Interferometer

Nanophotonics and Metrology Laboratory

Institute of Microengineering,

School of Engineering,

École Polytechnique Fédérale de Lausanne,

EPFL-STI-IMT-NAM

ELG 237

Station 11

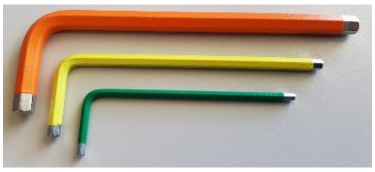
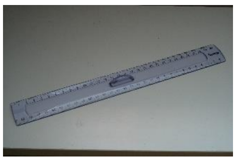
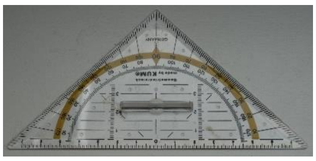
CH-1015 Lausanne

Web : http://nam.epfl.ch

Contact person: Dr. Karim Achouri,
Phone: +41 21 695 42 86
E-mail : karim.achouri@epfl.ch

List of material for the TP

1x board	
1x camera holder (2 parts)	 
1x camera	
1x source holder	
1x laser	 
1x lens cap with polariser	
1x 6 axis stage 1x adapter plate (red part)	
1x mirror	

1x linear stage 1x adapter plate	 
1x mirror on mount	
1x beam splitter	
4x small screws (triangular head) 6x large screws	 
9x large screws with cap 3x small screws with cap	 
3x Allen keys	
1x slotted screwdriver	
1x ruler 1x triangle	 

1 Background

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:

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

The refractive index n is the refractive index of the surrounding medium. The coherence length depends on the bandwidth (optical frequency) $\Delta\nu$, 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.

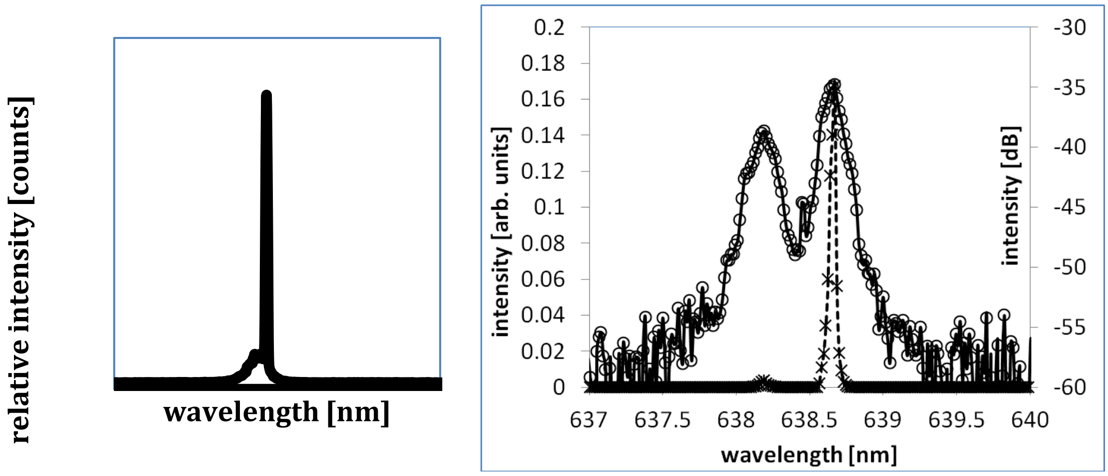


Figure 1. Spectral characteristics of the monomode laser diode measured at different resolutions. Left: as measured with a miniaturized grating spectrometer. Right: measured with an optical spectrum analyzer in linear and logarithmic scale. The logarithmic scale (right side) reveals that there are two 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.

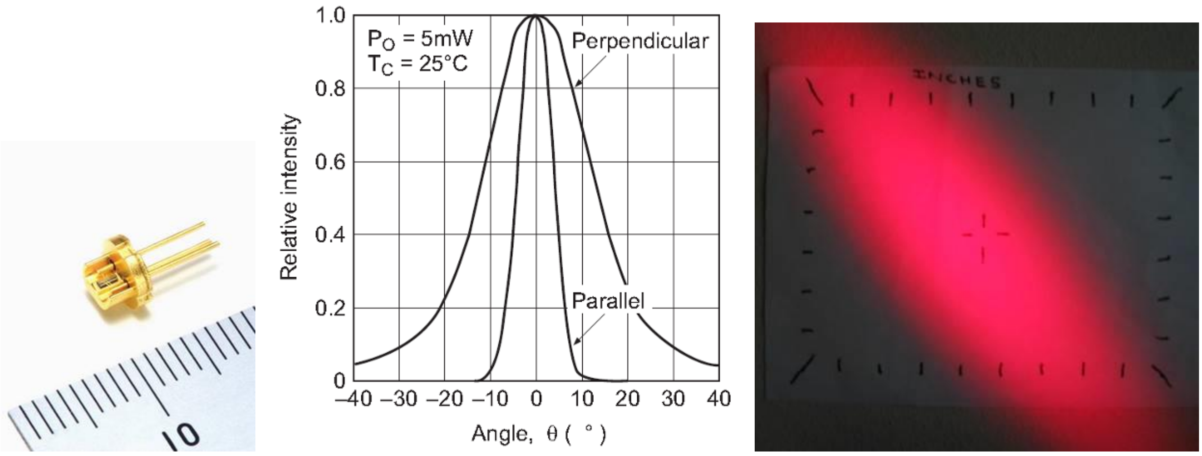


Figure 2. Appearance and emission profile of the laser diode. The emission profile is not symmetric and leads to an elliptical shape in the far field.

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 then 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:

$$E = E_1 + E_2 \qquad \text{Eq. 2}$$

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

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \qquad \text{Eq. 3}$$

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

$$\delta = \left(\mathbf{k_1} \cdot \mathbf{r} - \mathbf{k_2} \cdot \mathbf{r} + \varepsilon_1 - \varepsilon_2\right) \qquad \text{Eq. 4}$$

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 (through the vectors $\mathbf{k_1}$ and $\mathbf{k_2}$). Initial phase differences of interfering waves are put into the value ε_1 and ε_2. To get this equation, 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.

$$\cos\delta = \cos\left(\mathbf{k_1} \cdot \mathbf{r} - \mathbf{k_2} \cdot \mathbf{r} + \varepsilon_1 - \varepsilon_2\right) \qquad \text{Eq. 5}$$

So, the maximum and the minimum value of intensity for a given problem can be calculated. 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.

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad \text{Eq. 6}$$

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 considered. 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 calculate the fringe contrast and considers Eq. 1 which can be reformulated as

$$C=\frac{I_1+I_2+2\sqrt{I_1I_2}-I_1-I_2+2\sqrt{I_1I_2}}{I_1+I_2+2\sqrt{I_1I_2}+I_1+I_2-2\sqrt{I_1I_2}}=\frac{2\sqrt{I_1I_2}}{I_1+I_2} \qquad \text{Eq. 7}$$

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 ε_1 - ε_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 $\varepsilon_1 - \varepsilon_2=0$.

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

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 λ=635 nm. We get

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

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.

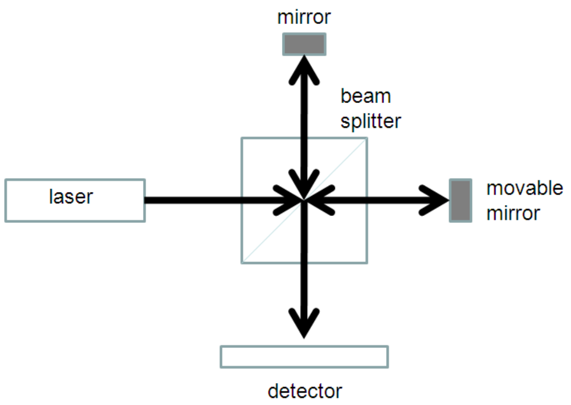


Figure 3. Geometry of a Michelson interferometer with the source (laser), beam splitter cube, two mirrors and a detector

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

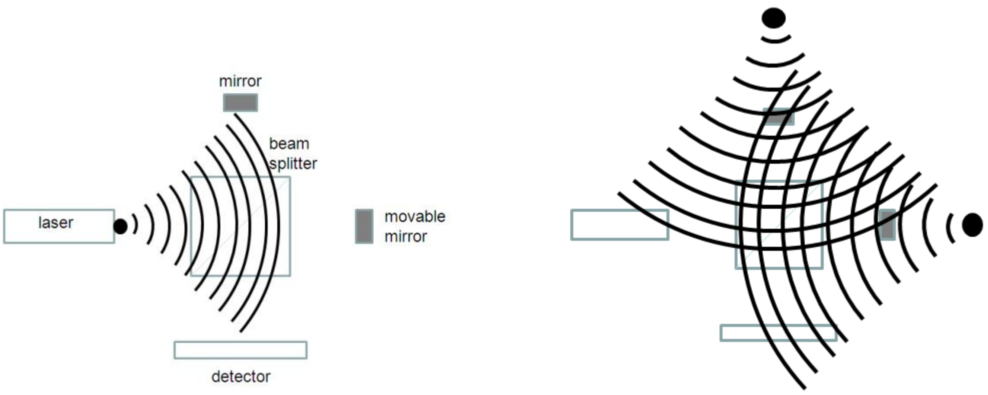
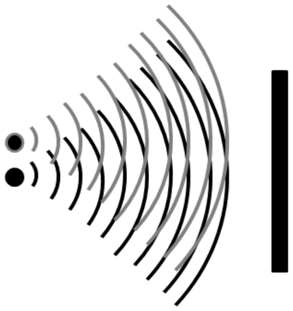


Figure 4. Point source illumination and the appearance of two virtual sources behind the mirrors of the interferometer.

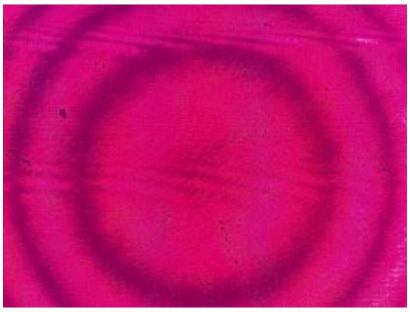
The beam splitter divides the incoming light which is then reflected at the mirrors. If we were looking inside the interferometer from the detector, we would see **two virtual point sources**. Depending on the position of the mirrors and the beam splitter, the virtual images of the sources may be found 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

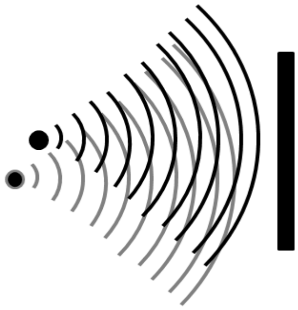
In the detector plane, two waves with equal curvature lead to a set of parallel fringes.

Point sources at the same position but at different depths

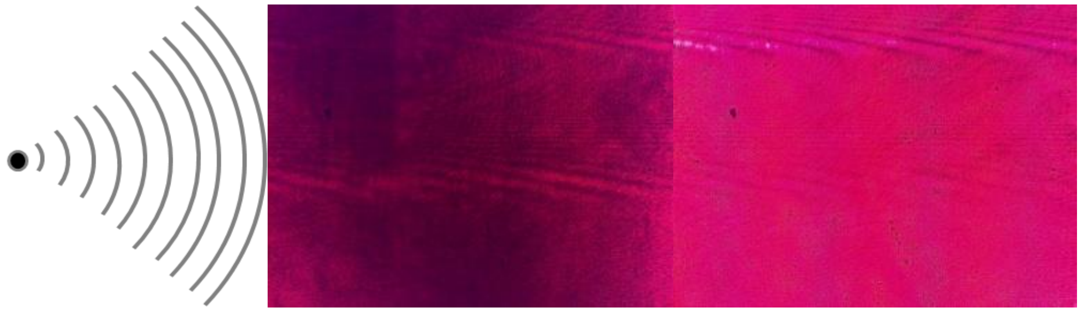
The curvatures of the superposed spherical waves are different and circular fringes become visible. Because the sources are approximately on axis (centered) with respect to the observation plane the fringes are symmetric and appear as nice circles.

Point sources at arbitrary 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.

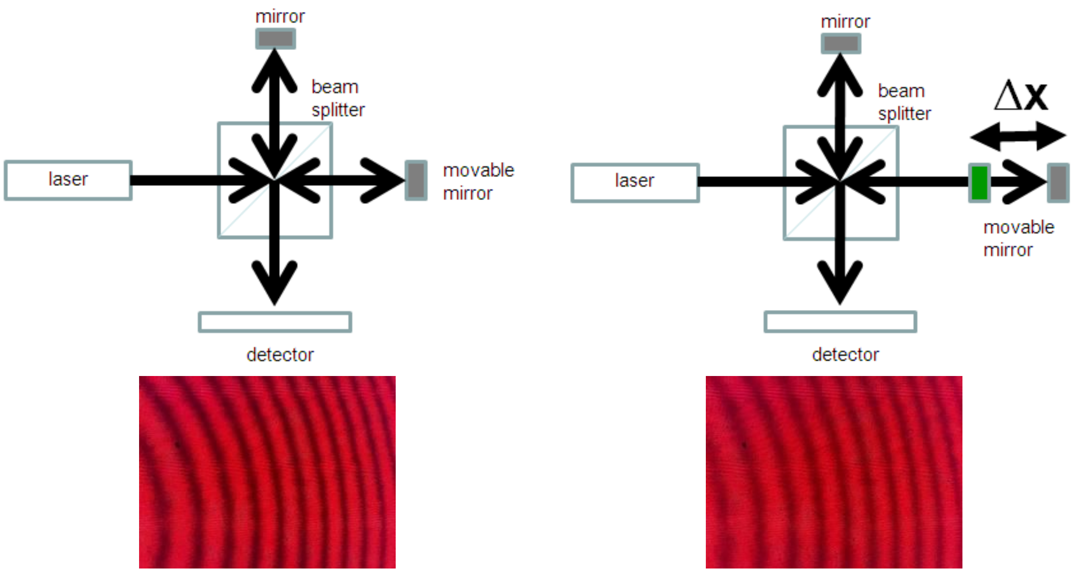
Zero optical path difference ZPD



This situation occurs when there is complete positional coincidence. In this case, a planar uniform 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 above 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.

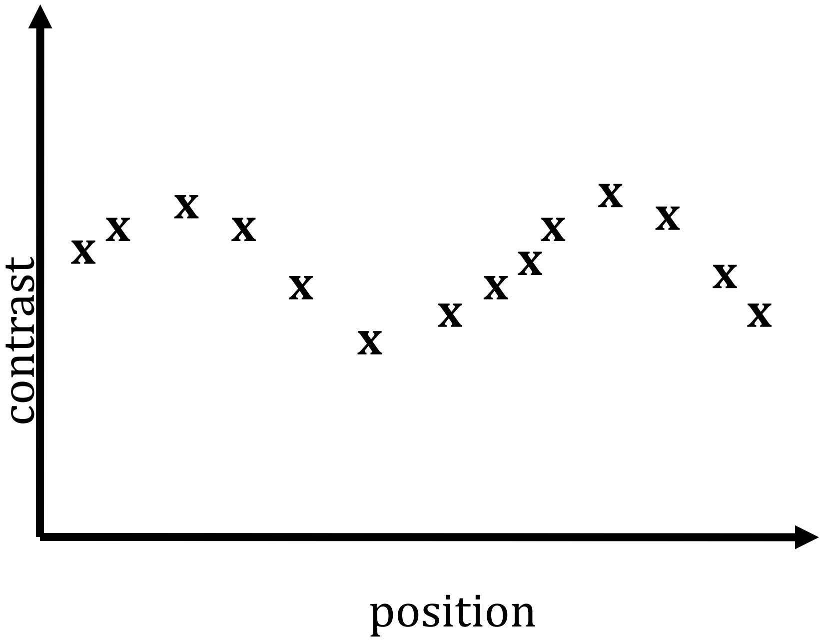


Figure 5. Contrast versus measurement position.

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

$$\Delta\lambda = \frac{\lambda^2}{\Delta z} = \frac{(635\text{nm})^2}{1.8\text{mm}} = 0.22\text{nm} \qquad \text{Eq. 12}$$

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

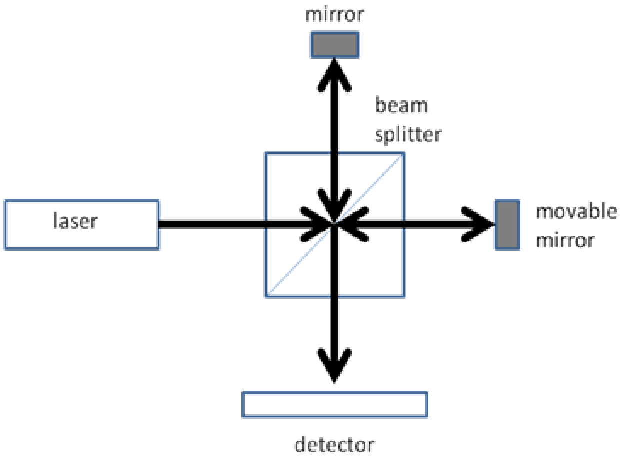
Figure 6. Fringe appearance for movements of 2 mm between each image.

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, only the contrast is important to evaluate the interference of sources with a certain spectral width and beating. The geometry of fringes is not considered.

2 Setup and equipment - tasks of the experimental work

2.1 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 USB camera
- Laserdiode, USB driven
- Mechanical setup

Mechanical holders and setup

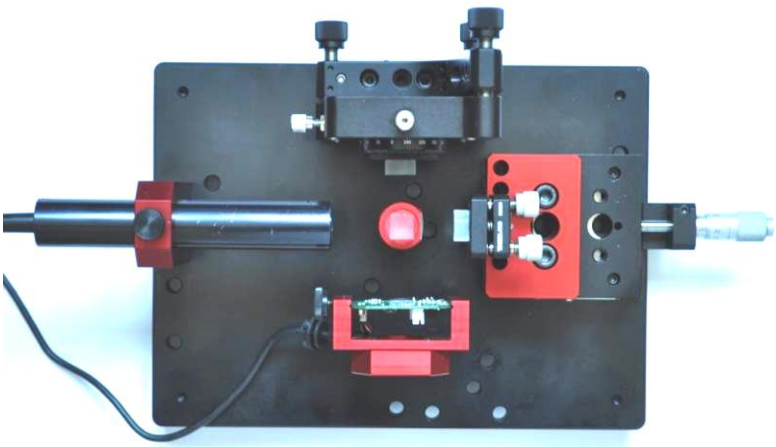


Figure 7: Top view of the Michelson interferometer

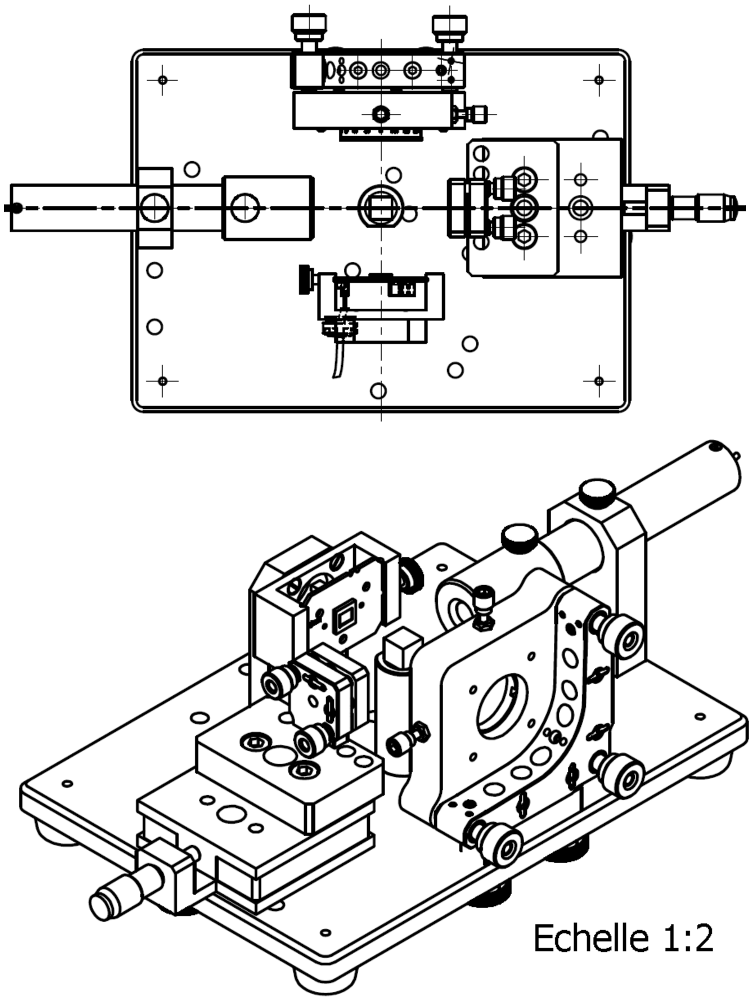


Figure 8: Schematic view of the mechanical setup; top view and perspective view with lens cap that is **ONLY** used in pre-alignment procedure.

Detached pieces

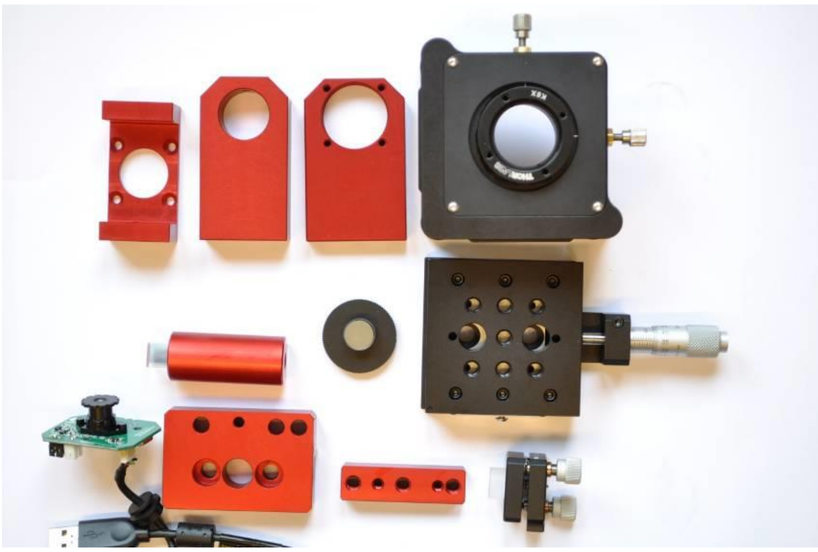
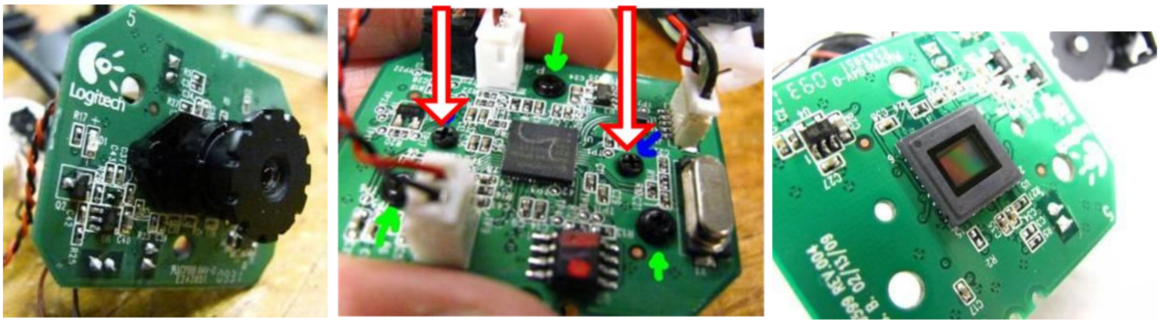


Figure 9: Separate elements provided for the experimental setup.

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.

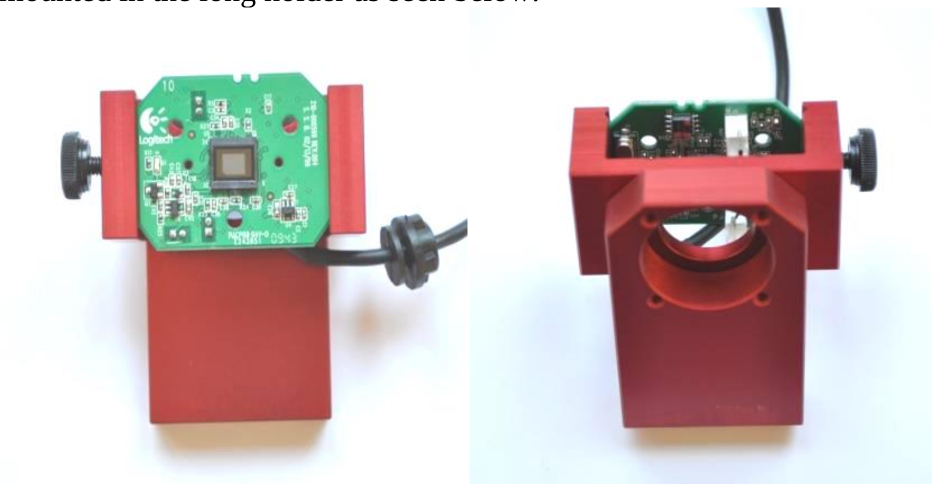


Figure 10: Close view of the CCD holder; a) front view, b) rear view. The camera is mounted in the holder without its objective.

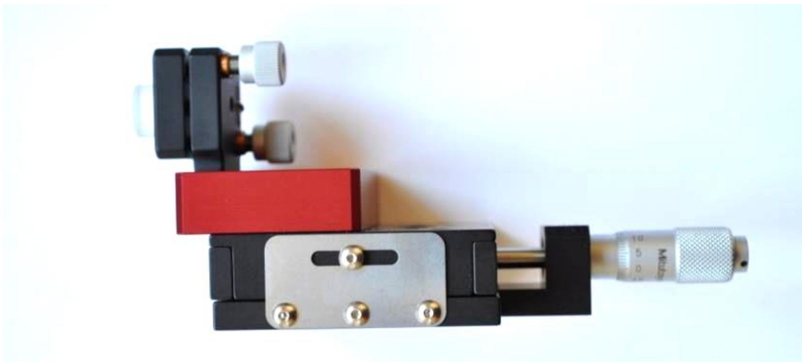


Figure 11: One mirror is mounted on the translation stage (side view).The other mirror is already mounted on a tilting stage to align its angle and **SHOULD NOT BE TOUCHED.**

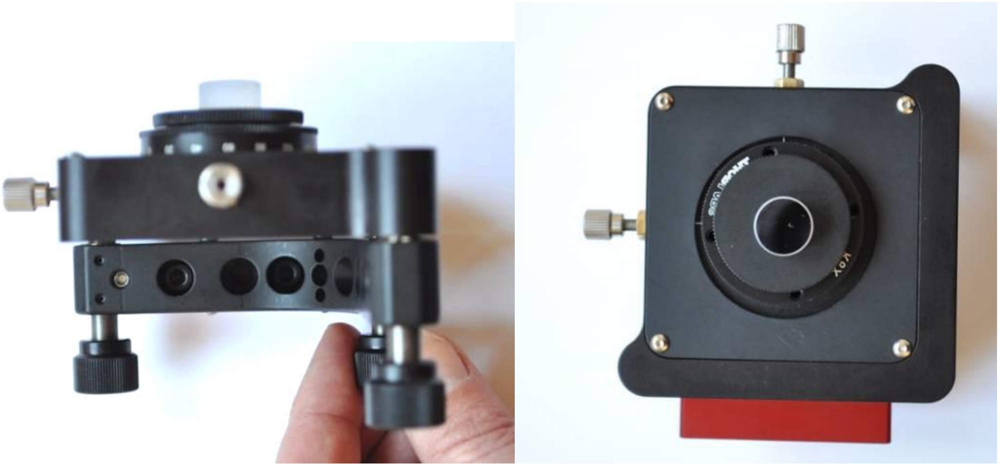


Figure 12 The second mirror is mounted on the six-axis stage; left: side view, b) front view, and **SHOULD NOT BE TOUCHED.**

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

CAUTION: Do not touch the 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 recommended to assure a good spatial alignment which consists in superposing 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.

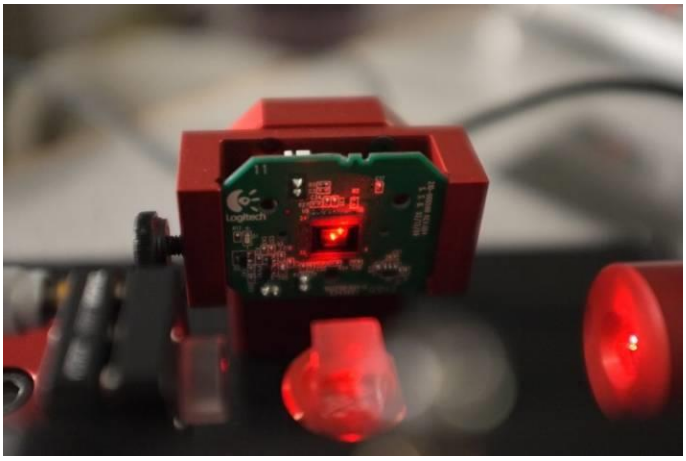


Figure 15. Focus spots at the detector during pre-alignment procedure. The two spots have to be superposed by adjusting the mirror position.

- 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

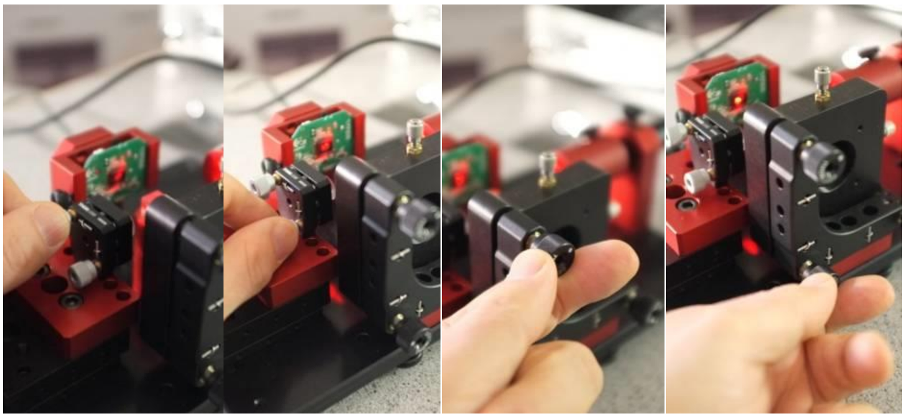


Figure 16. Adjustment screws of the tilting stages to align the spots over each other. Please note that all three knobs might be used!

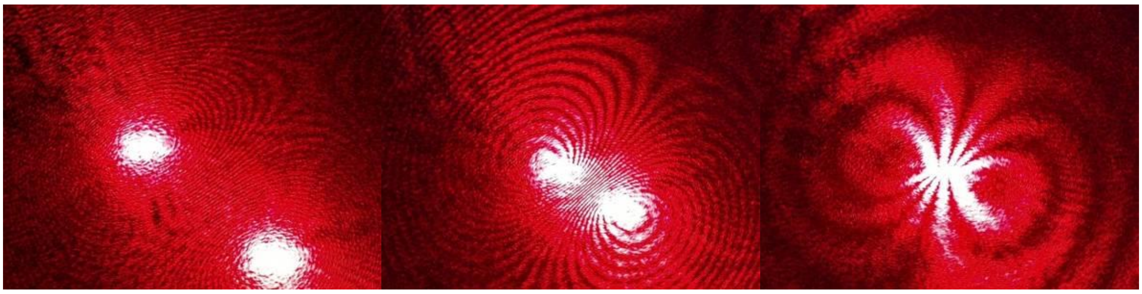
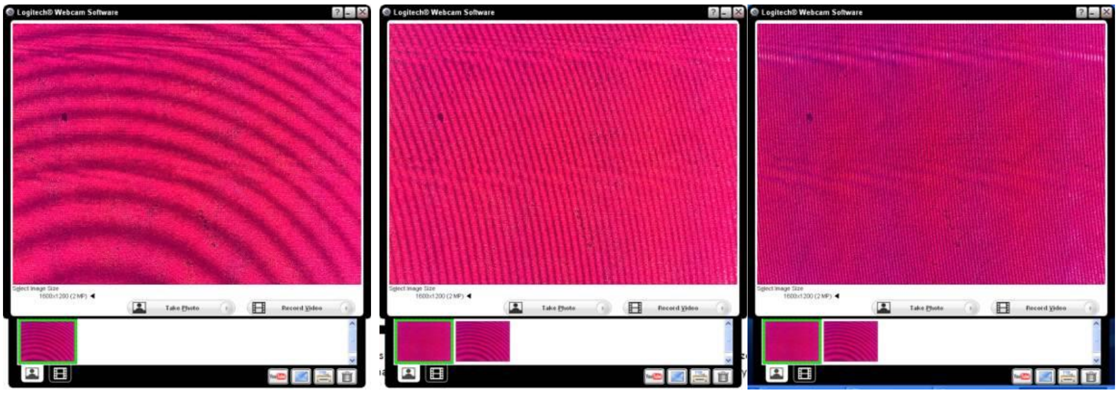


Figure 17. Images of the spots as seen on the detector at different stage of the alignment the two spots have to be superimposed as seen in the right image.

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

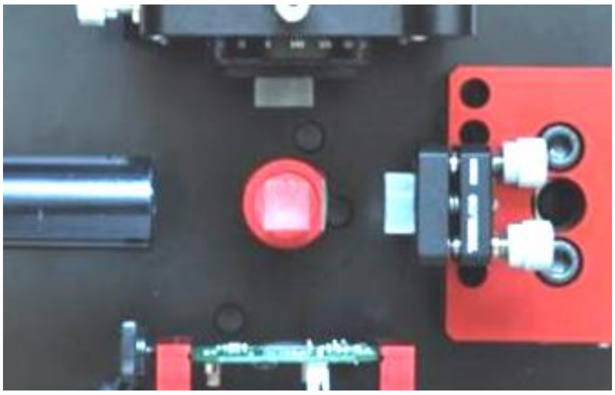
2.2 Zero optical path difference – ZPD and interferometer alignment

- Make sure that all components are fixed and that they do not move.
- Check the camera position (height should correspond to that of the beam splitter and the laser).
- 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 using the linear stage 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).

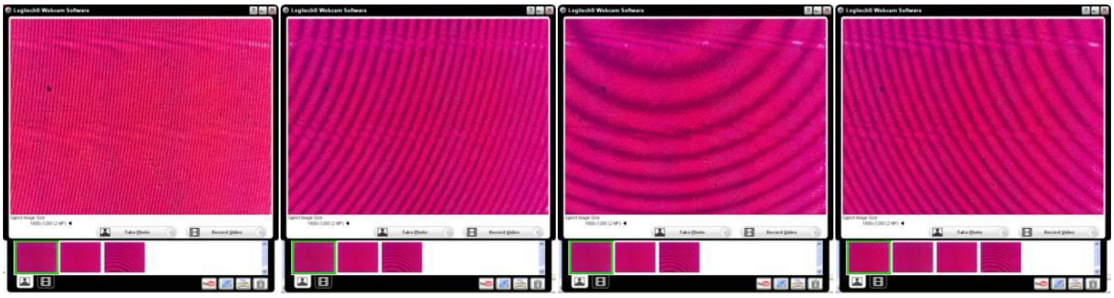
An interferometer can be aligned to its **zero optical path difference** position. That means that the distance between the beam splitter and the mirrors is aligned to a precision of less than a wavelength. In this case, there will be only one fringe (either black or white) on the detector. To find this 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:

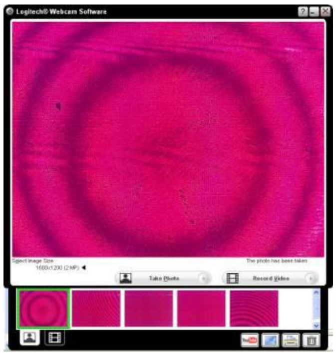
- Turn one knob in the direction of increasing fringe distance.
- At a certain moment the fringe distance will not increase anymore but fringes start to get closer again. Stop and use the other knob.
- Repeat until result is satisfactory!!!!

A possible sequence is shown below when turning only one knob of the alignment mirrors.



Small fringes are seen on the left image. Then, when turning one knob, the fringe period decreases until the central circle starts to appear. In the last image, the knob has been turned too much and the fringe period increases.

The final result gives you a **circular fringe picture** as 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 (OPD). At the OPD, fringes are straight lines and the spacing between them may 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

See the image below for an example for parallel fringes and 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 and 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 the 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.

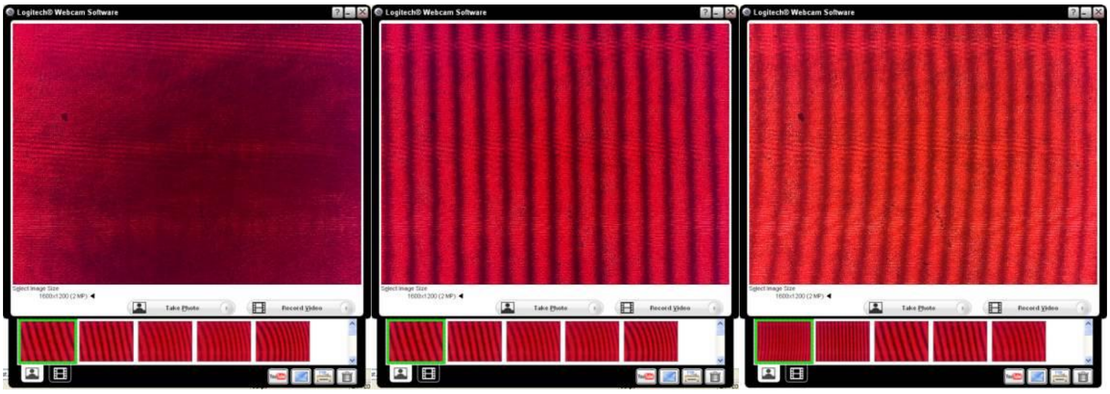
To do so, follow the procedure:

- 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 a number of fringes without saturation (B). Same situation after moving the mirror with the translation stage (C).



A B C

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

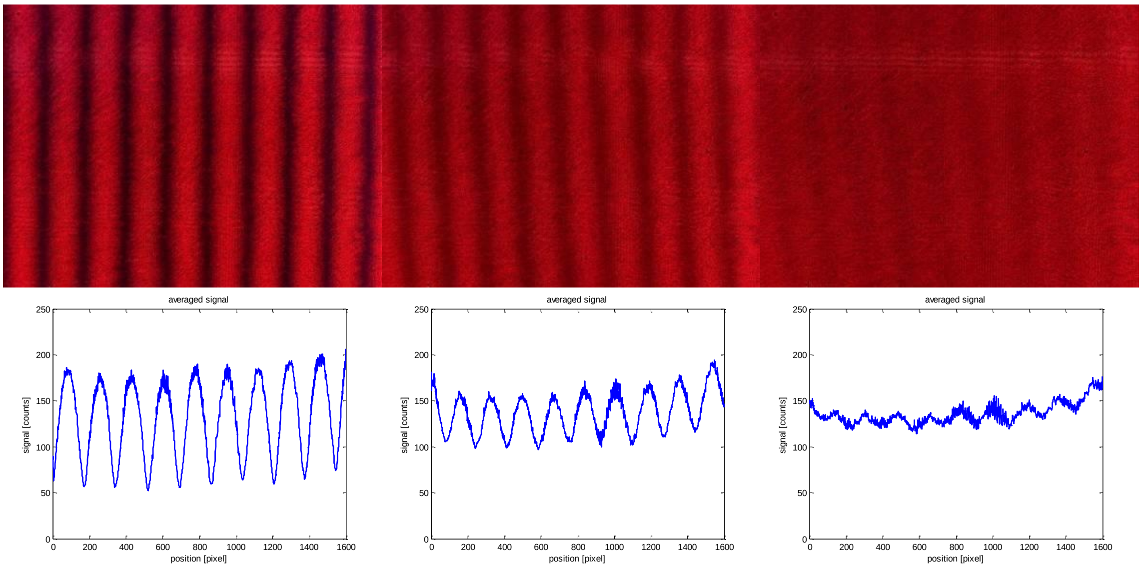


Figure 22. Examples of the fringe contrast obtained at different positions of the linear stage.

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.