A Universal and Stable All-Fiber Refractive Index Sensor System

A. Basgumus, F. E. Durak, A. Altuncu, and G. Yılmaz

***Abstract*— In this letter, a universal, simple, and stable all-fiber sensor system is proposed to measure the refractive index (RI) of liquids. The basic principle of the technique is based on the relative measurement of the Fresnel reflection from sensor probes. A quadruple of time-division multiplexed Fresnel reflected pulses are obtained from a single nanosecond input pulse owing to the latencies in fibers with different lengths. The measured RIs for the different liquids show that the proposed all-fiber RI sensor system enables linear and repeatable measurements. The performance of the system is compared with the previously published studies, and good agreement is observed, showing the accuracy of the measurements. The standard deviations of the measured RIs are obtained in a short-term measurement as 2.8×10^{-6} for distilled water, and in a long-term measurement as 2.99×10^{-5} for methanol, showing the high repeatability of the measurements.**

***Index Terms*— Fresnel reflection, optical fiber sensor, refractive index sensing.**

I. INTRODUCTION

A UNIVERSAL and stable detection of the refractive index (RI), which is an important optical parameter in liquids and gases, is commonly required in many fields of industrial applications. In recent years, Fresnel reflection based optical fiber RI sensors have become an attractive research area because of their advantages such as immunity to electromagnetic interference, small size, remote monitoring, high resolution, stable and fast measurement capability [1].

There are various fiber optic refractive index measurement techniques for liquids presented in the literature based on Fresnel reflection [1]–[8]. Remote RI measurement using optical time domain reflectometry technique has been demonstrated in [2]. The RI measurement range of this system was from 1.3486 to 1.4525. Another measurement technique uses a 1×2 optical switch, to measure the RI of various chemical liquids at 1550 nm wavelength. The temperature dependence of the RI in tap water was also presented in [3]. Multipoint fiber optic RI measurement systems for liquids based on Fresnel reflection and wavelength division multiplexing using an arrayed-waveguide grating were also presented in [4] and [5]. Kim and Su [6] have applied double pulse technique for the RI measurement of various liquids at 1310 nm and 1551 nm. A RI resolution of about 2.5×10^{-5} has been achieved using this technique.

In this letter, we demonstrate a universal, simple and stable all-fiber sensor system based on Fresnel reflection for measuring RI of various liquids. In this technique, a quadruple of time division multiplexed optical pulses reflected from the fiber-air interface (reference probe) and the fiber-liquid interfaces (sensing probes) are derived from a single input pulse. The time division multiplexed pulse technique with nanosecond input pulses and short fiber lengths provides highly accurate, repeatable and fast differential RI measurements for liquids. The proposed measurement system is quite simple exhibiting low signal loss due to having single passive optical component so that it can be manufactured as a portable compact device for both sensing of the RI of the liquids and gases as well as for analyzing the composite gases.

II. PRINCIPLE AND EXPERIMENTAL SETUP

The basic idea of the technique is to generate quadruple time division multiplexed Fresnel reflected optical pulses using a nanosecond pulsed laser source, and to determine the RI of liquids using differentially reflected pulses from fiber-air and fiber-liquid interfaces. The reflected pulse from the fiber-air interface of the reference probe is used to normalize the reflected pulses from the fiber-liquid interfaces of the all 3 sensor probes. The accuracy and stability of the RI measurement in our fiber optic sensor system is unaffected by the fluctuations in pulsed laser source power, photodetector response, and environmental factors such as temperature, humidity, etc. due to the normalization process. On the other hand, when the RI of a measured liquid is very close to the effective RI of the fiber used, the Fresnel reflected light intensity from the sensor probe approaches to the noise level of the photodetector. This situation limits the RI measurement range and accuracy of the sensor system.

The experimental setup of the proposed optical fiber RI sensor system is shown in Fig. 1. A stable optical pulse stream is generated by a nanosecond pulsed laser source with a pulse width of about 50 ns and a repetition frequency of 10 kHz (Fig. 2a) at 1550 nm and then is launched into one of two input ports of a 2×4 single mode splitter. The input pulse is divided into four ports with an average 25% splitting ratio. The fiber optical probes (reference and sensors 1-3) have standard telecommunication ferrules with a diameter of

Manuscript received August 13, 2015; revised September 20, 2015; accepted October 2, 2015. Date of publication October 7, 2015; date of current version December 11, 2015. This work was supported by the Dumlupinar University Scientific Research Project under Grant BAP/2014-4.

A. Basgumus, F. E. Durak, and A. Altuncu are with the Electrical and Electronics Engineering Department, Dumlupinar University, Kütahya 43100, Turkey (e-mail: arif.basgumus@dpu.edu.tr; firat.durak@dpu.edu.tr; altuncu@dpu.edu.tr).

G. Yılmaz is with the Electrical and Electronics Engineering Department, Uludağ University, Bursa 16059, Turkey (e-mail: gunesy@uludag.edu.tr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2015.2488040

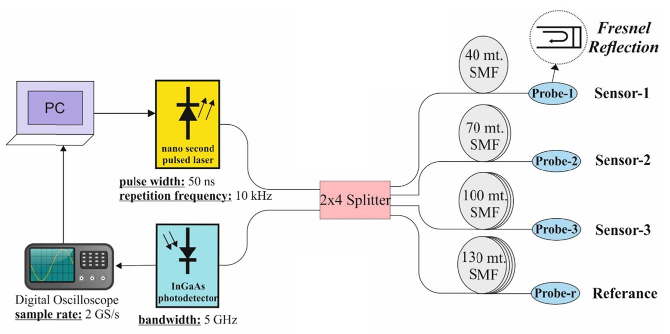

Fig. 1. The experimental setup of the Fresnel reflection-based all-fiber RI sensor system.

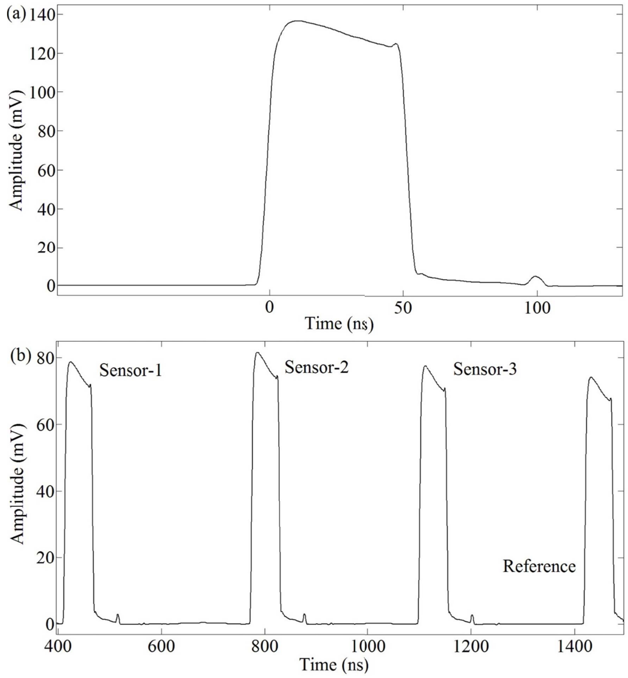

Fig. 2. (a) The input pulses with a 50 ns pulse width and a repetition rate of 10 kHz generated by a nanosecond pulsed laser source. (b) The quadruple time delayed reflected pulses from the air-fiber interfaces of reference and sensor probes 1-3 while all probes are in the air.

2.5 mm for protection and ease of cleaning the fiber tips. The time-separated pulses reflected from the reference and sensor probes 1-3 are shown in Fig. 2b as being delayed in time by $2L/c$, where $2L$ is the travelling path length difference (~60 meter) and c is the speed of light in the fiber. The Fresnel reflected pulses from the reference and sensor probes 1-3, are detected using a 5 GHz photodetector (Thorlabs DET08CFC), are measured in real-time using a 2 GS/s digital oscilloscope (Agilent DSOX2002A) and processed with a computer.

Assuming that all of the reference and sensor probes are equally excited using a single input pulse, an attenuation correction factor K_j can be obtained for the reflected pulse intensities to realize a differential measurement when the all reference and sensor probes 1-3 are in the air [7].

$$K_j = \frac{I_j}{I_r}, \quad j = 1, 2, 3 \tag{1}$$

where, I_j is the reflected pulse intensity of the sensor probes, I_r is the reflected intensity of the reference probe, j is the sensor probe number. Here, K_j is the attenuation correction factor related with the variations in the splitting ratios of the coupler ports 1-4, and sensor probe fiber lengths.

When the sensor probes 1-3 are dipped out the same liquid, the reflected pulse intensities are measured and then normalized by the reference probe reflection, thus the relative reflection can be obtained as [3]

$$R_j = \left(\frac{I_j'}{I_r}\right)\left(\frac{1}{K_j}\right), \quad j = 1, 2, 3. \tag{2}$$

The average relative reflection for the sensor probes 1-3 can then be calculated and related to the RI of the target liquid n_x as

$$R_{av} = \frac{1}{3}\sum_{j=1}^{3} R_j = \left(\frac{n_f + n_{air}}{n_f - n_{air}}\right)^2 \left(\frac{n_f - n_x}{n_f + n_x}\right)^2 \tag{3}$$

where n_f is the effective refractive index of the single mode fiber and the RI of air n_{air} is 1.0002739 [9].

The calculation of the square root of (3) leads to two different roots obtained for $n_x < n_f$ and $n_x > n_f$:

$$\begin{aligned} &for \quad n_x < n_f, \\ &n_x = n_f \left\{ \frac{\left(\frac{n_f + n_{air}}{n_f - n_{air}}\right) - \sqrt{R_{av}}}{\left(\frac{n_f + n_{air}}{n_f - n_{air}}\right) + \sqrt{R_{av}}} \right\} \\ &for \quad n_x > n_f, \\ &n_x = n_f \left\{ \frac{\left(\frac{n_f + n_{air}}{n_f - n_{air}}\right) + \sqrt{R_{av}}}{\left(\frac{n_f + n_{air}}{n_f - n_{air}}\right) - \sqrt{R_{av}}} \right\}. \end{aligned} \tag{4}$$

Here n_f the effective refractive index of the fiber, can be calculated using the known group refractive index n_g and dispersion relation as

$$n_f = n_g + \frac{dn_f}{d\lambda}\lambda. \tag{5}$$

The group refractive index n_g is 1.4681 for the operating wavelength of 1.55 μm [10]. For silica, the dispersion relation is given by the Sellmeier formula [11] and n_f can be given as a function of the signal wavelength:

$$n_f = \begin{pmatrix} 1 + 0.696166\dfrac{\lambda^2}{\lambda^2 - 0.0684043^2} \\ +0.407943\dfrac{\lambda^2}{\lambda^2 - 0.1162414^2} \\ +0.897479\dfrac{\lambda^2}{\lambda^2 - 9.896161^2} \end{pmatrix}^{1/2}. \tag{6}$$

From (5), n_f is 1.44953 at $\lambda = 1.55\mu m$.

III. RESULTS

The RI values of various common liquids are measured using our setup and compared with the results given in literature. All of the measurements were repeated for a time period of approx. an average 25 periods. All of the experiments were performed at a temperature of $22 \pm 0.5°C$ and with a

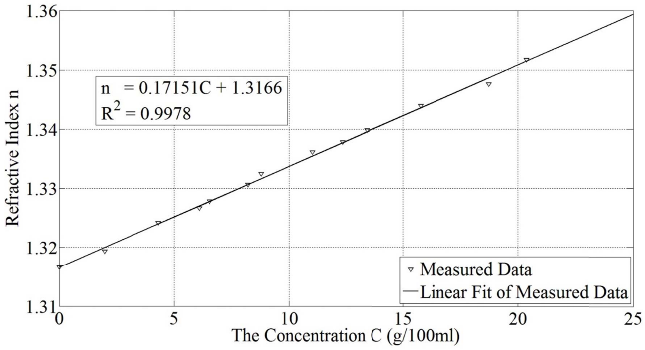

Fig. 3. The RI increase versus the concentration of salt solution fitted with a linear function. The fitted equation and the fitting degree is shown.

TABLE I

THE REFRACTIVE INDEX MEASUREMENTS FOR DIFFERENT LIQUIDS GIVEN IN THE LITERATURE AND THE MEASURED VALUES AT 1.55 μm

Solvent	Measured RI at $22 \pm 0.5°C$	Measured RI in [3]	Measured RI at $27°C$ in [13]	Measured RI at $20°C$ in [14]
1-Butanol	1.39311	-	1.3858	-
1-Propanol	1.37496	-	1.3738	-
Acetone	1.35042	1.3515	-	-
Acetonitrile	1.33699	-	1.3345	-
Benzene	1.47329	1.4157	1.4769	-
Ethanol	1.35534	1.3417	-	1.3520
Methanol	1.31725	1.3194	1.3172	-
Toluene	1.46932	-	1.4737	1.4778

relative humidity (RH) of 25 ± 2 %. Firstly, the all three sensor probes and the reference probe were kept in the air and the attenuation correction factors were obtained as 0.962, 0.966, 0.969, respectively. Then, the three sensor probes were dipped at the same liquid. We have measured the RI of the distilled water with the addition of linearly increased amount of salt to validate the linearity of the measurement results. The solutions with the defined concentrations have been prepared using the data for the mass of the salt (gr) and the volume of the distilled water (ml) before the measurement. The measured RI versus salt concentration of the solution is given in Fig. 3. It can clearly be seen that the measured RI variation of the salt solution is in very good agreement with a linear fit. The fitted value of $\partial n/\partial C = 0.17151$ is exactly the same value given in [7], and very close to the reported values in [4] and [12]. These results confirm the linearity of the measurement system and also the accuracy of the linear function is given with a fitting degree of 0.9978.

Table I shows the measured RI values of eight different organic solvents at 1.55 μm and their corresponding values given in the literature. The values of the temperatures used in [13] and [14] are 27°C and 20°C, respectively. However, the temperature value is not provided in [3]. Moreover, no RH values are presented in [3], [13], and [14]. One can see that

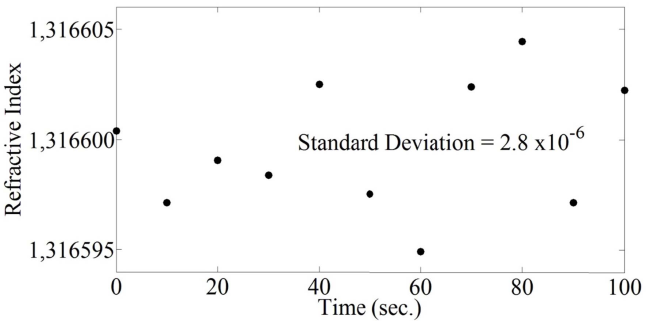

Fig. 4. The short-term stability of the multiple sensor system tested by the RI measurement of the distilled water at 1550 nm.

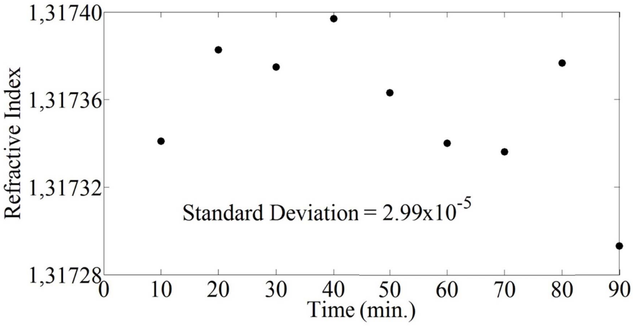

Fig. 5. The long-term stability of the multiple sensor system tested by the RI measurement of methanol at 1550 nm.

the measured RI values in our system are very close to the RI values given in [3], [13], and [14] for all solvents except the RI values of ethanol and benzene in [3]. The results show that the proposed Fresnel reflection based all-fiber RI sensor system is able to measure a relatively wide range of RI values for liquids accurately and simultaneously.

To test the short-term stability of the RI sensor system, the RI of the distilled water was measured repeatedly for a time period of 100 seconds. Fig. 4 shows the short-term stability of the measurement system. The standard deviation of the RI is 2.8×10^{-6} which is better than the result given in [3]. Our results reveal that the proposed time-division multiplexed fiber sensor system for RI measurement of liquids has a very good short-term stability.

To test the long-term stability of the RI sensor system, we measured the RI of methanol and its standard deviation for a time period of 90 minutes and this result is shown in Fig. 5. The standard deviation of the RI measurement is 2.99×10^{-5} and it reveals that the long-term stability of the system is relatively higher than the previous results given in literature. The quadruple-pulse technique based on relative Fresnel reflection corrects the unwanted errors arising from the fluctuations in pulsed laser source, photodetector and the environmental effects.

IV. CONCLUSION

In this study, a universal, simple, accurate and stable Fresnel reflection based all-fiber sensor system was presented for measuring RI values of liquids. The performance of the system was compared with the previous studies and a good agreement was observed showing the accuracy of the measurements. The slope of RI variation as a function of the concentration of salt solution has shown that the linearity of the measurement was quite high. The standard deviations of the measured refractive indices were obtained in a short-term measurement as 2.8×10^{-6} for distilled water, and in a long-term measurement as 2.99×10^{-5} for methanol which indicates the high repeatability. The proposed all-fiber sensor system can also be used for simultaneously sensing different volatile organic compounds (VOCs) or to analyze composite gases by using different types of sensor probes coated with sensitive thin films. This issue will be the following subject of our study. The proposed sensor system can be manufactured as a portable compact device due to its universal, simple, low loss and low cost properties.

REFERENCES

[1] A. Basgumus, F. E. Durak, S. A. Sadik, A. Altuncu, G. Yilmaz, and M. A. Ebeoglu, "Fresnel reflection based fiber optic refractive index sensor for liquid concentration dedection," in *Proc. IEEE Signal Process. Commun. Appl. Conf. (SIU)*, 2014, pp. 594–597.

[2] J. Yuan, C. Zhao, M. Ye, J. Kang, Z. Zhang, and S. Jin, "A Fresnel reflection-based optical fiber sensor system for remote refractive index measurement using an OTDR," *Photon. Sensors*, vol. 4, no. 1, pp. 48–52, Mar. 2014.

[3] W. Xu, X. G. Huang, and J. S. Pan, "Simple fiber-optic refractive index sensor based on Fresnel reflection and optical switch," *IEEE Sensors J.*, vol. 13, no. 5, pp. 1571–1574, May 2013.

[4] Y. T. Wu, X. G. Huang, and H. Su, "A quasidistributed fiber optic sensor for solute concentration measurement based on Fresnel reflection," *Appl. Phys. Lett.*, vol. 91, no. 13, pp. 131101-1–131101-3, Sep. 2007.

[5] C.-L. Zhao, J. Li, S. Zhang, Z. Zhang, and S. Jin, "Simple Fresnel reflection-based optical fiber sensor for multipoint refractive index measurement using an AWG," *IEEE Photon. Technol. Lett.*, vol. 25, no. 6, pp. 606–608, Mar. 15, 2013.

[6] C.-B. Kim and C. B. Su, "Measurement of the refractive index of liquids at 1.3 and 1.5 micron using a fibre optic Fresnel ratio meter," *Meas. Sci. Technol.*, vol. 15, no. 9, pp. 1683–1686, Jul. 2004.

[7] H. Su and X. G. Huang, "Fresnel-reflection-based fiber sensor for on-line measurement of solute concentration in solutions," *Sens. Actuators B, Chem.*, vol. 126, no. 2, pp. 579–582, Oct. 2007.

[8] J.-R. Zhao, X.-G. Huang, W.-X. He, and J.-H. Chen, "High-resolution and temperature-insensitive fiber optic refractive index sensor based on Fresnel reflection modulated by Fabry–Perot interference," *J. Lightw. Technol.*, vol. 28, no. 19, pp. 2799–2803, Oct. 1, 2010.

[9] R. C. Weast and S. M. Selby, *Handbook of Chemistry and Physics*, 48th ed. Cleveland, OH, USA: CRC Press, 1968, p. 160.

[10] *SMF-28 Corning Cable Product Information*, 2002, p. 3.

[11] J.-M. Liu, *Photonic Devices*, 1st ed. New York, NY, USA: Cambridge Univ. Press, 2005, p. 147.

[12] V. Krishna, C. H. Fan, and J. P. Longtin, "Real-time precision concentration measurement for flowing liquid solutions," *Rev. Sci. Instrum.*, vol. 71, no. 10, pp. 3864–3868, Oct. 2000.

[13] K. Moutzouris, M. Papamichael, S. C. Betsis, I. Stavrakas, G. Hloupis, and D. Triantis, "Refractive, dispersive and thermo-optic properties of twelve organic solvents in the visible and near-infrared," *Appl. Phys. B*, vol. 116, pp. 617–622, Sep. 2014.

[14] S. Kedenburg, M. Vieweg, T. Gissibl, and H. Giessen, "Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region," *Opt. Mater. Exp.*, vol. 2, no. 11, pp. 1588–1611, Nov. 2012.