Measuring the refractive index of air with a Mach-Zehnder interferometer

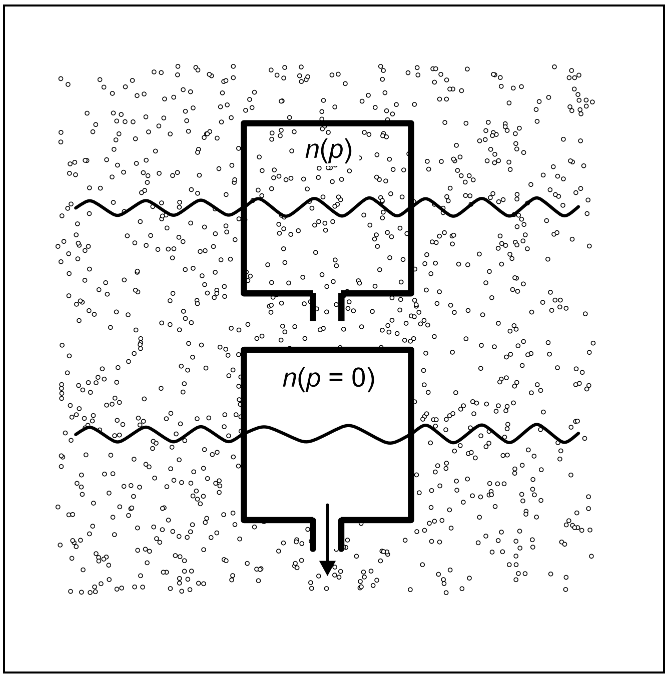
Objects of the experiment

- Assembling the Mach-Zehnder interferometer
- Observing the change in the interference pattern while evacuating a chamber previously placed in the beam path.
- Determining the refractive index of air.

Principles

Interferometry is an extremely precise and sensitive measuring method for determining e.g. changes in lengths, layer densities, refractive indices and wavelengths. The Mach-Zehnder interferometer, like the Michelson interferometer, belongs to the family of two-beam interferometers. It operates on the following principle:

The coherent light beam supplied by a suitable source is split into two parts by an optical component. These partial beams travel along different paths, are deflected using mirrors and channeled to another optical component, where they combine and are superimposed. The result is an interference pattern. If the path length of one of these partial beams, i.e. the product of the refractive index and geometric path, changes, this produces a phase shift with respect to the undisturbed beam. This in turn causes a change in the interference pattern, which allows us to draw conclusions about the changes in the optical path.



Unlike the Michelson interferometer, the light beams are not reflected into each other after division, but rather travel along separate paths until they are recombined. As a result, measurements on transparent materials, e.g. measurements of the refractive index, are easier to understand and thus make for better teaching exercises. However, it is not possible to determine changes in the length of the geometric path.

To determine the refractive index of air, an evacuable chamber is placed in the path of one of the partial beams of the interferometer. The optical path length of this partial beam is altered during the experiment by evacuating this vessel. We can then determine the refractive index of air on the basis of the change in the interference pattern and the corresponding pressure change. This measurement can also be conducted with the Michelson interferometer; however, we would then have to take into account that the beam passes through the chamber twice.

Apparatus

1 laser optics base plate	473 40
1 He-Ne laser, linearly polarized	471 840
1 laser support	473 41
6 optics bases	473 42
2 beam dividers . . . e.g.	473 432
2 holders for beam dividers	473 43
2 planar mirrors with fine adjustment	473 46
1 spherical lens, f = 2.7 mm	473 47
1 evacuable chamber	473 485
1 translucent screen	441 53
1 hand vacuum and pressure pump	375 58
1 small stand base, V-shape	300 021
1 universal clamp S	666 555
1 saddle base	300 11
1 wooden ruler	311 03

Safety note

The He-Ne laser fulfills the German technical standard “Safety Requirements for Teaching and Training Equipment – Laser, DIN 58126, Part 6” for class 2 lasers. When the precautions described in the Instruction Sheet are observed, experimenting with the He-Ne laser is not dangerous.

- Never look directly into the direct or reflected laser beam.
- Do not exceed the glare limit (i.e. no observer should feel dazzled).

Setup

Note: optical components with damaged or dirty surfaces can cause disturbances in the interference pattern.
Handle the planar mirrors, beam dividers and spherical lens carefully, store them free of dust and to not touch them with your bare hands.

Fig. 1 shows the setup of the Mach-Zehnder interferometer on the laser optics base plate. The components must be aligned particularly carefully with regard to the geometry of the beam path. To set up the experiment correctly, you must carry out the following steps:

Laser optics base plate and laser:

- Pump up the air cushion.
- Place the laser optics base plate **(a)** with air cushion horizontally on a sturdy laboratory bench.
- Mount the laser on the laser support and place it at the left edge of the base plate.
- Connect the laser and switch it on.
- Loosen the three lock nuts of the adjusting screws on the laser support.
- Using the adjusting screws, adjust the height and inclination of the laser so that the beam travels perfectly horizontally about 75 mm above the base plate (there is still enough play for subsequent adjustment). Measure the spacing with the ruler.
- Tighten the lock nuts.

Preliminary adjustment:

- Check whether the beam dividers **(b)** and **(c)** reflect the beam horizontally; to do this, place each beam divider on its optics base in the beam path at opposite ends of the laser optics base plate and reflect the light beam to a point next to the emission aperture of the laser.
- If necessary, correct the angle of inclination of the beam dividers, and thus the beam paths, using the two screws on the stand rod.
- Using the top adjusting screw, adjust the planar mirrors **(d)** and **(e)** so that they reflect the beam horizontally; to do this, place each planar mirror on its optics base in the beam path at opposite ends of the laser optics base plate and reflect the light beam to a point next to the emission aperture of the laser.

Beam dividers and planar mirrors:

Notes:

It is easier to adjust the setup in a somewhat darkened room.

In addition to the main beams, the multiple reflections also produce so-called parasitic partial beams of low intensity. These are subsequently screened out by the lens holders. The information given below applies only to the main beams.

The reflected and transmitted partial beams should always have similar intensities.
When using the variable beam divider (473 435), make sure that the laser beam strikes the beam divider more or less in the center.

- Place the beam divider **(b)** with optics base in the beam path at an angle of 45° as shown in Fig. 1; the partially transparent layer of the beam divider should face the laser.

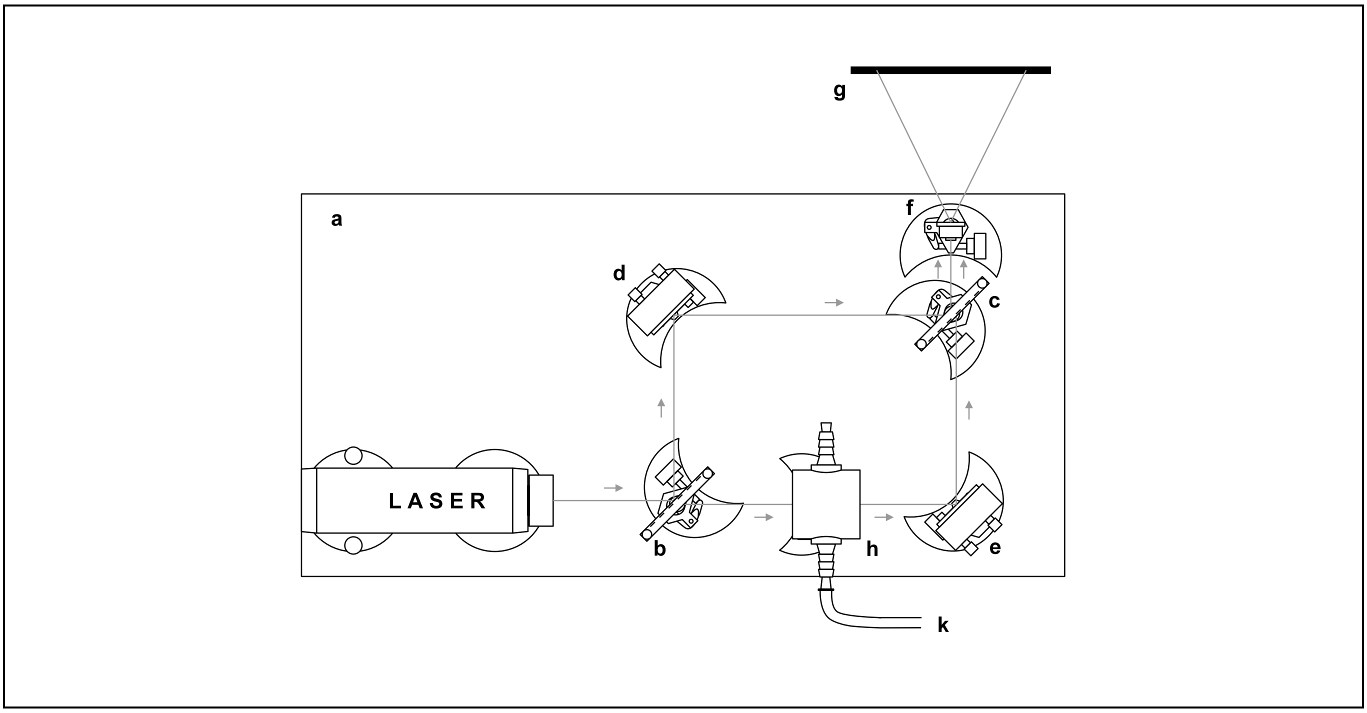


Fig. 1: Setup of the Mach-Zehnder interferometer on the laser optics base plate with evacuable chamber, top view
a laser optics base plate
b, c beam dividers
d, e planar mirrors with fine adjustment
f spherical lens
g translucent screen
h evacuable chamber
k hose connection for vacuum pump

- Place the planar mirror **(d)** in the partial beam reflected by the beam divider **(b)** so that the laser beam strikes it in the center.
- By turning the optics base on the interferometer base plate, align the planar mirror so that the beam is deflected by 90° and travels on a path parallel to the transmitted partial beam.
- Place planar mirror **(e)** in the transmitted partial beam opposite planar mirror **(d)** in the assembly as shown in Fig. 1 so that the laser beam strikes it in the center.
- By turning the optics base on the interferometer base plate, also align this planar mirror so that the partial beam is deflected by 90°.
- Fasten the translucent screen **(g)** in the base and set it up behind the laser optics base plate as shown in Fig. 1 so that the partial beam reflected by the planar mirror **(e)** strikes it in the center.
- Set up beam divider **(c)** antiparallel to beam divider **(b)** so that it is struck by both partial beams at an angle of 45°; make sure that the partially transparent layer is facing the screen **(g)**.

Subsequent adjustment:

The components are correctly arranged when the beam path from beam divider to beam divider forms a rectangle.

- Correct the beam path if necessary.
- Readjust the planar mirrors and beam dividers so that the most intensive beams of the two reflex groups coincide on the screen **(g)**.
- Change the distance between the screen **(g)** and the second beam divider **(c)** and check whether the reflexes of the two partial beams remain virtually coincident, i.e. sufficiently parallel.

a) Readjusting the vertical beam path:

If the partial beams diverge from the horizontal plane:

- Measure the heights of the partial beams over the laser optics base plate behind each optical component precisely using the wooden ruler, and correct the inclinations of the planar mirrors and beam dividers as necessary.
- Adjust the optical components so that the most intensive beams of the two reflex groups coincide on the transparent screen.
- Change the distance between the screen **(g)** and the second beam divider **(c)** again and check whether the reflexes of the two partial beams are parallel.
- Repeat the readjustment as necessary.

b) Correcting the horizontal beam path:

Ideally, the partial beams exit the beam divider at virtually the same point and recombine on translucent screen.

If the partial beams diverge in the horizontal plane:

- Check the paths of the partial beams from beam divider **(b)** to beam divider **(c)** and correct the alignment of the corresponding components if the beam paths do not describe a rectangle.
- Shift the planar mirror **(e)** parallel to the long side of the laser optics base plate and align it so that the partial beam it reflects coincides with that reflected from planar mirror **(d)** both on beam divider (c) and on the translucent screen **(g)**.

Spherical lens:

- Place the spherical lens **(f)** on the laser optics base plate between beam divider **(c)** and the translucent screen **(g)** (the small opening of the lens holder must face toward the beam divider).
- Adjust the height and lateral position of the spherical lens so that the two partial beams pass through it axially.
- If necessary, correct the beam path by readjusting one of the planar mirrors.

Fine adjustment:

If you do not yet see a pattern of lines on the translucent screen:

- Change the beam path by slightly changing the alignment of the beam dividers or the planar mirrors; readjust the spherical lens as necessary.

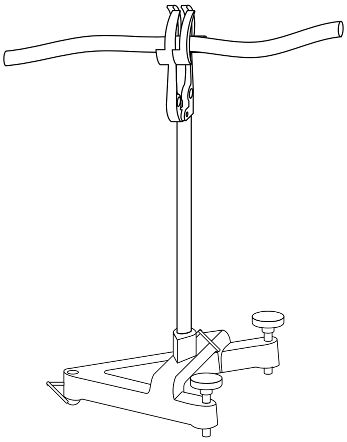
The more the partial beams run in parallel between the beam divider **(c)** and the screen **(g)**, the wider and farther apart the interference lines are.

- Adjust the interference pattern so that it is easy to observe by slightly changing the alignment of the beam dividers or the planar mirrors.

If you cannot achieve a satisfactory image by fine adjustment, repeat the interferometer adjustment procedure from the beginning.

The interference pattern is much brighter and easier to observe when the laser is switched to an output power of 1 mW. As this can change the beam path slightly, you may need to adjust the beam path or the position of the spherical lens.

Fig. 2: Strain-relief assembly for connecting the tubing to the evacuable chamber



Evacuable chamber and hand vacuum and pressure pump:

Note: reflections of the laser beam occur at the glass surfaces of the evacuable chamber. In some cases, these may even strike the emission aperture of the laser beam and affect the quality of the laser beam.
If this happens, turn the chamber somewhat.

- Seal one of the hose connections of the evacuable chamber tightly using a stopper (included in the scope of supply).
- Mount the evacuable chamber on an optics base and place it in the beam path e.g. between beam divider **(b)** and planar mirror **(e)** so that the partial beam passes through it axially. Do not change the positions of the other optical components.
- Connect the vacuum pump to the other hose connection of the evacuable chamber using the tubing, without pulling the chamber off the laser optics base plate by the tube; connect a suitable hose adapter to the hose connection.
- Set up a strain-relief fitting using the small stand base and the universal clamp S as shown in Fig. 2 and attach the tube next to the laser optics base plate so that the measurement cannot be falsified by twisting or shifting the evacuable chamber.

Carrying out the experiment

During the experiment:

- Avoid mechanical shocks to the laser optics base plate (e.g. do not shake or bump the table).
- Avoid air streaking in the setup, e.g. through breathing or drafts.
- Mark the position of an intensity maximum on the translucent screen **(g)** at which the passing interference lines can be counted.
- Evacuate the chamber **(h)** slowly, until the next intensity maximum has moved to exactly the marked point.
- Read off the corresponding underpressure on the manometer of the hand vacuum and pressure pump and write this value down.
- Repeat this process until the maximum possible underpressure is reached.

Recommended, but not absolutely necessary:

- Using the valve on the hand vacuum and pressure pump, let air into the vessel slowly until the previous intensity maximum is exactly at the marked position.
- Read off the corresponding underpressure on the manometer of the hand vacuum and pressure pump and write this value down.
- Repeat this process until the normal air pressure is reached.

Measurement example

Table 1: Number of shifts of interference maxima Z and differential pressure p_D, measured at ϑ = 22 °C and λ = 632.8 nm

Z	$\frac{p_D}{\text{mbar}}$	Z	$\frac{p_D}{\text{mbar}}$
1	40	19	930
2	100	18	880
3	150	17	830
4	190	16	780
5	240	15	730
6	290	14	680
7	340	13	630
8	390	12	580
9	440	11	530
10	480	10	480
11	530	9	430
12	580	8	390
13	630	7	330
14	680	6	290
15	730	5	230
16	780	4	190
17	820	3	140
18	870	2	80
19	920	1	20

Evaluation and results

In gases, the refractive index is linearly dependent on the pressure p.

$$n(p) = n(p = 0) + \frac{\Delta n}{\Delta p} \cdot p \quad \text{with} \quad n(p = 0) = 1 \qquad \text{(I)}$$

Thus, in the following evaluation we will determine the differential quotient

$$\frac{\Delta n}{\Delta p} = \frac{n(p + \Delta p) - n(p)}{\Delta p} \qquad \text{(II)}$$

from the measurement data.

The optical path length d in the evacuable chamber is the product of the geometric length s of the chamber and the pressure-dependent refractive index $n(p)$ of the gas in the chamber. By changing the pressure in the chamber from p to the value $p + \Delta p$, we change the optical path length by

$$\Delta d = n(p + \Delta p) \cdot s - n(p) \cdot s \qquad \text{(III)}$$

During evacuation, we may observe motion in the interference lines on the translucent screen. Starting from the ambient air pressure p_0, we can count $Z(p)$ shifts in the chamber until pressure p is reached. A shift of the maxima by exactly one position corresponds to a change of λ in the optical path length. Thus, the optical path length changes between pressure p and $p + \Delta p$ by

$$\Delta d = (Z(p) - Z(p + \Delta p)) \cdot \lambda \qquad \text{(IV)}$$

From (III) and (IV), we can conclude that

$$n(p + \Delta p) - n(p) = -(Z(p + \Delta p) - Z(p)) \cdot \frac{\lambda}{s}$$

and, on the basis of (II),

$$\frac{\Delta n}{\Delta p} = -\frac{\Delta Z}{\Delta p} \cdot \frac{\lambda}{s} \qquad \text{(V)}$$

The measurement quantity is not the pressure p in the chamber, but rather the difference from the ambient air pressure $p_D = p_0 - p$. Using the measurement data, we can thus determine the slope $\frac{\Delta Z}{\Delta p_D} = -\frac{\Delta Z}{\Delta p}$. From Fig. 3, we derive the value

$$\frac{\Delta Z}{\Delta p_D} = 0.020 \text{ mbar}^{-1}$$

and, because λ = 632.8 nm and s = 50 mm, we obtain

$$\frac{\Delta n}{\Delta p} = 2.6 \;\; 10^{-7} \text{ mbar}^{-1}$$

When we insert this value in (I), we obtain the value n = 1.00026 as the refractive index of air.

The corresponding literature value at standard temperature and pressure (p = 1013 mbar, temperature ϑ = 22 °C) and laser wavelength λ = 632.8 nm is n = 1.000269.

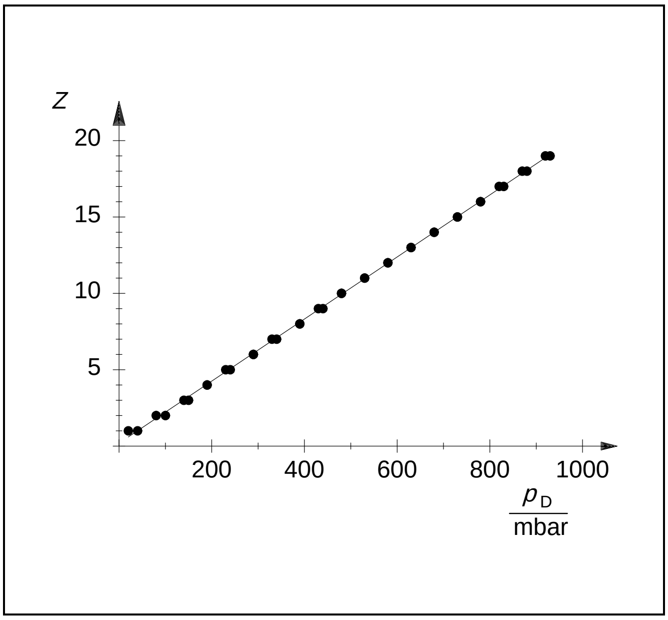


Fig. 3: Number of shifts of interference maxima Z as a function of the differential pressure p_D