Lab 2 -- Interferometry -- Fall 2011

Wave optics and interferometry

Note: The optical surfaces used in this experiment are delicate. **Please do not touch any of the optic surfaces** *to avoid scratches and fingerprints. Please use the optics holders provided to prevent damage.*

Introduction

For many purposes, you can consider light to propagate as rays, explaining phenomena such as shadows or imaging with a pin-hole camera. Even refraction of light at interfaces between transparent matter or vacuum can be understood in the framework of ray optics by introducing an index of refraction n and using Snell's laws of refraction. This explains lenses, prisms, or effects such as mirages. However, light is an electromagnetic wave. You can only neglect the wave nature of light and use a ray description if all sizes are much larger than the wavelength of light. And even this is only true if you have completely "incoherent" light, for example from the sun or from a light bulb. Things entirely change if sizes become small, or if you have pure light of a single color as it can be generated by a laser.

In today's lab we will explore both of these cases and explore the wave nature of light. We will also use light to carry out two precision measurements. We will measure the index of refraction of air, and the tiny displacement of a piezo actuator.
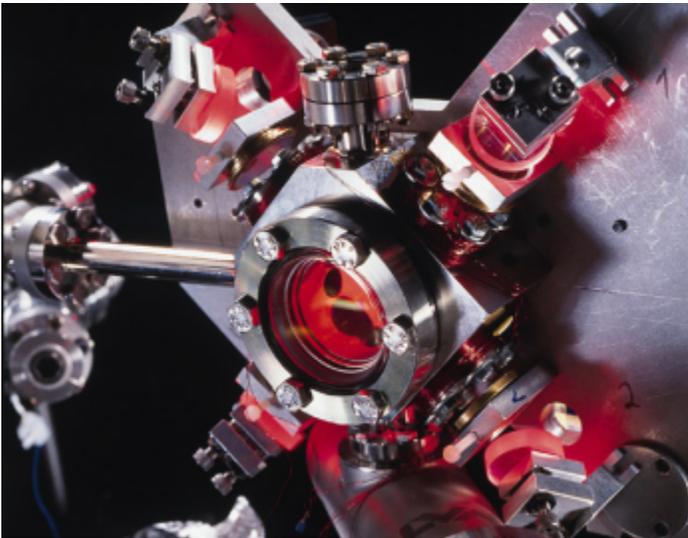
Lasers are used in many fields of research. In this "magneto-optical trap", for example, atoms are laser-cooled to a few microkelvin above absolute zero temperature.

Laser safety:

Do not stare into the beam. The light is safe for skin exposure, but do not shine the laser beams directly into your eyes!
Relevant laser classification:

Class 2M

LASER RADIATION DO NOT STARE INTO BEAM OR VIEW DIRECTLY WITH OPTICAL INSTRUMENTS CLASS 2M LASER PRODUCT

A Class 2M laser is safe because of the blink reflex if not viewed through optical instruments. As with class 1M, this applies to laser beams with a large diameter or large divergence, for which the amount of light passing through the pupil cannot exceed the limits for class 2.

LASER RADIATION AVOID DIRECT EYE EXPOSURE CLASS 3R LASER PRODUCT

A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the MPE can be exceeded, but with a low risk of injury. Visible continuous lasers in Class 3R are limited to 5 mW. For other wavelengths and for pulsed lasers, other limits apply.|

Wave Optics

Laser

The light source you will use in today's experiment is a helium-neon laser. How is a laser different from a usual light source like a light bulb or an LED? If you compare electromagnetic (EM) waves to sound waves, usual white light is just noise like you would hear it from a waterfall. In both cases you have many independent sources that create waves at random frequencies. Colored light is a bit less chaotic. For example, a blue LED emits light in a fairly narrow frequency range. However, it still consists of many independent sources and, in this analogy, could be compared to a hissing sound at a certain pitch.

How can you create light that is a pure sinusoidal EM wave, in analogy to a clean sound wave from a flute, an organ pipe, or a tuning fork? What you need is a single macroscopic oscillator that oscillates at a single frequency. For electromagnetic waves in the radio frequency range this is easy. You can just use an electronic circuit for that, similar to what we discussed in the ignition coil lab. Light oscillations, however, are much too fast for electronic circuits (400 Teraherz). However, a laser does the job.
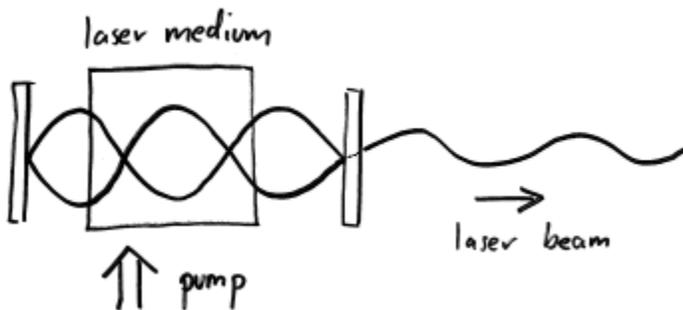

Figure: Working principle of a laser. A pure electromagnetic standing wave is created in a "laser resonator" formed by two laser mirrors. The laser medium is "pumped" externally to feed energy into the resonator and constantly increase the electromagnetic wave. One of the laser mirrors is slightly transparent. The wave that leaks out is the desired laser beam, consisting of a pure sinusoidal wave of plane wave fronts.

A laser consists of a resonator or optical cavity that is formed by two parallel mirrors. The light bounces back and forth between the mirrors, and a standing wave is formed (see figure) – just like with sound waves in an organ pipe. By choosing the distance between the mirrors and doing some other frequency filtering you can make sure that only one specific electromagnetic wave resonates in the resonator. Between the mirrors there is also a laser medium, for example a gas of atoms. You constantly pump energy into the atoms, for example by an electric discharge. The atoms can then emit light in a stimulated fashion. This leads to a constant buildup of the single standing light wave between the mirrors. One of the laser mirrors is slightly transparent. Through this mirror a little bit of your standing wave can leak out of the laser cavity. This is your clean laser light that consists of a plane wave and oscillates at a single frequency.

Lasers you see nowadays are often solid-state lasers in which the gas is replaced by solid laser material. Red laser pointers, for example, are diode lasers, which essentially consist of an LED with two mirrors around it. Green laser pointers are much more complicated. They first create infrared light that is then converted into different infrared light and finally frequency doubled (second harmonic generation) in a crystal. The light of both red and green laser pointers is unfortunately not pure enough for the experiment we do today. Therefore, we use helium neon gas lasers which produce a very pure light wave.
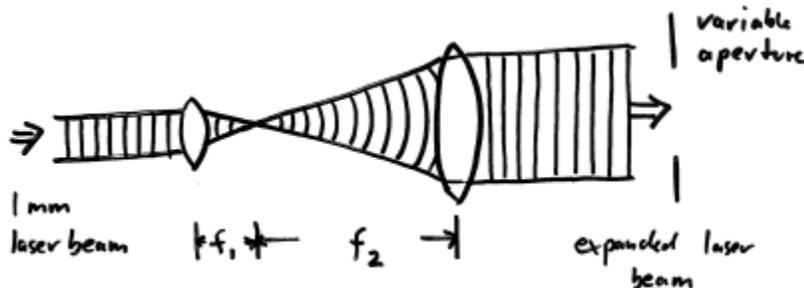

Figure: Telescope to expand laser beam to up to 25mm diameter. The lines denote parallel and spherical wave fronts, i.e. positions of constant

phase.

The light exiting a laser is a plane wave typically about a millimeter in diameter. For our experiment we want a larger diameter plane wave. Hence, we use a telescope in front of the laser (see figure). The telescope consists of two lenses. The first one focuses the 1mm collimated beam to a small focal spot. The second lens is placed such that it collimates the light again. Our beam expander has an aperture added and can create beams with diameter between 1mm and 25 mm.

Diffraction

When light wave hits an object on which the structure size approaches the wavelength of light, diffraction pattern become noticeable.

If light hits a series of slits in a mask, you get a diffraction pattern with a series of diffraction orders (see figure). To remind you about multiple slit diffraction, study the following pictures:
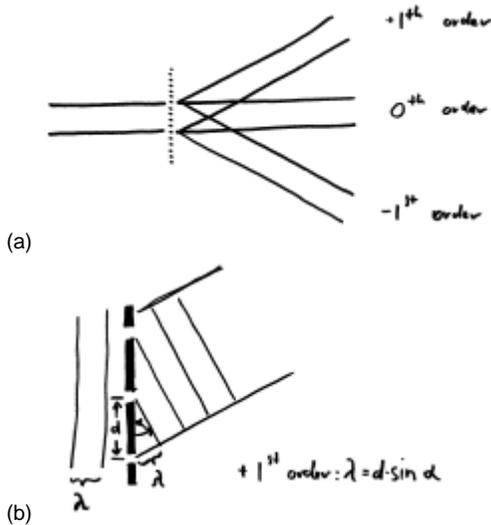

(a)

(b)

Figure: (a) Series of diffraction orders (+/- 1st order, 0th order, higher orders not shown). (b) The diffraction orders appear at the angle α under which the path length difference of light coming from neighboring slits (spaced by d) is a multiple of the wavelength of light λ.

You can get an intuitive picture for the diffraction by using Huygens principle: All slits emit a spherical wave. These waves interfere. In certain directions, the circular wave fronts add up constructively and form new parallel wave fronts, corresponding to the various diffraction orders. You can see this in the following picture:
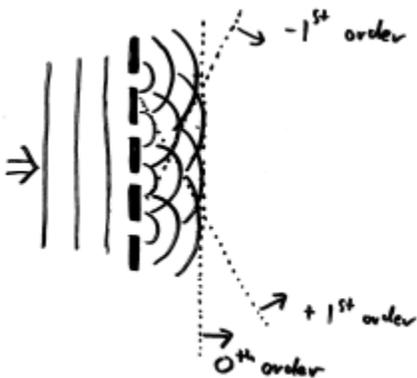

Figure: The Huygens principle shows you intuitively how the different diffraction orders arise. The lines denote wave fronts, i.e. positions of constant phase.

Lets first have a look at a piece of fabric. The fabric acts as a "diffraction grating", a periodic array of holes through which light travels. The holes are the small open areas between the threads of the woven fabric. Each hole emits approximately a spherical wave, and all of these waves interfere on the screen and give rise of the interference pattern you observe.

1. Switch on the laser. ***Keep the laser on during the entire lab, otherwise it might not restart for a while once it is warm, just like a video projector.*** Close the aperture to create a beam with small diameter (approx. 1mm). Shine the laser onto a screen, about 2m away from the laser. Hold the piece of fabric into the laser beam, close to the laser source. **What do you observe on the screen? Sketch the pattern. Discuss with**

your lab mates and TF what that pattern is, and briefly explain in your lab notes.

2. **Hold the fabric in front of your eye and look at a bright LED light source at a distance. What do you see? Discuss with your lab mates and TF.**

Note that the pattern on the screen is not a shadow image, it is an interference pattern – that is why the spacing on the screen behaves counter intuitively if you were to reduce the thread spacing (see prelab question).

Measuring the wavelength of light

We can now use a diffraction grating to measure the wavelength of our laser. Note that this is the same principle on which the the grating spectrometer in lab 1 operated.

3. Use the diffraction grating in the slide frame and hold it into the laser beam. This mask has smaller slit spacings (208 lines per mm for the double-axis gratings and 500 lines per mm for the single-axis gratings. The double-axis gratings are incorrectly marked 13,500 lines/inch). **Make all required measurements to determine the wavelength of your laser light. Estimate the error by estimating how well you were able to measure the distances. Check with your TF.**

Interferometry

Interference

If two waves come together that have the same phase, they add up. This is called *constructive interference*. If they have opposite phase, they cancel each other out. This is called *destructive interference*.
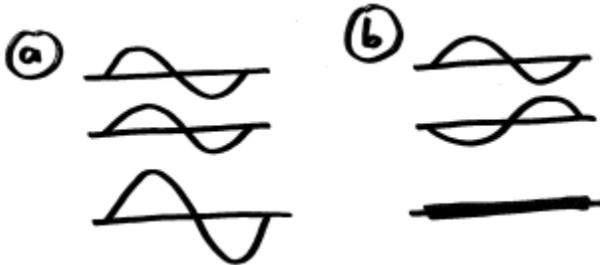

Figure: (a) Two waves in phase add up – constructive interference. (b) Two waves with opposite phase cancel – destructive interference.

This fundamental wave phenomena occurs for all types of waves, e.g. sound waves, waves in water, seismic waves, quantum mechanical matter waves, and of course electromagnetic waves. We already saw diffraction of light, which is based on wave interference. How can we study interference in a system that is a bit more straight forward?

One of the conceptually simplest ways to observe interference is to combine two plane waves, i.e. waves that have plane wave fronts and therefore travel straight in space. If such a plane wave hits a screen perpendicularly, the phase is constant across the screen, and the electromagnetic wave at the screen is just
$E_1(t) = E_0 \cos(\omega t)$

where E_0 is the overall wave amplitude, t is time, and ω is the angular frequency. If you add a second wave, this wave can have a relative phase $\Delta \phi$ with respect to the first wave, called **phase difference**. The amplitude of the second wave is
$E_2(t)=E_0 \cos(\omega t + \Delta \phi)$

The two waves add up, and so the total electric field amplitude on the screen is
$E(t) = E_1(t) + E_2(t) = E_0 [\cos(\omega t) + \cos(\omega t + \Delta \phi)]$

It is easy to see that if two identical waves interfere $(\Delta \phi = 0)$, they add up at all times t, and the amplitude doubles. If they are completely out of phase $(\Delta \phi = \pi)$ they cancel to zero.

The intensity is the absolute square of the amplitude, averaged over one oscillation cycle. It can be calculated by using trigonometric formulas, or by using complex notation and complex exponential functions. The result is:
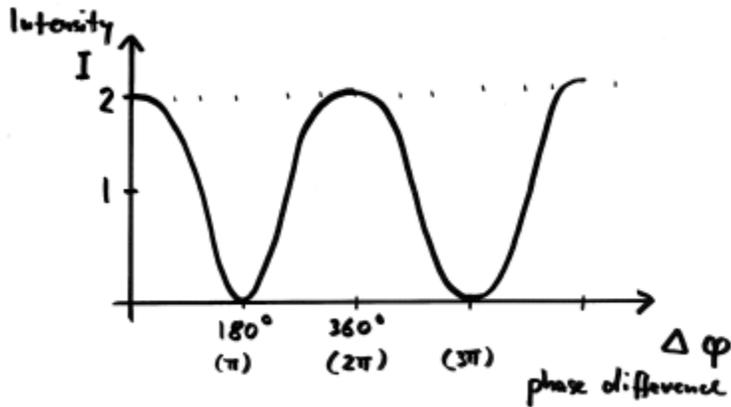$I = 2 I_0 \cos^2((\Delta \phi) /2)$

The function looks like this:

Figure: Intensity versus phase difference of interfering waves

In order to observe this interference function, we just have to overlap two plane waves and look at the intensity on the screen. It only depends on the relative phase $\Delta \phi$. This is what we will do in the next experiment.

Material and basic setup

In this lab we use modern optical lab equipment as it is used in optics research labs in many fields of research (see picture below).
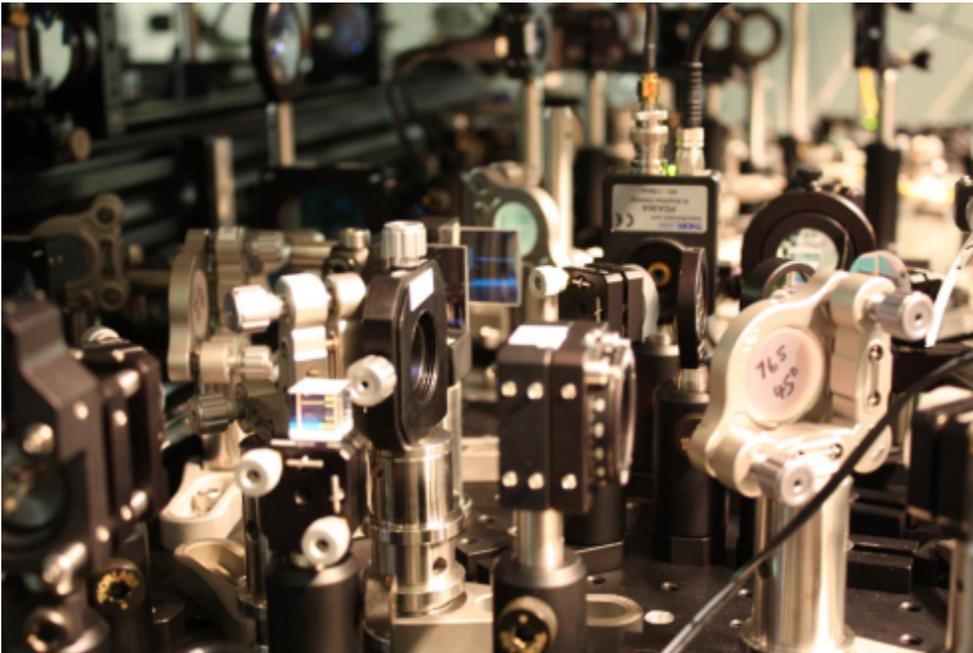

Figure: Optical components in a lab for ultracold quantum gases (Greiner lab). The components steer and manipulate laser beams.

Mirror

The mirror reflects light, in our case a plane wave. Our mirrors are so called dielectric mirrors – they reflect a certain wavelength range of light and transmit others. The coating is not metal like on bathroom mirrors. Also, the coating is on the front surface.

- **_Important:_ All the optical elements are sensitive. They can scratch since the coating is on the front surface, and touching them leaves residue on the mirror that degrades your plane wave upon reflection. Take care to not touch the optical surfaces, and to not tip over mirrors and beam splitters as they might chip or scratch.**

Two of the mirrors (M1 and M2) are mounted into adjustable mirror mounts. By turning the two adjustment screws you can precisely tilt the mirror and steer the plane wave.

4. **Inspect the mirrors. What color of light gets reflected? What color of light leaks through? Have a look how the adjustment works. Note that the adjustment screws have a certain range – always start mid range.**

The optical elements can be mounted precisely to the threaded aluminum plate. This plate is called "optical breadboard".

5. **Set up M1 such that it steers the plane wave along the front side of your breadboard. You can fasten the mirror post with a clamp that is screwed to the breadboard.**

  - **Use the adjustment screws on M1 to have the beam travel parallel to the hole pattern, and without change in height.**
  - **Make sure the adjustment screws are not beyond their travel range.**
  - **It might help to open and close the iris on the telescope to change beam size. Use a screen to confirm the beam position, and that the beam is not clipped with open iris. Show it to your TF.**
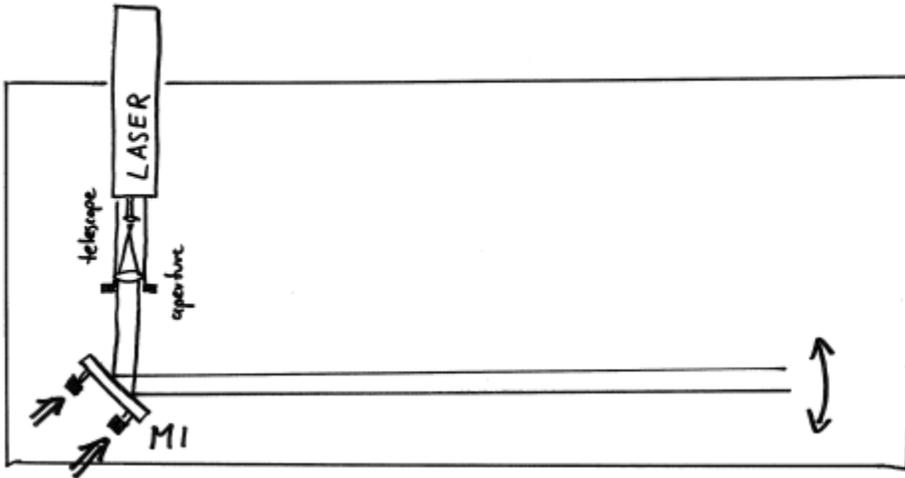

Figure: Align beam by adjusting mirror mount M1

Beam splitter

The next optical element we use is a beam splitter. The beam splitter is also a dielectric coated glass plate, but the coating is designed such that 50% of the light is reflected, and 50% of the light is transmitted.

  - _**Reminder:** Do not touch the optical surfaces of mirrors and beam splitters. Handle with care.**_

6. Place the beam splitter BS1 into the beam path and steer the beams as shown in the figure below. Make sure the beam path is roughly aligned with the hole pattern. The splitter splits the plane wave into two identical plane waves E_1 and E_2. **Confirm position of the beams and splitting ratio by visually inspecting the beam on a screen. Make sure neither of the beams is clipped when the aperture is open.**
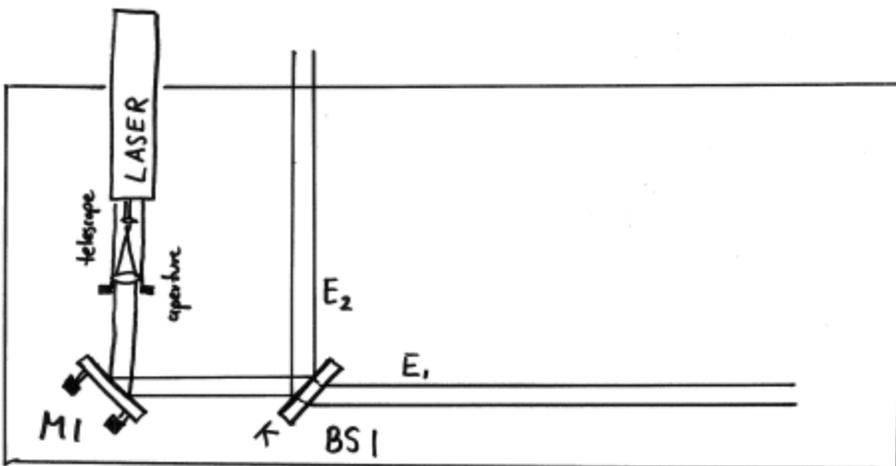
Figure: The beam splitter BS1 splits the plane wave into two separately traveling beams.

Mach Zehnder interferometer

Now we know all optical elements that we need to build a Mach-Zehnder interferometer. The idea is to first split up our plane wave into two as you just did, but to then recombine them to let them interfere. To recombine the two waves we use a second beam splitter. Depending on the relative phase of the two waves they either add up or cancel out.

7. **Let's put the interferometer together:**

- Place a second mirror (M3) into the beam path as shown below. Make sure the beam is aligned well and does not clip with open aperture
- Place a second beam splitter BS2 into the beam path as shown. Make sure the beam is aligned well and the reflected beam does not clip with open aperture. The transmitted beam will be clipped some, that is ok.
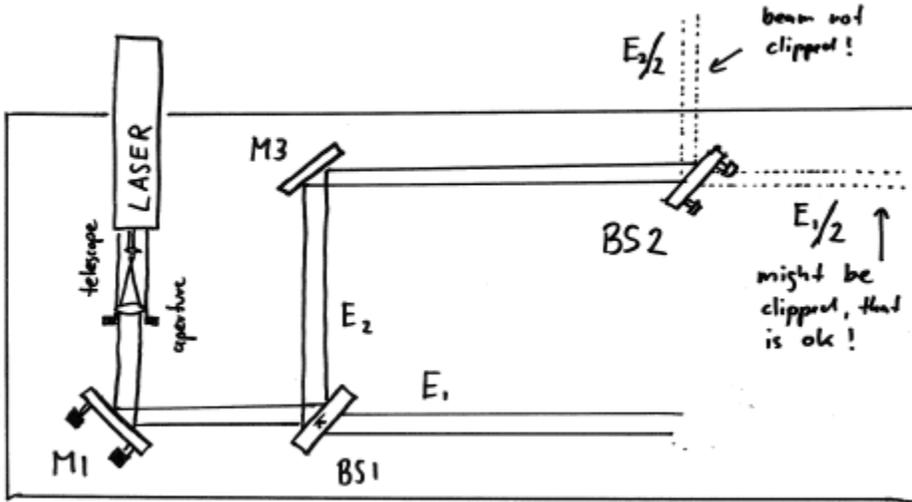

Figure: A second mirror M3 and a second beam splitter BS2 is added.

- Now, add the third mirror (M2). Make sure the beam is reflected at about right angle.
- In order for the beams / plane waves to interfere, there have to be precisely aligned onto each other. The position has to be identical, and the direction of the beams has to be identical.
- To overlap the position of the beams, first close the aperture of the laser to make a small beam. Then, place a screen directly behind BS2 (see figure). Use the adjustment screws at M2 to overlap the beams directly behind BS2.
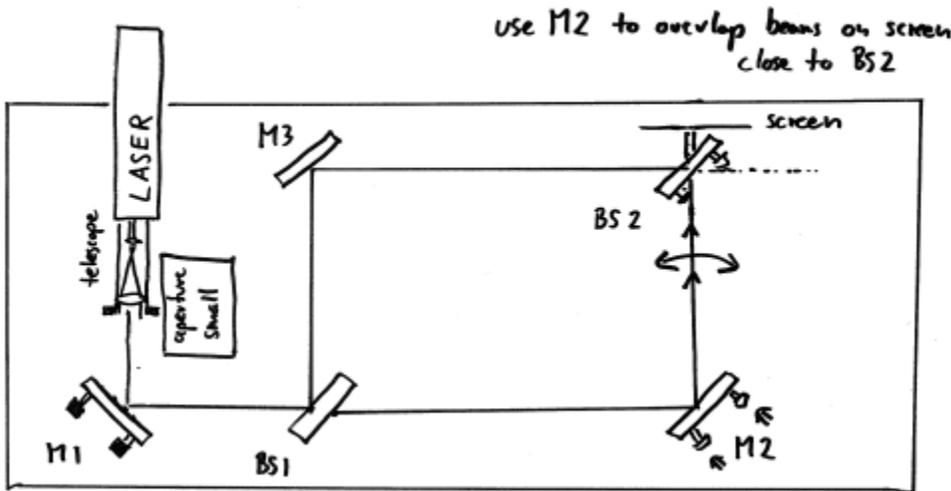

Figure: With adding mirror M2 the interferometer is complete. M2 is turned to adjust the beam overlap behind BS2 (screen).

- Now, use the set screws on BS2 to align the direction of the beams parallel. For this, place a screen far away to observe the direction of

the beams (see fig. below).
- Iterate the last two steps until the overlap is good at both screen positions. Have a TF help you if you have any difficulties.
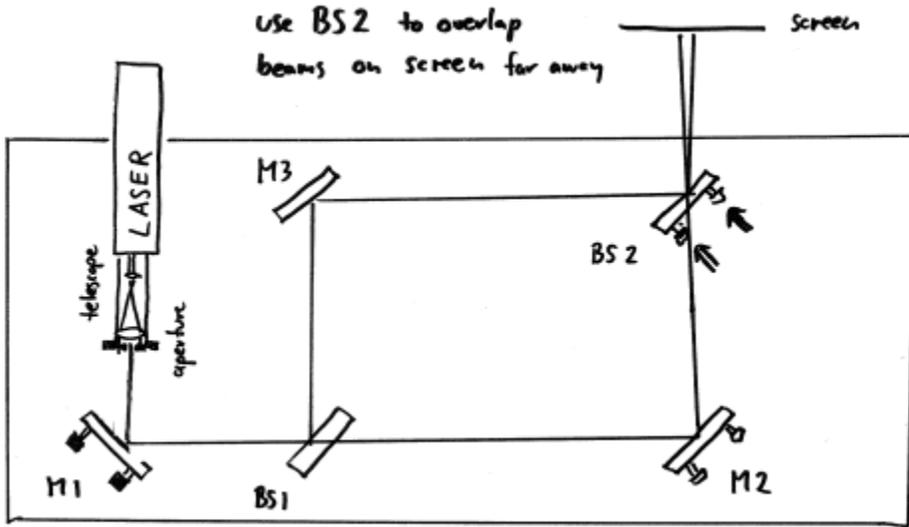

Figure: Use BS2 to co align the direction of the beams.

- The interferometer should be roughly aligned now. Open the aperture, and see whether you can see any interference pattern on the screen. This should be a stripe pattern, of many fine or a few broad stripes. If not, slightly turn the screws on M2 back and forth, or repeat the previous alignment.
- If you see stripes, then the beams interfere, however they are not completely copropagating. If two beams interfere under an angle, they form a striped interference pattern.
  Figure: If two waves overlap under an angle alpha, they create an interference pattern that can be captured on a screen. The interference pattern is a series of stripes with distance d. The connection between the angle, wavelength and fringe spacing is the same as for the diffraction grating we discussed earlier:$d sin \alpha = \lambda$; the derivation is analog.
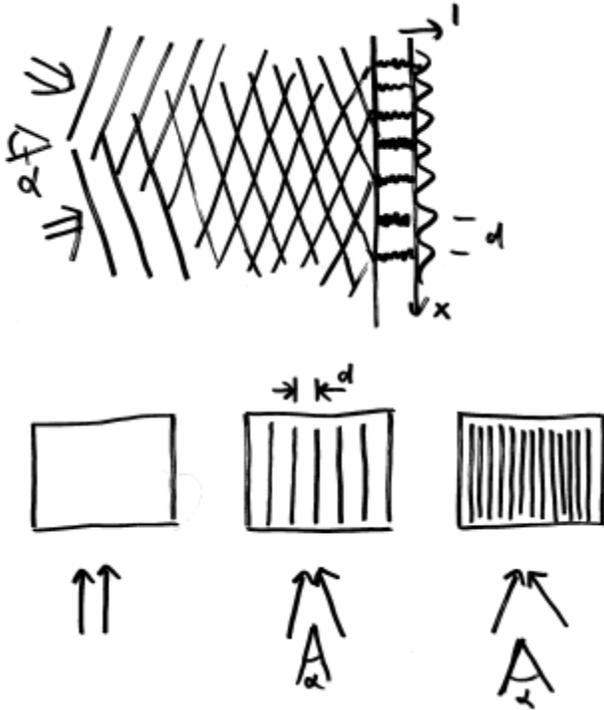

Figure: Striped interference pattern: For a larger angle, the stripe pattern is very small. As the angle between the beams is reduced, the stripe pattern becomes larger. For parallel beams, the pattern disappears.
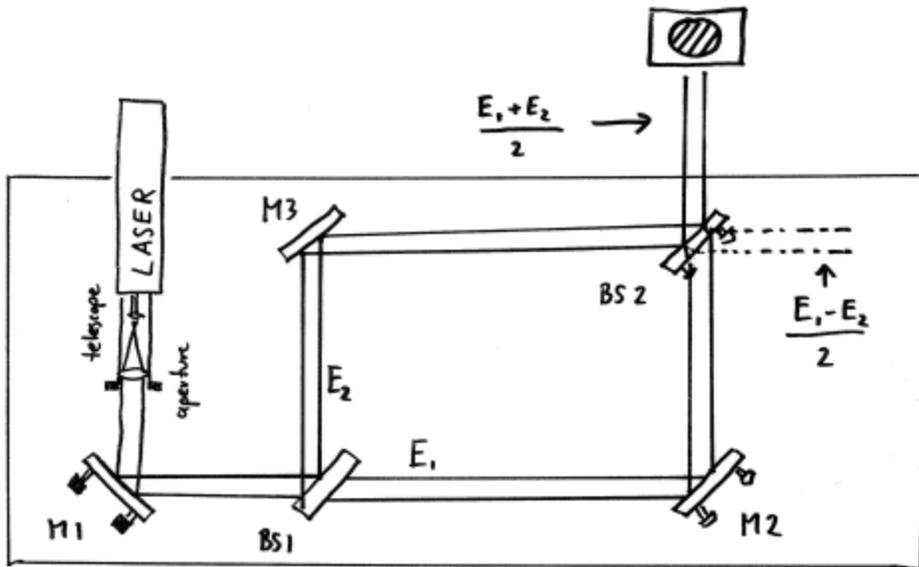
Figure: The complete interferometer setup. The interference pattern of the two interfering beams is visible on the screen.

- Set the adjustment screws of M2 such that you see 5 interference stripes over the 25mm aperture. **You already calculated the relative angle alpha between the beams in the prelab, but for a given wavelength of 550 nm. What is the relative angle alpha between the beams at the wavelength you calculated for the actual laser you are using?**
- Set the adjustment screws such that the fringes nearly disappear, or to a few fringes. Explore what happens as you touch the breadboard, mirror holders etc.

The interference pattern moves as you move mirrors or deform the breadboard. This is because you change the relative phase of the two waves E1 and E2 as you change their optical path length before they are recombined. The phase difference depends on the difference in path length as $\Delta \phi = 2 \pi (\Delta l)/\lambda$.

In other words, if the path length difference equals the wavelength in the medium, the fringes get shifted by one period. Or, if the beams are parallel and you have no fringes, you cycle once between constructive and destructive interference.

8. Paradox: Where does the light go if beams cancel each other? Align the interferometer so that the beams are parallel (fringes nearly disappear). Close the aperture so that the beam is only a few mm large. If you now touch the breadboard, the beam oscillates between bright and dark due to constructive and destructive interference. Where does the light go? It should be conserved (energy conservation) unless it is absorbed somewhere. **Explain (and discuss with TF).**

Precision measurement: Index of refraction of air

The speed c with which light travels in matter is smaller then the speed of light in vacuum c_0. This means that the wavelength λ is smaller than the wavelength in vacuum λ_0:
$\lambda = \lambda _0 /n$

where *n* is the index of refraction. So n=1 for vacuum, n=1.5 for glass. The index of refraction of air is very close to the index of refraction of vacuum, but slightly larger. You can see this by looking at the shimmering air on a hot roof or hot street in the summer, which is based on refraction and therefore requires modulation in the index of refraction. We can measure the index of refraction of air by placing a gas cell into one arm of the interferometer. When we evacuate the cell, the light wavelength inside the cell becomes slightly larger then in air. This will change the effective optical path length and shift our fringes. **The cell has an effective length of 61 mm**.

9. Put the gas cell into one of the beam paths and tweak the interferometer such that you can see a few stripes. Now, evacuate the gas cell and close it with a hose clamp. Slowly open the hose clamp until the fringes start to move as air starts to flow in. Count by how many fringes the pattern moves until the cell is back at ambient air pressure. What is the index of refraction of air? (Hint: How many wavelengths fit into the cell under vacuum? How many more fit in (as you measured) if the cell is filled with air?)
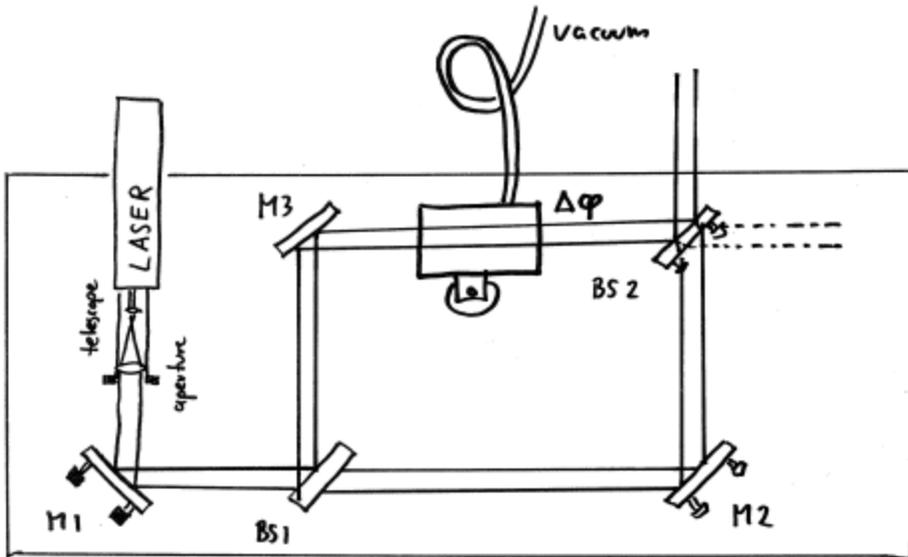
Figure: Gas cell in one interferometer arm to measure the index of refraction of air.

Interferometric imaging

An interferometer can be used to image an object that does not absorb light, but merely changes the phase of a light wave by modulating the index of refraction. (This is similar to phase contrast imaging that you might have heard of in the context of biological imaging).

10. Take the gas cell back out and put a candle flame into the beam instead.

- Play with the beam alignment until you can nicely see a phase relief of the object. **Why is the index of refraction in the flame different (possibly two reasons)? By how many fringes is the center of the flame shifted.**
- **Block the other beam, what happens?** Open the beam again.
- Instead of the candle, image the gas nozzle of a lighter. Look at the shadow image – can you see the gas?
- Hold a piece of transparent material (overhead projector slide etc.) into one of the beams. Can you explain the chaotic interference pattern you observe? ... This should explain why the optical components in this lab are quite pricy ... .

Piezo effect

Replace the mirror M3 by the smaller mirror that is mounted onto a piezo actuator. By applying a voltage to the piezo crystal, it deforms and moves the mirror.

11. **Vary the voltage and count the fringes. How much does the optical path length change per volt?**

Piezos are used in many precision positioning applications not only for optics. For example, the probe tip of a scanning tunnel microscope or atomic force microscope is moved with piezo crystals.

If you have time left: Optional problem:

Polarization

Use the polarizers to try and make the interference pattern disappear. You will find that waves with orthogonal polarization do not interfere.

If you are interested in quantum mechanics: This effect has an interesting interpretation in the context of quantum mechanics: Each of the photons in the light beam travels "simultaneously" through both beam paths. You could test this by reducing the laser power to a point where only single photons are in the interferometer. You would still see the same interference pattern. However, according to quantum mechanics, you can only observe an interference pattern if you can not distinguish through which of the two paths the photon went. If one of the paths is horizontally polarized, and the other one vertically, you can tell which path the photon went by looking at its polarization. Hence, the interference should disappear – and it does as you can see in the experiment.

This last point was too fast? Don't worry. I hope you enjoyed the lab.