Optics Laboratory

The Michelson Interferometer

1. OBJECTIVES

- Measurement of small displacements with white light.
- Measurement of the refractive index of a dielectric plate.
- Estimation of the spectral width of a LED source.

2. THEORY

The Michelson interferometer to be used in this practice is the one shown in Figure 1.

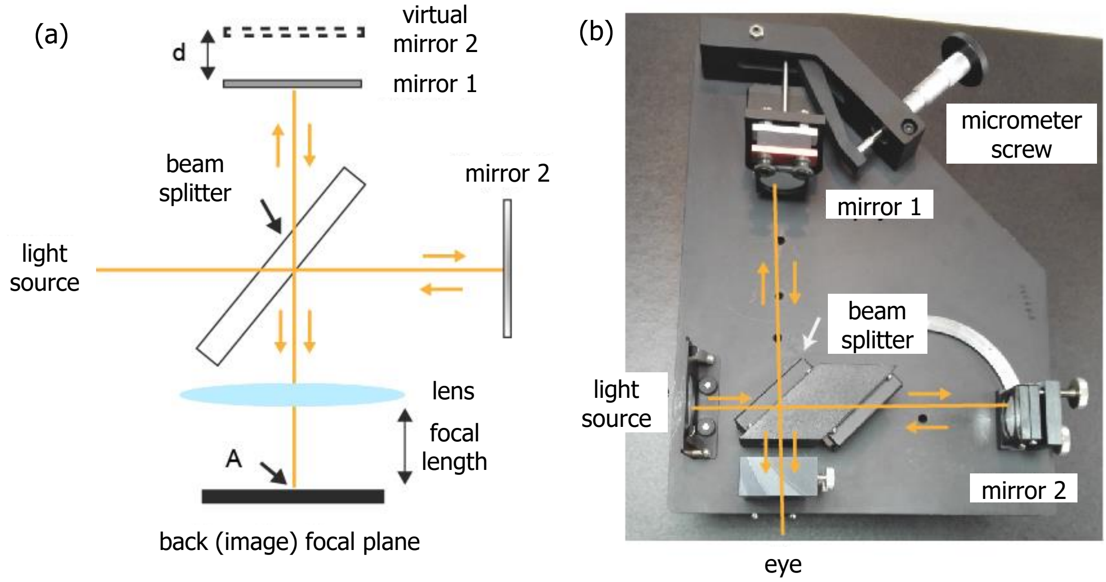

Figure 1. (a) Sketch of a Michelson interferometer. (b) Michelson interferometer that is going to be used in the laboratory to perform the experiments.

The expression governing the minimum formation is:

$$2nd\cos\theta = m\lambda, \tag{1}$$

which represents a series of concentric rings, where n is the refractive index of the medium (in our case, air, n=1), d the path difference traveled by the two beams, θ the angle formed with the normal to the mirrors by the beam incident on them, m the interference order of the ring (integer) and λ the wavelength of the light used.

When the two beams travel the same optical path ($nd=0$) the interferometer is in **optical contact** or in its zero-path difference (ZPD) configuration.

3. EXPERIMENTAL METHOD

Before carrying out any measure with white light, it is important a proper calibration of the interferometer, which includes its correct alignment and preparing it in its optical contact or zero-path difference (ZPD) configuration ($d = 0$).

3.1 Alignment of the interferometer

The elements of the setup are a Michelson interferometer, whose scheme is shown in Fig. 1, three different light sources (sodium lamp, white light lamp, LED), a diffuser plate that will act as an extensive source, spectrometer with optical fiber, focusing system and computer.

Alignment: Place the sodium lamp as the light source and remove the diffuser plate. Observation from the 'eye' position will allow several images of the source to be seen. Then turn the screws of Mirror 2 until these images match perfectly. In this position, the mirrors will be perpendicular, and interference fringes will be visible. To improve the observation conditions, place the diffuser in position and fine tune the alignment to obtain concentric rings.

3.2 Zero path difference (optical contact) configuration

Next, the ZPD configuration must be found, which ensures that the path difference between the two arms vanishes and, therefore, that we have a reference position to start measuring displacements or any other distance-based quantity (e.g., the refractive index). It can be determined following these steps:

1. Using the sodium lamp, start moving mirror 1 with the micrometer screw such that the size of the interference rings gradually increases. Note that by acting on this screw, the displacement d (the size of the two interferometer arms) is being changed. Keep going with this operation until you observe that the intensity maximum occupies the full field of view. Then, without using mirror 1, slightly misalign mirror 2 until you start observing interference fringes again. Getting back to mirror 1, it can be seen that if the micrometer screw is turn in one direction, the fringes acquire a certain curvature; if it is turned in the other direction, the curvature will start changing until getting the opposite sign. The ZPD configuration is somewhere in between, with the fringes being straight and parallel.

2. Due to the high coherence of the sodium light, it is difficult to discern the exact position for equal paths (ZPD). Therefore, once fringes are found to be straight and parallel, the sodium lamp is replaced by a white light source. Moving gradually and very slowly the micrometer screw in one direction or the other, we shall find a rather narrow train of straight fringes, which become more colorful (due to dispersion) as they are further from the center of the ensemble. Now, we have to manage to cover the full field of view with nearly one single color (wavelength) of one of the fringes, which is done by very carefully operating with the displacement of mirror 1 (if we observe that the ensemble of fringes disappears from

the field of view) and the misalignment of mirror 2 (to increase the size of the colorful fringes until accommodating a single color in our field of view). Once this is done, the ZPD configuration has been achieved.

WARNING: Due to the lever, the displacements produced by the micrometer screw attached to mirror 1 are 5 times more sensitive than the read given by the screw. Therefore, any position taken from it should be divided by 5 (e.g., if you measure a displacement of 0.10 mm, the real displacement is 0.10/5 = 0.02 mm = 20 mm).

3.3 Measurement of displacements with white light

Theory

When a white light source illuminates the Michelson interferometer, the intensity (I) of the interference pattern that is observed at the center of the back focal plane (A point in Fig. 1) is

$$I(\lambda, d) = I_1(\lambda) + I_2(\lambda) - 2\sqrt{I_1(\lambda)\, I_2(\lambda)}\cos\left(\frac{4\pi}{\lambda} d\right), \tag{2}$$

with d being the path different between the two "arms" of the interferometer, and $I_1(\lambda)$ and $I_2(\lambda)$ the intensities associated with the waves that have traveled along them. The minus sign of the oscillating term arises from a π phase difference between the two interfering beams, because one of the beams is reflected at the internal face of the beam splitter, while the other does it at the external one.

For non-monochromatic light (e.g., white light), the total intensity at the focal plane is the sum (integral) over the intensities corresponding to each wavelength. As it can be noticed from Eq. (1), for a given, nonvanishing distance d, wavelengths contribute differently. Now, if the spectrum at the point A is examined, i.e., the intensity (2) is represented as a function of the wavelength (or, equivalently, the frequency), it is seen that it is an oscillatory function of the wavelength. The minima of the spectrum lie at those wavelengths that fulfill the relation

$$d = m\frac{\lambda}{2}. \tag{3}$$

Here, m is called the *interferential order*. When this parameter vanishes ($d = 0$), both optical paths coincide and light at A cancels out for all wavelengths [provided $I_1(\lambda) = I_2(\lambda)$; otherwise, the intensity reaches a minimum background value, without displaying any interference]. In any other situation, with $d \neq 0$, there is an oscillating spectrum that can be profitably used to determine small displacements, $\Delta x = d_2 - d_1$, with a high accuracy given the sensitivity of interference, as it is shown with the laboratory experiences here proposed.

Experimental procedure

Once the interferometer is aligned and at the ZPD configuration, the system converging lens + optical fiber is accommodated at the exit of the interferometer. The optical fiber is connected to a digital spectroscope, which in turn is connected to a laptop, so that we can analyze the spectrum at A in Fig. 1 by means of the software **SpectraSuite**, installed in the accompanying laptop. When this program is open, it is possible to observe the spectrum as a function of the wavelength (nm) or the frequency (GHz) (to switch from one to the other, just select **Processing/X-axis Units/Gigahertz**). The spectrum observed is in real time; to analyze it and make measurements, pulse **Pause**, on the upper menu bar. By double-clicking with the mouse left button, there will appear a vertical green line; the wavelength or frequency selected by this line will be on display below the graph. In the case of being in the ZPD configuration, we shall observe an intensity distribution with no interference (it does not vanish, because the partial intensities are different). If you slightly moved back or forth mirror 1 with the micrometer screw, the oscillations would change, becoming more closely packed as mirror 1 moves further away from the ZPD configuration.

3.4 Measurement of the refractive index of thin plates

If a thin glass plate is now inserted into one of the interferometer arms when the device is in the ZPD configuration, **SpectraSuite** shows a highly oscillatory interference figure. The glass refractive index induces an increase of the optical path length in the arm where the plate has been inserted, which leads the interferometer to a displacement from its ZPD configuration even if mirror 1 continues in its position. This is evidence that, in optics, what matter is the optical path length and not that much the Euclidean length (unless the refractive index is the same everywhere).

To recover ZPD conditions, the position of mirror 1 must be conveniently adjusted by displacing the mirror back or forth (depending on the arm where the glass plate has been inserted) until **SpectraSuite** shows again the non-oscillatory figure characterizing the ZPD condition. It can be shown (as it is required in the Questionnaire) that the relationship between the displacement Δx of mirror 1 is related by means of a simple expression with the refractive index n and the thickness of the glass plate t, which reads as

$$\Delta x = (n-1)\,t\,. \tag{4}$$

where n is the refractive index of the medium and t is the thickness of the film.

3.5 Estimation of the spectral width of a LED source

With the interferometer aligned and at the ZPD configuration, replace the white light lamp with the LED source. Our aim is to estimate the spectral width of the LED from its coherence length obtained from its spectrum in the spectroscope. To review the fundamental concepts of coherence, review the file provided for this purpose in the virtual campus.

The measurement of the spectral width Δv by coherence will be made by using the $\Delta\nu = 1/\tau_c = c/L,$ where τ_c is the coherence time and L the coherence length, representing the maximum delay between two copies of the same wave that allows interference to be observed. The coherence length L can be measured by moving mirror 1 from optical contact (the interference maxima and minima begin to be seen) until they cease to be seen, reading the displacement on the screw, which must finally be multiplied by two since the light travels through the arm in both directions.

4. BIBLIOGRAPHY

[1] A. Ghatak, *Optics* (McGraw-Hill, 6th Ed., 2017).

[2] F. L. Pedrotti, L. M. Pedrotti and L. S. Pedrotti, *Introduction to Optics* (Pearson Int'l Edition, 2006).

[3] J. F. James, *An Introduction to Practical Laboratory Optics* (Cambridge University Press, 2014).

QUESTIONNAIRE

- **In this practice, <u>all quantities must be given with their corresponding uncertainties</u>.**
- **For an easier identification of the answers, please, specify in a visible place the number of the question responded (unless you have included explicitly the question).**

Answer before performing any measurement

1. With the white light source, and after having observed a single color at the interferometer exit with the naked eye, determine with a higher accuracy the ZPD condition by observing the corresponding spectrum (substitute your eye by the optical fiber that acts as the detector). Act the micrometer screw until you get the ZPD condition and annotate its value. Comment briefly on the procedure followed.

Measurement of displacements with white light

2. Gently turn the micrometer screw, slightly displacing mirror 1 from the ZPD condition. Cut with your hand the passage of light through one arm of the interferometer, and then proceed the same way with the other. What do you observe? Why? (**Warning:** *Be careful not to touch involuntarily the screws of the mirrors with your hands, arms or sleeves; due to the high sensitivity of the apparatus, it could cause its misalignment*.)

3. Demonstrate that, recasting the argument of the cosine in Eq. (2) in terms of the frequency, interference minima (or maxima) are evenly spaced. (**Warning:** *This demonstration can be brought from home*.)

4. Use the theoretical result found in point 3 to devise an experimental method to determine d from results obtained by the spectrometer working in frequency units with the interferometric method.

5. Use the method devised in point 4 to measure the distance between two positions of the micrometer screw. From the optical contact position move the mirror an exact number of micrometer screw divisions, for example three, which is equivalent to six microns. Using the interferometric method estimate the value of the displacement d and compare it with the direct measurement from the screw.

6. Compare the distance value obtained with the interferometric method (point 5) with the direct measure on the micrometer screw. By inspecting the corresponding errors, determine and discuss which method is more accurate.

Measurement of the refractive index of a thin dielectric plate

To proceed with this part, first make sure that mirror 1 is back again to the ZPD position. Then, insert a thin glass-made plate, with a 150 or 170 μm thickness, in one arm of the interferometer.

7. Taking into account the definition of optical path length, applied to the context of the Michelson interferometer, demonstrate Eq. (4). Note that this result (the sign in it) depends on the arm of the interferometer chosen to insert the plate. (**Warning:** *This demonstration can be brought from home*.)

8. Determine the value for the refractive index of the glass that the plate is made of. Briefly explain the procedure that you have followed.

Spectral width measurement

9. Estimate the spectral width of the LED available in the assembly by measuring the coherence length and with the spectroscope. No error calculation is needed in this part.

Additional Comments

10. If you have observed or thought about something else that has not been previously considered in any of the above points, you can add it here.