An Arduino based automated procedure for measuring refractive indices of optical materials for educational purposes using Michelson's interferometer

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Abstract

Interference, as a technique, constitutes a powerful tool in the study of visual phenomena, by creating interference patterns-hence the term "interferometer". Interferometers as research tools used in many fields of optical technology, regardless of their size or structure, act as light splitters (division of amplitude) thus splitting a beam of light into two parts. Each part is made to travel a different path and brought back together where they interfere according to their path length difference. The interference pattern conveys information relative to the optical wave or transparent media which is rotated in one of the two parts.

This work deals with the technique for measuring the refractive index of materials based on the interferometry of a rotated parallel plate. The apparatus employs a Michelson interferometer, a sample rotation system consisting of a circular platform placed on the rotation axis of a servo motor controlled by an Arduino UNO, Rev3 microcontroller and an optoelectronic registration system. The refractive index of a parallel plates sample is determined by its rotation through measuring simultaneously a shift of interference fringes. Although this technique is well known, a considerable increase of accuracy is reached in our case by an automation of the measuring procedure. In the fully automated measurement process, Pasco's Rotary Motion Sensor, combined with the PASPORT Light Level Sensor and Data Studio software from the same company, was used.

Key words: Interferometry, Michelson's interferometer, Refractive index, Arduino Optical materials

1. Introduction

The refractive index as a physical quantity is one of the most important characteristics of optical materials, the calculation of which is a considerable task in their characterization during an experiment or research process in several disciplines of science and technology. There are several techniques for the measurement of the refractive index in the visible spectrum, the most common being the determination of the minimum angle of deviation [1], the immersion [2,3], the ellipsometry [4, 5] and interferometric-turning methods [6, 7].

Each of these methods has its advantages and a corresponding application field. For instance, the ellipsometry can be used in the determination of the refractive index of thin film materials deposited on substrates, while the immersion technique, where the refractive indices of a crystalline material and the immersion liquid are compared, cannot be used in many materials due to the fact that the refractive index of the liquid is limited in the range of ($1.4 \leq n \leq 1.8$). On the other hand, the technique of minimum deviation requires that the sample is in a wedge or prism form and provides, in fact, quite high accuracy in the determination of the refractive index. However, this procedure is time-consuming and requires a substantial amount of a crystal material, from which the prism or wedge would be made [8]. Moreover, this method obviously cannot be used in expensive materials, since part of the material is lost during the preparation process whereas the remaining prisms are frequently not suitable for further use. In many practical applications, where it is not possible or desirable to cut samples in a wedge or prism form, the interferometric technique may be used as a precise, non-destructive approach. In this case we assume a (semi) transparent sample with perfectly plane-parallel surfaces. This method measures the change in the optical path of light when the sample rotates in one of the two arms of a interferometer and is used both in solid samples and liquids. More precisely, if a flat plate of optical material with a refractive index n is placed normally to direction of one a the light rays in a Michelson interferometer, the optical path of the light will increase by 2(n-1)d, where d being the thickness of the plate. This introduces a path length difference of $N\lambda$ between the light rays which travel along the two arms of the interferometer, with λ being the wavelength used and N the increase in the interference order when the sample is rotated away from normal incidence.

If the plate is rotated by a small angle θ, the path of the light ray incident on the plate will be changed and N interference fringes, corresponding to this change, will be recorded. This is due to the fact that, as the plate rotates, the path length of the light will increase by an amount of $d/\cos\theta$ and consequently the number of wavelengths will increase thus changing the interference pattern. By increasing the angle of rotation θ the value of $\cos\theta$ decreases and therefore the ratio $d/\cos\theta$ increases. When projected on a screen, it can be seen that the fringes collapse or appear as the plate is rotated. The change of the path through the plate depends upon the thickness of the plate, the angle through which it is rotated and the index of refraction. So the index of refraction may be calculated if the other two values are known.

In his paper we describe the design and development of a fully automated interferometric device based on a Michelson interferometer, to measure optical diffraction characteristics. In the automation process, Pasco's related educational equipment was used in conjunction with microcontroller technologies and other devices.

2. Method description

A typical diagram of the automated device developed to measure the refractive index of optical materials is shown in Fig. 1. The method is based on a modified Michelson interferometric device and is suitable for parallel plate samples. The sample is set into the one arm of the interferometer noted in Fig.1 as the reference arm. A beam of He-Ne laser at 632.8 nm is led to the beam splitter structured on the interferometer where it splits up into two beams: the first part (reference arm) hits mirror 1 and is reflected back while the other part passes through the sample, reflects on mirror 2 and passes the sample again to reach the beam splitter. The two beams are overlapped in the beam splitter, creating thus the interference fringes, which are recorded by a photodetector

(Fig.1). The output of the photodetector connects to the control module which registers the shift of the interference fringes caused by a sample rotation and relative to the angle of rotation.

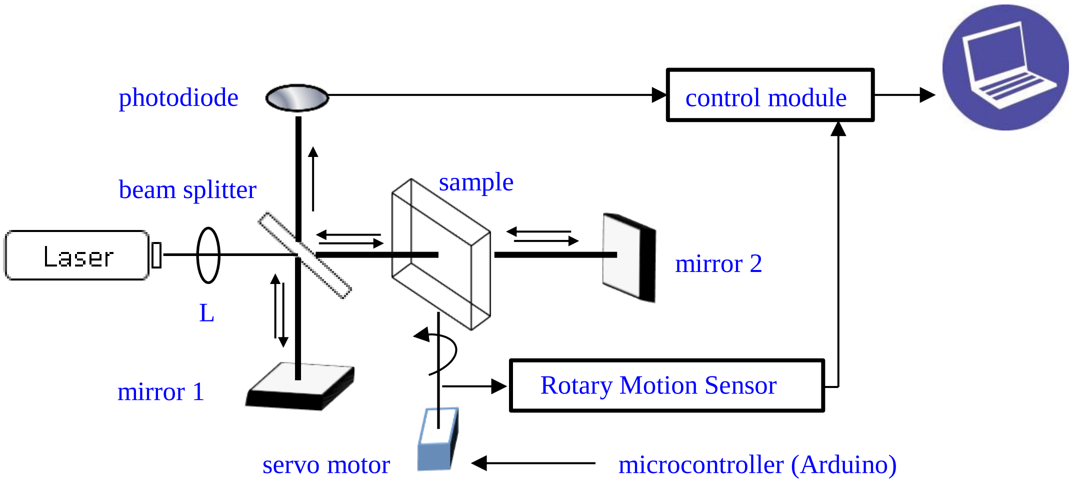

Fig.1: The setup of the automated experimental apparatus based on the interferometry of a rotating parallel plate.

A partial view of the experimental arrangement is shown in Fig. 2. The rotating stage, a disc, where the transparent sample is mounted (a microscope glass plate in this case) of which we will determine the refractive index, is connected through a rubber band and a pulley to Pasco's rotary motion sensor, so that the rotation angle of the disc can be measured. The measuring process is completely automated. The task of automatically controlling the rotation of both sample and sensor discs is undertaken by an Arduino microcontroller UNO REV3 through a DC servo motor (0^o – 180^o). Each time the value of the angle rotation, as well as the change rate of it and the start and ending of the measuring procedure are set as parameters into the microcontrollers' software program.

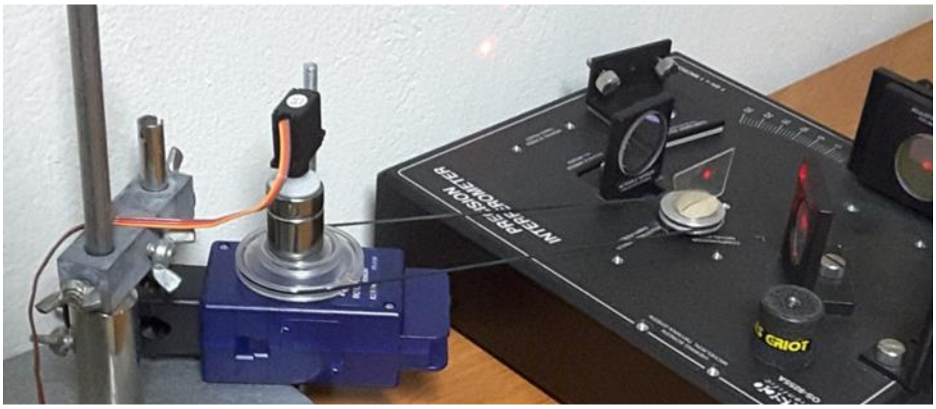

Fig.2: Photograph of the apparatus showing the belt connecting the rotation sensor pulley to the rotating stage.

The same microcontroller is used in the calibration process of the apparatus and in carrying out the first experiment where the precise wavelength of the He-Ne source used here is determined. For that, a second servomotor is mounted on the interferometers' rotation knob (micrometer) and operates separately from the first, receiving commands from the microcontroller (Fig. 3).

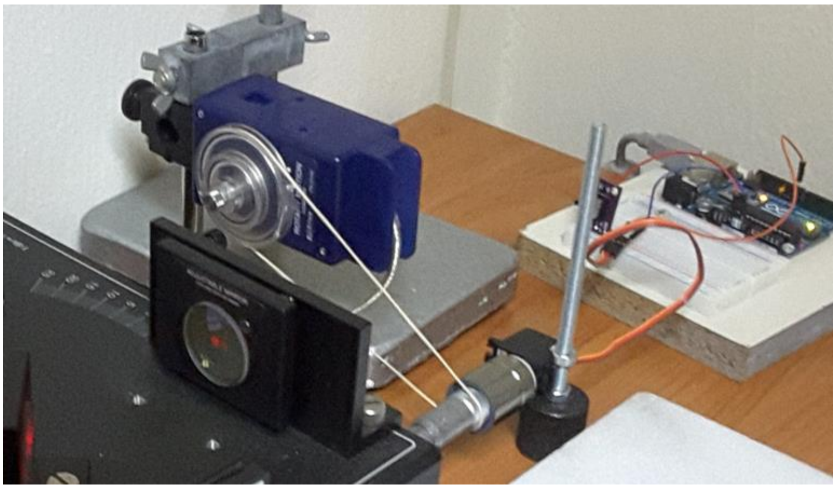

Fig.3: Photograph of the apparatus showing the servo motor as adapted to the interferometers' turning knob (micrometer) and the belt connecting it to the rotation sensor pulley.

The capture in Fig. 4a shows a typical interference fringe pattern obtained after both the reflected beams are recombined and the He-Ne laser beam encountering the beam splitter has been wided by placing a converging lens with a focal length of 18 mm in its path. The lens is inserted between the light beam and the beam splitter so that the light source lies at the focal point, since only enlarged light spots can exhibit interference rings.

This interference pattern will come alive when mirror M2 moves back and forth by

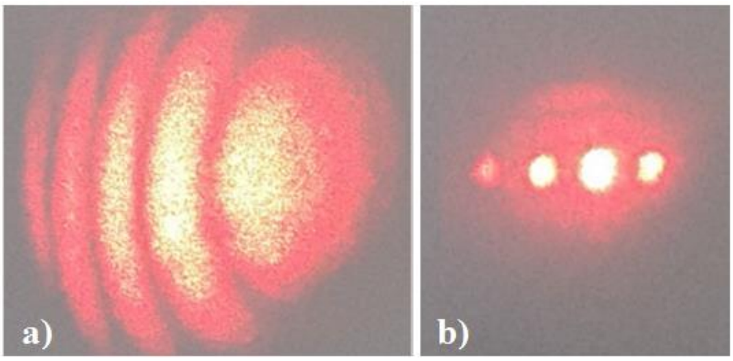

Fig. 4: The intensity fringe patterns as seen on screen a) with and b) without a laser beam enlargement lens.

rotating the micrometer knob on the side of the interferometer (first experiment) or by rotating the stage which holds the sample (second experiment). That is, as mirror M2 is moved or the angle by which the beam falls on the sample changes, so as the path lengths of the two beams change, the fringes move inward towards the center of the pattern or outward away from it. In both cases the number of fringes passing through a set point, the measuring point, at each change in either the position of the mirror or in the angle of rotation has to be noted down very carefully. This is done by the optoelectronic recording system used in the apparatus. A photodiode placed at the plane where the interference pattern is observed, detects changes in light intensity as the fringes move and outputs them to the control module which connects to a computer. The Pasco Light Sensor is used here with the corresponding Data Studio program (Fig.5).

In thin optical lenses where their surfaces are parallel only in a small region around the optical center, measurements as to determine the refractive index are made by keeping the laser beam narrow, thus the light incident on the lens covers only this area (case of a parallel plate sample). This is done by not introducing the 18 mm converging lens between the light beam and the beam splitter. The resulting interference pattern is captured in Fig. 4b.

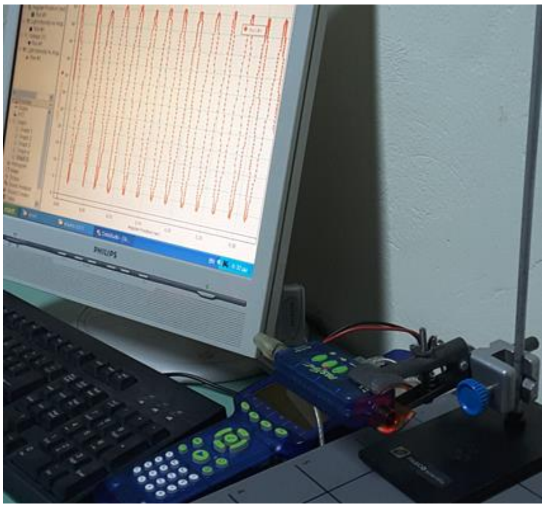

Fig. 5: Plotting the light intensity signal of the fringe pattern collected by the sensor, with respect to the angle of rotation.

As an alternative to Pasco's Light Sensor we used a signal photodiode connected to an analog input of the Arduino. The detected by the photodiode variations in light intensity of the interference pattern was processed by the microcontroller and matched with the corresponding angle of sample rotation, the value of which was known since the rotation of the servo motor's axis was translated into degrees with an appropriate calibration where a speed reduction pulley was used to achieve greater accuracy.

3. Measurements and results

Device calibration

A calibration of the device is needed before any measurements can be made. On one hand, as the movement of mirror 2 is controlled by the servo motor which turns the micrometer knob through the pulley stage, the accurate displacement value of the mirror has to be given in terms of distance units. That is, the set angle values have to be translated precisely from degrees to submicrons (Fig. 3). On the other hand an analogous procedure must be carried out, as the angle of the rotating stage has to be set accurately. This is needed because of the speed reduction, due to pulley – belt mechanism, during its rotation (Fig. 2).

For the first part, a series of measurements were made, were each time the set rotation angle of the DC servo motor's axis was correlated with the exact shifting of mirror's 2 position. This was done by counting the number of N fringes that crossed the center of the sensor's surface when the mirror was moving, for an m number of different angles. A train of *N* fringes will behave as m = N λ, where λ denotes the wavelength of the He-Ne laser (λ=632.8 nm). From the mean values of the measurements the shifting of the mirror's position corresponding to angular resolution (minimum torsion angle) of the servo motor, was calculated. For the second part, the accurate value of the rotation angle θ of the sample holder rotation mechanism, resulted as a submultiple of the corresponding angular resolution of the servo motor as m = k.θ, with k being the gearing coefficient. A value of k was obtained for the arrangement of Fig. 3, after an appropriate calibration. The rotation angle values were, in both cases, checked against the values obtained from Pasco's rotation sensor connected to servo motor. This sensor was also calibrated for use in conjunction with the recording and processing of measurements through Pasco's Data Studio software program (Fig. 5).

Measuring the refractive index

Measurements on thin plate specimens (a microscope glass slide and plexiglas plate) were made to determine their refraction index which is then calculated from the no. of interference fringes shifted during the rotation of the glass/plexiglass plate. The following equation is used to calculate the index of refraction of the sample [8].

$$n = \frac{(2d - N\,\lambda)\,(1 - cos\theta) + N^2\lambda^2}{2d(1 - cos\theta) - N\,\lambda}$$

where λ the laser wavelength used, d the thickness of the plate, N the number of interference fringes shifted during the rotation and θ the angle of rotation. The term $N^2\lambda^2$ can be omitted without any impact on n, as $N^2\lambda^2 << 1$.

Table 1 shows the results of calculating the refractive index of two plates, a glass and a plexiglas, as measured by the number of fringes passing through the photodiode and the corresponding angle of rotation of the specimen, with the existing experimental arrangement and its application the above formula. These values show a relatively good approximation to the corresponding values in the literature given the errors involved in the measurement.

Table 1. Measurement results and calculation of refractive index values

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Material	Angle	No. of Fringes	Index of refraction	Theoretical value
microscope glass slide	20	65	1.48	1,5035
Plexiglas plate	10	50	1,48	1,4940

4. Conclusions

The experimental apparatus presented here proposes the idea on how the widespread microcontroller technology along with common sensors already existing in a physics laboratory can be merged into apparatuses such as a conventional Michelson interferometer. Through such an upgrade the laboratory environment becomes more accessible and attractive to students, while extra resources are not required to carry out the experiments. In addition, the same experimental apparatus, with an appropriate change in its layout, may be used in performing more experiments, such as the determination of the laser wavelength or the thickness of various samples and the self-oscillating frequency of the mechanically stimulated experimental bench where the apparatus lies. The latter can be done through the time-varying signal being recorded and its processing with the FFT function provided by Pasco's Data Studio program or any other similar program. The measuring of the refractive indices of optical materials with values being very close to the theoretical values, as a result shows that this apparatus can be used to carry out various experiments in an optics laboratory.

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