Laboratory #40: Michelson Interferometer, The Refractive Index of a Gas

Goal: Measure the refractive index of gases using a Michelson interferometer

Equipment: Michelson interferometer, gas cell, compensator, absolute pressure gauge, cylinder with helium gas, vacuum pump.

1. Experimental setup:

The Michelson interferometer is illustrated in Fig. 1. A bundle of light from the light source falls on the beam splitter, which on its rear surface has a reflecting coating. The beam splitter divides the light into two beams, one transmitted toward the fixed mirror M2, the other reflected toward the moveable mirror M1. Both mirrors return the light to the reflecting surface where the two rays recombine and proceed toward the observer. The recombined rays interfere with each other, which results in bright and dark regions in the field of view. A change of half a wavelength in either of the two legs will be a visible effect.

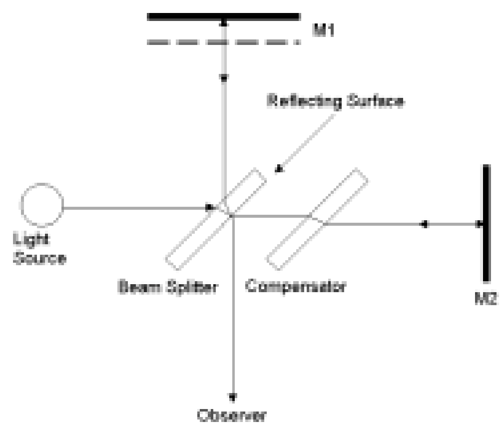

Figure 1: Michelson Interferometer

The interferometer must be aligned before it can be used. This is achieved by means of the two adjustment screws that allow you to tilt the mount of mirror M2, and with the main micrometer screw which moves mirror M1 a directly measured distance perpendicular to its plane (there is a 5:1 gain caused by the lever).

First you have to set the moveable arm such that the path length in the two legs is the same. This is done by measuring with a ruler the distance from the center of the beamsplitter to the center of each mirror.

The second step is to align the mirrors M1 and M2 exactly perpendicular to one another. Illuminate the beamsplitter with a quasi-monochromatic source. In our case, this is a mercury light source, diffused by a ground glass screen, followed by an interference filter that passes only the green λ = 546.1 nm line. To help with the alignment, a pin is mounted between the light source and the beam splitter. When the two mirrors are misaligned, *two* images of the pin appear in the field of view. Adjust the screws on mirror M2 untill the two images coincide. When this is done, interference fringes will appear across the field of view. Continue to use the tilt controls to bring the center of the fringes into the center of the field of view.

Finally, adjust the position of the moveable mirror such that the path difference is close to zero. As the path length difference approaches zero, the circular fringes become larger and widely separated, the contrast between blackness and maximum brightness slowly disappears, and it will be quite difficult to discern the fringe pattern, especially when the central fringe covers the whole field of view (see top row of Fig.2). *Note that the length difference becomes less as the fringes move inward toward the center of the fringe pattern. When the direction of the fringe pattern movement inverses, zero path difference has been passed*. At this point, white light is substituted for the quasi-monochromatic source, and the final but also most difficult adjustment of the position of mirror M1 is made until the center of the field of view will be dark. The optical path lengths of the two arms are now exactly equal and the entire spectrum of wavelengths is in phase.

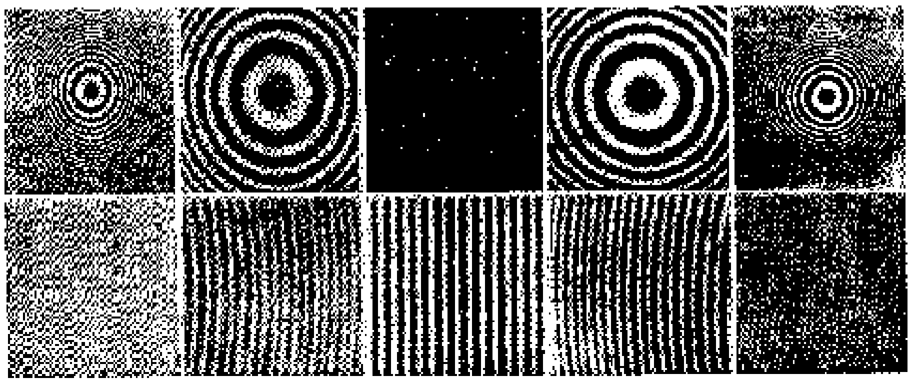

***Figure 2:** Appearance of circular fringes (upper row) and localized fringes (lower row) in the Michelson interferometer. Path difference increases outward, in both directions, from the center*

A comparatively easier method is to use localized fringes in the field of view. Localized fringes can be obtained by tilting mirror M2 slightly away from the position where its surface is perpendicular to that of the plane of mirror M1. Then M1 and M2 are inclined at a small angle. The observed fringes are slightly curved (see bottom row of Fig. 2). As the path length difference decreases toward zero, these localized fringes become straighter and the curve in the opposite direction as the path length difference increases beyond the region where the planes of M1 and M2 intersect (the image of M2 near M1). The setting where the localized fringes become straight and few in numbers correspond to zero or near zero path length difference. At this point the quasi-monochromatic light source is replaced by white light. A slight adjustment of the moveable mirror places the dark fringe of zero path length difference in the center of the field of view. The central dark fringe is bordered on either side by 4 to 8 colored fringes.

2. Measuring the Index of Refraction of a Gas

A gas cell is placed in one of the arms of the interferometer. The cell has three tubing connections, one to pump out the cell, one to measure the pressure in the cell and one to admit gas to the cell. The latter is connected to a needle valve for fine control of the gas flow. Initially this valve is open to air, later you will connect it to the helium inlet.

The pressure is measured by a pressure transducer that is connected to a computer interface, as well as by a mechanical gauge. The mechanical gauge measures the pressure difference between the cell and a reference volume. Initially you should reduce the pressure in the reference volume to zero by pumping on it.

Adjust the interferometer for zero path length difference using localized fringes. Switch back to the green mercury light. Place a thermometer adjacent to the cell in order to record its temperature. To start a measurement, evacuate the cell. Then slowly open the needle valve, admitting air to the cell. As the pressure in the cell increases the number of wave lengths inside the cell increases, and the interference pattern changes. The rate of pressure increase should be such that you can conveniently observe the fringes moving by.

It is best if one observer counts fringes aloud while the other reads the manometer and records the results. Repeat the whole procedure a number of times, since random errors enter into both the manometer reading and fringe counting. Try also using the computer to record the pressure as a function of the fringe number.

Plot the manometer reading *P* versus the fringe number *N*. This should be a straight line. From this line the slope *dN/dP* is obtained. If you are using the computer there is an analysis tool that directly gives you the slope. Assuming that the ideal gas law holds, the index of refraction n_0 of air (or gas) at *T*=273K and *P*=760Torr can be calculated as follows

$$n_0 - 1 = \frac{\lambda}{2\ell}\frac{dN}{dP}\left(760torr \cdot \frac{T}{273K}\right)$$

Here λ is the wavelength of the light used, ℓ the length of the gas cell, and *T* the temperature in K.

The length of the brass block on which the two glass windows are mounted is ℓ = 63.44 ± 0.03 mm. The thickness of the glass windows is 4.17 mm. It cannot necessarily be assumed that the glass windows come into contact with the metal body of the cell.

The whole procedure should be carried out for air as well as helium gas. Compare your results with the mechanical gauge and with the transducer to each other and to values of the respective refractive indices that you find in the literature.

When you evaluate the experimental errors, there are a number of systematic effects that you should consider. The mechanical gauge reading depends on pressure (see the operating manual at the station). The assumption of an ideal gas is not exactly true (use the Van der Waals equation to estimate the size of this effect). The cell length may change due to the atmospheric pressure pushing from the outside. The interferometer may drift during observations (is there a change of the pattern over time, even if you do not change the pressure in the cell?)

In case of the *air* measurement, there is a possible effect of the humidity of the air. Refer to the appendix below to learn about this effect. In order to evaluate the humidity correction you have to know the water partial pressure at the time of the measurement (see Auxiliary Lab #90: Humidity). You also need to know the ambient temperature, and the ambient pressure (see Auxiliary Lab #92: Atmospheric Pressure).

3. Reference

[KAY95] G.W.C. Kaye and T.H. Laby, Tables of Physical and Chemical Constants, 16th ed., Longman, Burnt Mill, Essex, England, ISBN 0-582-22629-5 (QC61.K3 1995)

4. Appendix: excerpt from ref. [KAY95]:

Refractive index of air

The wavelength λ_{air} of a radiation in air is related to its vacuum value λ_{vac} by $\lambda_{vac} = n\lambda_{air}$, where n is the refractive index. For standard air (dry air at 15 °C and 101 325 Pa, containing 0.045% by volume of carbon dioxide) the refractive index n_s is given by the dispersion equation (Birch, *Metrologia*, 1994, **31**, 315)

$$(n_s - 1) \times 10^8 = 8\,342.54 + 2\,406\,147(130 - \sigma^2)^{-1} + 15\,998(38.9 - \sigma^2)^{-1}$$

where $\sigma = 1/\lambda_{vac}$ and λ_{vac} is expressed in µm. This equation is based upon observations within the range 200 nm to 2 µm, and is in better agreement with recent measurements than the previous equation (Edlén, *Metrologia*, 1966, **2**, 71) mainly due to the increase in ambient carbon dioxide levels.

In the visible region (405–705 nm) the following approximate expression is more convenient and gives a maximum discrepancy of only 1.4×10^{-8},

$$n_s - 1 = 0.047\,2326(173.3 - \sigma^2)^{-1}$$

For air at a temperature t °C and a pressure p Pa, the refractivity is given by the equation

$$n_{tp} - 1 = (n_s - 1) \times \frac{p[1 + p(60.1 - 0.972t) \times 10^{-10}]}{96\,095.43(1 + 0.003\,661t)}$$

The refractivity of water vapour is less than that of air, so that if the air is moist its refractive index will be smaller than the value calculated for dry air. This water vapour term is dependent upon wavelength. In the visible region (405–644 nm) the relationship is

$$n_{tpf} - n_{tp} = -f(3.7345 - 0.0401\sigma^2) \times 10^{-10},$$

where n_{tpf} is the refractive index of air containing water vapour at a partial pressure of f Pa, the total pressure still being p. This equation is valid only for conditions not deviating very much from normal laboratory conditions ($t = 20$ °C, $p = 100\,000$ Pa, $f = 1500$ Pa).