PHASE REFRACTIVE INDEX MEASUREMENTS OF WATER BY the INTERFEROMETRY OF BROAD LIGHT SOURCE

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Abstract. We present a new experimental technique for determining the group refractive index and phase refractive index of water based on a low-cost broadband light source spectrum delivering diffraction-limited light in the range from 450 to 2400 nm. The experimental results indicated that the group refractive index and phase refractive index of water is similarly the theoretically results. In addition, the experimental kit can be used to determine the refractive index of the cuvette material as well as the refractive index of other liquids.

Keywords: *Refractive index, phase refractive index of water, Michelson interferometer*

I. INTRODUCTION

The refractive index is the ratio of the velocity of light in a vacuum to the velocity of light in a transparent material, which is an important parameter in interferometric length measurements. This parameter is also useful in designing optical lenses or controlling qualitative materials, and the identification of different materials that are transparent or translucent to the ray of light. There are various methods to determine the refractive index of material using interference effects, a high accuracy method, which is using Michelson interferometer with white light sources, has been studied intently in the past decades by Petr Hlubina et al. [1-5].

When using a broad light source, the effect of the interferometer can be observed in the time domain or frequency domain. Base on observing spectrum split interference fringes in the vicinity of standing phase point or equilibrium position of wavelength [4], in which optical path difference of interfering beams is zero, the refractive index of materials or material medium can be calculated. The main drawback of this method is that with thick or highly dispersive materials, points that are far from the point of equilibrium are hard to resolve. In the case of a group refractive index, however, the position of a mirror in the interference branch can be adjusted to change the position of wavelength balance [1,2].

In our work, an experiment kit has been designed to measure the group refractive index of solid materials, the group refractive index and phase refractive index of water by wavelength. Grounded theory determines the refractive index by the interference method is demonstrated in Section II. Results and discussion in Section III.

II. THEORY AND EXPERIMENT

2.1. Theory

The principle diagram of interference with two beams of light is illustrated in Figure 1. Let $\Delta L(\lambda_0) = L_0 - l$ is the optical path difference (OPD) between two beams of light in Michelson interferometer, L_0 is the initial position of mirror M_2, l is the optical path of the beam after reflecting on the M_1 mirror (the first branch), t is the thickness of cuvette, λ_0 λ_0 is the equalization wavelength. When the cuvette has no liquid, the group refractive index of cuvette N (λ_0) is given by [2].

$$N(\lambda_0) = 1 + \frac{\Delta L(\lambda_0)}{t}. \quad (1)$$

When the cuvette is filled with a liquid given refractive index n_l, the optical path difference $\Delta'_M(\lambda)$ between two beams of light in the Michelson interferometer is given by

$$\Delta'_M(\lambda) = 2(L' - l) - 2t(n-1) - 2d(n_l - 1), \quad (2)$$

where, L' is the optical path of the beam after reflection on the M_2 mirror (the second branch), n is the phase refractive index of the cuvette, d is the thickness of the liquid in the cuvette.

When the incident light is a broad-spectrum light, the period of fringe spacing measured by interferometer is calculated as follows [2]:

$$\Lambda(\lambda) = \frac{\lambda^2}{\Delta_M}, \quad (3)$$

where λ is the wavelength, $\Delta_M{}'$ is the group optical path difference between two interference branches. The group optical path difference displacement of the equation (2) is written as follows:

$$\Delta'_{M(g)}(\lambda) = 2(L' - l) - 2t\left[N(\lambda) - 1\right] - 2d\left[N_l(\lambda) - 1\right], \quad (4)$$

Where $N(\lambda)$ is the group refractive index of the cuvette, $N_l(\lambda)$ is the group refractive index of water.

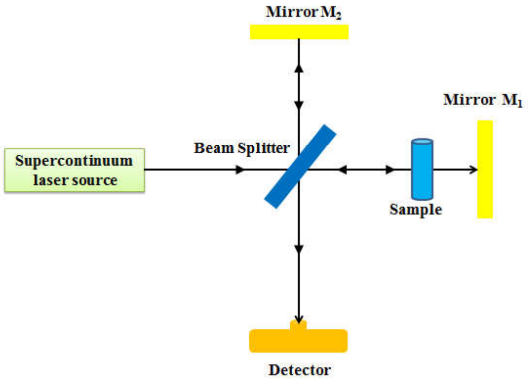

Fig. 1. *The schematic of the experimental set up with a Michelson interferometer*

At the position of the equalization wavelength, the optical path difference is equal to zero. Therefore, the position of mirror M_2 is determined by the following equation:

$$L'(\lambda_0) = l + t[N(\lambda_0) - 1] + d[N_l(\lambda_0) - 1]. \quad (5)$$

If $\Delta L'(\lambda_0) = L'(\lambda_0) - L_0 = L'(\lambda_0) - l$ is the distance between mirror M_2 and its initial position, the group refractive index of liquid as a function of the equalization wavelength λ_0 is given by

$$N_l(\lambda_0) = 1 + \frac{\Delta L'(\lambda_0) - t[N(\lambda_0) - 1]}{d}. \quad (6)$$

Finally, the phase refractive index of the water is determined by equation (7):

$$N(\lambda) = n(\lambda) - \lambda \frac{dn}{d\lambda}. \quad (7)$$

2.2. Experimental setup

The experimental setup used in the application of the Michelson *interferometer* with a *broad light source* to determine the group refractive index and the phase refractive index of water, as illustrated in Figure 2. It concludes a *broad light source,* SuperK COMPACT Supercontinuum laser with the wavelength from 450 nm to 2400 μm, a Red Tide Spectrometer with a wavelength range of 350-1000nm, an Avantes Spectrometer with useable range 1000-1700nm; a Michelson interferometer. The spectral interferograms are performed at room temperature when the position of mirror M_2 in the Michelson interferometer is adjusted with a precision of 0.01 mm. The interference fringes of the two beams are recorded by the detector which connected to a computer for data processing.

The light from a supercontinuum laser source (1) to beam splitter (2) is split into two parts. One part of the light travels to mirror M_2 (3) and reflects toward the detector (4). Another part of the light travels through a cuvette containing water (5) and reflects on mirror M_1 (6). After traversing these different path lengths, the two parts of the light are brought together to interfere with each other. The interference fringes of the two beams that reach the detector (4) are connected to a computer for data processing.

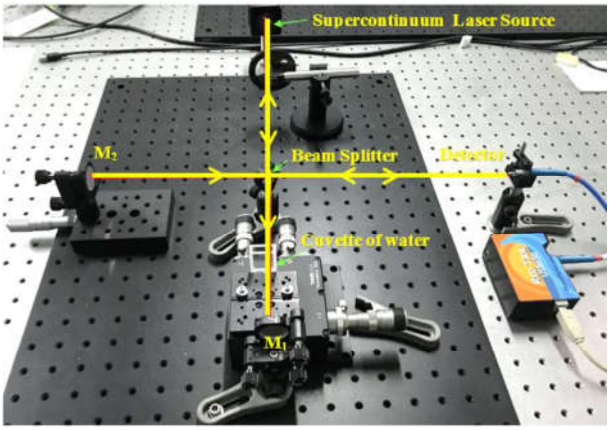

Fig. 2. *The schematic of the Michelson interferometer with a supercontinuum laser source*

III. RESULTS AND DISCUSSION

3.1. Determine the group refractive index of the cuvette

Firstly, the position L_0 was determined by adjusting mirror M_2 to the equalization wavelength position (the non-dispersive Michelson interferometer), recorded value of wavelength to determine the period of spectral modulation $\Lambda\left(\lambda_0\right)$, and used equation (3) to calculate the OPD $\Delta'_M(\lambda)$. The displacement ΔL_0 of mirror M_2 from the position L_0 is equal to half of the OPD $\Delta'_M(\lambda)$, which was determined in this way with a precision better than 0.01 mm. Secondly, a cuvette with a thickness of t = 5.49 mm was put into the optical path of the beam that strikes on mirror M_1. Then, the mirror M_2 was adjusted to such a position to resolve spectral interference fringes in accordance with the theory and recorded the value L' of mirror M_2. Continuously, the above steps were repeated with different values of mirror

M_2, we have obtained the dependence of the adjusted displacement of mirror M_2 on the equalization wavelengths. The spectral interference is illustrated in Figure 3.

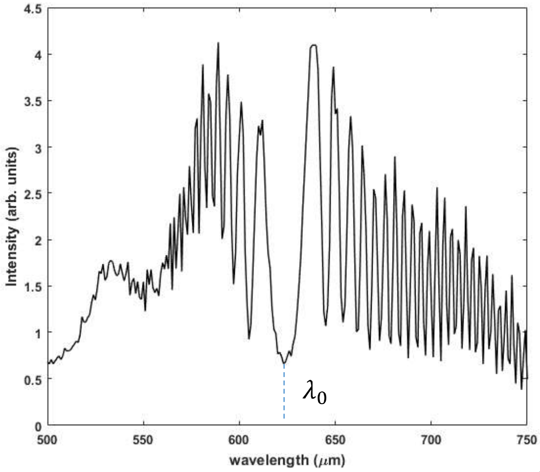

Fig. 3. *The spectral interference pattern of the mirror position is $L^{'}$ = 12,69mm, the thickness of cuvette t = (5.49 mm) and the thickness of water d = (5.05mm).*

The dependence of the group refractive index of the cuvette on wavelength was determined by equation (6). The experimental results are analyzed with the helping of MATLAB software in order to calculate the group refractive index of the cuvette, as shown in Figure 4.

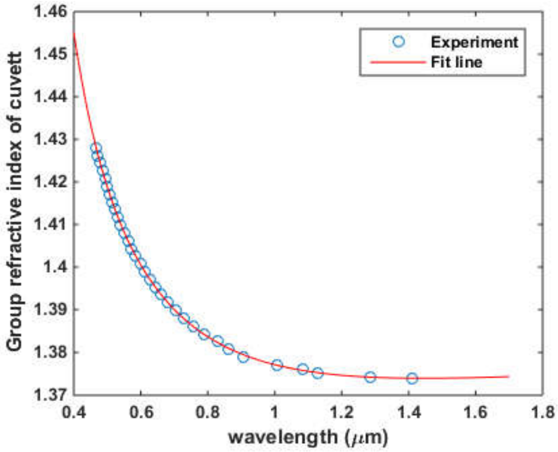

Fig. 4. *The group refractive index of cuvette material as a function of the wavelength for the thickness t = 5.49 mm. Blue circles and red solid lines correspond to the experiment results and fit line, respectively.*

3.2. Determine the group refractive index of water

To determine the group refractive index of water, a cuvette filled with water is put into the first branch of the interferometer, then the position of mirror M_2 is adjusted until the central interference fringe coincided with the initial position. The wavelength of light is the same value with the value of the equalization wavelength λ_0.

In the changing position of the mirror M_2, we get the values of the balance wavelength corresponding with the positions of the mirror M_2. The relation between the position of the mirror and the wavelength balance are shown in Figure 5. The result showed that the positions of the mirror have a coordinate range from 3.75 µm to 4.2 µm that corresponding with the values of balance wavelength in the spectral range from 1.2 µm to 0.45 µm.

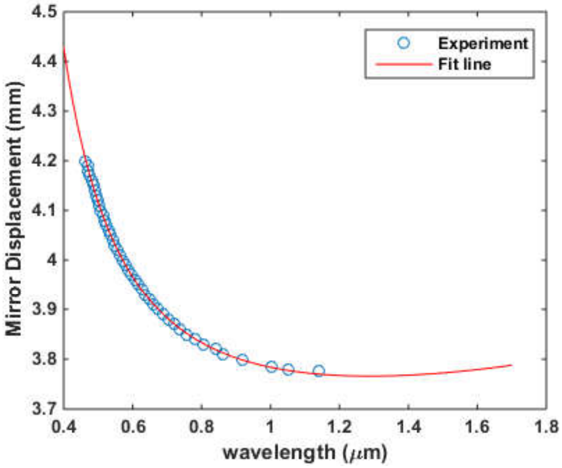

Fig. 5. *The measured mirror displacement as a function of the wavelength for the thickness of cuvette t = (5.49mm) and the thickness of water d = (5.05mm) (blue circles). The red solid line is a fit line.*

Phase refractive index of water as a function of the wavelength will be expressed as the following formula [7]:

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{C_1\lambda^2}{\lambda^2 - D_1}, \quad (8)$$

with parameter values $A_1 = 0.75831$, $B_1 = 0.01007$, $C_1 = 0.08495$, $D_1 = 8.91377$ (9).

Combining (8) with (7) we get the formula to measure the group refractive index of water as a function of the wavelength as follow:

$$N(\lambda) = n + \frac{\lambda^2}{n}\left(\frac{A_1B_1}{(\lambda^2 - B_1)^2} + \frac{C_1D_1}{(\lambda^2 - D_1)^2}\right) \quad (10)$$

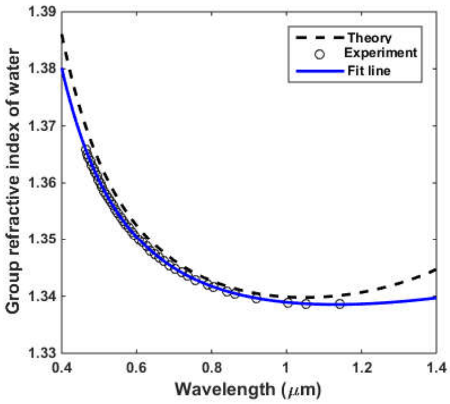

Fig. 6. *The measured group refractive index of water as a function of the wavelength. The black circles are the experiment results and the black solid is the results of theory [7].*

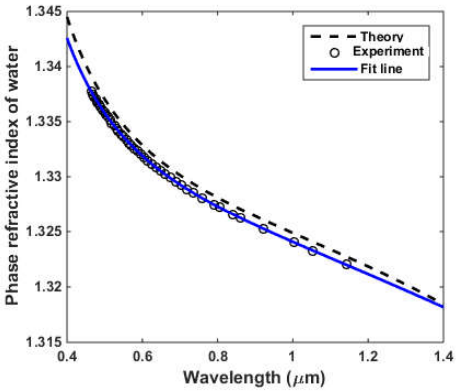

Fig. 7. *The measured phase refractive index of water as a function of the wavelength. The black circles are the experiment results and the black solid is the results of theory [7].*

From the experimental results, we can write the formula of the relation between the phase refractive index and group refractive index of water with the wavelength of the light source as shown in equation (10).

The results showed that the experimental results are similar to those of theory. This proves the experimental system to determine the refractive index using the Michelson interferometer with a wavelength-changeable light source that we designed has high accuracy and reliability, which can be applied to determine the refractive indices of different properties of materials.

IV. CONCLUSION

We have designed an experiment kit with the Michelson interferometer using a broad light source to measure the refractive index of different materials.

The results from the experiment with materials used to make cuvette and water inside the cuvette show that when changing the optical path length of light beams in the interferometer, the central fringe also changes. In the case of the laser source that can change the wavelength in a wide range, with every value of optical path difference, we can choose the value of wavelength so that the central fringe can return to its original position. From the results that we calculated from the data, we have found the values of the phase refractive index of materials that use to make cuvette, group refractive index and phase refractive index of water.

The obtained results show that there is a match between the experimental results obtained from our experiment kit and the announced theoretical results [7]. This shows that our experiment kit can be used to determine the refractive index of different materials.

V. ACKNOWLEDGMENTS

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