Coherence and width of spectral lines with Michelson interferometer (Item No.: P2220600)

Curricular Relevance

Area of Expertise: ILIAS

Education Level: Physik

Topic: Hochschule

Subtopic: Licht und Optik

Experiment: Beugung und Interferenz

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Difficult	20 Minutes	20 Minutes	2 Students

Additional Requirements:

Experiment Variations:

Keywords:

Fraunhofer and Fresnel diffraction, interference, spatial and time coherence, coherence conditions, coherence length for non punctual light sources, coherence time, spectral lines (shape and half width value), broadening of lines due to Doppler effect and pressure broadening, Michelson interferometer, magnification

Introduction

Overview

The wavelengths and the corresponding lengths of coherence of the green spectral lines of an extreme high pressure Hg vapour lamp are determined by means of a Michelson interferometer. Different double slit combinations are illuminated to verify the coherence conditions of non-punctual light sources. An illuminated auxiliary adjustable slit serves as a non-punctual light source.

Fig. 1: Experimental set-up to determine coherence and wavelength of spectral lines.

Equipment

Position No.	Material	Order No.	Quantity
1	Michelson interferometer	08557-00	1
2	High pressure Hg Lamp, 50 W	08144-00	1
3	Power supply 230 V/ 50 Hz for 50 W-Hg-lamp	13661-97	1
4	Optical bench expert, l = 1000 mm	08282-00	1
5	Object holder, 5x5 cm	08041-00	1
6	Iris diaphragm	08045-00	1
7	Swinging arm	08256-00	1
8	Lens, mounted, f +200 mm	08024-01	1
9	Slide mount for optical bench expert, h = 30 mm	08286-01	5
10	Base for optical bench expert, adjustable	08284-00	2
11	Lens holder	08012-00	3
12	Colour filter, 525 nm	08414-00	1
13	Slit, adjustable.up to 1 mm	11604-07	1
14	Barrel base PHYWE	02006-55	2
15	Lens, mounted, f +20 mm	08018-01	1
16	Stand tube	02060-00	2
17	Measuring magnifier	09831-00	1
18	Diaphragm, 4 double slits	08523-00	1
19	Ground glass screen,50x50x2 mm	08136-01	1
20	Diaphragm holder, attachable	11604-09	2

Tasks

1. Determination of the wavelength of the green Hg spectral line as well as of its coherence length.
2. The values determined in 1. are used to calculate the coherence time and the full width at half maximum value of the spectral line.
3. Verification of the coherence condition for non punctual light sources.

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Set-up and procedure

Fig. 1 shows the experimental set-up to determine coherence and wavelength. The halfopened iris diaphragm, set in a lens support, is situated directly in front of the light exit tube of the Hg-lamp. The lens (f = 20 mm) and the green filter are placed about 30 cm from the iris diaphragm. Both components are placed together in the plug-on diaphragm support. The distance between the carrying plate of the interferometer and the lens is about 16 cm. The ground-glass screen, on which the interference pattern may be observed with the assistance of the f = 200 mm lens, is placed perpendicularly to the direction of the incident light beam.

To start with, the two images observed on the screen should be brought to complete mutual coverage, using the two adjusting screws at the back of one of the mirrors. If the mirror which can be shifted linearly is situated at the position indicated on the interferometer (in this case, the optical paths of the interfering light beams are equal), interference stripes should be observed as a rule. Through careful adjustment of the corresponding screws, the interference pattern is now set to the desired concentric shape.

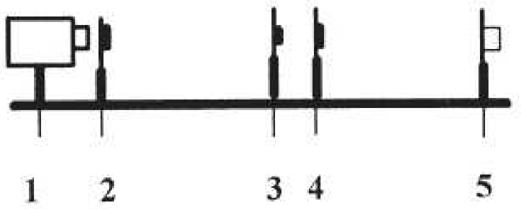

Fig. 2: Schematic illustration of the experimental set-up to verify the coherence condition.

1 = Hg-Lamp (position on the optical bench = 2.5 cm);
2 = Slit S_1 and green filter (11 cm);
3 = double slit (72 cm);
4 = lens f = 200 mm (77.5 cm);
5 = measuring magnifier (97.5 cm)

The verification of coherence conditions requires the experimental set-up to be modified according to the schematic illustration in Fig. 2. Slit S_1, with the adjustable width *a*, is used as a light source of variable size. Together with the green filter, slit S_1 is put on the diaphragm support (2) that in turn is mounted on a lens support and placed directly in front of the Hg-lamp (1).

S_1 is used as a light source of finite extension which illuminates the different double slit combinations (3). The f = 200 mm lens (4) and measurement magnifying glass (5) are used to project the image and observe the corresponding interference patterns. The Hg-lamp and S_1 must be adjusted so that the axis of the conical light beam coincides with the optical axis. Furthermore, it must be made sure that S_1 and the double slit being used are parallel to each other.

It is advantageous to start with double slit g = 0.25 mm / b = 0.1 mm and to increase the width a (0.1 mm scale division) of S_1 in small steps, until the edges of the interference pattern of the double slit no longer are sharp. Proceed in the same way with the other double slits. To avoid troublesome influences, the neighbouring double slits are covered up. A more precise determination of slit width a is obtained by projecting S_1 using the f = 200 mm lens to a distance of a few metres and measuring it. The actual width of the slit can be determined with the image scale.

Theory and evaluation

The following conditions must be fulfilled, so that two waves coming from the same emitting centre will interfere:

1. The two interfering waves must be longer than their path difference up to the point of interference.
2. The phase relation of overlapping waves must be constant during the time of observation.
3. Furthermore, for extended light sources, the coherence condition (Verdet's condition) must be fulfilled.

The duration of an elementary light emission (transition time from an excited atomic state to the basic state) is approximately 10^{-8} s. Taking into account the propagation velocity of light, the length of the emitted wave corresponding to this time is about 300 cm.

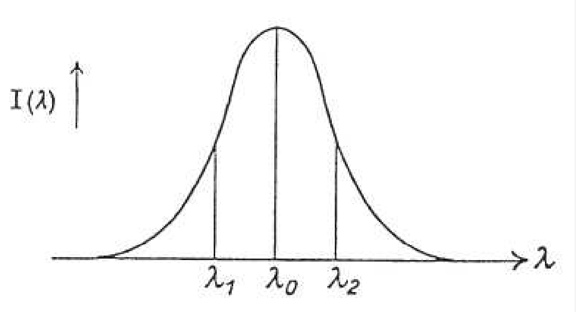

Fig. 3: Intensity distribution of a spectral line.

If the light emitted during an elementary process is split into two partial beams, and if one of these is reflected so that the directions of the two partial beams cross each other, interference can only be observed at the crossing point if the difference of paths L of both waves is smaller than the length of the wave. L is called coherence length. However, every spectral line consists of a spectral distribution with a central wavelength (λ_0, as shown in Fig. 3). The full width between the points with intensities half as much as the maximum value $\Delta\lambda = \lambda_2 - \lambda_1$ is called the width of the line. Using these magnitudes, the coherence length is found to be

$$L = \frac{\lambda_1 \lambda_0}{2(\lambda_0 - \lambda_1)} \approx \frac{\lambda^2{}_0}{\Delta\lambda} \quad (1)$$

and for the corresponding coherence time τ one thus finds

$$\tau = \frac{L}{c} = \frac{1}{c}\frac{{\lambda_0}^2}{\Delta\lambda} \quad (2)$$

If both the coherence length L and the wavelength centre λ_0 are known, the line width $\Delta\lambda$ can be calculated according to (1) and the corresponding coherence time τ according to (2).
For spectral lines in the visible spectrum, the line width obtained for L = 300 cm is $\Delta\lambda \approx 10^{-14}$ m. However, this value cannot be obtained with conventional spectral lamps. A considerable broadening of the lines results from the Doppler effect, which is caused by the random movement of the emitting atoms. This broadening grows linearly with the translation velocity of the atoms. So-called pressure broadening has a yet stronger effect if the time between two atomic collisions is shorter than the time of emission. This collision time decreases when gas density and temperature increase. Under normal conditions, the line width due to pressure broadening is approximately $\Delta\lambda = 10^{-10}$ m.
Fig. 4 is a schematic representation of the interferometer set-up according to Michelson, which allows to determine both the wavelength of used light and the corresponding coherence length.

The beam emitted by the light source is divided into two half beams which have the same intensity each, by a semi-transparent mirror S_3 set up at an angle of 45° against the direction of the incident beam. The partial beams impinge on a fixed mirror S_1 and onto a mirror S_2 which can be shifted perpendicularly to S_1 . After being reflected by these mirrors, the partial beams are reunited. A concentric ring interference pattern is observed on a screen, the centre of which is dark or clear, depending on the path difference of the partial beams and the resulting phase shifts. If the centre of the interference pattern is dark, the path difference between the partial beams is an uneven multiple of $\lambda/2$.

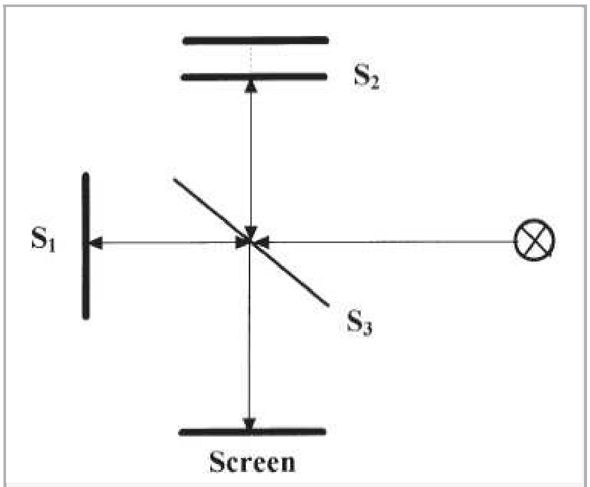

Fig. 4: Beam path in Michelson's interferometer.

Shifting the mirror S_2 by a distance D and observing the aberration of n dark zones, the wavelength is obtained from the following equation:

$$\lambda = \frac{2D}{n} \text{ (light travels twice over path } D\text{)} \qquad (3)$$

Using the green Hg-line, one finds a mirror displacement of D = 27 scale marks (= 27 µm) as an average value obtained over several measurements. According to (3), the wavelength obtained from these values is:
λ = 540 nm (literature value: λ (Hg-green) = 546 nm).

To determine coherence length L , a shift value of the mirror of D = 145 µm, obtained as an average value from several measurements, causes complete extinction of the interference stripes.

Together with the previously determined wavelength, and with $2D = L$, this yields a line width of $\Delta\lambda \approx 1 \cdot 10^{-9}$ m. The operating values of the extreme high pressure Hg-vapour lamp (p ≈30 bar, T ≈approx. 700 °C), are significantly higher than those for normal conditions, so that line broadening can be attributed to so-called pressure broadening. If one tries to determine the coherence length immediately after switching on the cold Hg-lamp, when both operating pressure and temperature are still low, on finds that the maximum possible shift of the adjustable mirror is not sufficient to cause the extinction of the interference rings. This means that the influence of pressure broadening is smaller, and thus, that coherence length is greater, which means that the spectral lines have become sharper.

When using non punctual light sources, interference can only be observed when the following spatial coherence condition

$$2a \sin\frac{\epsilon}{2} < \lambda; 2a \tan\frac{\epsilon}{2} = 2a\frac{\frac{1}{2}(g+d)}{L} < \lambda) \qquad (4)$$

is fulfilled (Fig. 5).

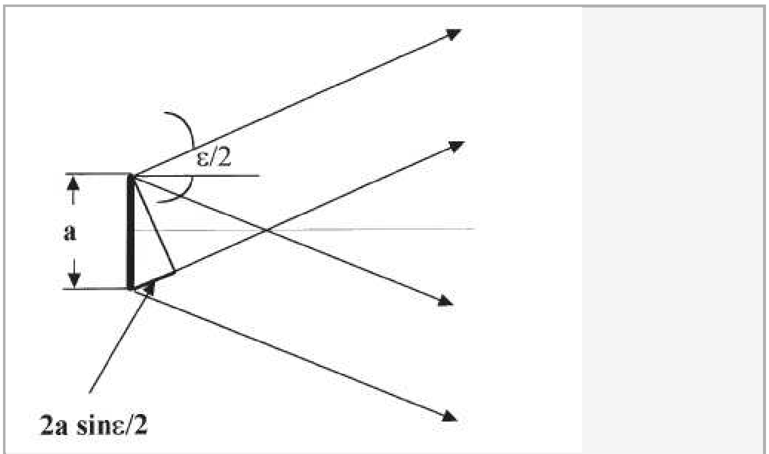

Fig. 5: Path difference between the edge beams of a non punctual light source.

(λ = wavelength; a = extension of the light source; ε = angle of aperture of the conical light beam used to generate interference; g = distances between the slit centres of the double slit; d = slit width of the double slit; L = distance between light source and double slit).

Table 1 gives the values of slit widths a determined experimentally for different double slit systems (with L ≈ 60 cm), for which the corresponding interference patterns loose their contrast. In this case, the coherence condition is no longer fulfilled.

Table 1:

g	b	a	$2a$ 1/2$(g+b)$
1.0 mm	0.1 mm	0.18 mm	330 nm < λ = 546 nm
0.5 mm	0.1 mm	0.35 mm	350 nm < λ = 546 nm
0.25 mm	0.1 mm	0.60 mm	350 nm < λ = 546 nm