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A single-element interferometer for measuring refractive index of transparent liquids

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ABSTRACT

A simple and stable method based on a single-element interferometer for accurately measuring refractive index of transparent liquids was demonstrated. The refractive index is measured by rotating a rectangular optical glass cell which contains sample liquid and air simultaneously, and by calculating interference fringe shift number which is detected from an interferogram. This method was successfully used to measure the refractive indices of various transparent liquids including distilled water, ethanol and NaCl–water and ethanol–water solutions at various concentrations. The temperature- dependent refractive index of distilled water was also measured. Furthermore, our method is simple to implement, vibration insensitive, and of high accuracy up to 10^{-4}.

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1. Introduction

Accurately measuring the refractive index of liquids is critical in various applications, such as biosensor [1], waveguide design [2], etc. Accurate knowledge of refractive index and its variation with concentration are used for material identification and characterization. Nowadays, different techniques have been developed for the refractive index measurement. The minimum angle of deviation method is a relatively simple method when high precision or accuracy is not required but the problem is that an error occurring in determining the angle is probably high [3]. Critical angle method measured the critical angle at the boundary between the prism and the liquid [4], which needs an accurate value of the refractive index of the prism. A transparent capillary filled with liquid is used as a cylindrical lens method based on an image-forming principle [5], while it needs an accurate value of the refractive index of the capillary or another standard liquid. The core-cladding mode interferometry method is simple and low cost but precision is only ~0.001 [6]. Optical fiber sensors have also been used to measure the refractive index of liquid solutions for many advantages such as high sensitivity, small size and remote sensing capability. Most of them are based on the evanescent field interaction with the liquid, such as long period grating [7,8], etched fiber Bragg gratings [9], and photonic crystal waveguides [10]. In these approaches, evanescent-field based sensors suffer from large temperature cross sensitivity and nonlinear refractive index response. Furthermore most of the sensors need to be fabricated by complex and bulky techniques.

In addition, interferometric measurement techniques have been widely applied for measuring the refractive index of liquids. With interferometric methods, the accuracy is not affected because the real path length difference is measured. These methods with a higher resolution have also been proposed, such as Michelson interferometer [11], and Mach–Zehnder interferometer [12]. The disadvantages of these methods lie in the strict conditions on interferometer stability and in a critical dependence on the distance between the optical elements of the system and their position. The accuracy of the measurement is easily perturbed by the environment. A fiber sensor based on Fabry–Perot (FP) interferometer is another method [13]. Since the tip of the fiber sensor is immersed in the liquid sample, it may have an adverse effect on fiber when measuring some special solutions and the sample may be contaminated.

In this work we proposed a new, simple, stable method for measuring the refractive index of transparent liquid sample which is based on the principle of a single-element interferometer [14]. The refractive index is determined by rotating a rectangular optical glass cell which contains sample liquid and the air simultaneously, and by calculating interference fringe shift number. The fringe shift number is easily detected from the interferogram formed by the object beam which passes through the liquid and the reference beam which passes through the air from a beam-splitter cube. We have mainly studied the refractive index of NaCl–water, ethanol–water solutions at various concentrations. Also the temperature-

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dependent refractive index of distilled water was measured. This method is vibration insensitive, with high accuracy up to 10^{-4}, and experimental realization is simple for measuring transparent liquid samples.

2. Experimental setup and principle of measurement

The setup and principle of operation of the interferometric system are depicted in Fig. 1. The experimental setup is considerably simple. A laser beam ($\lambda = 636.94$ nm) which was expanded and collimated to a diameter of $\sim$20 mm is vertically incident on the sample along the z-axis. The sample is placed between the laser and beam-splitter cube with splitting ratio of 50:50. A rectangular optical glass cell with wall thickness of 1 mm and internal size of 20 mm $\times$ 10 mm is fixed on a rotation stage which had a computer-controlled stepping motor with steps of 0.00067°. The cell is divided into two parts by a partition, so that it can simultaneously contain sample liquid and the standard liquid (or air). Air is taken as a reference in this experiment. The surfaces of the cell have a flatness tolerance of less than 1 μm and their deviation from parallelism is of the order of 10 μm. Half of laser beam passes through the empty portion of the cell as a reference beam (Path 1). The other part of the laser beam passes through the filled liquid portion of the cell as an object beam (Path 2). And then the two beams pass through the beam-splitter cube and form two controllable parallel equidistant straight interference fringe patterns. The interference fringe patterns are divided into two by a beam-splitter, one passes through the lens and then arrives at a counter which was made by us to count the integer part of the interference fringe shift number, and the other arrives at the observation plane of a CCD camera (Microview, Model MVC-II-1 MM, pixel size: 5.2 μm $\times$ 5.2 μm) which captures the initial image and the final image at a certain rotation angle θ for counting the fractional part of the interference fringe shift number. On the other hand, the fringe spacing can be enlarged to an appropriate size by rotating the cube around an axis orthogonal to a plane of illustration in Fig. 1 in order to improve the accuracy of the measurement.

The proposed single-element interferometer is depicted in illustration of Fig. 1. It shows the ray trajectories in the beam-splitter cube (BS). A light wave is incident along the z-axis on the beam-splitter cube with its central semi-reflecting layer placed along the propagation direction. The top half of the light beam (Path 1) acts as the reference light and the other bottom half beam (Path 2) as the object light, or vice versa.

Let the electric fields of two halves of the input beam at the plane $\sum_{in}$ be $E_1(x', y')$ and $E_2(x', y')$, the interference of the transmitted and reflected lights at the plane $\sum_{out}$ is obtained, and then intensity patterns of the Output 1 and the Output 2 are represented as follows:

$$\begin{aligned} I_{Output\ 1} &= |E_1(d-x,y)\exp[i\pi/2] + E_2(x-d,y)|^2 \\ &= |E_1(d-x,y)|^2 + |E_2(x-d,y)|^2 \\ &\quad + 2|E_1(d-x,y)||E_2(x-d,y)| \cos(\xi_1(d-x,y) \\ &\quad - \xi_2(x-d,y) + \pi/2) \end{aligned} \tag{1}$$

$$\begin{aligned} I_{Output\ 2} &= |E_1(d+x,y) + E_2(-x-d,y)\exp[i\pi/2]|^2 \\ &= |E_1(d+x,y)|^2 + |E_2(-x-d,y)|^2 \\ &\quad + 2|E_2(d+x,y)||E_2(-x-d,y)| \cos(\xi_1(d+x,y) \\ &\quad - \xi_2(-x-d,y) - \pi/2) \end{aligned} \tag{2}$$

where ξ_1, ξ_2 are the phases of the fields E_1, E_2, respectively. (We neglect the splitter-ratio of the beam-splitter cube in above expressions.)

When the incident light is plane wave of constant amplitude (E_0), we have

$$E_1(x', y') = E_0; \quad E_2(x', y') = E_0 \exp[i\xi(x', y')] \tag{3}$$

where $\xi(x', y')$ is phase distribution of the sample placed in Path 2.

If the beam-splitter ratio is 50:50, Eqs. (1) and (2) can be rewritten as

$$I_{Output\ 1} = I_0\{1 + \cos[\xi(x-d,y) - \pi/2]\} = I_0\{1 + \sin \xi(x-d,y)\} \tag{4}$$

$$I_{Output\ 2} = I_0\{1 + \cos[\xi(-x-d,y) + \pi/2]\} = I_0\{1 - \sin \xi(-x-d,y)\} \tag{5}$$

where $I_0 = E_0^2$.

It is easy to see that the optical path difference between the two beams is changed when rotating the sample. Let the refractive index of a transparent liquid sample with thickness d be n, and rotation angle of the sample be θ, the interference fringe shift number N is given by

$$N = \left(\sqrt{n^2 - n_0^2 \sin^2\theta} - n_0 \cos\theta - n + n_0\right) d/\lambda \tag{6}$$

where $n_0 = 1$ is the refractive index of air, λ is the optical wavelength. We can obtain the expression of the refractive index

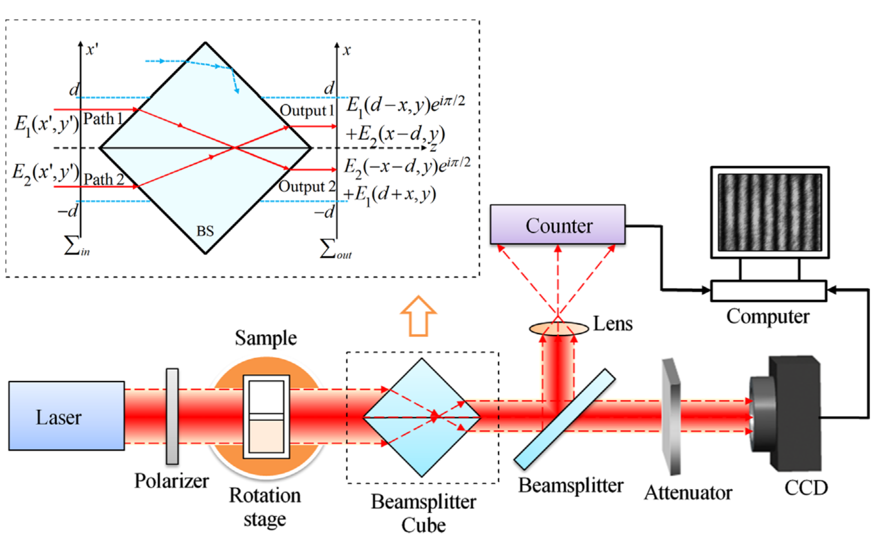

Fig. 1. Experimental setup. The illustration shows ray trajectories in the beam-splitter cube. d is the size of the working region in the x-direction.