3B SCIENTIFIC® PHYSICS

Mach-Zehnder Interferometer 1014617

Instruction manual

07/15 ALF

1. Safety instructions

The interferometer is intended for use with a class 2 He-Ne laser. Looking directly at the beam can cause burning of the retina and should be avoided at all costs.

- The safety instructions supplied with the laser must be strictly obeyed at all times.

The beam splitter labelled (4) not only reflects laser light onto the two mirrors (9), but also downwards (as set up in Fig. 1). In addition, in some experiment set-ups, a laser beam can also emerge from the second beam splitter propagating beyond the perimeter of the base plate.

- To protect those conducting experiments, opaque screens should be set up around the equipment if local conditions so dictate.
- The interferometer should be set up on a stable table or any other suitable location, where it cannot fall and cause injuries to people due to its weight.

The lifting nubs (6) allow the interferometer to be lifted so that a good grip can be obtained under the base plate.

The maximum permissible pressure in the vacuum cell (11) is 200 kPa (2 bars), corresponding to 100 kPa (1 bar) over atmospheric pressure.

- Should the glass of the cell become damaged, e.g. in the form of scratches or cracks, the vacuum cell is to be taken out of use immediately and sent for repair.
- In experiments using pressure in excess of atmospheric pressure, care should be taken to ensure that no one enters the area which could be affected by explosion of the cell. Protective goggles should be worn if necessary.

2. Equipment supplied

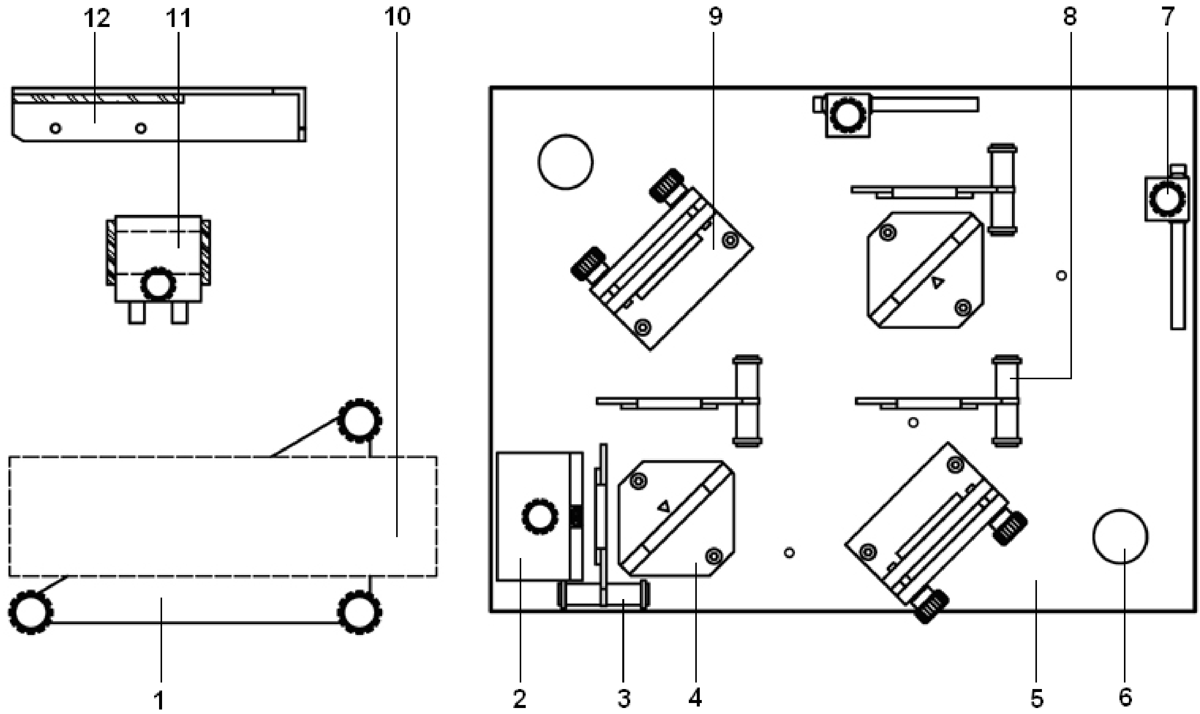

Fig. 1 Equipment supplied and other components which might be needed

1 Laser support
2 Diverging lens
3 Polarisation filter, film (2x)
4 Beam splitter (2x)
5 Base plate
6 Lifting nub
7 Screen (2x)
8 Polarisation filter, glass (2x)
9 Adjustable mirror surface (2x)
10 Laser (not included)
11 Vacuum cell (included in supplementary set 1002652)
12 Glass plate on holder (included in supplementary set 1002652)

Not illustrated:
13 Rugged plastic holder
14 Hex screwdriver
15 Adjustment tool for beam splitters
16 Instruction manual

3. Description

The Mach-Zehnder interferometer is a development of a Jamin interferometer. It was introduced by Ludwig Zehnder in 1891 and was also developed at roughly the same time by Ludwig Mach, although his first mention of it was not until 1892.

Incident light is separated by a beam splitter into two separate beams, which travel via two different routes until they reach a second beam splitter, where there are superimposed again. Due to the differing lengths of the optical paths taken by the two beams, interference then occurs (constructive or destructive interference).

If the wavelength of the light is known, the interferometer can be used to measure very short distances, which is important for the measurement of surface quality in optical instruments, for example.

The following experiments are among those which can be carried out using the Mach-Zehnder interferometer:

1. Investigation of changes in polarisation direction at the beam splitter and mirror surface

2. Surface quality of optical components (qualitative rather than quantitative comparison) *

3. Determining the refractive index of air **

4. Experiments to demonstrate analogies with the quantum eraser effect (the experiments are only analogous as they do not work with individual photons.)

5. Interference with white light ***

* Requires accessory set for the interferometer (1002652)

** Requires accessory set for the interferometer (1002652) and vacuum hand pump (1012856)

*** Requires optical lamp with pinhole aperture (1017284)

Thanks to the pre-defined positions of the components, it is possible to convert the apparatus for use in the various experiments quickly and easily.

The Mach-Zehnder interferometer equipment set consists of two beam splitters, two mirror surfaces, two observation screens and four polarisation filters. The high-quality optical instruments set up on a heavy and rigid base plate guarantee that measurements are precise and reproducible. The large optical components make it possible to produce clear and well-focussed interference patterns, which can even be viewed in daylight, as the two reflective screens can be adjusted in their inclination, thus ensuring that preparation time for the experiments is kept extremely brief.

Includes a rugged plastic box for storing the interferometer in assembled and configured form, along with the support for the laser.

4. Technical data

Beam splitters:	
Diameter:	40 mm
Planarity:	λ/10 (front), λ/4 (rear)
Mirror surface:	
Dimensions:	40 x 40 mm
Planarity:	<λ/2
Polarisation filter:	
Diameter:	30 mm
Adjustment range:	±105°
Material:	Glass (2x), film (2x)
Angle scale:	3°, 15°
Base plate:	
Weight:	5.5 kg
Dimensions:	245 x 330 x 25 mm

5. Operation

5.1 Laser set-up

- Set up the laser on the laser support.

The laser support is designed for various different lasers. It has three bores for countersunk bolts (M5 or M6) of which only one will be needed in most cases. The correct hole to use for the laser in question depends on its centre of gravity and the options for attaching it. After mounting, the centre of gravity of the laser should be roughly above the centre hole.

The height above the base plate required for the light beam is 60-62 mm. If the adjustment range of the knurled screw is insufficient to achieve this, a suitable spacer washer or similar component should be fitted underneath the laser.

The length of the fastening bolt should be selected such that it does not damage the laser's housing or internal components.

- To make sure of this, it is logical to determine the maximum depth to which a bolt can be tightened into the laser fastening hole. Then a bolt can be selected which has a thread about 2 mm shorter than that (a bolt and a square nut are supplied which should be suitable for commonplace fittings).

5.2 Beam splitters

The glass of the beam splitter is treated on one side to reduce reflections, whereas the other side has a coating allowing 50% of light to pass through it. This side is indicated by a triangle, which is also shown on the experiment set-up drawings.

5.3 Assembly, basic configuration

The way the components are set up on the base plate is illustrated in Fig. 1. The following set-up description assumes that all the basic settings need to be configured.

- 1. Loosely screw down the beam splitters (note ∇). Place the adjustment tool on top and screw it in place (cf. Fig. 2). It should now be possible to move the mirrors together for a minimal distance on the base plate. When screwing the mirrors down properly, check that no gap arises between the mirror holders and the adjustment tool. Remove the tool when you are ready.

Fig. 2 Assembly tool for beam splitters

- 2. Set the gap between both mirror surfaces and the back walls behind them to 4 mm all the way round (see Fig. 3).
- One aid to setting up the gap would be to use two 10 euro cent coins. First screw the mirrors loosely onto the base plate. When fastening them tightly, push the mirrors outwards to make sure that the play in the bore holes does not cause the mirrors to become inclined with respect to the beam splitters.

Fig. 3 Basic setting for mirror surfaces

- 3. Fit the screens.
- 4. Screw the lens loosely into place and align it parallel with the base plate.
- 5. Turn on the laser and align it with the lens in such a way that a spot of light appears roughly in the middle of both screens.
- 6. Turn the lens anti-clockwise by about 90° so that it is out of the beam.

On the screens it should now be possible to see two bright spots and other less bright ones (if by chance you have achieved an optimum set-up already, only one bright spot will be visible).

- Turn the knurled screws for each of the mirrors until the bright spots coincide.

When they coincide properly, there may also be some flicker (interference) visible.

- Turn the lens back into the beam.

With luck, interference bands will already be visible. If not, then carry out a scanning procedure as follows:

- Turn the knurled screw at the bottom of one mirror slowly by about +90°, then turn it back. This time turn it slowly by -90° and then back to 0°.
- If no interference bands at all appear after doing this, then turn the top knurled screw by a maximum of +30° (= distance between two notches of the knurled screw) and then slowly turn the bottom screw again by ±90°. Repeat this action with the top screw turned by -30°, +60° and -60°. The scanning procedure can be halted as soon as interference bands do appear. If they still remain absent, start the assembly of the beam splitters again from the beginning.
- Once the interference bands have appeared, adjust the knurled screws <u>very slowly</u>. This should make the bands increase in thickness until they finally reach to the centre of the interference pattern.

Since this procedure results in beam paths of very nearly the same length, the centre of the interference pattern takes the form of a large bright or dark spot. IT may be observed that patterns on the two screens are mutually complementary.

7. To obtain an interference pattern with “nice looking” rings, the beam paths need to be different in length.

- To achieve this, screw in the three bolts of the back mirror surface by about one and a half turns (to make the path longer) and screw out the three bolts for the front mirror by one and a half turns as well (making the path shorter).
- 8. Turn the diverging lens out of the beam.

Interference now occurs, not when the bright spots coincide, but when they are about 6 - 7 mm apart, whereby the spot from the front mirror appears on the left-hand side of the rear screen (on the right-hand screen it is at the right).

- To find the interference pattern, carry out the scanning procedure described under step 6.

This completes the basic configuration.

Alternative 1: The lengths of the optical paths can also be changed by inserting a vacuum cell into one path (positioned as in Fig. 7). Steps 7 and 8 of the above configuration instructions can then be omitted.

Alternative 2: Once steps 1 to 5 of the configuration instructions have been completed, the diverging lens can also be set up at the exit point of the light. This may mean adjusting the laser slightly until one or two light spots appear on the right-hand screen. The spots can be caused to interfere by slightly adjusting the knurled screws of the mirror surfaces. With this set-up, however, there is no need to try and obtain a ring pattern

Fig. 4 Alternative 2

5.4 Cleaning optical components

- The mirror surfaces, the beam splitters, the glass polarisation filter, the diverging lens and the panes of the vacuum cell should be carefully wiped clean using a soft cloth soaked in ethanol (white spirit).
- Do not apply pressure when rubbing with the cloth. It is better to use a lot of ethanol but little force.
- The glass plate on the holder (12) should only be wiped clean with a dry cloth (you can gently breathe on it if you like), as otherwise the strip of adhesive film may become unstuck.
- The foil polarisation filters should only be cleaned by blowing on them.

6. Example experiments

6.1 Polarisation experiments

These preliminary experiments may be omitted, but they are useful for interpreting unexpected effects in your own interference experiments using polarisation filters.

Polarisation of the laser used in the experiments

If a laser with a specified polarisation direction (usually horizontal or vertical) is used, the polarisation situation is obvious. Quite often, though, the polarisation direction is specified to be “random”, i.e. not uniquely definable. A distinction should be made between the following circumstances:

1. The laser has only one polarisation direction but it was not taken into account when the laser was set up (diode lasers always have only one plane of polarisation).

2. The laser has two polarisation planes (normally these would be orthogonal to each other) but the two are not radiated with the same constant intensity over a period of time.

3. The laser has more than two polarisation planes. However, this only tends to occur with lasers which have very long tubes and such lasers do not fall into laser class 2.

The direction of polarisation of the laser being used can easily be determined using one of the two glass polarisation filters. Compare with the experiment set-up shown in Fig. 7 but omitting the glass plate and using only one glass filter. What you need to determine is the angle at which the laser light experiences the maximum amount of attenuation. The polarisation plane will then be at 90° to this angle.

Recommended lasers are either an He-Ne laser or a stabilised diode laser, since simple laser diodes emit slightly different wavelengths depending on the temperature and temperature fluctuations may cause multiple wavelengths to be emitted simultaneously. This may mean that no obvious interference pattern becomes visible (tip: warming up the diode by holding it in your hand may help).

Polarisation of light due to reflection by beam splitter

- Set up an experiment as shown in Fig. 5.
- Set up the two glass filters at positions 1 and 2 and place the diverging lens at position 4. In this case the lens is only used to interrupt the beam.

- Set the angle of the beam incident on the first polarisation filter to an angle α.
- Now turn the polarisation filter behind the beam splitter around until the spots on the screen are at their minimum brightness. Make a note of corresponding angle γ.

The main polarisation angle β for the reflected light is at an angle of 90° to γ.

The following table summarises some typical results

Polarisation angle α at entry	Polarisation angle γ at exit in darkness	Polarisation angle β at exit = γ - 90°
0°	90°	0°
15°	81°	-9°
30°	69°	-21°
45°	57°	-33°
60°	39°	-51°
75°	18°	-72°
90°	0°	-90°

Polarisation of light passing through the beam splitters

- The two glass beam splitters should now be placed at positions 1 and 3 as marked in Fig. 5, with the diverging lens at position 2 in order to interrupt the upper beam.

Polarisation of light after reflection by mirror

- For this experiment the two glass beam splitters should be set up at positions 3 and 4. The diverging lens should remain at position 2.

Fig. 6 summarises the results of the three experiments. It can be seen that reflection causes the horizontal component to be mirrored whereas the vertical component remains the same. The curvature of the two beam splitter curves indicates a slight degree of optical activity.

Double refraction by transparent sticky tape

One interesting experiment on double refraction can be carried out if the “Glass plate on holder“ from the supplementary equipment set is available. The relevant experiment set-up can be found in Fig. 7.

- Set the two polarisation filters to angles of 45° and -45°, so that in the absence of a glass practically no light can be seen on the observation screen.

If a glass plate with sticky tape on it is now placed in the beam, a spot of light will then appear on the screen. With a combination of 90° for the first beam splitter and 0° for the second, the screen still remains in the dark even if there is sticky tape in the path (i.e. a combination of angles perpendicular to one another, along with about ±10° due to the tolerance of the sticky tape).

The double refraction at the sticky tape comes about in the following way. During the manufacturing process, the backing material is heavily stretched in one direction, meaning that the carbon polymer chains from which it is made are also extended and aligned in that direction. This means that the refractive index differs depending on whether the electrical vector of the light wave oscillates in a direction parallel or perpendicular to the alignment of the extension.

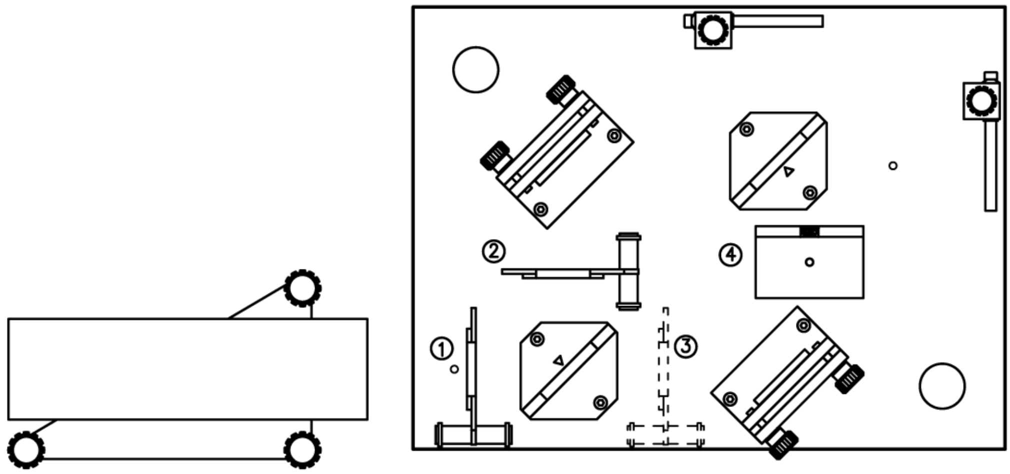

Fig. 5 Experiment set-up for investigations into polarisation. The purpose of the diverging lens here is simply to interrupt the path of one of the light beams.

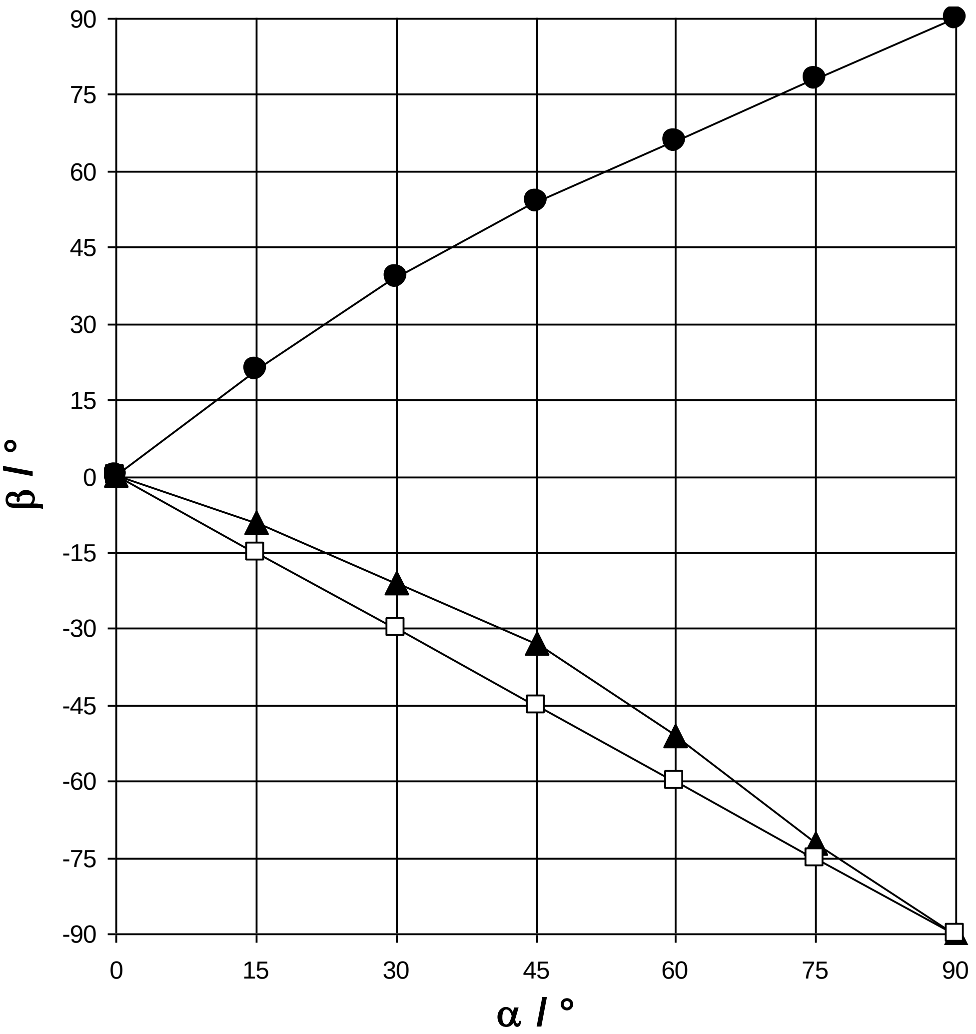

Fig. 6 Results of polarisation experiment. Filled in circles = route straight through beam splitter, triangles = reflections from beam splitter, unfilled squares = reflection from mirror surface

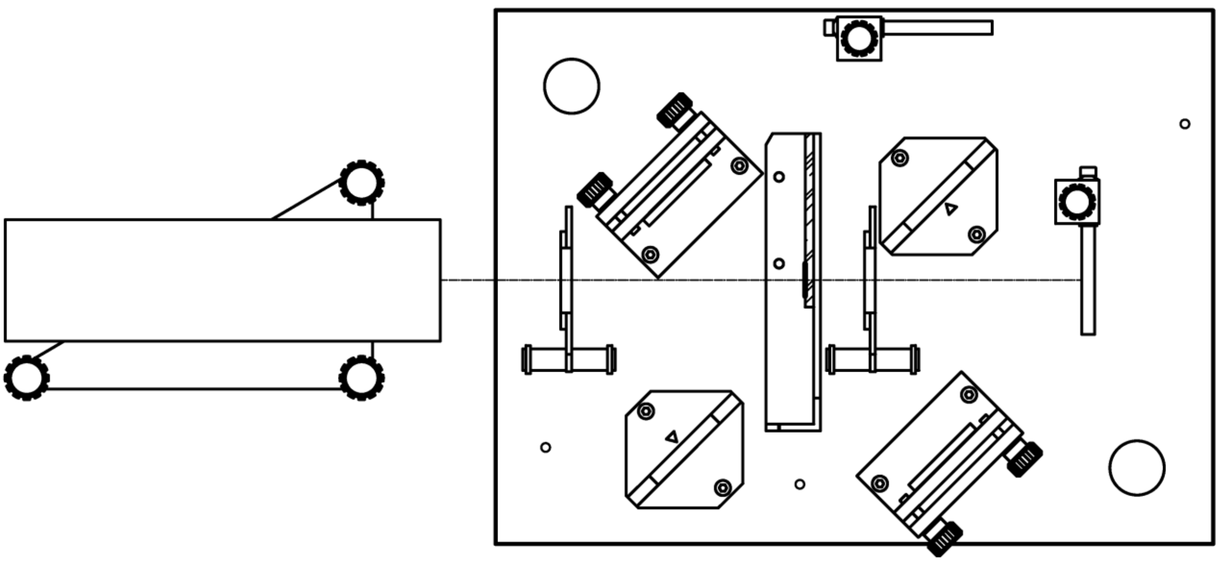

Fig. 7 Experiment set-up for investigating double refraction from transparent sticky tape

6.2 Surface quality of optical components

This experiment allows for a qualitative evaluation of the surface quality of optical instruments. Normally, such measurements are made using a Twyman-Green interferometer, where the (laser) beam is made wider but kept parallel. To understand the principle in a qualitative way, however, it is possible to use a widened beam which is not necessarily parallel.

Some transparent sticky tape may be used as an example of an optically poor surface. It should be stuck to a glass plate in such a way that it looks uniformly transparent when seen normally by the human eye.

- Set up the experiment as shown in Fig. 8.
- Once the basic configuration has been made as in section 5 and interference rings can be seen in the middle of both screens, the glass plate on its holder can be slotted into the right-hand beam.

When the sticky tape enters the beam, the interference beams will become fringed, while bright spots may appear in some of the dark sections of the pattern and vice versa. This is caused by the uneven, bumpy surface of the sticky tape. Even small changes in the thickness of the adhesive coat can become apparent in the form of shifts in the interference rings.

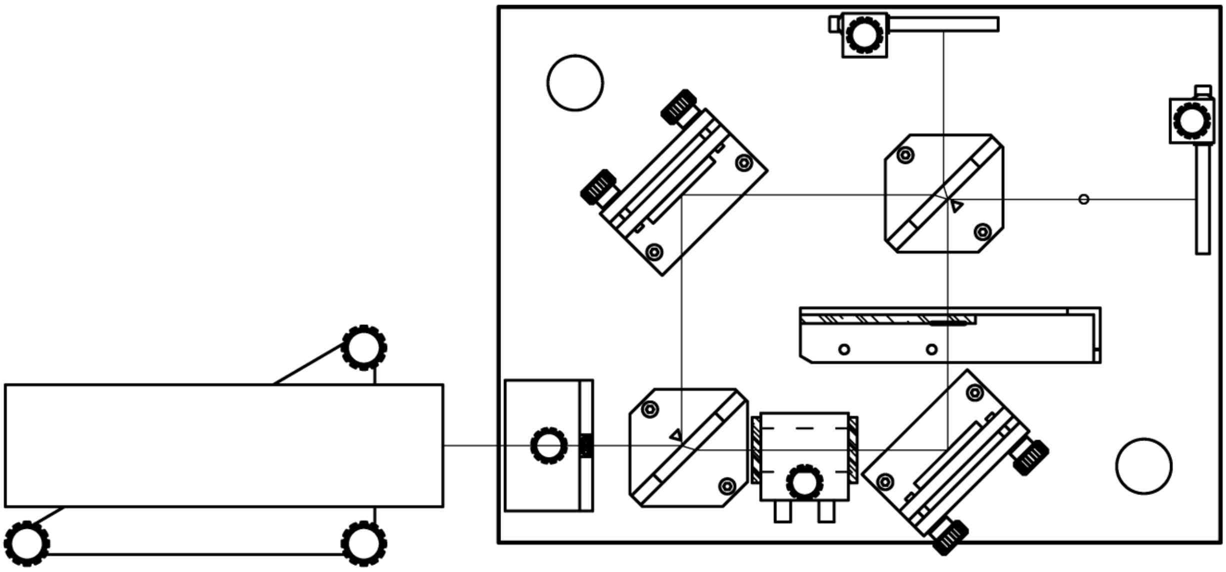

Fig. 8 Experiment set-up for measuring surface quality of optical instruments (not including vacuum cell) and for measuring the refractive index of air (without the glass plate on its holder)

6.3 Refractive index of air

Experiment set-up

- Set up the experiment as shown in Fig. 8.
- Once the basic configuration has been made as in section 5 and interference rings can be seen in the middle of both screens, slide the vacuum cell into the lower beam and screw it into place.
- You might need to adjust the mirror surfaces to obtain interference rings in the centre of the rear screen.

Procedure

- Connect a suitable manual vacuum pump to the vacuum cell and make a note of the pressure displayed p.
- Now slowly evacuate the cell and count the number of rings *m*, which arise.
- Make a note of the pressure and the associated number of rings at regular intervals.
- When the minimum pressure has been attained (about 10 kPa for a simple hand pump), let the vacuum cell fill back up with air.
- Now carry out a set of measurements at pressure above atmospheric (up to a maximum of 200 kPa, which corresponds to 1 bar above atmospheric).

Evaluation

At a pressure of p = 0 the refractive index n (p = 0) = 1. As pressure rises, the refractive index also increases according to the following equation:

$$n(p) = 1 + \frac{\Delta n}{\Delta p} p$$

To determine the refractive at normal pressure therefore, it is necessary to first determine the slope $\Delta n / \Delta p$. An initial approximation is given by the following:

$$\frac{\Delta n}{\Delta p} = \frac{\lambda}{l_Z} \left| \frac{\Delta m}{\Delta p} \right|$$

Here, m is the number of rings which emerge or vanish, λ is the wavelength of the light and l_Z is the internal length of the vacuum cell (41 mm in this case). For instance, if pressure is reduced by Δp = 80 kPa and the change in the number of rings Δm is found to be 14, then $\Delta n / \Delta p$ = $2.7 \cdot 10^{-9}$ per pascal. This leads to a figure for the refractive index of air at normal ambient pressure (100 kPa) of n = 1.00027. Literature cites values of n = 1.00029. (H. Stöcker, Taschenbuch der Physik, Deutsch, 1998)

6.4 Experiment demonstrating quantum erasure by analogy

- Set up the experiment as in Fig. 9.
- Once the basic configuration has been made as in section 5 and interference rings can be seen in the middle of both screens, set one polarisation filter to 45° and place it between the diverging lens and the first beam splitter.

This is needed because the polarisation plane of lasers is not usually set to 45° and polarisation at angles of 0° or 90° would lead to widely differing light intensities for the two split beams.

The interference rings on the screens will now be slightly dimmed, but should remain clear to see. If annoying reflections from the polarisation filter back to the laser should occur, it may help to slightly tilt the filter.

- Next, place one of the two glass polarisation filters into each of the two beams.

The optimum light intensity for this experiment is obtained when the left-hand filter is set to 0° and the right-hand one to 90° (cf. Fig. 6: beyond the beam splitter, the reflected beam is at a slight angle towards 0°, whereas the beam that passes straight through is slightly turned towards 90°).

The interference rings will now have disappeared from the screens, since orthogonal waves can neither reinforce nor destruct one another.

- Now set the second film polarisation filter to 45° and place that between the rear beam splitter and the screen.

Now it should be possible to see interference rings once again. Information regarding the path taken by the individual quanta appears to have been erased.

According to wave theory, this is actually unsurprising, but in quantum mechanics, photons are regarded as indivisible quantised objects and only if the information about the path (polarisation) through the beam splitter, which in principle would be inherent, were to be erased would the photons be able to demonstrate interference again. In the extreme case, it would then be possible to observe interference even for extremely weak laser light, such that practically speaking only individual photons would be entering the interferometer, in spite of the indivisibility of photons and the impossibility of traversing two different paths at once. Even Erwin Schrödinger had problems visualising this – in 1926 he said, "If one has to stick to this damned quantum jumping, then I regret ever having been involved in this [quantum theory] thing."

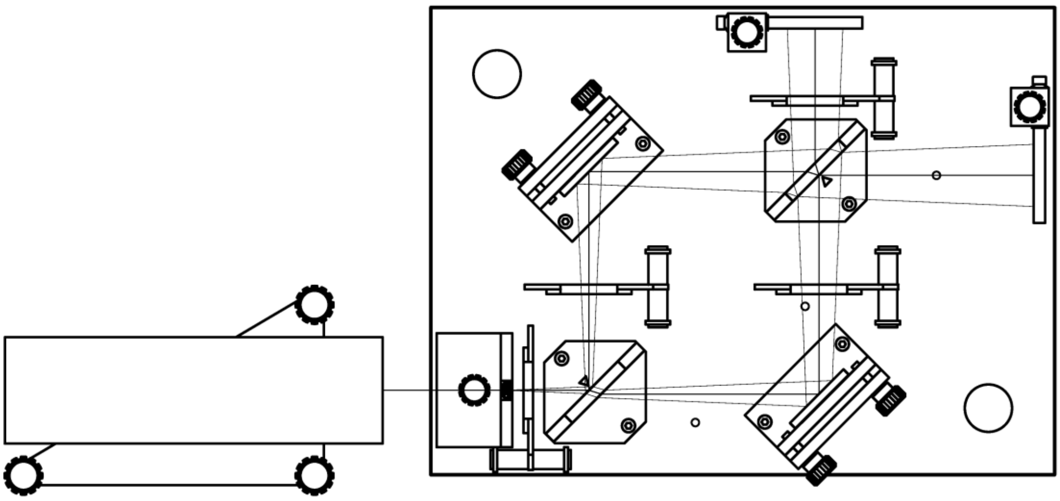

Fig. 9 Experiment set-up for experiment to demonstrate quantum erasure by analogy. The path of the beams corresponds to an identical light path for both split beams and therefore differs from the experiment descriptions for the interference rings experiment.

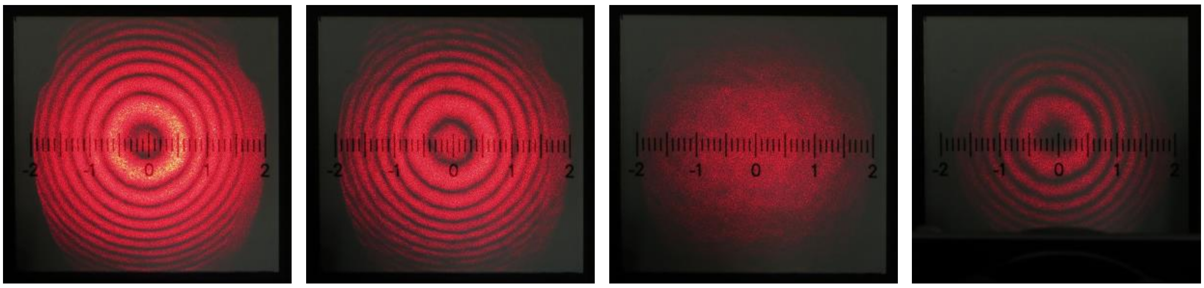

Fig. 10 Left to right: 1. Without polarisation filter, 2. One polarisation filter (45°) between lens and beam splitter, 3. Two more polarisation filters (0°or 90°) in both split beams, 4. A fourth polarisation filter (45°) between second beam splitter and screen

6.5 Interference with white light

Due to its wide spectrum, the distance over which white light can remain coherent (coherence length) is very short. This means that for interference to be observed with such light, the paths taken by the light beams must be very nearly equal in length. This requirement can in principle be accomplished with the help of a Mach-Zehnder interferometer, although it requires patience and delicacy to set it up properly.

Experiment set-up: The set-up for the experiment is shown in Fig. 11. The diverging lens is initially set up between the laser and the first beam splitter.

- Set up the basic configuration using laser light as described in Section 5.3, items 1 to 6. Make sure the two surface mirrors for the 4-mm slit between the mirror holder and the rear wall are set up very accurately.
- The laser should also be carefully adjusted for height.

After setting up the basic configuration, the centre of the interference rings should be visible on the screen as a large bright or dark spot.

- Now fold over the rearmost mirror and project the pattern an another screen (piece of paper or white wall) at least 0.5 mm further away.

This larger distance prevents false interpretation of any scratches or scrapes while making the subsequent settings, which are all carried out on the **front** mirror:

- 1. Turn the lens out of the beams.
- 2. Turn the upper knurled screw of the mirror back and forth. If the point of light which is thereby caused to move lies to the right of the other one, then unscrew the Allen key until the leftward movement of the moving point takes it as far to the left of the stationary point as it was previously to the right (ignore the height setting).
- 3. Use the two knurled screws to make the two points coincide, then swing the lens back into the beam and set things up gain such that the interference rings are in the middle.
- 4. Keep repeating steps 1 to 3 until you can achieve no further improvement.
- Now remove the laser and replace it with an optical lamp with pinhole aperture at about 25 cm in front of the base plate, such that the front edges of the base and the light holder are flush with one another.
- Turn the aperture till the 0.7-mm diameter hole is in front of the LED.
- Turn the lens out of the beam, fold the rear screen back up and set up the polarising filter as in Fig. 11, such that the shadows cover about 1 cm on the rear screen.

The edges of the shadows make it easier to carry out the following settings:

- A. Very slowly turn the screw for the front screen back and forth, in such a way that the respective edge of shadow moves about 1-2 mm to the left or right.
- B. If no interference bands are visible, then turn the lower knurled screw for the rear mirror clockwise by about one fiftieth of a revolution (1/50), which corresponds to about 1 mm of circumference of the screw head or one of the knurled grooves, and then carry out step A again. If you have repeated this process several times without success, then go back and try turning anti-clockwise.
- C. If necessary, check the settings for the laser, paying specific attention to the vertical adjustment, as it may be that the upper knurled screw for the mirrors may have moved slightly out of alignment in the meantime.
- D. If even a very narrow white-light interference pattern is visible on the screen, then you can add the diverging lens in order to magnify it, as shown in Fig. 11.

Tip: If a narrow colour filter is held in front of the light, then the interference pattern should be visible even if the adjustment is less than precise.

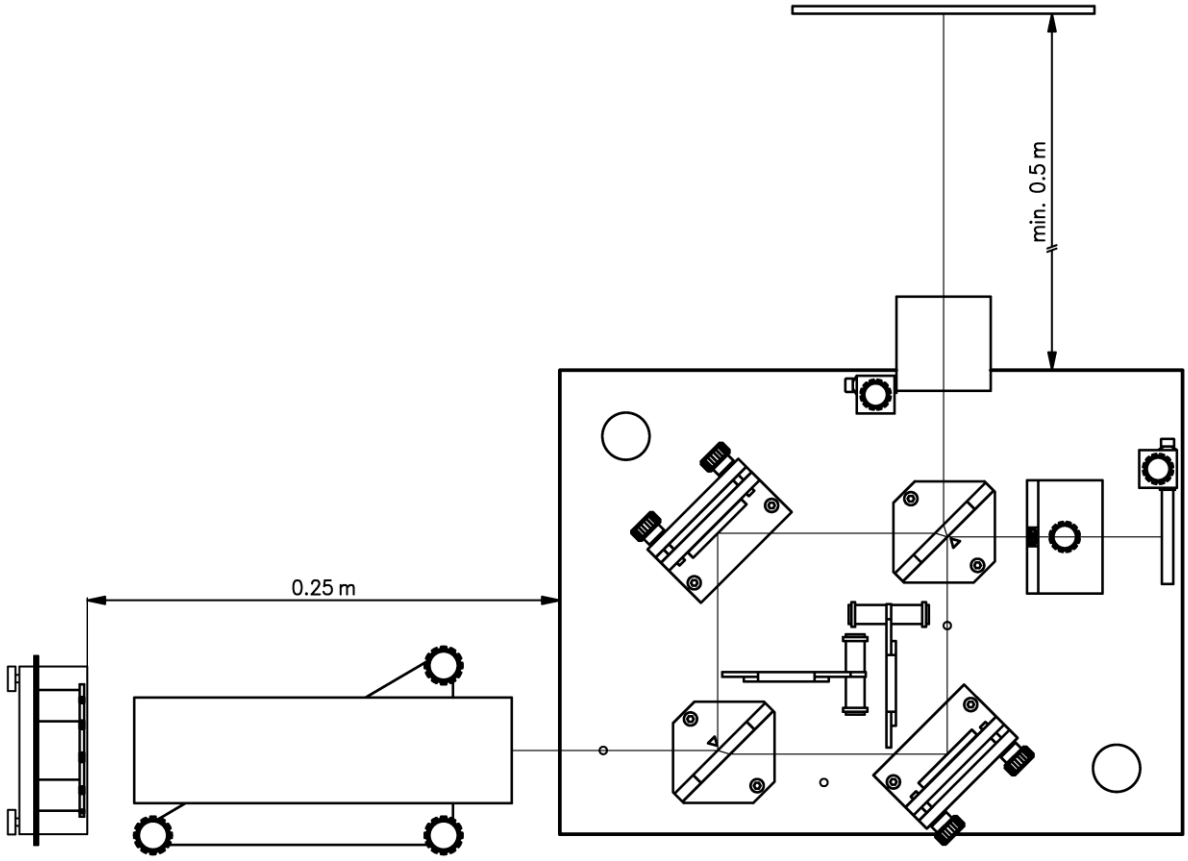

Fig. 11 Experiment set-up for interference using white light

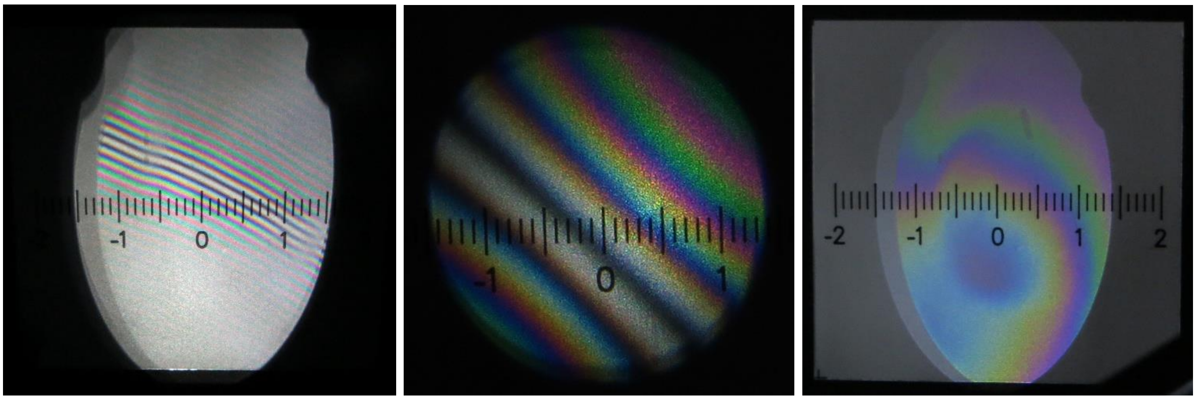

Fig. 12 White-light interference pattern. The left-hand image shows how bands may look on the rear screen if the set-up is not yet ideal. The centre image shows how the bands may appear magnified with a diverging lens included. The right-hand image once again depicts the rear screen but with better adjustment.