Development of an open path laser interference technique to determine refractive index of liquids

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Abstract

This paper presents the development of an optical instrument for measuring refractive index of transparent liquids. The optical train consists of a laser source, an in-house design liquid sample chamber, a focal lens, a magnify lens and a projection screen. The laser beam is directed to the sample chamber where a portion of the light reflects at the window in front of the chamber. The other portion of the incoming light refracts and passes the window and the liquid sample before reflecting off the chamber at the direction parallel to the first reflected beam. The reflected and the refracted light are defined as the reference and the object beams respectively. The distance between the reference and the object beams depends on the refractive index of the liquid sample which can be inferred from the interference pattern of the two beams when being brought into intersection by the focal lens. The proposed open path set up, the sample chamber is separated from the setting of the probe beams so that it yields space for the users to conveniently specify the constraints of the sample chamber e.g. increasing its temperature, changing mixing ratio of the liquid sample and etc. The instrument has been tested by measuring refractive index of standard water and water-ethanol mixtures at controlled temperature and compares the results with those obtained from the classical Abbe-refractometer measurements. It has been shown that the measured refractive indices obtained by the proposed measurement technique are accurate up to the second decimal place when comparing with those obtained from the Abbe-technique.

***Keywords**:* Interference, Refractive index, Gaussian beam, water – ethanol mixtures

1. Introduction

Optical measurement techniques have been becoming more important in diagnostics of liquid drops either individual or cloud of drops. With the optical measurement, properties such as drop-size distributions and temperature of the liquid drops could be obtained by analyzing the results of the interaction between the laser and the liquid drops [1]. The interactions depended mainly on the refractive indices of the liquids which being the functions of density, wavelength, temperature, and type of substances [2].

Unlike the Abbe refractomenter which takes small amount of sample from a well constraint liquid, this paper proposes to development an in situ technique to determine refractive index of the liquids. In the proposed setup, the sample chamber was distanced away from the laser sources and from the image receiving plane. This yielded space for the users to specify the constraints on the sample conveniently. The sample chamber was designed to receive a finite amount of liquid sample such that the liquid temperature or mixing ratio can be changed on site.

The principle of liquid-light interaction in the proposed method was similar to that used in [3] where the refractive indices were measured from the displacement of the transmitted laser beam from the incident beam when impinging obliquely on a rectangular cell filled with the interested liquid. In the proposed method, we split one laser beams into two, the first part reflected at the front surface and the other refracted passing the object and reflected at the rare surface of the sample. The distance between the two beams travelling at different optical paths were measured. Section 2 shows the proposed optical train and the calculation method. The instrument had been tested by measuring refractive index of distilled water and water-ethanol mixtures at controlled temperature. The results obtained were compared with those from the Abbe refractometer measurements.

2. Theoretical Background

The principle idea used on the development of the measurement technique is to construct an instrument that being able to receive interference fringes from two intersected beams coming from different angles. From the interference fringes, the angle of intersection can be determined by fitting the theoretical to the measurement patterns. The distance between the two beams and hence the refractive indices of the sample are further calculated based on the known angle of intersection between the two beams.

Fig.1 shows the schematic diagram demonstrating the concept used to measure the refractive index, n_2 of a transparent object of thickness, t. In the receiving part, the reflected and the refracted beams were defined as the reference and the object beams respectively. The two beams were directed to cross each other, using a focal lens forming the interference fringes.

To facilitate the measurement of the fringes, the interference fringes at the focal point of the two beams were magnified by a short focal length lens and projected onto the receiving lens to obtain the new image of the fringes at a measurable size where a DSLR camera has been used for capturing the image of the fringes. These form the receiving part of the apparatus.

The interference patterns of two Gaussian beams intersected at a plane was derived and being simulated at various conditions of the two intersected beams [4].

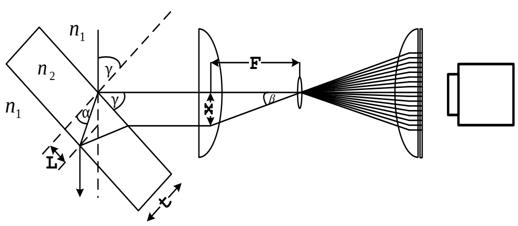

Fig. 1 Schematic diagrams: transmitting and receiving parts of the optical train.

In this paper, the intensity equation has been further derived for the cases where the incoming angles of the two beams with respect to the lens's axis are different. One angle is fixed as zero $(\phi=0)$ and the other (β) being arbitrarily.

$$E_1(x,y,+\beta)=A\exp\left(\frac{-x^2+y^2\cos^2\beta}{\sigma^2}\right)\exp[-i(\omega t-ky\sin\beta+kz\cos\beta)] \quad (1)$$

$$E_2(x,y,+\phi)=A\exp\left(\frac{-x^2+y^2\cos^2\phi}{\sigma^2}\right)\exp[-i(\omega t-ky\sin\phi+kz\cos\phi)] \quad (2)$$

$$I(x,y)=|E_1|^2+|E_2|^2+E_1E_2^*+E_1^*E_2 \quad (3)$$

Where

$$|E_1|^2=A^2\exp\left[-\frac{2(x^2+y^2\cos^2\beta)}{\sigma^2}\right]$$

$$|E_2|^2=A^2\exp\left[-\frac{2(x^2+y^2\cos^2\phi)}{\sigma^2}\right]$$

$$E_1E_2^*+E_1^*E_2=A^2\exp\left[\left(\frac{-(x^2+y^2\cos^2\beta)}{\sigma^2}+\frac{-(x^2+y^2\cos^2\phi)}{\sigma^2}\right)\right]\times$$
$$[2\cos(-ky\sin\beta+kz\cos\beta+ky\sin\phi-kz\cos\phi)]$$

Theoretical interference pattern at an arbitrary intersected angle β can be determined from equation (3), then the patterns are fitted with interference pattern obtained from the experiment, to determine the intersected angle β .

As Fig.1 shown, once the angle β is known the distance x can be determined given the focal length of the focus lens. Finally the unknown refractive index, n_2 is realized by applying with Snell's law:

$$n_1\sin\gamma=n_2\sin\alpha \quad (4)$$

3. Experimental Procedures and Results

Fig. 2 shows the components of the transmitting part; the 30-mW, 632.8-nm He-Ne laser, the in house design sample chamber sitting on an adjustable jack and the focal lens of 300-mm focus length.

The front window of the sample chamber is a fused silica type having refractive index equal 1.45702. The mirror at the back of the chamber is a protected silver coated mirror with more than 98% reflectivity [5]. To determine the thickness of the windows, the reflected part of the incoming beam is the reference beam. The refracted part travels through the window, being reflected at its rare surface, then refracts again at the front surface and travels along the direction parallel to the reference beam (see Fig. 1). The later beam is called the object beam.

The two beams are directed to cross each, using a lens of 300-mm focal length. At the intersection, interference patterns are formed. The magnified lens of 4-mm focal length has been placed to magnify the image of the fringes. The magnified image was captured by a 300-mm focus length lens and a screen, see Fig.3.

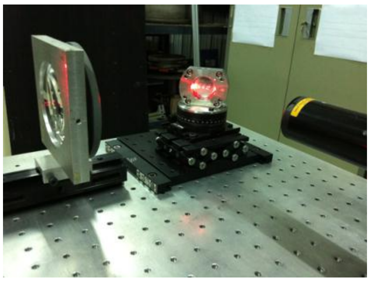

Fig. 2 Transmitting part

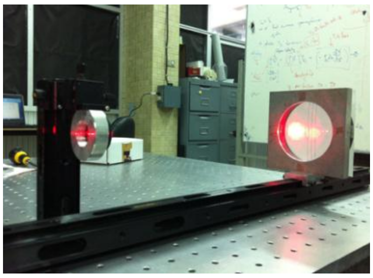

Fig. 3 Receiving part

By using the given refractive index of the window, the thickness of the window was determined by fitting the theoretical to the measured interference patterns.

To avoid the translation mismatch between the measurement and the simulated signals in spatial domain, the fitting is performed in Fourier domain.

In the fitting process, the measurement fringes are firstly transformed into the Fourier space using FFT algorithm. The simulated interference signals given by (3) are also transformed into the function in Fourier domain and being fitted to the measurement data for an optimal intersection angle. The distance between the two beams before the intersection is in turn determined and the value being equal to 3.993 mm.

In the Fourier space, both the experiment and simulated functions are normalized to the same scale and being compared only by their frequency profile.

The final results are presented in spatial domain as shown by intensity of the fringes comparing between the simulated and the measured patterns, as shown by Fig. 4.

It is remarked here that the spatial plot, Fig.4, shows only the qualitative comparison, the amplitudes of the fringes are arbitrary.

The width of the chamber were measured using the same principle but given an additional refractive index of air in the chamber which was 1.0003 [6].

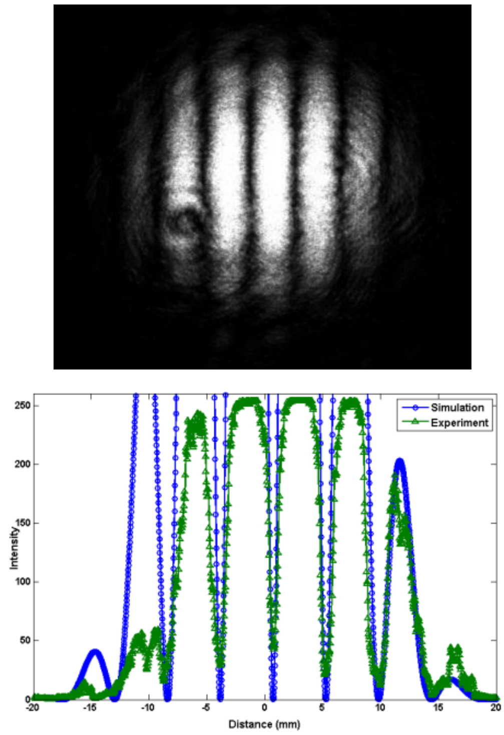

Fig. 4 Interference pattern of fused-silica window (a), compared pattern with simulation (b)

Fig. 5 shows the interference fringes used for measuring the width of the chamber. It was showed that there were more fringes when comparing with the number of the fringes generated by the window alone. This was due to the longer travelling distance of the object beam. The width of the sample chamber was found to be 5.3036-mm.

When the chamber was filled with distilled water, it had been shown that there appears less fringes than those of the empty chamber, see Fig. 6. This was due to the fact that the liquid had more refractive index than air which decreases the optical path of the object beam.

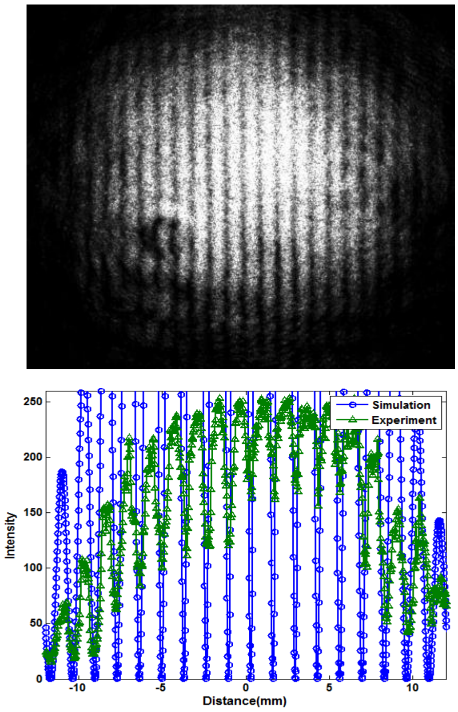

Fig. 5 Interference pattern of air (a), compared pattern with simulation (b)

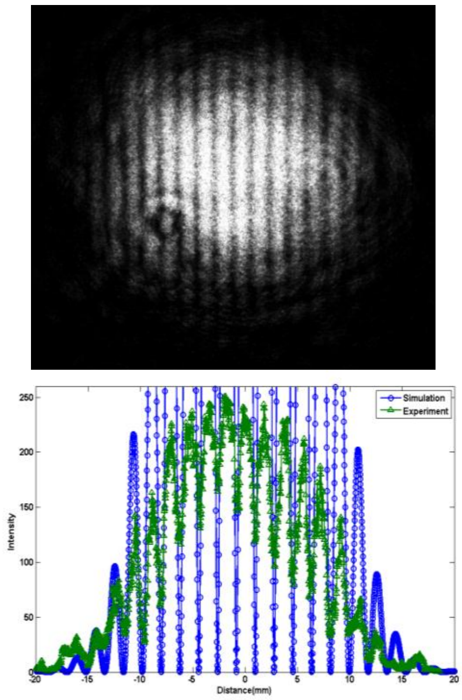

Fig. 6 Interference pattern of water (a), compared pattern with simulation (b)

The width of the chamber had been recalculated by using the standards refractive index of water, which gave 1.3318 at 24°C [7]. It was found from the curve fitting that the width of the chamber was 5.3443-mm when using the refractive index of water in the calculation. The width obtained from the measurement deviated from the previous one where the medium in the chamber was air by the second digit of millimeter.

This measurement results assured the accuracy of the measurement procedures. The thickness based on the water being the refracted medium, was further be used as reference value in order to calculate the refractive index of the water-ethanol mixtures.

The measurement result of the refractive index of the water-ethanol mixtures has shown in Table 1. It has been shown that the refractive index of the mixture increased with the percentage of the ethanol in the mixture. The accuracy of the measurement is to the third decimal which being enough to differentiate the 10%-mixing ratios of the mixture.

Table. 1 Refractive Index for different substances

Substance		Refractive Index	
% water by volume	% ethanol by volume	Average Value	Abbe
100	0	1.3318	1.3334
90	10	1.3336	1.3380
80	20	1.3375	1.3427
70	30	1.3433	1.3477
60	40	1.3483	1.3530

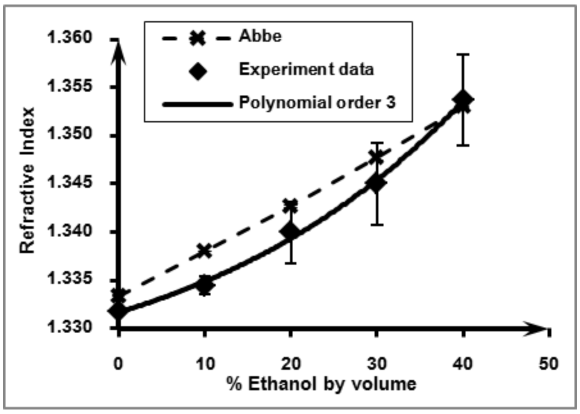

Fig. 7 Comparing with standard Measurement

The last column of Table 1 showed the values of the refractive index of the mixture at different mixing ratio, but measuring by the Abbe refractometer. It can be seen that the proposed method underestimates the values of the refractive index when comparing with those obtained the classical technique. The discrepancies for all refractive index values are from 0.002 to 0.005.

To compare the changes of the refractive index with mixing ratio to those obtained from the Abbe-measurement, the experimental values are plotted and shown in Fig. 7. It is shown that a similar trend can be observed from both measurement techniques.

4. Conclusion

The open laser interference measurement technique had been tested by measuring the water-ethanol mixtures and calibrated by using distilled water. The measurement results were compared with the classical ABBE-refractometer. Although the measurement results agreed well, it had been found that the proposed analyzed method had limited measurement accuracy.

To improve the measurement accuracy, the fitting between and the theoretical and measurement data should be done in space domain, the wavelet technique comes to mind. The proposed accuracy target of the refractive index is up to the fourth digit.

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6. References

[1] S. Saengkaew, D. Bonin, A. Garo, G. Gréhan, "Co-combustion of gas and liquid bio-fuel: Simultaneous measurements of droplets" Third European Combustion Meeting ECM, 2007.

[2] Soraya A. Khodier, "Refractive index of standard oil as a function of wavelength and temperature" Optical & Laser Technology 34, pp.125-128, 2002.

[3] Shojiro Nemoto, "Measurement of the refractive index of liquid using laser beam displacement" Applied Optics, Vol. 31, Issue 31, pp. 6690-6694, 1992.

[4] H. Mishina and T. Asakura, "Two Gaussian Beam Interference" Nouv. Rev. Optique, t. 5, no 2, pp.101-107, 1974.

[5] Edmund Optics, Reflectivity technical data.

[6] Philip E. Ciddor. Refractive index of air: new equations for the visible and near infrared, Appl. Optics 35, 1566-1573, 1996.

[7] Optical Constants of Water in the 200-nm to 200-Mm Wavelength Region," Vol. 12, No. 3, Applied Optics, pp. 555-563, 1973.