A NEW REFRACTOMETER BY COMBINING A VARIABLE LENGTH VACUUM CELL AND A DOUBLE-PASS MICHELSON INTERFEROMETER†

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Abstract

A new refractometer with a variable length vacuum cell has been developed, where the refractive index of air is determined by measuring the changes in the optical path difference between the air of interest and a vacuum as a function of the changes in the cell length. An uncertainty of 4×10^{-9} in the index has been achieved.

Introduction

At the National Institute of Standards and Technology (NIST), an SI watt experiment [1] is being conducted for determination of fundamental physical constants. When a voltage-to-velocity ratio is to be determined in the experiment, the displacement of a moving coil is measured by an optical interferometer. Since the experiment is set up in air, the refractive index of air must be known with an uncertainty of better than 1×10^{-8}.

In a conventional refractometer, a fixed length cell is used, where an optical path difference before and after evacuating the cell is measured. Since optical windows for the cell are deformed by the evacuation, a relatively large correction for changes in the optical path length in the windows is necessary [2]. The uncertainty in the refractive index of air determined by this method is usually about 3×10^{-8}.

In order to overcome the problems due to the window deformations, a variable length vacuum cell [3] is implemented in the present refractometer, where the refractive index of air is determined by measuring the changes in the optical path difference between the air of interest and a vacuum as a function of the changes in the cell length. Since the deformations in the optical windows are constant during the cell length change, any errors due to the window deformations can be eliminated.

A double-pass Michelson interferometer [4] is also developed for this purpose so as to measure the changes in the optical path difference and the changes in the cell length simultaneously. In order to achieve a very high resolution in measuring the small optical path difference, a phase modulation technique and a dark fringe detection method are implemented.

Principle

Figures 1 (a) and (b) show the principle of a variable path length refractometer. A bellows is used to change the length of a vacuum cell. In Fig. 1 (a), a linearly polarized incident light beam is separated into two polarized components p and s by a polarizing beam splitter PBS; p for the air path, and s for the vacuum path. After passing through the cell, they are combined by the PBS. The optical path difference between the air and the vacuum causes an order of interference d. In Fig. 1 (b), an optical layout to measure the changes in the cell length is shown. The layout is exactly the same with that of Fig. 1 (a) except that a part of the optical windows is coated to reflect the light beams so that the effect of any pitch and yaw of the moving window can be canceled. The distance between the two windows causes an order of interference L.

The refractive index of air n_a is then determined by the following simple formula:

$$n_a = 1 + \Delta d / \Delta L \, , \qquad (1)$$

where Δd and ΔL are changes in the orders of interference d and L respectively.

Interferometer

Figure 2 shows a schematic drawing of the double-pass Michelson interferometer which measures the Δd and ΔL simultaneously. A total of eight laser beams is used in the interferometer: four for Δd measurements, and the others for ΔL measurements. Beam positions are chosen to be so symmetrical that any change in L would result in a correct change in d.

For ΔL measurements, the light beam from the interferometer is divided into four beams. They are then 0°, 90°, 180°, and 270° phase shifted for reliable quadrature fringe counting. An up/down counter keeps track of the displacement of the moving window.

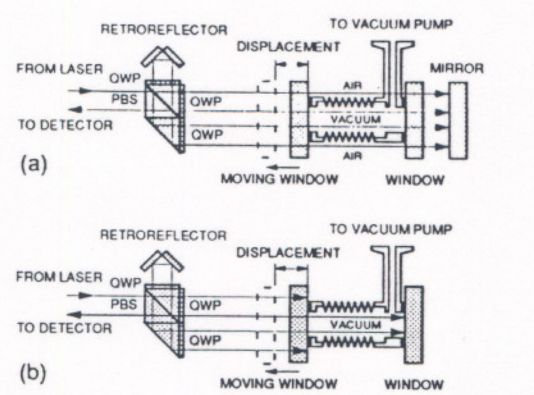

Fig. 1. Principle of the variable path length refractometer. PBS: polarizing beam splitter, QWP: quarter wavelength plate. (a) A layout for measuring the changes in the optical path difference between the air and the vacuum. (b) A layout for measuring the changes in the cell length.

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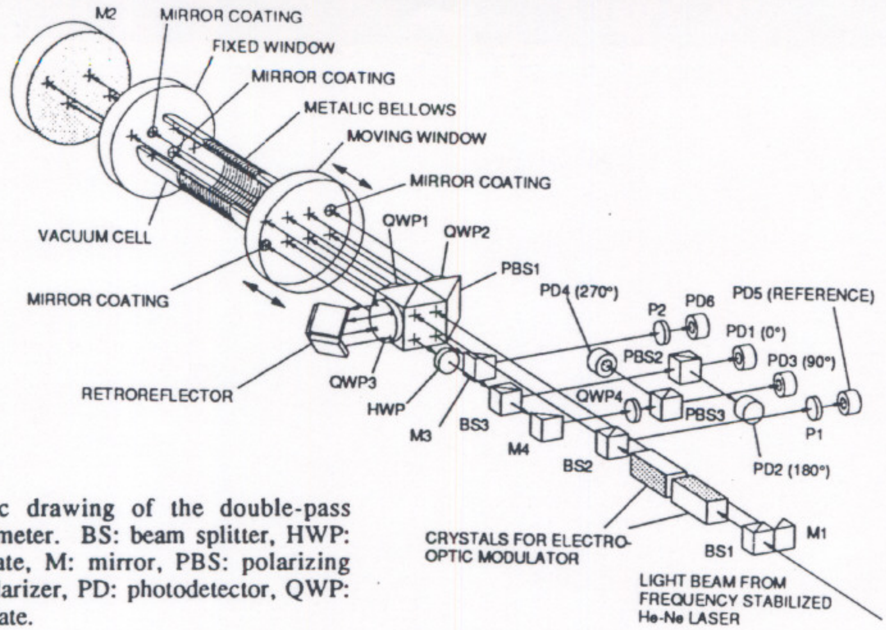

Fig. 2. Schematic drawing of the double-pass Michelson interferometer. BS: beam splitter, HWP: half wavelength plate, M: mirror, PBS: polarizing beam splitter, P: polarizer, PD: photodetector, QWP: quarter wavelength plate.

Readings of the counter are recorded in a computer.

For Δd measurements, an electro-optic modulator (EOM) is used to modulate the phase difference between the two polarized components s and p. To stabilize the dc bias phase difference between the two components, the light beam is separated into two beams after passing through the EOM: one for a reference photodetector, and the other for the Michelson interferometer. The signal from the reference photodetector is demodulated by a lock-in amplifier, integrated, and then fed to a dc bias input of an EOM driver. This servo system keeps the reference interference at a dark fringe position.

The light beam from the Michelson interferometer is demodulated by a lock-in amplifier. The readings near zero-crossing points (dark fringe positions) are recorded by the computer as a function of ΔL to compute ΔL_i at an ith dark fringe position. The value $(\Delta d/\Delta L)$ is computed from a series of ΔL_i's by a method of least squares to calculate n_a from Eq. (1).

To translate the moving window, an inchworm motor is used because of its non-magnetic properties. In actual measurements, successive 15 dark fringes are detected for a cell length change of about 9 mm. This means that a cell length change of about 0.6 mm causes

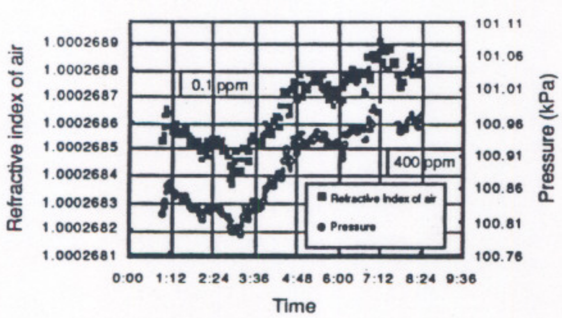

Fig. 3. An example on the measurements of n_a.

a unit fringe change in d. Since the quadrature fringe counter is used for measuring the changes in the cell length, a single fringe change in d is divided into about 15,000 counts, achieving a very high resolution in the optical path difference measurements.

Results

Figure 3 shows an example of the measurement results on n_a. A total of 143 data points are plotted for a period of about 7 hours. Air pressure readings are also plotted in the figure. Since the measurements were performed in an open-air condition, most of the changes in n_a are caused by the changes in the air pressure.

The measurement uncertainty in n_a can be estimated from a standard deviation in fitting a straight line to the data ΔL_i's. The results have shown that the standard deviation in Δd measurements is 300 microfringes, achieving an uncertainty of 4×10^{-9} in n_a.

References

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