating refractometer using evanescent field refractive index fiber sensor. None of these can be used for long-term monitoring.

In this paper, we report a simple fiber optic sensor liquid refractometer which is based on frustrated total internal reflection effect [8,9]. One end of a step-index multimode optical fiber is polished to form a curve-shaped tip so that a part of the forward propagating modes is reflected back from the tip–air interface by the effect of total internal reflection. So long the tip is in air, a certain number of modes will be back-reflected to the entry port of the fiber. But as it comes into contact with liquid medium, the critical angle condition for back-reflected light will change and thus smaller number of modes is back-reflected to the entry port of the fiber.

Depending on the refractive index of the liquid medium different number of modes is back-reflected from the fiber tip–liquid interface and thus, intensity of the back-reflected light is modulated with index of refraction of the liquids. Fig. 1 shows the photograph of three such fibers with different radii of curvature.

2. Measurement principle

The FOS reported here is an intrinsic type. One end of a poly methyl methacrylate (PMMA) multimode optical fiber of diameter 980/1000 μm is polished to form a curve-shaped tip while the other end is made perfectly flat. If lightwave is allowed to propagate through flat-end of the fiber then a part of the forward moving modes will be back-reflected from the fiber tip–air interface. For such a fiber tip, all the low order modes become leaky modes while the higher order modes, for which the angle of incidence at the core–air interface is greater than the critical angle will be reflected back to the flat-end of the fiber. The critical angle for the back-reflected mode is given by

$$\theta_c(\lambda) = \arcsin\left[\frac{n_a(\lambda)}{n_1(\lambda)}\right] \quad (1)$$

For fiber tip–air interface, $n_a = 1$ and $n_1 = 1.4673$ giving $\theta_c(\lambda) \sim 43^\circ$. Since the tip is curve in shape, all the back-reflected modes subtend

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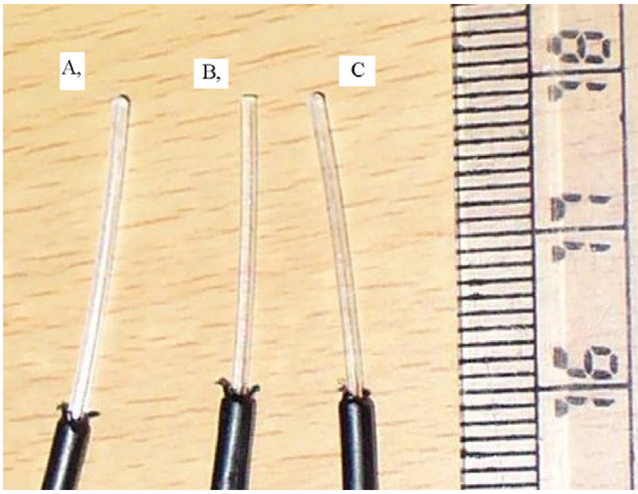

Fig. 1. Photograph of curve-shaped fiber tips, with radius of curvature: (A) ∼700 μm, (B) flat-end tip and (C) ∼500 μm (a millimeter scale is also shown in the figure).

an angle ranging from 43° to 90°. The leakage of modes into surrounding medium is proportional to the refractive index of liquids which would replace the air medium. This leads to proportional decrease in intensity of the back-reflected modes which would reach the detection unit of the sensor.

3. Experimental arrangement

Fiber tip fabrication: For sensing investigation, we have chosen three pieces of 980/1000 μm diameter PMMA multimode optical fiber each of length 20 cm. After removing the polyethylene jacket the tip is polished to form a curve-shaped tip with radius of curvature ∼500 μm (C) as shown in the Fig. 1. Also to compare the sensitivity of the sensor, two more tips have been prepared one (B) with flat-end while the other (A) having radius of curvature nearly 700 μm.

The experimental set-up for liquid refractive index measurement is shown in Fig. 2. Light from a laser diode (5 mW, 670 nm) is focused at one end of the fiber. The flat-end of the fiber is placed at the focal point of the lens (f = 25 mm) so that all the modes within the fiber can be excited. The front end-face of the fiber serves both as entry and exit path for light modes while the other end as the sensing probe for our sensor system. A 50:50 beam splitter is used to direct the back-reflected light to a photodiode (PD). A part of the incoming light from the diode laser is monitored by another PD which measures the intensity at the input end of the fiber and also ensures that there is no fluctuation of intensity in the source itself. The voltage readings from these two PDs (operated in photoconductive mode) are monitored through a computer. The data acquisition system has been developed for this purpose using C programming language. The performance of the fiber tip is estimated by the extinction ratio E_r [8] defined as

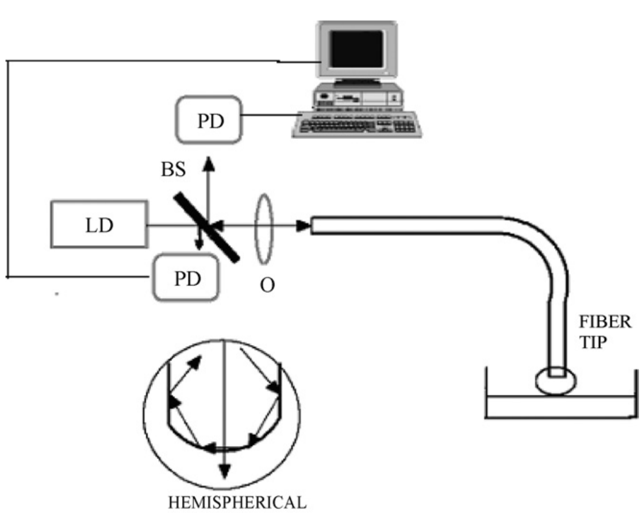

Fig. 2. Experimental set-up for liquid refractive index measurement.

Table 1

Outstanding medium	Refractive index	Critical angle, θ_c (°)
Air	1.000	42.96
Water	1.3314	65.14
Propylene glycol sample		
S1	1.3435	66.29
S2	1.3544	67.37
S3	1.3745	69.51
S4	1.3854	70.76
S5	1.3963	72.16
S6	1.4107	74.30
S7	1.4156	74.74

$$E_r = -10\log\left(\frac{P_1}{P_2}\right)\,\mathrm{d}B \tag{2}$$

where P_1 is the output power when the tip is in air and P_2 is the power when it is inside the liquid medium. In our case, measurements have been done in voltage scale, and the power delivered is proportional to the square of voltage (provided same load resistance is used); hence, extinction ratio becomes

$$E_r = -20\log\left(\frac{V_1}{V_2}\right)\,\mathrm{d}B \tag{3}$$

where V_1 and V_2 represent the corresponding PD voltages for the back-reflected modes. Depending on the refractive index of the surrounding medium, different number of modes will leak from the fiber tip–liquid interface and hence, there is proportional variation of PD voltage at the receiving end.

4. Results and discussion

To study the sensor characteristics of the refractometer, propylene glycol has been chosen as a test liquid. Refractive index of propylene glycol can be tuned by adding pure water into it. Several samples of different refractive index have been prepared by adding pure water into it. Refractive index of all the samples was initially measured by Abbe's refractometer. Table 1 summarizes the refractive index of liquids taken for our measurement and the corresponding critical angle for back-reflected propagating modes.

Fig. 3 describes the sensor variation for different refractive index of propylene glycol solutions. It is evident from this graph that with increasing index of refraction, the critical angle for back-reflected modes also increases. Thus, only few numbers of modes will reach the receiving end of the sensor. The sensing fiber tip has to be cleaned with water and should be allowed to dry after each reading. The cleanliness of the tip can be ensured when the PD returns to initial level of voltage.

To compare the sensitivity of the refractometer, similar investigations have been carried out with flat-end and other curve-shaped (∼700 μm) fiber tip. Fig. 4 describes the sensor reading for these three types of fiber tips. It is evident from these results that the sensitivity (change in sensor PD voltage for unit change in index of refraction of the liquid) of the refractometer with sensing tip

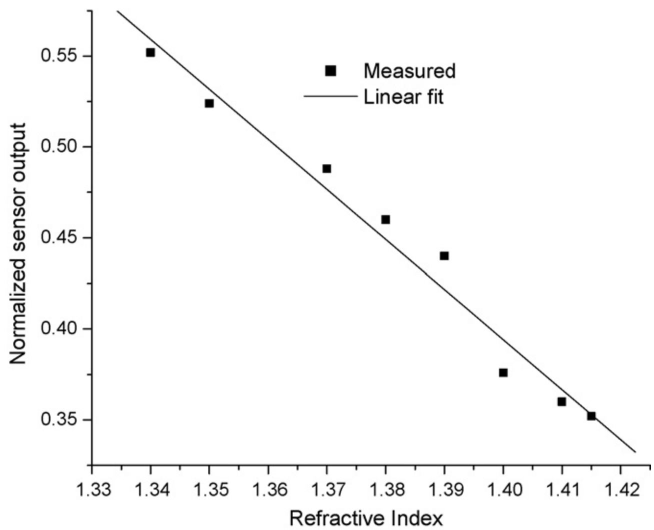

Fig. 3. Sensor readings for different index of refraction of propylene glycol.

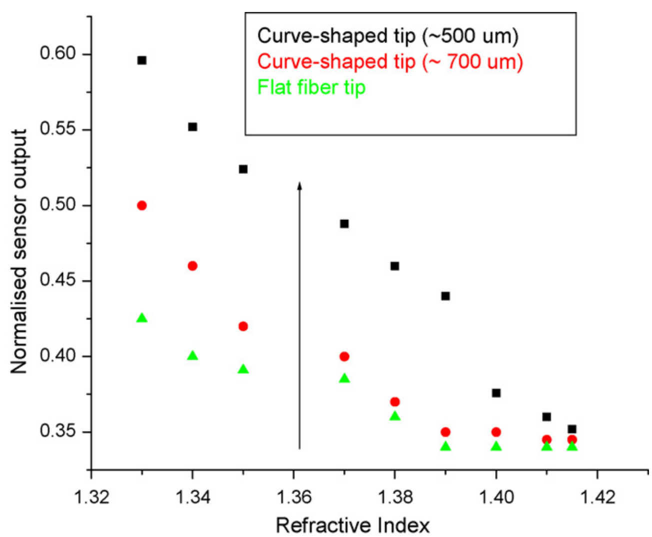

Fig. 4. Normalized sensor output for different fiber probes.

radius of curvature 500 μm the highest among all the tips being investigated. Also, a wide range of refractive index measurement is possible with our sensing technique which clearly indicates a higher dynamic range of the refractometer.

With our existing experimental set-up, refractive index variation as small as 0.002 RIU can be measured accurately and with high repeatability. Both resolution and sensitivity of the refractometer can be enhanced further by using bigger core diameter and shorter length optical fiber. With a thick core diameter fiber, a large number of light modes can be accommodated within the fiber and hence it shows significant leakage of modes for unit change in index of refraction of liquid medium. Also, with a short length optical fiber, the amplitude of the back-reflected light will be higher than that of a long-length fiber and thus, gives better photocurrent in the PD circuit. Also, the outer surface of the sensing tip should be fine polished for better sensitivity of the sensor.

In the present study, liquid of refractive index up to 1.42 has been investigated. However, if the study continued for liquids of refractive index nearly equal or greater than fiber core index value (1.4673), there will be a slow variation in sensor output and finally gives a steady output. This can be attributed to the leakage of all the forward going modes in to the solution. The condition of total internal reflection does not meet at the fiber tip–liquid interface when refractive index of the solution is same as that of the fiber core. The steady sensor reading is due to back-reflection of incident light, a part of which is from the entry-face of the fiber and another from the objective lens.

While investigating the refractive indices of liquids, special care should be taken in maintaining constant temperature of the solution as it may perturb the index of refraction of the liquids. Curve-shaped fiber tip with smaller core diameter fiber can also be prepared but it requires a sophisticated polishing technique.

5. Conclusion

A simple intensity modulated all fiber-optic liquid refractometer is described in this paper. The sensor is based on the principle of frustrated total internal reflection. Refractive index variation as low as 0.002 RIU can be measured with this scheme. The upper limit of refractive index measurement is determined by the index of refraction of the core and in our case it is equal to 1.4673. The sensing principle can be useful for real time monitoring of sugar solution concentration in sugar industries.

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