Building a Michelson interferometer and measuring Magnetostriction in metals and the refractive index of air

Principle

With the aid of two mirrors in a Michelson arrangement, light is brought to interference. Using this device very small changes in length can be measured and this will be used to measure the magnetostrictive effect, where one of the mirrors is shifted by variation in the magnetic field applied to a sample, and the refractive index of air.

There are three parts to the experiment:

1. To build a Michelson interferometer.
2. To use this to measure the magnetostriction of different metal samples.
3. To measure the refractive index of air.

Theory

If two waves having the same frequency, ω, but different amplitudes and different phases are coincident at one location, they superimpose to

$$Y = a_1 \sin(\omega t - \alpha_1) + a_2 \sin(\omega t - \alpha_2) \qquad (1)$$

The resulting wave can be described by the following:

$$Y = A \sin(\omega t - \alpha) \qquad (2)$$

with the amplitude

$$A^2 = a_1^2 + a_2^2 + 2a_1 a_2 \cos\delta \qquad (3)$$

and the phase difference

$$\delta = \alpha_1 - \alpha_2 \qquad (4)$$

In a Michelson interferometer, the light beam is split into two beams (amplitude splitting) by a half-silvered glass plate (beam splitter), each of these beams is reflected by a mirror, and brought to interference on a screen placed behind the beam splitter (fig. 1). In order to see circular interference fringes, the light beam is expanded between the laser and the glass plate by a lens **L**. If one replaces the real mirror $\mathbf{M_4}$ with its virtual image $\mathbf{M_4'}$,which is formed by reflection by the glass plate, a point **P** of the real light source appears as the points **P'** and **P''** of the virtual light sources $\mathbf{L_1}$ and $\mathbf{L_2}$.

As a consequence of the different light paths traversed, and using the designations in fig. 2, the phase difference is given by:

$$\delta = \frac{2\pi}{\lambda} 2d \cos\theta \qquad (5)$$

λ is the wavelength of the laser light used.

Maxima thus occur when δ is equal to a multiple of 2π, hence

$$2d \cos\theta = m\lambda \quad ; m = 1,2,... \tag{6}$$

i.e. there are circular fringes for selected, fixed values of *m*, and *d*, since θ remains constant (see fig.2).

If one alters the position of the movable mirror $\mathbf{M_3}$ (cf. fig.1) such that *d*, decreases, according to (6), the circular fringe diameter would also diminish since *m* is defined for each ring. Thus, a ring disappears each time *d* is reduced by $\lambda/2$. For $d = 0$ the circular fringe pattern disappears. If the surfaces of mirrors $\mathbf{M_4}$ and $\mathbf{M_3}$ are not parallel in the sense of fig. 2, one obtains curved fringes, which gradually change into straight fringes at $d = 0$.

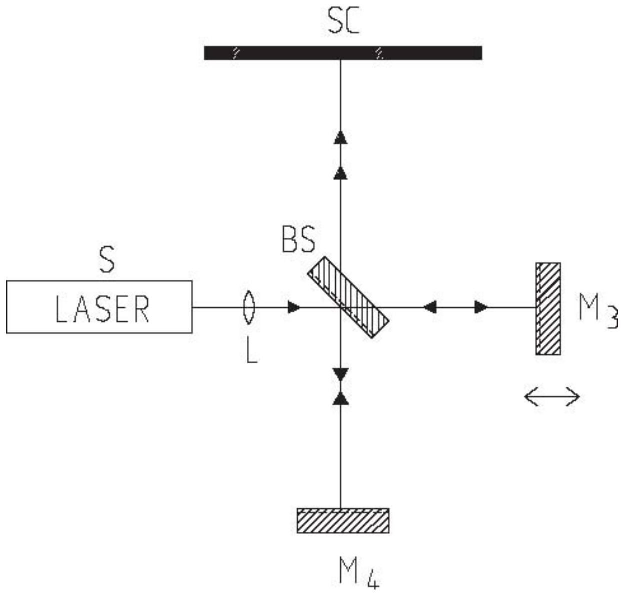

Figure 1. Michelson arrangement for Interference. S represents the light source; SC the screen.

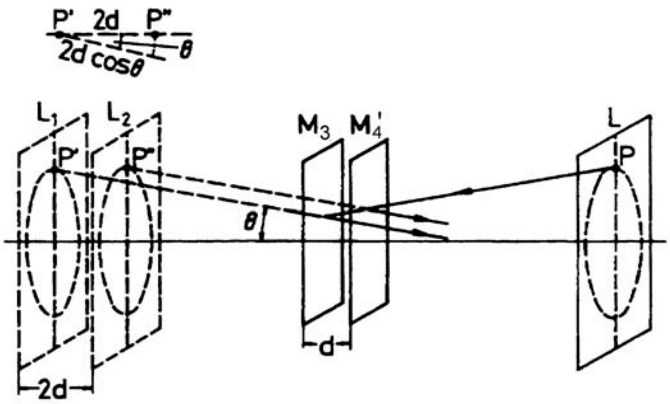

Figure 2. Formation of circular interference fringes.

Part 1 To build a Michelson interferometer

Task

- Construction of a Michelson interferometer using separate optical components.

Set-up and procedure

In the following, the pairs of numbers in brackets refer to the co-ordinates on the optical base plate in accordance with Fig. 3. These co-ordinates are only intended to be a rough guideline for initial adjustment. Do not place all the components in their final position straight away. The interferometer will not work. Follow the instructions below.

- Check that the height of the laser beam is approximately 130 mm.
- The lens **L** [1,7] must not be in position when making the initial adjustments.
- By adjusting the beam path with the adjustable mirrors $\mathbf{M_1}$[1,8] make sure the beam is passing along the 1st x co-ordinate of the base plate.
- Insert mirror $\mathbf{M_2}$[1,4] adjust the beam to be along the 4th y co-ordinate of the base plate.
- Place mirror $\mathbf{M_3}$ onto the appropriate end of the nickel rod and screw it into place.
- Now, insert the nickel sample into the coil in such a manner that approximately the same length extends beyond the coil on both ends so that a uniform magnetisation can be assumed for the measurement. Fix the sample in position with the laterally attached knurled screw.
- Next, insert the coil **C**'s shaft into a magnetic base and place it at position [11,4] such that the mirror's plane is perpendicular to the propagation direction of the laser's beam(see fig. 3) and tighten the screw to hold the rod in position.
- Adjust the beam in a manner such that the beam reflected by mirror $\mathbf{M_3}$ once again coincides with its point of origin on mirror $\mathbf{M_2}$. This can be achieved by coarse shifting of the complete unit of coil with magnetic base or by turning the sample rod with mirror $\mathbf{M_3}$ in the coil and by meticulously aligning mirror $\mathbf{M_2}$[1,4] with the aid of its fine adjustment mechanism.
- Next, position the beam splitter **BS** [6, 4] in such a manner that one beam still reaches mirror $\mathbf{M_3}$ without hindrance and the other beam is passing along the 6th x co-ordinate of the base plate. The metallized side of BS should be facing the final position of the mirror $\mathbf{M_4}$.
- Insert mirror $\mathbf{M_4}$ [6, 1] so that the beam is striking it in the centre and adjust the position of $\mathbf{M_4}$ so that there are two spots on the screen **SC** [6,6].
- Adjust $\mathbf{M_4}$ to make the two spots coincide and a slight flickering of the spot can be seen.
- Positioning lens **L** [1,7] and adjust it until an illuminated area with interference patterns appears on the screen. To obtain concentric circles, meticulously readjust mirror $\mathbf{M_4}$ using the adjustment screws

You will notice that the interferometer is very sensitive and any vibration is sufficient to cause movement of the interference pattern. Therefore do not lean or put objects on the optical bench. If the interference patter is very sensitive to people walking by ask the technicians to check if the optical bench is floating properly. The bench rests on compressed air dampers and sometimes they run out of air and need to be pumped up.

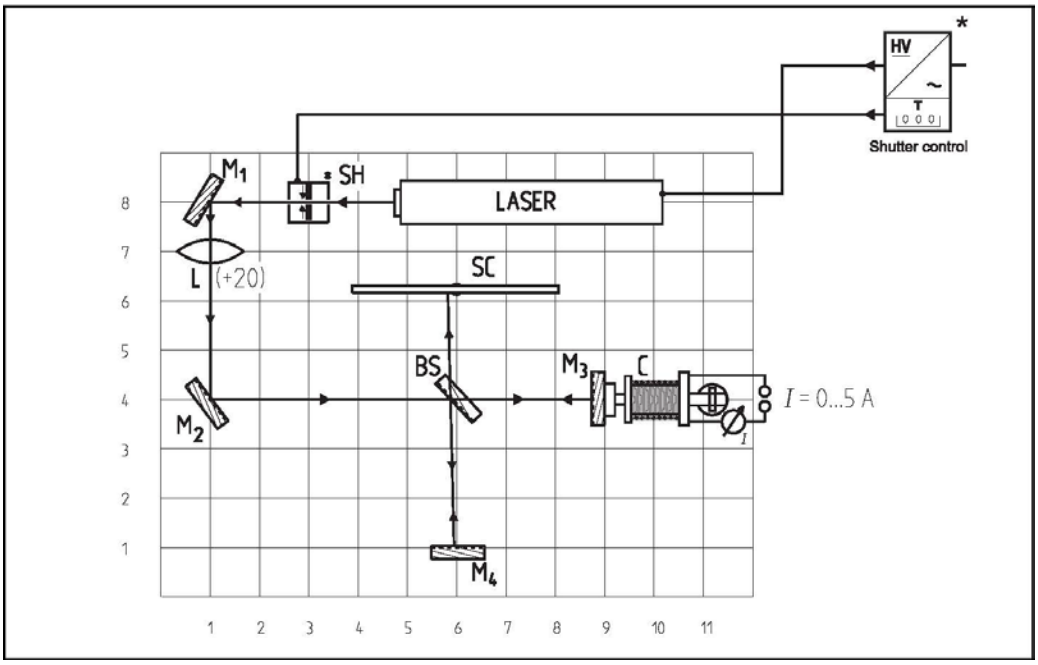

Figure 3. Schematic of the experimental set-up of the Michelson interferometer for the measurement of magnetostriction of different ferromagnetic materials. Note the shutter is not used in this experiment.

Part 2 To measure the magnetostrictive effect on a number of metal samples

Tasks

- Testing various ferromagnetic materials (nickel and iron) as well as a non-ferromagnetic material (copper) with regard to their magnetostrictive properties.

Set-up and procedure

- After connecting the coil to the power supply set the DC-voltage to maximum and DC-current to minimum value. Then slowly adjust the current. For the measurements the resulting currents will be up to ~3 A. Count the changes from maximum to maximum (or minimum to minimum) at a point in the interference pattern. In addition, pay attention to the direction in which the circular interference fringes move (sources or sinks). Repeat measurements will improve the accuracy and help you to estimate the errors.
- Repeat this procedure using different samples and different currents. (Only use currents > 3 A only for a short time as the coil will start to heat up this causes the rod to heat and expand and produces extra changes in the interference pattern).
- Notes: The materials require a certain amount of premagnetisation; therefore, the current should be run up and down several times for each individual determination before performing the intensity change measurement. The blank trial with a copper rod as sample should serve to demonstrate that the longitudinal deformation effect is due to magnetostriction and not to other causes.

Magnetostriction

Ferromagnetic substances undergo so-called magnetic distortions, i.e. they exhibit a lengthening or shortening parallel to the direction of magnetisation. This is the source of the humming noise which is sometime heard from transformers. Such changes are termed positive or negative magnetostriction. The distortions are on the order of $\Delta l/l$ ~10^{-8} to 10^{-4} in size. Due to magnetostriction, which corresponds to a spontaneous distortion of the lattice, a ferromagnet can reduce its total - anisotropic and elastic - energy.

Evaluation of the measuring results

The magnetic field strength of a cylindrical coil is given by:

$$H_m = \frac{NI}{\sqrt{4r^2 + l_S^2}} \qquad (7)$$

where H_m = magnetic field strength at the centre of the coil in Am^{-1}

r = Radius of a winding (here: 0.024 m)

l_S = Length of the coil (here: 0.06 m)

N = Number of windings (here: 1200)

On condition that the field is homogenous, and that the length of the rod, $l >> r$, which are both true in this experiment, the field strength is given by

$$H = \frac{NI}{l} \qquad (8)$$

Here we assume, as a first approximation, that the magnetic field strength H_m acts on the entire length of the rod (l = 0.15 m).

The alteration in length Δl with an applied magnetic field is obtained from the number of circular fringe changes n; the separation per circular fringe is $\lambda/2$ (λ= 632 nm):

$$\Delta l = n\,\lambda/2 \qquad (9)$$

You should see that the change in radius of the interference fringes is different for iron and nickel. This is because the iron rod initially becomes larger with applied field whereas the nickel rod becomes shorter. Whether you see the radii increase or decrease depends on the relative length of the two arms of the interferometer. As mentioned earlier if the two arms are exactly equal you see straight fringes rather than circular. If the arm containing the rod is the shorter of the two then increasing the length of the rod increases this difference and shortening it reduces the difference. However, if the arm containing the rod is the longer then the reverse is true. In copper no alteration in length should be seen. Plot your data and compare it with that presented in figure 4

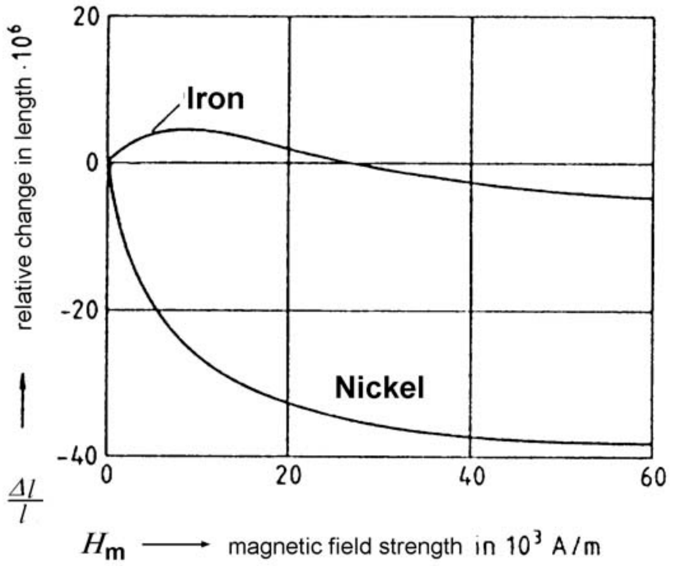

Figure 4. Magnetostriction of different ferromagnetic materials with their relative change in length $\Delta l/l$ plotted against applied magnetic field strength H_m.

Part 3 To measure the refractive index of air

Tasks

- Measure the number of fringe changes as a function of the air pressure in a cuvette and use this to determine the refractive index of air

Set-up and procedure

A measurement cuvette is placed in one of the beam paths of the Michelson interferometer. This cuvette can be evacuated using the hand pump. The refraction index of air is determined through the changes in the interference pattern. The pressure gauge on the pump allows you to measure the pressure in the cuvette.
To determine the refraction index of air, pressure in the cuvette is gradually reduced with the manual pump. During this process, the interference rings move, and alternating darkness and light is observed at the centre. The number, N, of new fringes appearing is plotted against the corresponding values of air pressure. The measurement should be repeated several times, with the cuvette being vented between every measurement series.

Determination of the refraction index of air

The refraction index n of a gas is linearly dependent on pressure, p,

$$n(p) = n(p=0) + \frac{\Delta n}{\Delta p} p \tag{10}$$

Theoretically, if $p = 0$ there is an absolute vacuum and $n = 1$. The change in refractive index with pressure, $\Delta n/\Delta p$, can be determined from the measurement data using,

$$\frac{\Delta n}{\Delta p} = \frac{n(p+\Delta p) - n(p)}{\Delta p} \tag{11}$$

The optical path length, x, is related to the refractive index of the gas

$$x = n(p).s \tag{12}$$

where s is the geometrical length of the evacuated cuvette and $n(p)$ the refractive index of the gas contained in the cuvette. Varying pressure in the cuvette by Δp, the optical wavelength is changed by Δx,

$$\Delta x = n(p + \Delta p).s - n(p).s \tag{13}$$

By starting at ambient pressure, p_0, and decreasing the pressure in the cuvette, one observes N times the restoration of the initial position of the interference pattern up to a given pressure p. A change from minimum to minimum corresponds to a change of the optical path by a wavelength λ. Thus, between pressures p and Δp, the optical path changes by,

$$\Delta x = \{n(p) - n(p + \Delta p)\}\lambda \tag{14}$$

Taking into account the fact that light travels twice through the cuvette, equations (13) and (14) yield,

$$n(p + \Delta p) - n(p) = \{N(p) - N(p + \Delta p)\}.\frac{\lambda}{2s} \tag{15}$$

and using equation (11) one obtains,

$$\frac{\Delta n}{\Delta p} = -\frac{\Delta N}{\Delta p}.\frac{\lambda}{2s} \tag{16}$$

Plot the number of fringe changes against the corresponding pressures, p. The slope of this line will give you $\Delta N/\Delta p$ and using equations (16) and (10) (with s = 10 mm, λ = 632.8 nm and $n(p = 0) = 1$) calculate the refractive index of air and the associated error.

The value found in literature for normal pressure (p = 1013 mbar) at a temperature of 22 °C and for a wavelength of λ = 632.8 nm, is n = 1.000269.