EPFL

Interferometer

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Nanophotonics and Metrology Laboratory

Institute of Microengineering,

School of Engineering,

École Polytechnique Fédéderale de Lausanne,

EPFL-STI-IMT-NAM

ELG 237

Station 11

CH-1015 Lausanne

Web : http://nam.epfl.ch

Contact person: Dr. Toralf SCHARF,
Phone: +41 21 6954286
E-mail : toralf.scharf@epfl.ch

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1 Objective and overview

The practical work should introduce the following subjects to you:

- Understand the operation principle of a Michelson interferometer
- Evaluate conditions for fringe contrast and form under different conditions
- Measure the (temporal) coherence properties of a laser diode
- Measure a surface tilt with phase shifting interferometry

To get this done you need to read the reference document provided.

2 Safety Issues

In this experiments laser sources and low power electrical equipments are used. The laser is of class II. Class II: low-power visible lasers that emit a radiant power below 1 mW. The concept is that the human aversion reaction to bright light will protect a person. Only limited controls are specified. (http://www.osha.gov, Laser Hazards)

The laser is safe because the blink reflex of the eye will limit the exposure to less than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Intentional suppression of the blink reflex could lead to eye injury. In our experiment the laser sources are collimated and should be handled with care. A strongly divergent beam will not be focussed on the eyes retina and represents often no danger. Collimated beams will lead to small focus spots onto the retina special care is needed. ***Do not stare into a collimated beam!***

The electrical equipment used in the experiments is based on USB power (5V, 0.5 A, 2.5 W) and not subjected to any particular security issues. Nevertheless you should **not produce short circuits** on the printed circuit board (PCB) or to the computers USB connection to avoid damage to the material. Make proper use of screwdrivers. Do not force any mechanical parts.

3 Background

Camera

In our experiment we use a pixelated camera. The pixels are arranged in a regular array that is produced at very high precision. The camera chip has 1600 x 1200 pixels and is 4.536mm x 3.416mm wide and large respectively. Pixel pitch is 2.835 micron in both directions (square). We can safely assume that there is no deviation of pixel position.

Interference and coherence

The addition of coherent light beams results in intensity modulation: the interference fringes. The important term is coherent. Coherence has two aspects

- Spatial coherence
- Temporal coherence

Spatial coherence is linked to the physical size of the source. A monomode laser (one wavelength, one polarization) for instance is a coherent source with the highest spatial coherence but still has a finite coherence length. To see interferences, light has to be superposed with path differences within the coherence length. If a spatially extended source is used the superposition of coherent areas in the spatial domain has to be assured. This is achieved by observing multiple images of the source that overlap in the plane of observation.

Temporal coherence is linked to the **spectral properties** of light. Thin (limited) spectra have higher coherence than wide spectra. It is possible to quantify the coherence by the **coherence length l_c**. There are different definitions based on the measurement of contrast of fringes in an interferometer. We use the following formula:

$$l_c = \frac{1}{n}\frac{c}{\Delta v} = \frac{1}{n}\frac{\lambda^2}{\Delta \lambda} \qquad \text{Eq. 1}$$

The refractive index n is the refractive index of the surrounding medium. The coherence length depends on the bandwidth (optical frequency) Δv, the speed of light c. It can be expressed in wavelength λ and spectral width $\Delta \lambda$. We work mainly in air, therefore, we set n=1. The table below gives indicative values of coherence lengths for the different sources we use

Source	Center wavelength	Spectral width	Coherence length
Halogen lamp (visible)	550 nm	300 nm (400 – 700 nm)	1 μm
LED	635 nm	20 nm	20 μm
Monomode laser	635 nm	0.2 nm	2 mm

The coherence properties of the light emitted by different sources are determined by measuring the contrast of fringes in an interferometer. In an interferometer the light propagation is well managed and fringes of defined geometry appear.

Laser source

Interference is easily observed with a laser. As a laser source, a **monomode laser diode** (model Opnext_Laserdiode-HL6354_EN) was chosen. The spectral properties are shown below. The width of a single peak is below 0.2 nm FWHM. If no special measures are taken lasers have several modes. The spectral separation and spectral width of the modes are determined by the geometry of the laser resonator (Fabry Perot effect!). The pumping (electrically or optically) of the system gives its power generation properties.
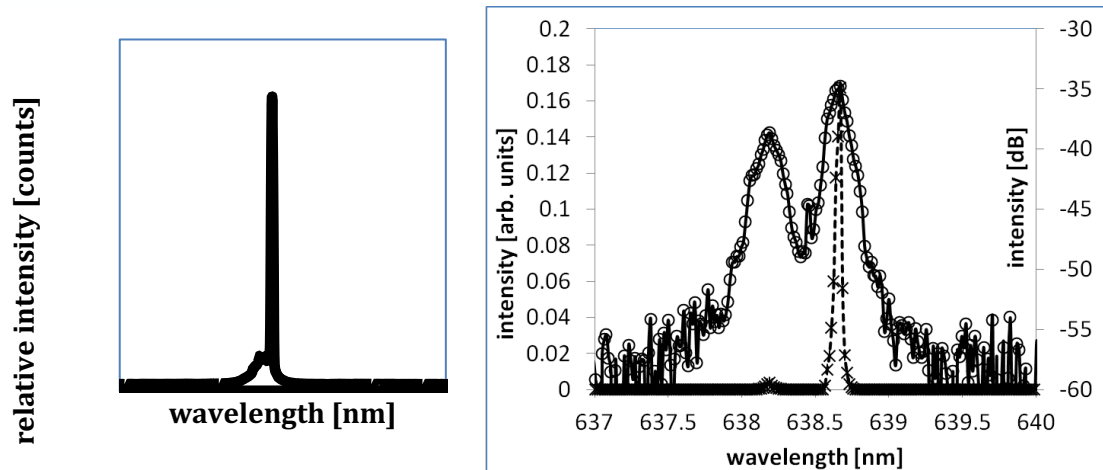
Figure 1. Spectral characteristics of the monomode laser diode measured at different resolutions. Left: as measured with a miniaturized grating spectrometer. Right: measured with an optical spectrum analyzer in linear and logarithmic scale. The logarithmic scale (right side) reveals that there are two peaks of different intensity and that the laser is not strictly monomode (only one peak is allowed)

The laser diode has a very small active zone which leads to diffraction. Because the active zone is not symmetric the emission profile is elliptical.
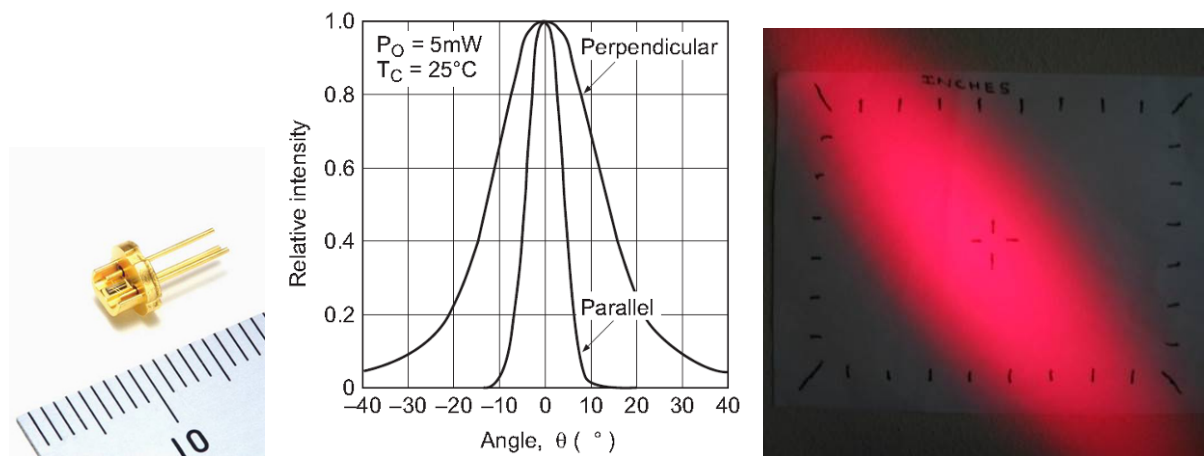
Figure 2. Appearance and emission profile of the laser diode. The emission profile is not symmetric and leads to an elliptical shape in the far field.

For our experiments, it is important to note that the laser has at least **two** wavelengths. This will lead to particular properties (beating) in space and can be detected with the Michelson interferometer.

Interference and contrast

Interference is a wave phenomenon. It appears when coherent waves are superposed. The spatial and temporal coherence of the waves have to be considered. The result of interference phenomena are interference fringes in space. The mathematical description of interference can be easily done for the one dimensional case. It can be extended to three dimensions. Here, we

repeat the description for the one dimensional case to define the fringe contrast and the fringe period.

The amplitude of the electric field E has to be considered. For two waves of the same frequency, the superposition gives:

$$E = E_1 + E_2$$

Eq. 2

The irradiance I is the square modulus of the field (see for instance Hecht, Optics Addison Wesley 1998 page 377 ff).

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\delta$$

Eq. 3

The irradiance values of the two waves I_1 and I_2 are given by the time average of the electric field. The last term in the equation is the interference term. It is usually written as

$$\delta = \left(\mathbf{k_1} \bullet \mathbf{r} - \mathbf{k_2} \bullet \mathbf{r} + \varepsilon_1 - \varepsilon_2\right)$$

Eq. 4

One considers a position in space **r** (vector) and this equation is a vectorial equation taking into account all dimensions and the direction of propagation (trough the vectors $\mathbf{k_1}$ and $\mathbf{k_2}$). Innitial phase differeneces of interfering waves are put into the value ε_1 and ε_2. To get this equations it is important to consider the time average of the measurement. This is because our detector will not see the fluctuation at light frequencies. The phase difference δ governs the intensity found in Eq. 3. The phase difference can take any value but the final term describing the intensity is the cosine of that and hence varies between -1 and 1.

$$\cos\delta = \cos\left(\mathbf{k_1} \bullet \mathbf{r} - \mathbf{k_2} \bullet \mathbf{r} + \varepsilon_1 - \varepsilon_2\right)$$

Eq. 5

So the maximum value of intenisty and the minimum value of intensity for a given problem can be caluclated. We will consider two examples.

Fringe contrast for monochromatic wave

An important parameter is the **contrast** of the interference fringes. The contrast is defined as the difference of intensities divided by the sum of intensities.

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Eq. 6

We consider a one dimensional problem and wave travelling along the same direction at the same wavelengths. The wave vector $\mathbf{k_1}$ and $\mathbf{k_2}$ are equal $\mathbf{k_1} = \mathbf{k_2}$ and only the initial phase delay ε_1 and ε_2 have to be condsidered. Here ε_1 and ε_2 represent optical path differences hence path lengths of the travel to the observation points **r** at the same speed of light c. Equation 4 has values from -1 to and 1 and a maximum and minimum intensity can be found. We caluculate the fringe contrast and considers Eq. 1 which can be reformulated as

$$C = \frac{I_1 + I_2 + 2\sqrt{I_1 I_2} - I_1 - I_2 + 2\sqrt{I_1 I_2}}{I_1 + I_2 + 2\sqrt{I_1 I_2} + I_1 + I_2 - 2\sqrt{I_1 I_2}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}$$

Eq. 7

If the intensities are equal the formula gives a contrast of 1. If the intensities differ then the contrast is less than one.

Interference with several frequencies (beating)

Another very interesting case is when the wave vectors $\mathbf{k_1}$ and $\mathbf{k_2}$ are pointing in the same direction but have different values because the wavelength is not the same. The general case is rather complex and is the basis of Fourier transform spectroscopy. We consider here two wavelengths only. We are interested in the contrast of fringes induced by this effect and we do not consider additional phase delay. We set $\varepsilon_1 - \varepsilon_2$ to zero. We reformulate the phase delay using a one dimensional form with scalar values of k, writing z for the position and taking $\varepsilon_1 - \varepsilon_2 = 0$.

$$\cos\delta = \cos\left((k_1 - k_2)z\right) \qquad \text{Eq. 8}$$

The wave vectors are related to the wavelengths through $k_1 = 2\pi/\lambda_1$ and $k_2 = 2\pi/\lambda_2$. One can find

$$k_1 - k_2 = \frac{2\pi}{\lambda_1} - \frac{2\pi}{\lambda_2} = 2\pi\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) = 2\pi\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) \approx 2\pi\frac{\Delta\lambda}{\lambda^2} \qquad \text{Eq. 9}$$

$$\cos\delta = \cos\left(2\pi\frac{\Delta\lambda}{\lambda^2}z\right) \qquad \text{Eq.10}$$

For a given position in space r (or z) we will find a particular value of the phase difference δ and a certain intensity corresponding to its cosine value. If we change z the intensity will change and will lead to a full modulation over a distance that is given by the periodicity of the cosine function as a multiple of its period which is $\lambda^2/\Delta\lambda$. One full intensity variation is obtained when moved by $\Delta z = \lambda^2/\Delta\lambda$. Consider a concrete example. Assume we have a laser with a spectral width of $\Delta\lambda = 0.2$ nm at $\lambda = 635$ nm. We get

$$\Delta z = \frac{\lambda^2}{\Delta\lambda} = \frac{(635\text{nm})^2}{0.2\text{nm}} = 2\text{mm} \qquad \text{Eq. 11}$$

It is possible to show that this "beating" behaviour of varying contrast is not only found for the intensity but also for the contrast of fringes in an interferometer.

Michelson interferometer

The Michelson interferometer is only one of a multitude of different interferometric arrangements. The figure below shows its geometrical layout. It is a wavefront splitting interferometer and it uses either a beam splitter cube or beam splitter plates to divide the intensity of the beam in two directions or paths. In the example below, the laser send light onto the beam splitter and propagates further to the mirrors. The light is reflected back from the mirrors, recombines at the beam splitter and reaches the detector. In our case, the detector is a camera that allows to see the form of the fringes. Note that the same amount of light is send back towards the source (laser) and might influences the source radiation conditions for some particular cases.
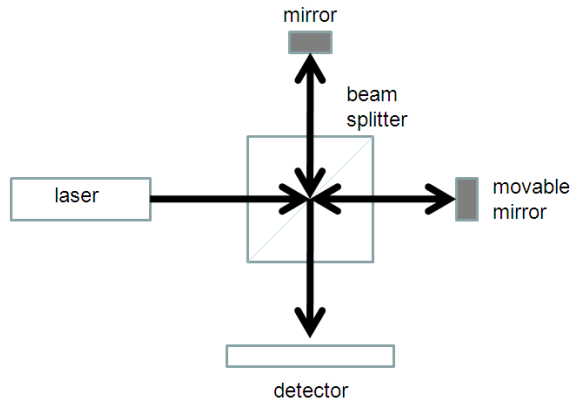
Figure 3. Geometry of a Michelson interferometer with the source (laser), beam splitter cube, two mirrors and a detector

When we illuminate the interferometer with a point source (monomode laser diode). The radiation is not collimated. The figure below shows what will happen.
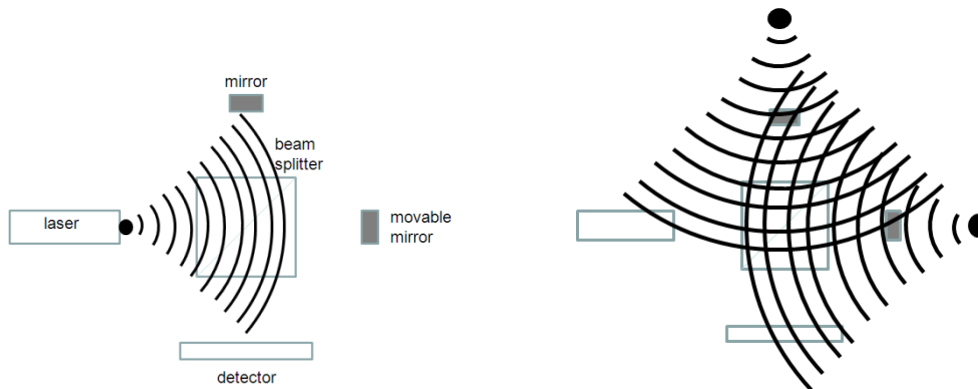

Figure 4. Point source illumination and the appearance of two virtueal sources behind the mirrors of the interferometer.

The beam splitter divides the incoming light which is then reflected at the mirrors. If we were looking inside the interferometer from the detector, we would see **two virtual point sources**. Depending on the position of the mirrors and the beamsplitter the virtual images of the sources may be found at different positions. There are particular configurations that lead to well defined fringe geometries. A few examples are given below

Point sources at the same depth but different positions
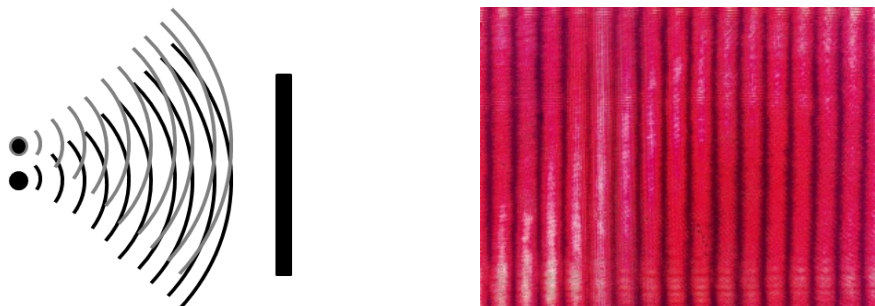
In the detector plane two waves with equal curvature arrive and lead to a set of parallel fringes.

Point sources at the same position but at different depths
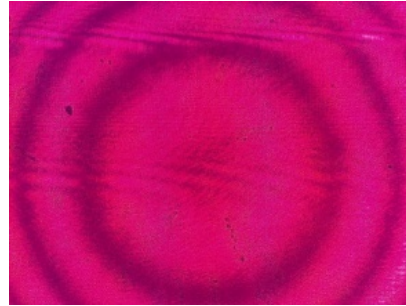

The curvatures of the superposed spherical waves are different and circular fringes become visible. Because the sources are approximately on axis (centered) with respect to the observation plane the fringes are symmetric and appear as nice circles.

Point sources at arbitratry positions
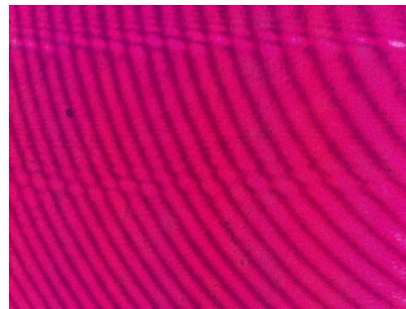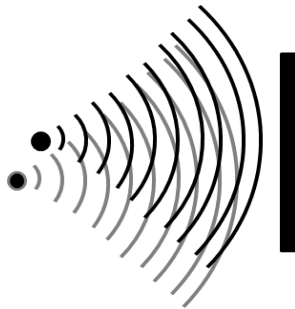
In this general case the point sources are displaced in both directions. Curved fringes of different spacing appear. The spacing of the fringes could be very narrow (!) and may be difficult to detect.

Zero optical path difference ZPD
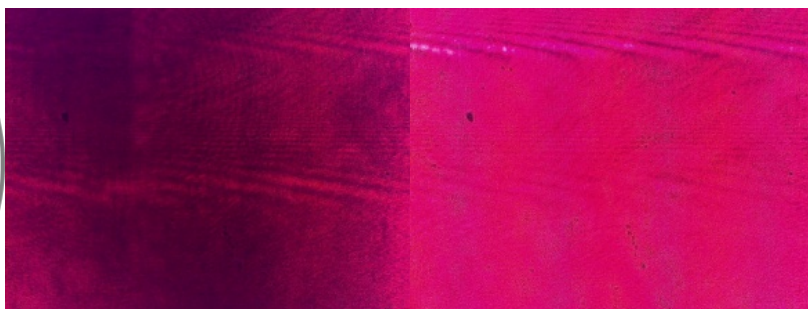
The most exclusive position appears when there is complete positional coincidence. In this situation, the direct fringe intensity is observed. It might be bright or black. The interferometer is now aligned. The source images are superimposed within a precision better than one fringe that is half the wavelength (at 635 nm this means better than 300 nm). If the intensity is very uniform the alignment is even better.

Optical path difference and fringe contrast

As discussed above the spectral characteristic of the laser (two wavelengths) will lead to a beating effect. To make this visible the optical path on axis in the interferometer has to be changed. The figure below shows the principle.
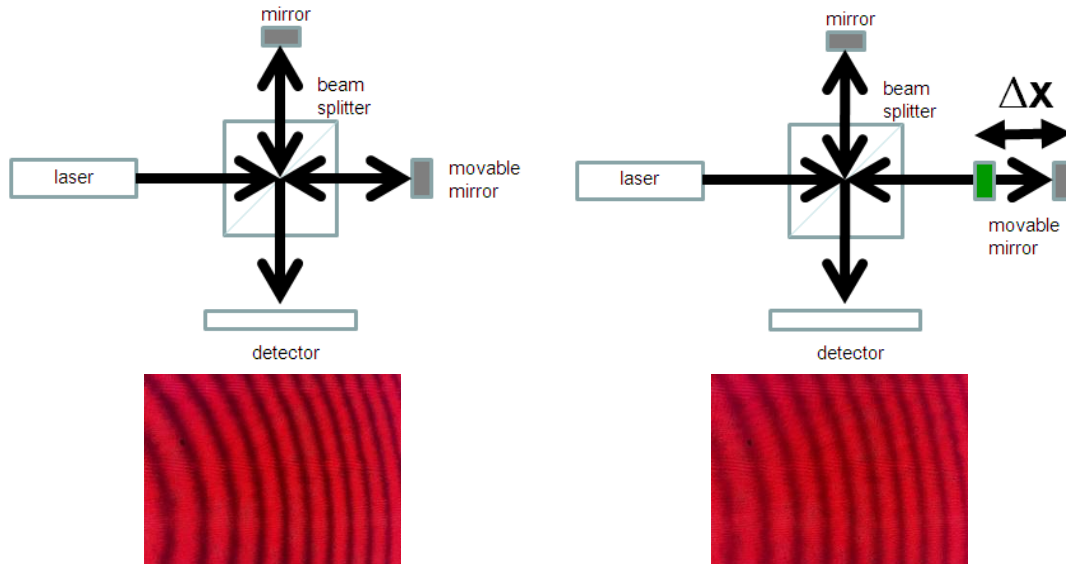
The images of fringes below show the contrast variation as a function of position Δx. The contrast variation depends on the laser and its operation conditions and varies very much between different sources of the same type.
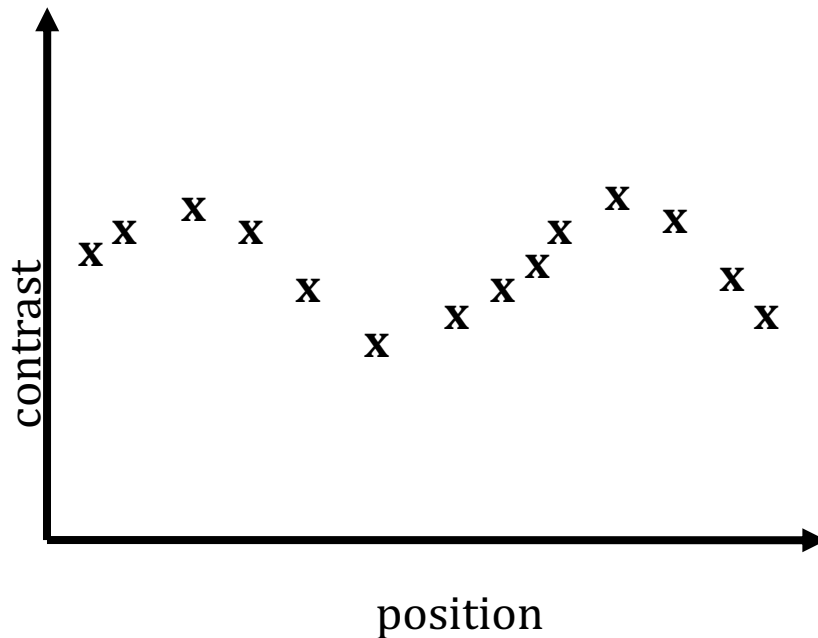
Figure 5. Contrast versus measurement position.

As an example, we show in the figure above the measured contrast for the monomode laser. The contrast shows two maxima at a distance of approximately 1.8 mm. Using Eq. 9, one can calculate the spectral width (or distance of beating frequency). Here we have Δz=1.8mm and λ=635nm

$$\Delta\lambda = \frac{\lambda^2}{\Delta z} = \frac{(635\text{nm})^2}{1.8\text{mm}} = 0.22\text{nm}$$

Eq. 12

Note that when moving the mirror the contrast and the fringe geometry are changing. A sequence of frame is shown below.


Figure 6. Fringe appearance for movements of 2 mm between each image.

The fringes show different contrast and the curvature increases, a typical sign of depth difference of the two sources in the interferometer. In the experiment to evaluate the interference of sources with a certain spectral width and beating only the contrast is important. The geometry of fringes is not considered.

4 Setup and equipment - tasks of the experimental work

4.1 Setup and alignment

A Michelson interferometer is a beam dividing device to interfere light. In our case a laser beam is divided by a beam splitter and sent on two mirrors as shown below.
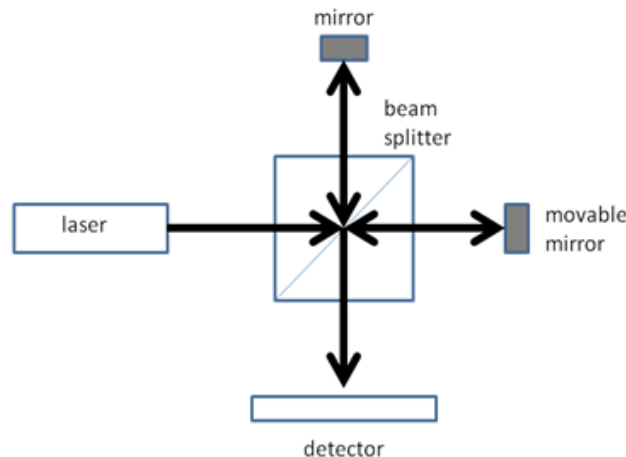
The mirrors reflect the light and a detector (CMOS camera) is used to visualize the result. Because of the beam splitting, the detector sees light coming from two virtual sources. A laser is a highly coherent source and allows to create interferences over large surface areas and large movement distances of the movable mirror. In our case we use directly the laser diode without collimation. The laser produces a diverging light cone that is sent to the interferometer.

Materials

- A CMOS camera (1600x1200 pixels, colour, pixel size 2.835 um) C600 from Logitech
- Laserdiode, USB driven
- Mechanical setup
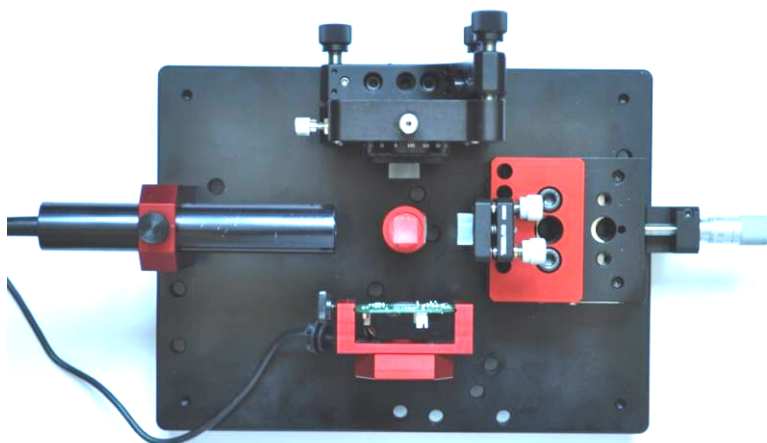
Mechanical holders and setup

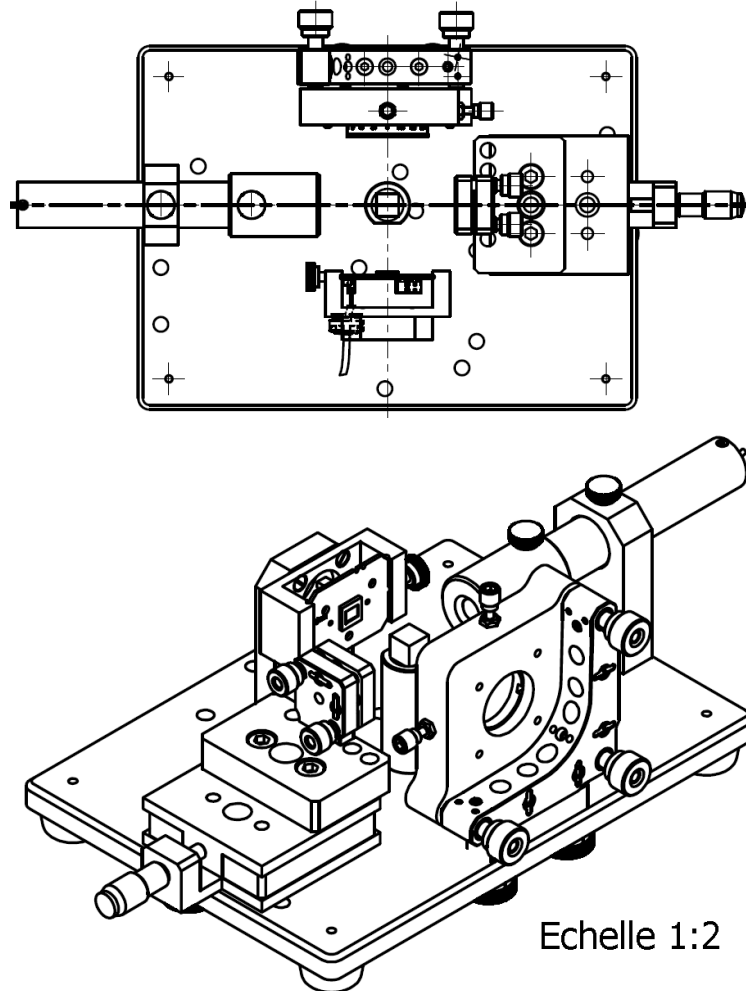Figure 7: Top view of the Michelson interferometer

Echelle 1:2

Figure 8: Schematic view of the mechanical setup; top view and perspective view with lens cap that is **ONLY** used in pre-alignment procedure.
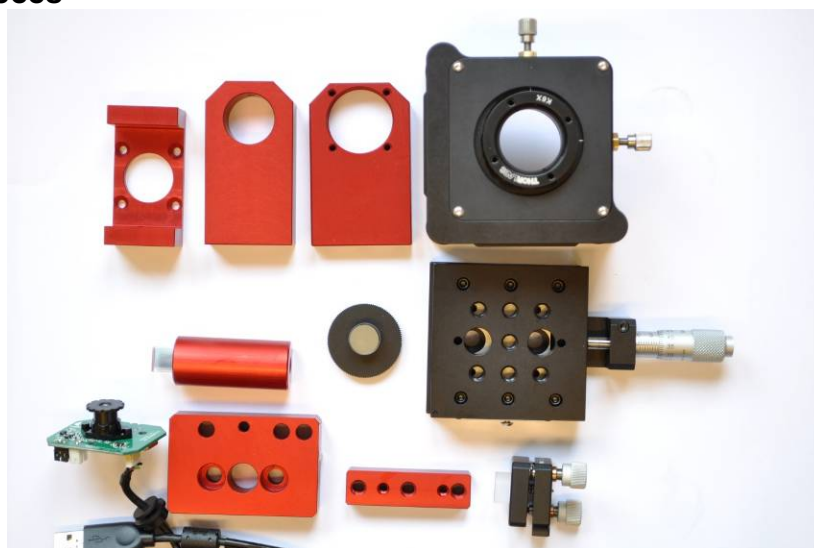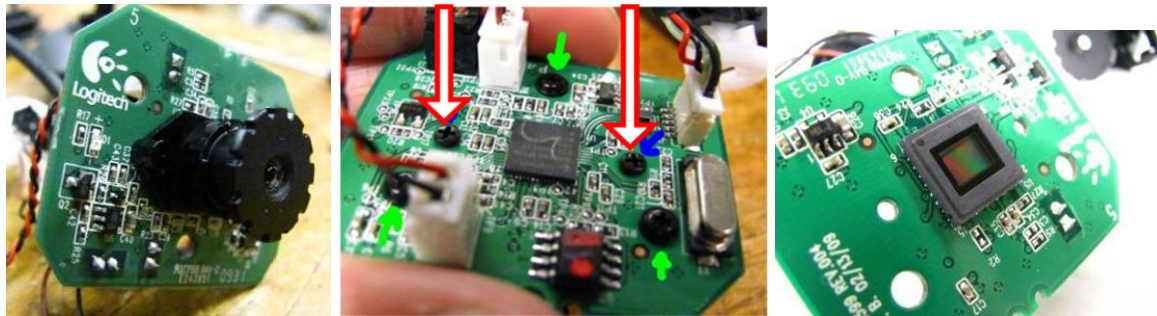
Detached pieces

Figure 9: Separate elements provided for the experimental setup.

The linear stage has to be mounted with 45° movement direction with respect to the source and the camera. The camera is used without objective and IR filter to allow direct access to the camera chip.

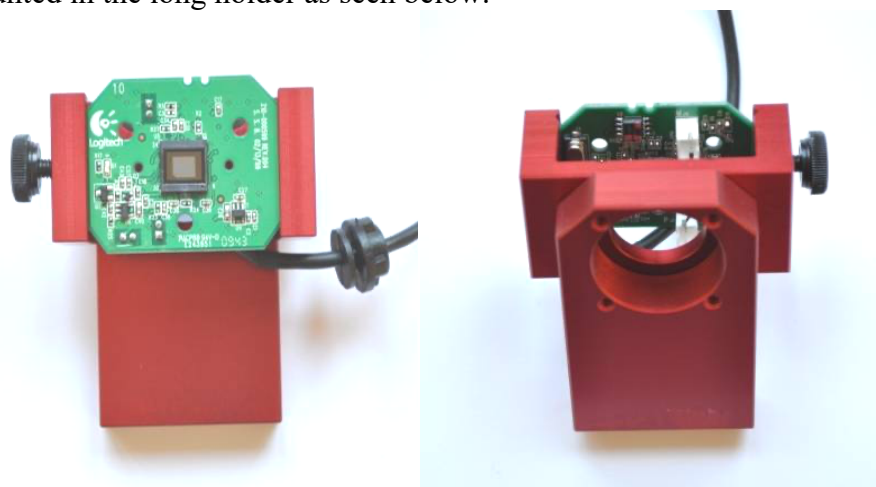Camera is mounted in the long holder as seen below.

Figure 10: Close view of the CCD holder; a) front view, b) rear view. The camera is mounted in the holder without its objective.
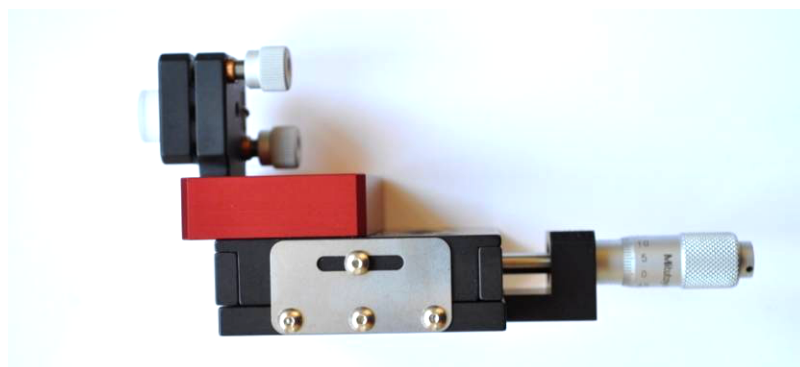

Figure 11: One mirror is mounted on the translation stage (side view).The other mirror is already mounted on a tilting stage to align its angle and **SHOULD NOT BE TOUCHED.**
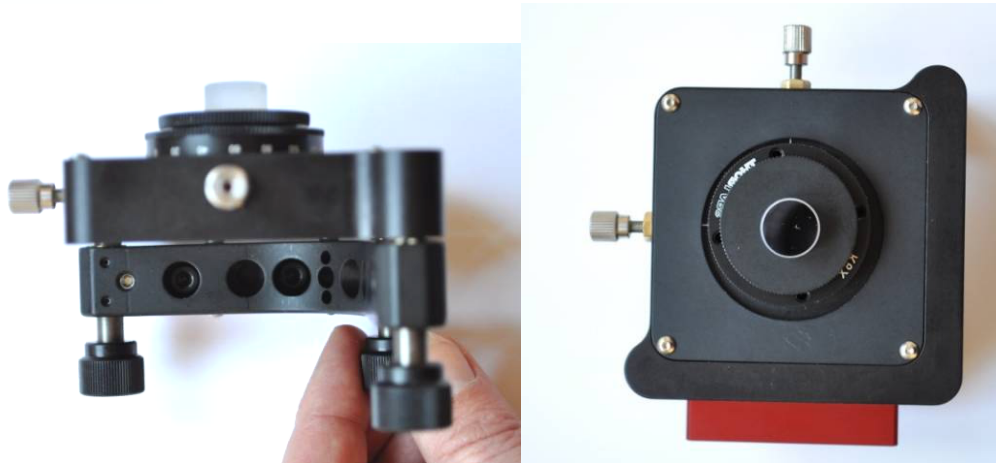
Figure 12 The second mirror is mounted on the six axis stage; left: side view, b) front view, and **SHOULD NOT BE TOUCHED.**

Figure 13 The beam splitter is a 10 mm cube mounted on a cylinder and **SHOULD NOT BE TOUCHED.**

CAUTION: Do not touch optical surfaces of the mirrors and the beam - splitter cube!

Consider the following details:
- The laser source is fixed with its special holder.
- Start by setting the linear movement stage to its central position (at about 6 mm).
- **Take care that the beam splitter is in the right position and sends light to both mirrors!**
- Move the angular adjustment of the mirrors to set small angles at the beginning. Avoid position of the alignment screws at the end of movement range.

Pre-alignment procedure

An interferometer is a high precision instrument and need carful alignment. It is recommend to assure a good spatial alignment which is nothing else than to superpose the source images on the detector. This is done by creating an image of the source in the detector plan. To do so, use the lens cap.
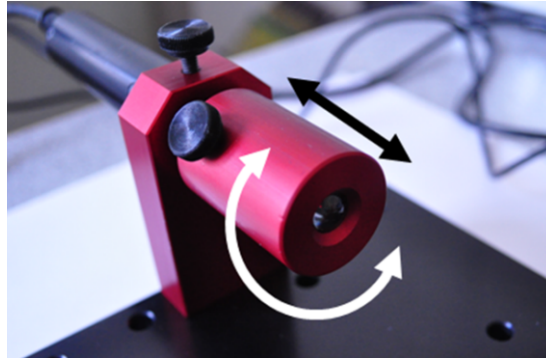
Figure 14. Focalization (black arrow) and intensity adjustment with the lens cap.

- Make sure that all components are well fixed.
- Check camera position (height should correspond the beam splitter and laser).
- Focus the laser on the surface of the detector.
- Adjust intensity.
- Check by naked eye where your focus spots are. You should see two spots that correspond to images created by the two arms of the interferometer. You need to rotate the beam splitter to adjust position.
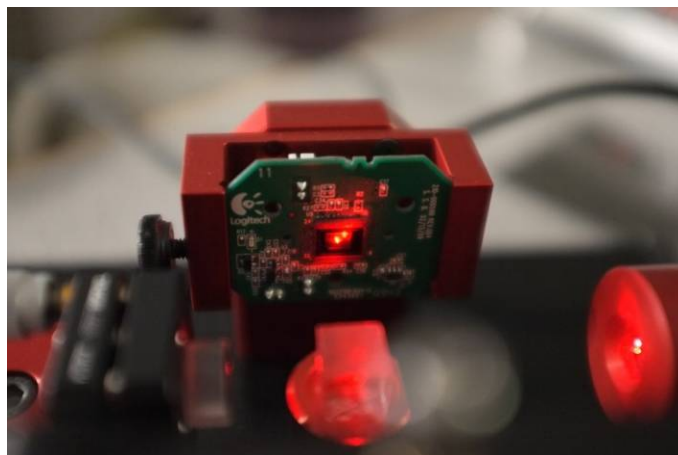

Figure 15. Focus spots at the detector during pre-alignment procedure. The two spots have to be superposed by adjusting the mirror position.

- Identify the image from each mirror on the detector by turning the tilt alignment screws for the two mirrors separately.
- Superpose the images in the middle of the detector by adjusting the tilt of the mirror
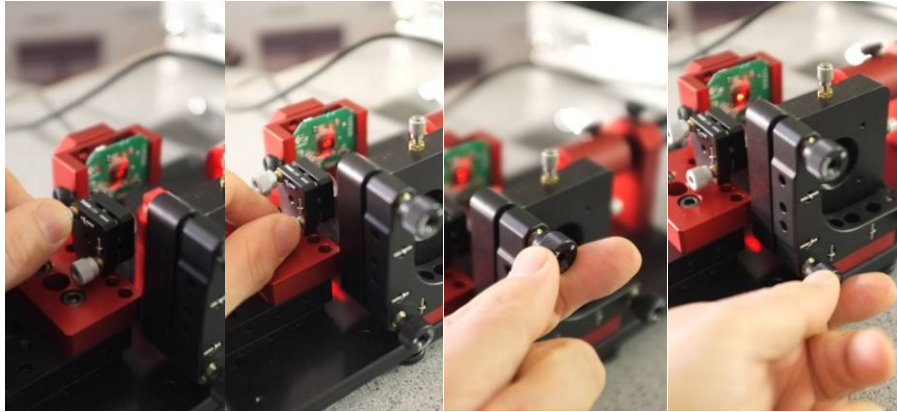
Figure 16. Adjustment screws of the tilting stages to align the spots over each other. Please note that all three knobs might be used!
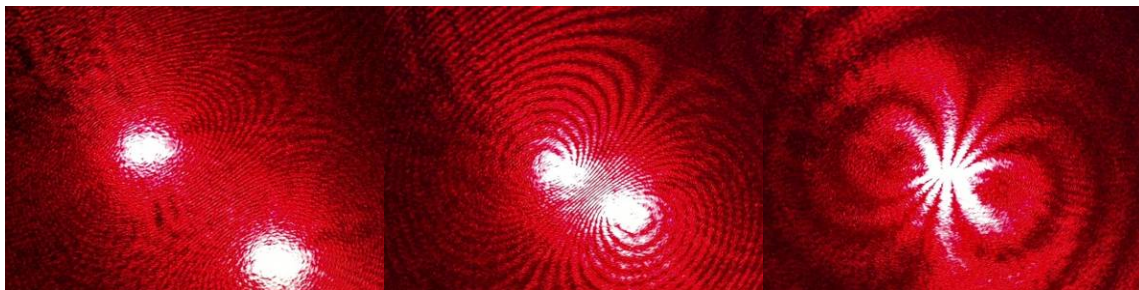

Figure 17. Images of the spots as seen on the detector at different stage of the alignment the two spots have to be superimposed as seen in the right image.

The pre-alignment procedure is done. **You can remove the lens cap and look at the interferogram directly.**

4.2 Zero optical path difference – ZPD and interferometer alignment

- Make sure that all components are fixed and do not move.
- Check camera position (height should correspond the beam splitter and laser).
- Set the camera exposure conditions to automatic for adjustment.
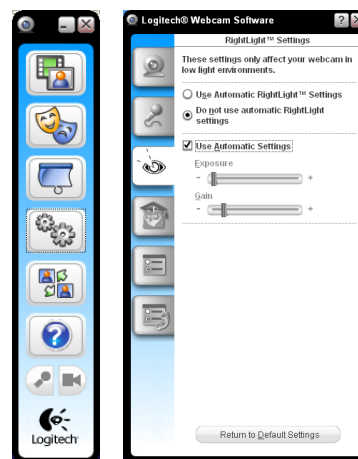
- If the detector is saturated or needs more light increase or decrease the distance of the laser to beam splitter respectively. (intensity follows a square law with distance)
- Move SLOWLY the linear motion table to find fringes on your detector. This might look like shown below. The fringe distance can vary very much depending on initial alignment.

- HINT: The laser has an elliptical emission profile by turning the laser you can optimize (minimize) the stray light (light that is reflected by components in the setup but not used for the functionality).

An interferometer can be aligned to its **zero optical path difference** positions. That means that the distance between the beam splitter and the mirrors is aligned to a precision of less than a wavelength. In this case there will be only one fringe (either black or white) on the detector. To find this position the alignment knobs of the mirrors have to be turned to increase the spacing between fringes. It is recommended to use the knobs at the small mirror as shown below.
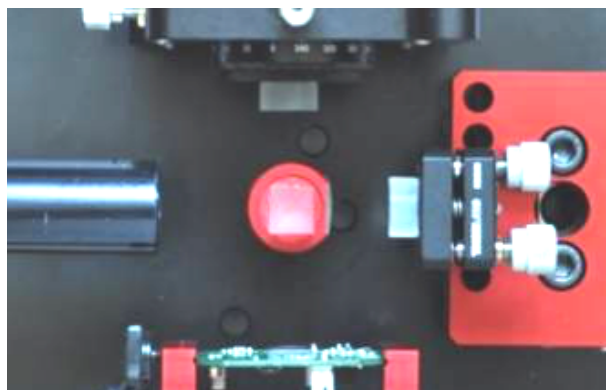
Procedure:

- Turn one know in then direction of increasing fringe distance.
- At a certain moment the fringe distance will not increase anymore but fringes start to get closer again. Stop and user the other knob.
- Turn one know in then direction of increasing fringe distance.
- At a certain moment the fringe distance will not increase anymore but fringes start to get closer again. Stop and user the other knob.
- Repeat until result is satisfactory!!!!

A possible sequence is shown below when turning only one knob of the alignment mirrors.
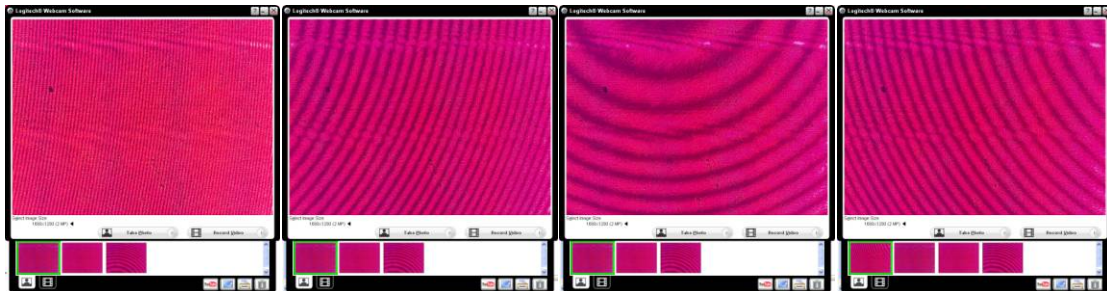
Small fringes on the left and one knob is turned. At the third image the knob is changed and fringe distance still increases.

The final result if well done give you a **circular fringe picture** like shown below.
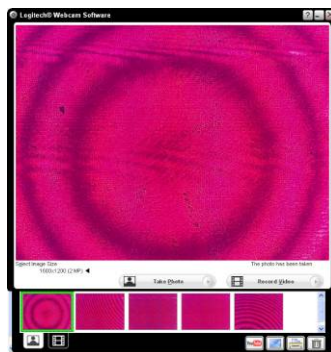
To correct this **curvature** you have to **move the linear motion stage** and eventually correct the angular alignment again until you find the position of zero optical path difference. At the OPD zero position fringes are straight lines and spacing can be very large until one sees only one fringe.

- Move the linear stage until fringes get linear and do not show any curvature
- It can be that the contrast of the fringes during that procedure changes and even leads to a complete invisibility. Just continue to move the stage and the fringes will reappear.
- The zero optical path difference has very high contrast. All settings with curved fringes or low contrast do not correspond to the zero optical path difference
- Try to adjust the system by using all knobs to get only a single fringe

SWITCH OFF the automatic exposure to get best results of fringe contrast.
See the image below for an example for parallel fringes and the zero OPD. The fringe intensity in the OPD zero position with one fringe could be high or low. Touching the setup and deforming slightly the setup allows you to choose one or the other fringe intensity.

To be done for the report: Find the zero OPD position and plot the intensity profile as well as a surface plot for the low intensity state and the high intensity state. ((**2 images 2 surface plots**). Take care that you use **equal exposure** conditions (no auto mode!!!) for both states to show the contrast correctly. Comment why it is so difficult to align for the ZPD.

4.3 Measurement of laser fringe contrast

The interferometer allows to measure the coherence properties of a laser. In the present case we can assume that the laser has several emission lines. This will influence the fringe contrast when studied out of zero optical path difference condition. More precisely it will vary the contrast of the interference fringes. The task is to measure precisely the contrast of the interference fringes as a function of the distance of the mirror.
To do so follow the procedure:

- Find the zero optical path difference position.
- Adjust the interferometer to get a number of fringes (between 10 and 20).
- Record the distance on the translation stage.
- Adjust the exposure and intensity setting to avoid saturation.
- Move the translation stage and record images for different positions.
- Evaluate the fringe contrast with Matlab.

Contrast is given as the difference of the maximum and minimum intensity over the sum of maximum and minimum intensity.

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Image at zero OPD position (A), after adjustment to have number of fringes without saturation (B) and at a position x when moved with the translation stage (C)

| A | B | C |
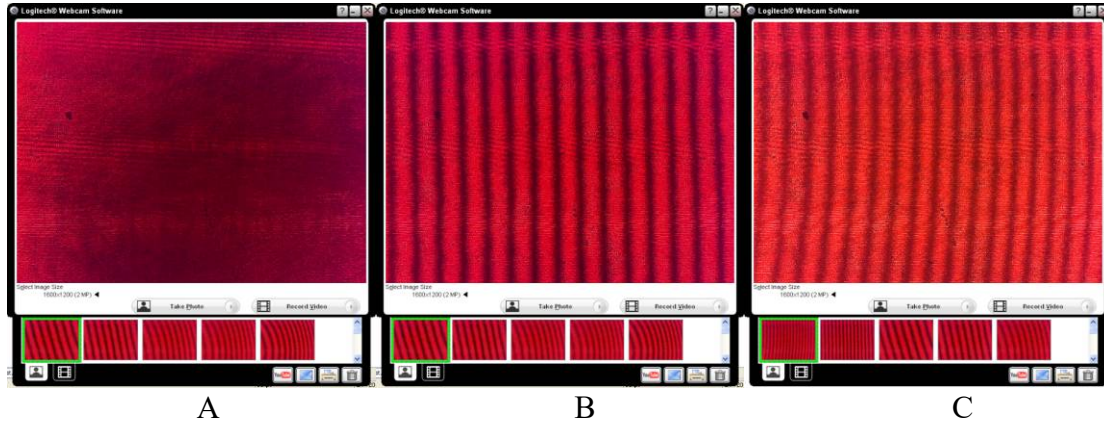
An example Matlab routine is stored under the file name "fringes_center_line_red.m"

```matlab
% Read image 1
I_1 = imread('picture 166.jpg');

% select a channel
Red_1 = I_1(:,:,1);

%plot the channel
figure
imagesc(Red_1,[0 255]);
xlabel('position [pixel]')
ylabel('position [pixel]')

% format conversion
Red_1 = double(Red_1);

% select a line of interest ROI (1 x 1600), here center line
CenterLine_Red = Red_1(600:600,1:1599);

%plot a single line
figure
plot(CenterLine_Red);
xlabel('position [pixel]')
ylabel('signal [counts]')

%average over several lines (vertical)
% select a region of interest ROI with several number of lines N (N x
% 1600), here 200 lines are averaged
ROI_Red_1  = Red_1((600-100):(600+100),1:1599);

%caculate the mean of the RIO obver several rows
N_Avg_Red_1 = mean (ROI_Red_1);

%plot the averaged line
figure
plot(N_Avg_Red_1);
xlabel('position [pixel]')
ylabel('signal [counts]')
```

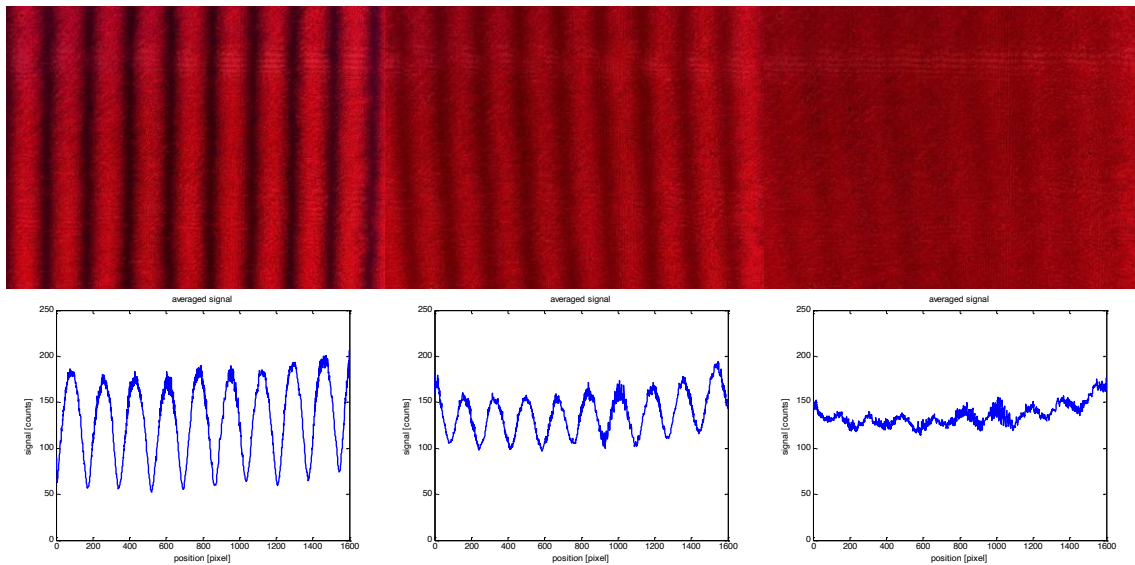The corresponding images and line plots in Matlab are given below.

Figure 22. Examples of the fringe contrast obtained at different positions of the linear stage.

The contrast changes between pictures varies between the lasers and might be difficult to evaluate. The use of line averaging in the Matlab script help in reducing the noise. To apply line averaging, you have to avoid saturation of the image and avoid deformation of the fringes!! Do not use too many lines.
The curve is periodic. This model allows to judge the spectral width (coherence) of the source.
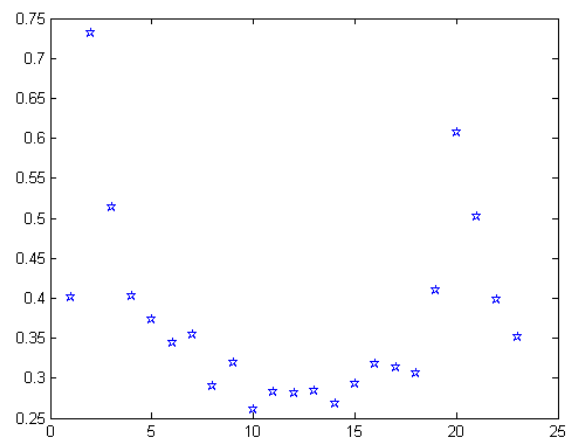

Figure 23. Contrast as a function of measurement position for a real measurement. x-axis is the measurement point number taken each 100 micron. y-axis is the contrast value. The distance between two maxima is approximately 2 mm. Don't forget to label axis!

To be done for the report: Show **three pictures** with different contrast and plot their line curve. (**3 line plots**) Measure the contrast as a function of position of the translation stage (over more than 1 full cycles of contrast variation, minimum 30 points, use the table). Plot the values. (**one graph**) Calculate the spectral widths of the source using the period of the variation. (Eq. 12, where Δz is the period found in your measurement!). Estimate the error of the measurement

5. Summary of tasks of the experimental work

4.2 Zero optical path difference – ZPD (90 min)

Find the zero OPD position and plot the intensity profile as well as a surface plot for the low intensity state and the high intensity state. (**2 images 2 surface plots**). Take care that you use **equal exposure** conditions (no auto mode!!!) for both states to show the contrast correctly. Comment why it is so difficult to align for the ZPD.

4.3 Measurement of laser fringe contrast (45 min)

Show **three pictures** with different contrast and plot their line curve. (**3 line plots**) Measure the contrast as a function of position of the translation stage (over more than 1 full cycles of contrast variation, minimum 30 points, use the table). Plot the values. (**one graph**) Calculate the spectral widths of the source using the period of the variation. (Eq. 12, where Δz is the period found in your measurement!). Estimate the error of the measurement

4.4 WEB - Example

Find an example of an application where interferometry is the key technique. Print a picture; give a **short explanation** and parameters that are measured. Cite correctly.