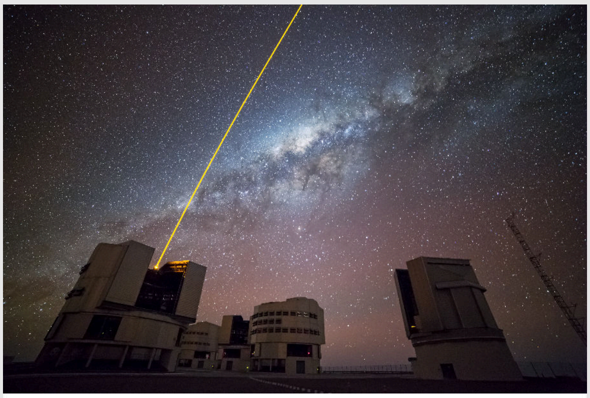
Coherence and width of spectral lines with the Michelson interferometer

Physics | Light & Optics | Diffraction & interference

Difficulty level	Group size	Preparation time	Execution time
-	-	-	-

General information

Application



The VLT's (Very Large Telescope) laser guided star

Light coherence plays an important part in modern optics. In fact, a laser differs from other light sources because of its coherence, which is very important in applications such as holography, modal analysis, optical communications, and so on.

The phenomenon of light coherence is both space and time dependent. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting. Temporal coherence allows them to emit light with a very narrow spectrum. It is intimately related to interferometry and usually measured by means of a Michelson interferometer, which is an interferential device based on the division of light amplitude.

Robert-Bosch-Breite 10
37079 Göttingen
Tel.: 0551 604 - 0
Fax: 0551 604 - 107
info@phywe.de
www.phywe.de

Other information (1/2)

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Prior knowledge

In Michelson interferometer, a coherent light beam is split into two beams of equal intensity, that travel in different optical paths, which are then recombined to produce interference.

Scientific principle

1. Spatial coherence refers to the phase difference between two points in a wavefront of an electromagnetic field remains constant with time.
2. Temporal coherence occurs when the phase difference between two time instants at a given point remains constant with time.

Other information (2/2)

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Learning objective

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.

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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37079 Göttingen

Tel.: 0551 604 - 0
Fax: 0551 604 - 107

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Safety instructions

- The common rules of safe experimentation in scientific education apply in this experiment.
- Handle the optics with care and gently

Theory (1/8)

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.

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Fax: 0551 604 - 107
info@phywe.de
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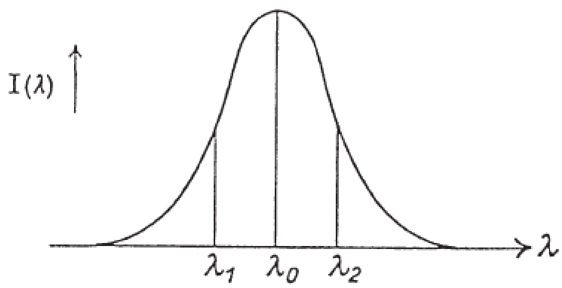
Theory (2/8)

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 of both waves is smaller than the length of the wave *L*, which is called coherence length.

However, every spectral line consists of a spectral distribution with a central wavelength λ_0. 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.



Intensity distribution of a spectral line

Theory (3/8)

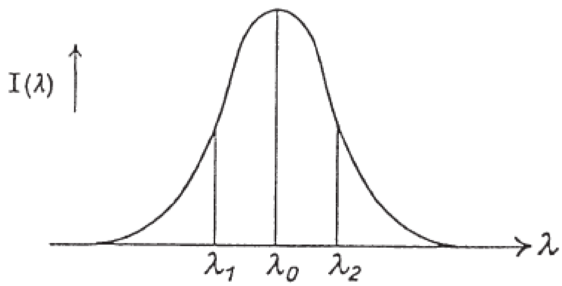
Using these magnitudes, the coherence length is found to be

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

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).



Intensity distribution of a spectral line

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Theory (4/8)

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.

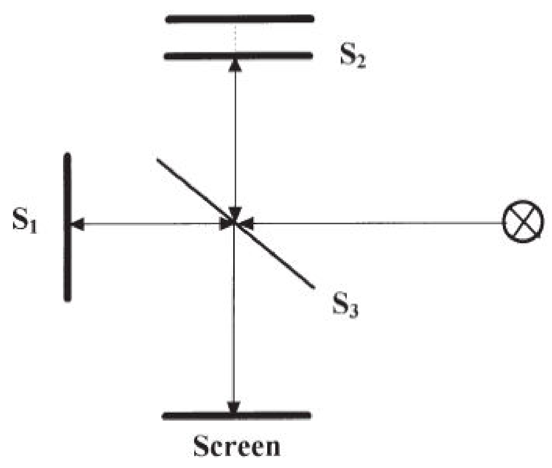
Under normal conditions, the line width due to pressure broadening is approximately $\Delta\lambda \approx 10^{-10}\ m$.

Theory (5/8)

The beam emitted by the light source is divided into two half beams which have the same intensity each, by a semi-transparent mirror S3 set up at an angle of 45° against the direction of the incident beam.

The partial beams impinge on a fixed mirror S1 and onto a mirror S2 which can be shifted perpendicularly to S1 . 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.



Beam path in Michelson's interferometer

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37079 Göttingen
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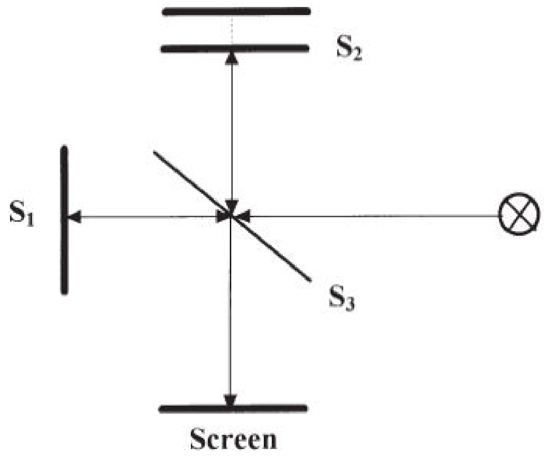
Theory (6/8)

If the centre of the interference pattern is dark, the path difference between the partial beams is an uneven multiple of $\lambda/2$.

Shifting the mirror S2 by a distance *D* and observing the aberration of *n* dark zones, the wavelength is obtained from the following equation:

$$\lambda = \frac{2D}{n} \qquad (3)$$

(2D: light travels twice over path *D*)



Beam path in Michelson's interferometer

Theory (7/8)

The coherence length *L* is determined with a shift value of the mirror of 2D = L, whereby the distance *D* causes complete extinction of the interference stripes. Together with the previously determined wavelength, this yields a line width of $\Delta\lambda$.

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.

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Theory (8/8)

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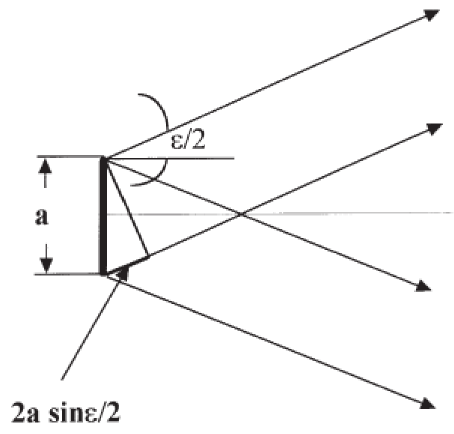
When using non punctual light sources, interference can only be observed when the following spatial coherence condition

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

is fulfilled.

(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).



Path difference between the edge beams of a non punctual light source

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Equipment

Position	Material	Item No.	Quantity
1	Michelson interferometer	08557-00	1
2	High pressure Hg Lamp, 50 W	08144-00	1
3	PHYWE 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	Base for optical bench expert, adjustable	08284-00	2
6	Slide mount for optical bench expert, h = 80 mm	08286-02	5
7	Lens holder	08012-00	3
8	Universal Holder, rotational	08040-02	2
9	Barrel base expert	02004-00	2
10	Lens, mounted, f +20 mm	08018-01	1
11	Lens, mounted, f +200 mm	08024-01	1
12	Iris diaphragm	08045-00	1
13	Colour filter, light green, 480...570 nm, 45% @ 525 nm	08414-00	1
14	Ground glass screen,50x50x2 mm	08136-01	1
15	Diaphragm holder, attachable	11604-09	1
16	Measuring magnifier	09831-00	1
17	Slit, width adjustable up to 1 mm	11604-07	1
18	Diaphragm, 4 double slits	08523-00	1
19	Stand tube	02060-00	2

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Setup and procedure

Setup (1/5)

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Using the Hg lamp

Darken the room as much as possible when performing the experiments.

Avoid touching optical lenses and mirrors, especially on the Michelson interferometer, to reduce errors in the results.

Ensure the Hg lamp is connected to the power supply before switching on, and wait several minutes for the lamp to warm up before carrying out the experiments. The lamp may be adjusted vertically and horizontally with the adjusting knobs on the back of the lamp if needed.

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Setup (2/5)

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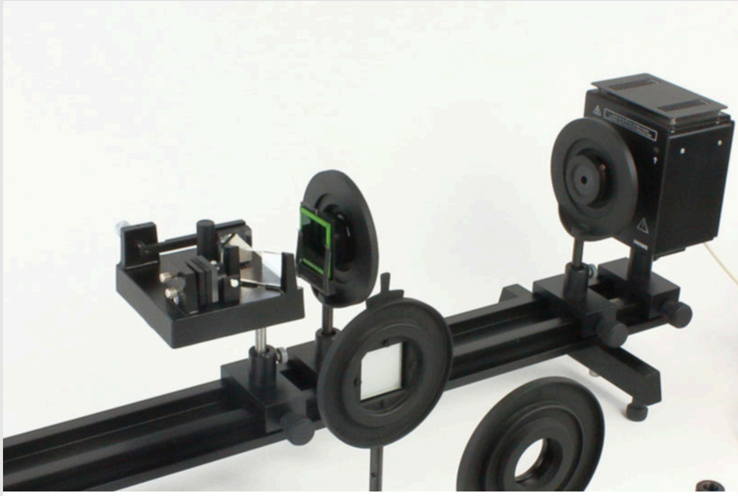

Placing lens and filter

Determination of coherence and wavelength

The half-opened 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 attachable diaphragm holder and mounted on a lens holder.

Setup (3/5)

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Determination of coherence and wavelength

The last component on the optical bench is the Michelson interferometer. The ground glass screen on an object holder is placed perpendicularly to the direction of the incident light beam from the Michelson interferometer.

The interference pattern may be observed on the screen with the assistance of the f = 200 mm lens on a lens holder.

These two components offset the optical bench are each placed on a support rod stablalized with a barrel base expert.

Material	Position (cm)
Hg Lamp	3.5
Iris diaphragm	12
Lens, f + 20mm and green filter	41
Michelson interferometer	47
Ground glass screen	perpendicular
Lens, f + 200 mm	perpendicular

Positions on the optical bench to determine coherence and wavelength of spectral lines

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Setup(4/5)

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Verification of the coherence condition

The verification of coherence conditions requires the experimental set-up to be modified according to the figure.

A slit with the adjustable width *a* is used as a light source of variable size. Together with the green filter, the slit is put on the attachable diaphragm holder that in turn is mounted on a lens holder (without any lens attached) and placed directly in front of the Hg-lamp.

Experimental set-up to verify the coherence condition

Setup (5/5)

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Verification of the coherence condition

S_1 is used as a light source of finite extension which illuminates the different double slit combinations on the object holder. The *f* = 200 mm lens on a lens holder and measurement magnifying glass on an object holder are used to project the image and observe the corresponding interference patterns.

The Hg-lamp and must be adjusted so that the axis of the conical light beam coincides with the optical axis. Furthermore, it must be made sure that and the double slit being used are parallel to each other.

Material	Position (cm)
Hg Lamp	2.5
Slit S_1 and green filter	11
Double slit	71
Lens, f = +20mm	76.5
Measuring magnifier	97.5

Positions on the optical bench to verify the coherence condition

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Procedure (1/2)

Determination of coherence and wavelength

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 side of 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.

Experimental set-up to determine coherence and wavelength of spectral lines

Procedure (2/2)

Verification of the coherence condition

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 S1 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 S1 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.

Experimental set-up to verify the coherence condition

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Evaluation (1/4)

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No.	n	D / μm
1		
2		
3		

$\overline{D}$ = ________________

$\overline{\lambda}$ = ________________

Determination of coherence length

$\overline{D}$ = ________________

$L = 2D$ = ________________

$\Delta\lambda$ = ________________

Determination of coherence and wavelength

Using the green Hg-line, one finds a mirror displacement of D as an average value obtained over several measurements. The wavelength is obtained according to (3). (Literature value: λ(Hg-green) = 546 nm).

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

Evaluation (2/4)

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g/mm	d/mm	a/mm	$2a\frac{\frac{1}{2}(g+d)}{L}/nm$
1.0	0.1		
0.5	0.1		
0.25	0.1		

$\overline{2a\frac{\frac{1}{2}(g+d)}{L}}$ = ________________

Verification of the coherence condition

The light coherence is verified according to (4). The values of slit widths a is determined experimentally for different double slit systems with $L \approx 60$ cm, for which the corresponding interference patterns lose their contrast.

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Evaluation (3/4)

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Describe the properties of light coherence:

The light coherence is both time and ______ dependent. The temporal coherence defines the time over which the ______ is stable and for which the phase is known at any point along the wave train. The ______ coherence gives a measure of the allowed path difference between two coherent sources and still ______. For (non-existent) ideal perfect coherence, the spatial and temporal coherence would be ______.

- interfere
- frequency
- distance
- spatial
- infinite

Check

Evaluation (4/4)

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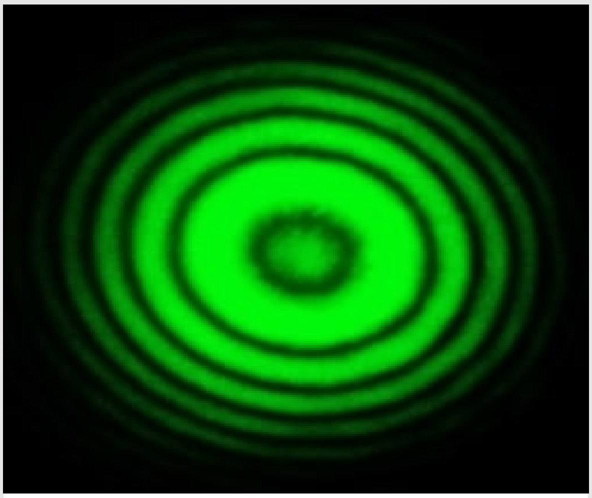
The interference fringes can be observed, if

- [ ] The relative phase of the light waves is fixed
- [ ] The spatial coherence is infinite
- [ ] The path difference is smaller than the spatial coherence

Check



Interference rings using Michelson Intererometer

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Slide	Score / Total
Slide 25: Properties of light coherence	**0/5**
Slide 26: Interference fringes	**0/2**

Total Score 0/7

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