Interferometer

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1 Background

Interference and coherence

The addition of coherent light beams results in intensity modulation: the interference fringes. The coherence of light has two aspects

- Spatial coherence
- Temporal coherence

Spatial coherence is related to the spatial extent of the source. For example, a single-mode laser (emitting light of a single wavelength and polarization) is a highly spatially coherent source, but it still has a finite coherence length due to the spatial extent of this emitting area.

To observe interference patterns, the optical path difference between superimposed beams of a light source must be smaller than the coherence length of the source. If a spatially extended source is used, achieving spatial coherence requires careful consideration of the coherent areas within the source. In this case, the superposition of light from these coherent regions must occur in the observation plane. The spatial coherence of a source may typically be increased by using a pinhole or a lens to ensure that overlapping images of the source are formed in the plane of observation, allowing interference to occur.

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 also be expressed using the wavelength λ and spectral width $\Delta\lambda$. We work mainly in the 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.

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.

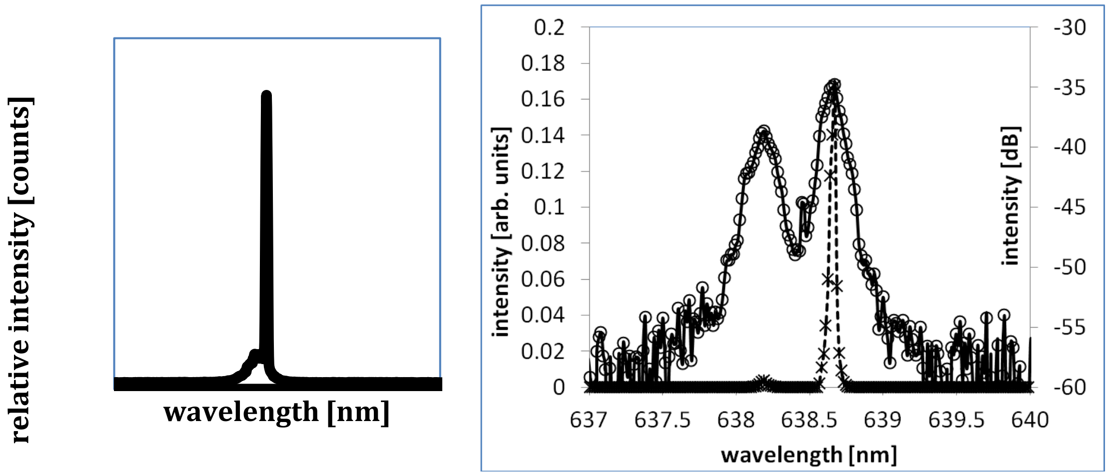


Figure 1. Spectral characteristics of the monomode laser diode measured at different resolutions. Left: as measured with a miniaturized grating spectrometer. Right: measured with an optical spectrum analyzer in linear and logarithmic scale. The logarithmic scale (right side) reveals that there are two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

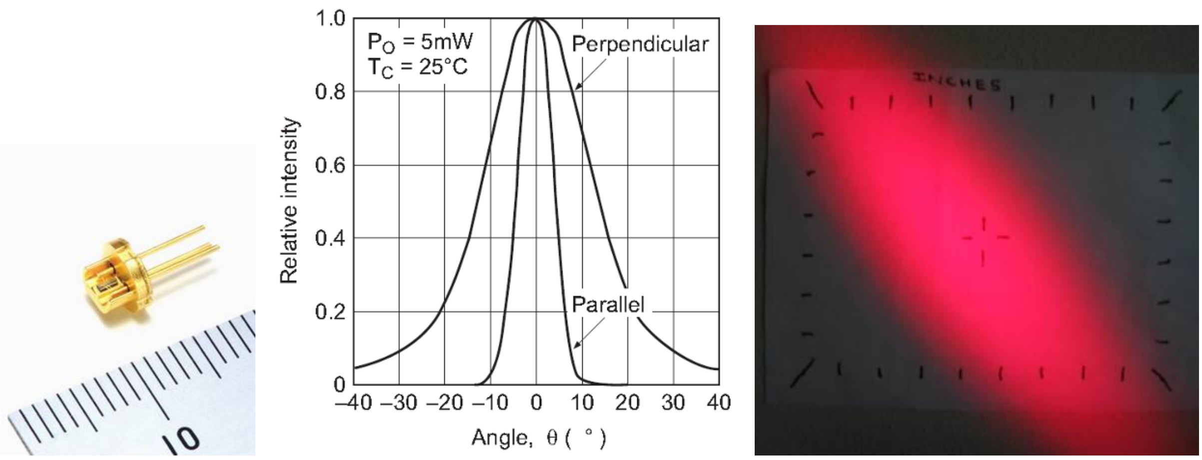


Figure 2. Appearance and emission profile of the laser diode. The emission profile is not symmetric and leads to an elliptical shape in the far field.

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 superimposed. The result of an interference phenomena is the presence of interference fringes whose contrast depend on the spatial and temporal coherence of the waves. The mathematical description of interference can be easily obtained for a one-dimensional problem. It can then be extended to three dimensions. Here, we consider the description for the one-dimensional case to define the fringe contrast and the fringe period.

The amplitude of the electric field E for the superposition of two waves of the same frequency, is given by

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

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 and depends on the phase shift between the waves given by

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

For a given position vector **r**, this equation provides the phase difference between the two waves as function of their direction of propagation (through the vectors $\mathbf{k_1}$ and $\mathbf{k_2}$). The values ε_1 and ε_2 correspond to the initial phase of the two waves. It is important to remember that this equation corresponds to a time average quantity. This is because, when we perform a measurement, our detector is not able to capture the fluctuation at light frequencies and can thus only measure the time-averaged intensity of the field. 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 easily calculated.

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 5 has values from -1 to and 1 and a maximum and minimum intensity can therefore be easily defined. We now calculate the fringe contrast by considering Eq. 3, this allows us to reformulate Eq. 6 as

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

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, assuming propagation in the z-direction and taking $\varepsilon_1 - \varepsilon_2 = 0$, Eq. 5 becomes

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

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 that

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

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

For a given position in space r (or z), we can 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 moving 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 sends 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 us 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 in some particular cases.

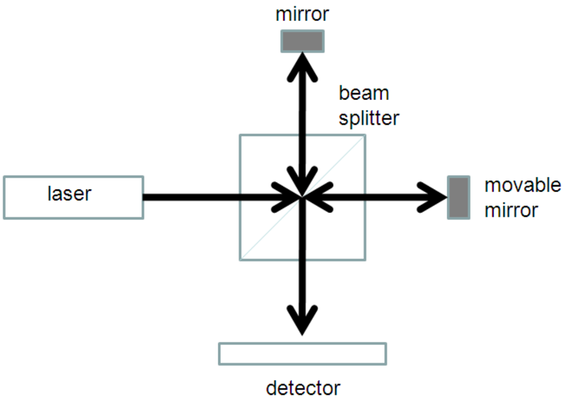


Figure 3. Geometry of a Michelson interferometer with the source (laser), beam splitter cube, two mirrors and a detector

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

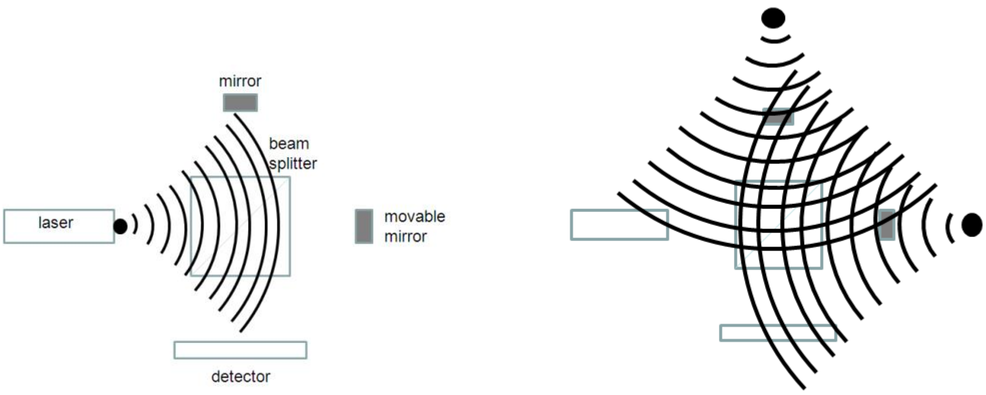
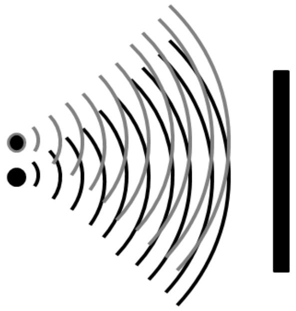


Figure 4. Point source illumination and the appearance of two virtual sources behind the mirrors of the interferometer.

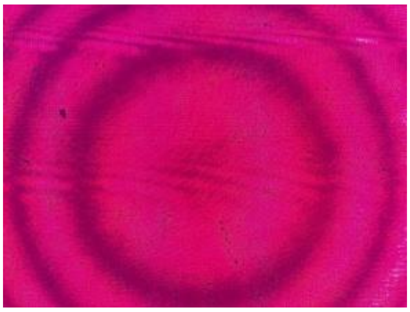
The beam splitter divides the incoming light, which is then reflected at the mirrors. If we were looking inside the interferometer from the detector, we would see **two virtual point sources**. Depending on the position of the mirrors and the beam splitter, the virtual images of the sources may be found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



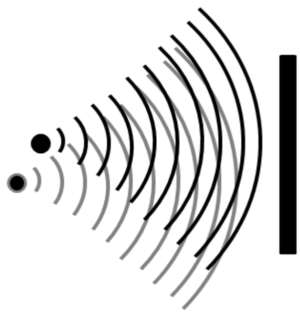

In the detector plane, two waves with equal curvature leads to a set of parallel fringes.

Point sources at the same position but at different depths

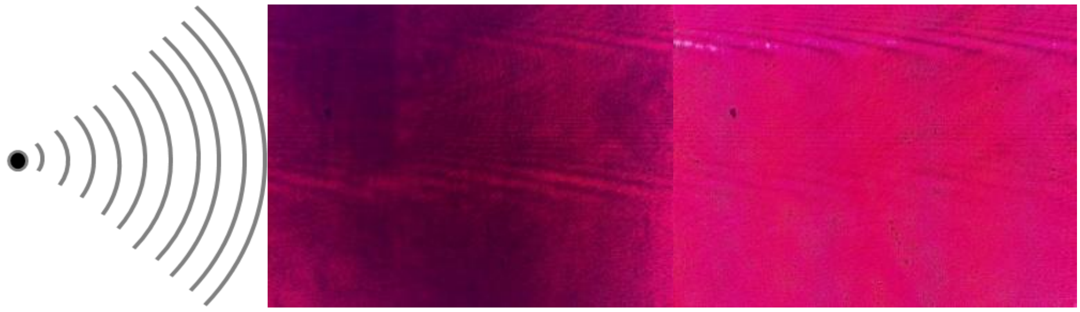
The curvatures of the superimposed spherical waves are different and circular fringes become visible. Because the sources are approximately on axis (centered) with respect to the observation plane the fringes are symmetric and appear as nice circles.

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.

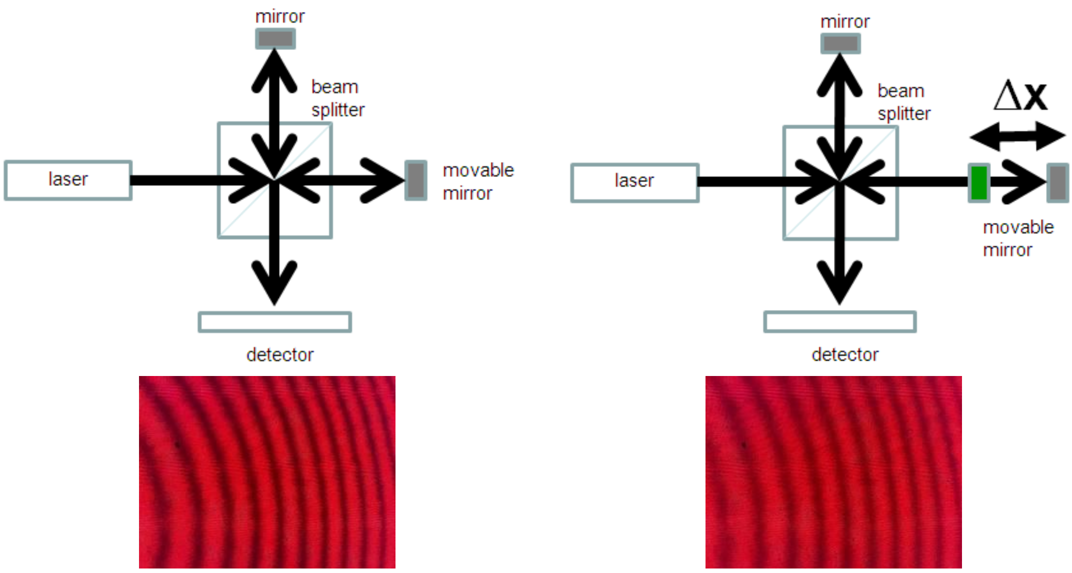
Zero optical path difference (ZPD)



This situation occurs when there is complete positional coincidence between the two virtual sources. 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 modified. The figure below shows the principle.



The images of fringes above show a **variation of contrast** as a function of the displacement Δx of the linear stage. This contrast variation depends on the laser and its operation conditions and varies very much between different sources of the same type.

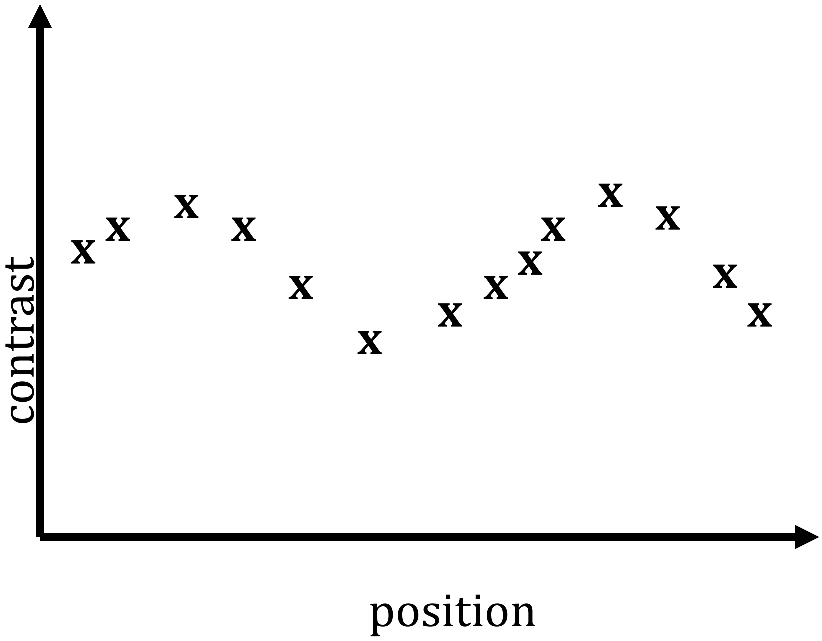


Figure 5. Contrast versus measurement position.

As an example, we show in the figure above the measured contrast for a monomode laser. The contrast shows two maxima at a distance of approximately 1.8 mm. Using Eq. 11, one can calculate the spectral width (or distance of beating frequency). Here, we have Δz=1.8mm and λ=635nm, and a spectral width of

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

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

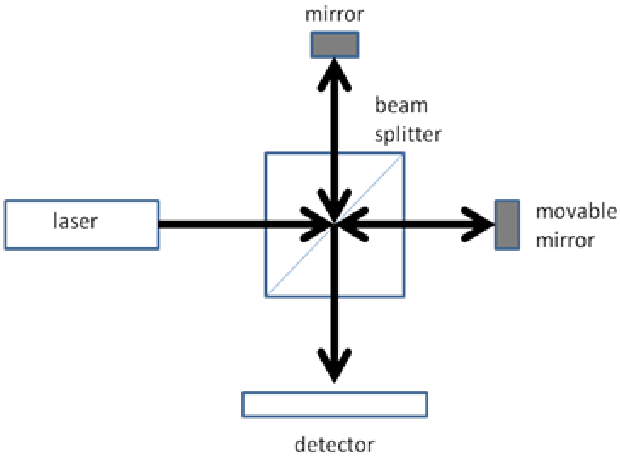
Figure 6. Fringe appearance for movements of 2 mm between each image.

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, 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

2.1 Setup and alignment

In this lab, we will realize a Michelson interferometer. In our case, the 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 creating interferences over large surface areas and large displacements of the movable mirror (using the linear stage). We will 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
- Mechanical setup

Mechanical holders and setup

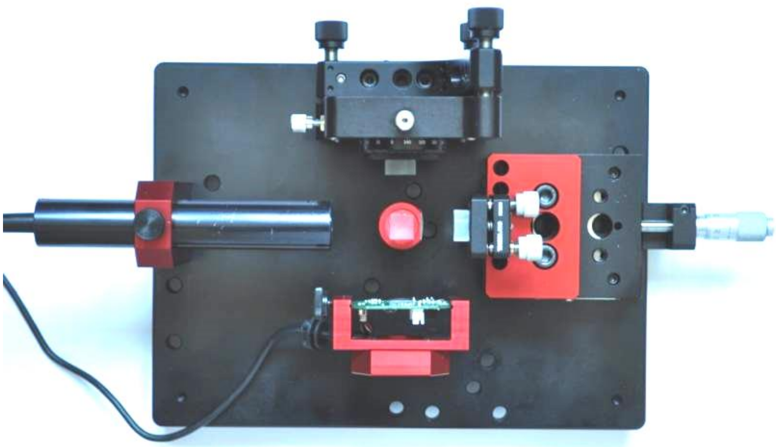


Figure 7: Top view of the Michelson interferometer

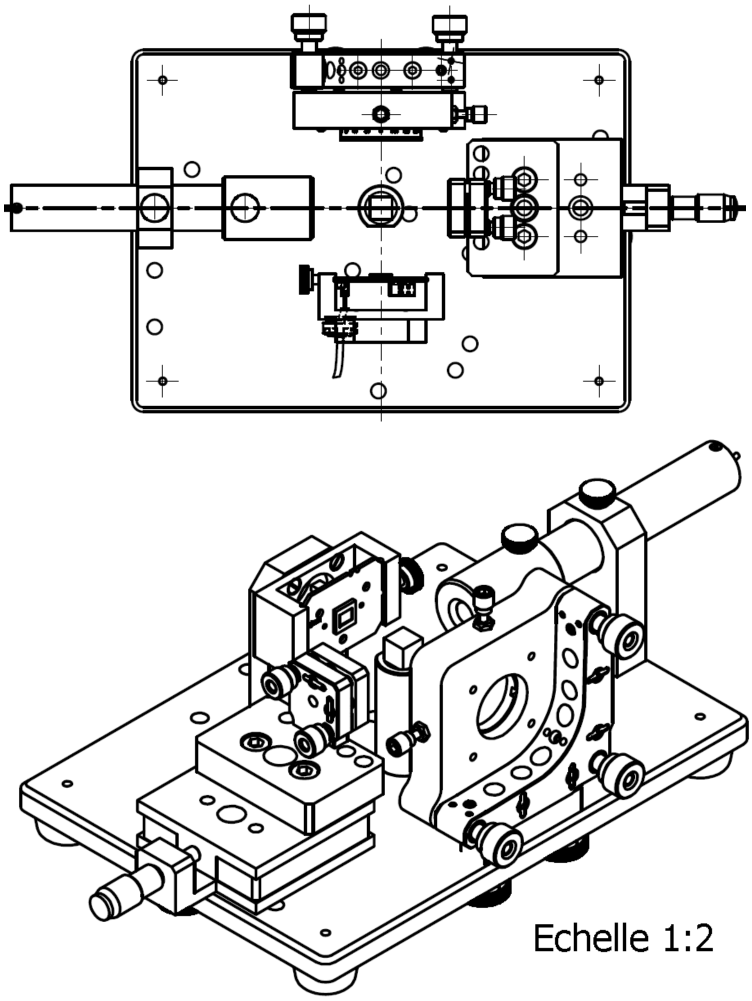


Figure 8: Schematic view of the mechanical setup; top view and perspective view with lens cap that is **ONLY** used in pre-alignment procedure.

Detached pieces

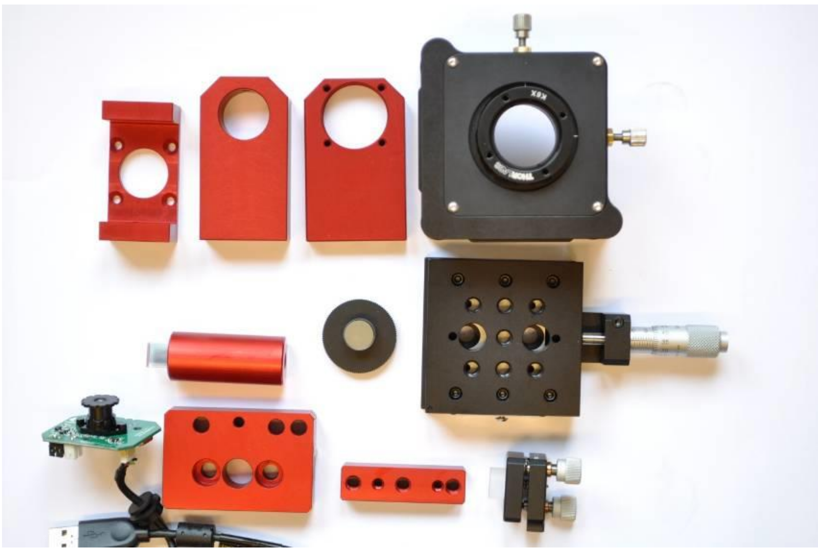
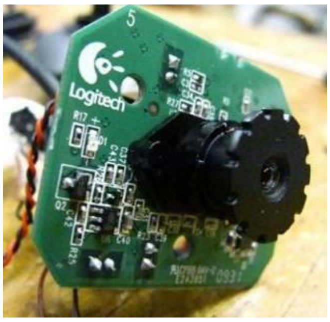
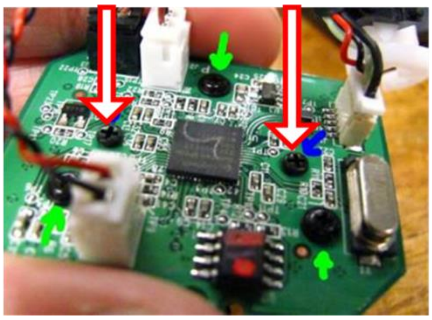
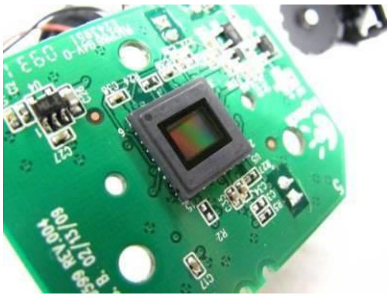


Figure 9: Separate elements provided for the experimental setup.

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.

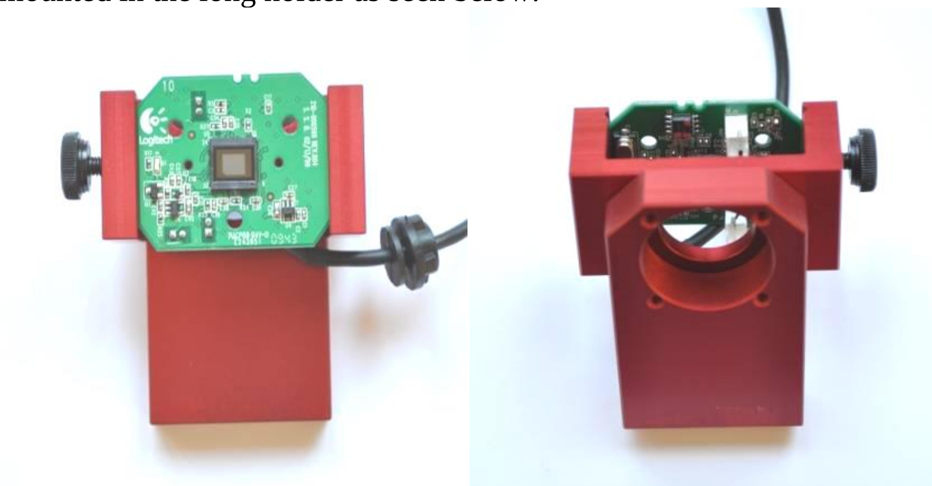


Figure 10: Close view of the CCD holder; a) front view, b) rear view. The camera is mounted in the holder without its objective.

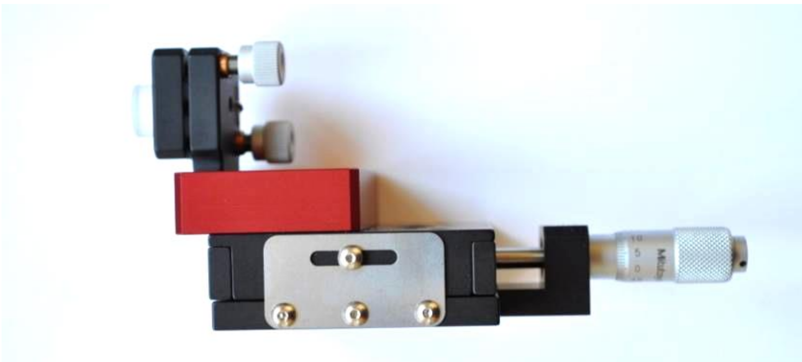


Figure 11: One mirror is mounted on the translation stage (side view).

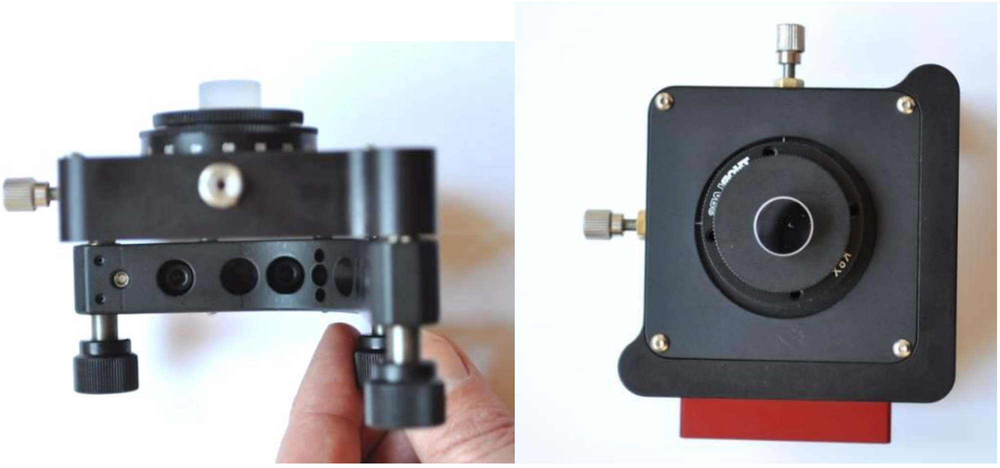


Figure 12 The second mirror is mounted on the 6-axis stage; left: side view, b) front view**.**

Figure 13 The beam splitter is a 10 mm cube mounted on a cylinder.

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.
- **Take care that the beam splitter is in the right position and sends light to both mirrors!**
- Move the angular adjustment screws of the mirrors to the middle of their movement range.

Pre-alignment procedure

An interferometer is a high precision instrument and needs carful alignment. It is recommended to assure a good spatial alignment, which consists in superimposing 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 (you will remove it later to do the measurement of the fringes), as shown in Fig. 14.

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 to that of 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 the images created by the two arms (mirrors) of the interferometer. You need to rotate the beam splitter to adjust position.

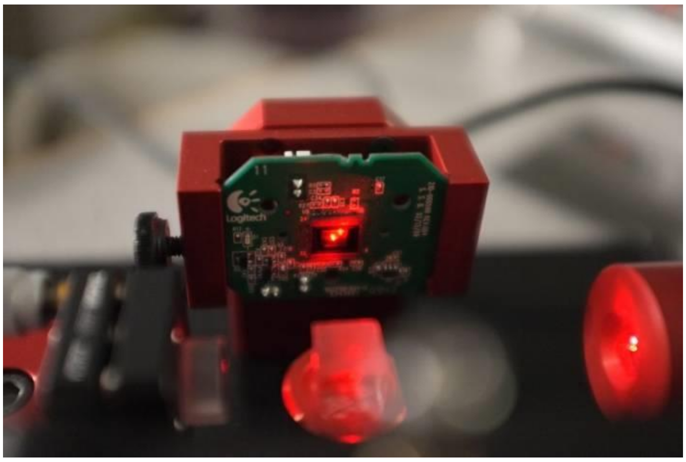


Figure 15. Two focus spots are visible on the detector during the pre-alignment procedure. The two spots have to be superimposed by adjusting the mirrors positions and angular orientations.

- Identify the image from each mirror on the detector by turning their tilt alignment screws separately.
- Superimpose the spots in the middle of the detector by adjusting the positions and angular orientations of the mirrors, as shown in Fig. 16.

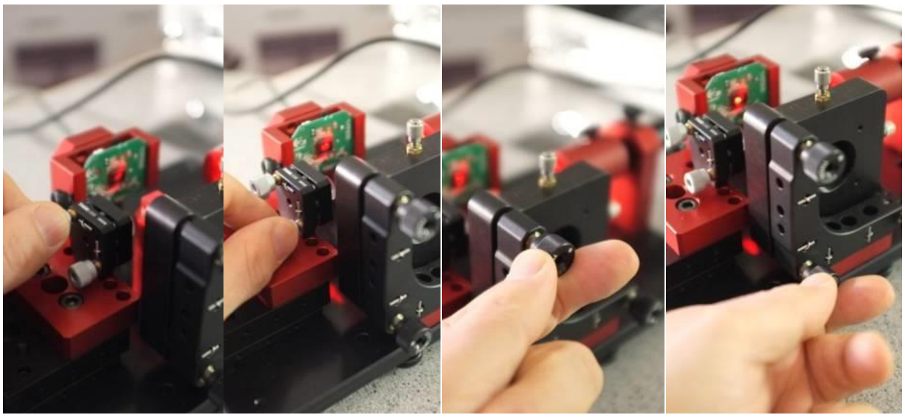


Figure 16. Adjustment screws of the tilting stages to align the spots over each other. Please note that all three knobs might be used!

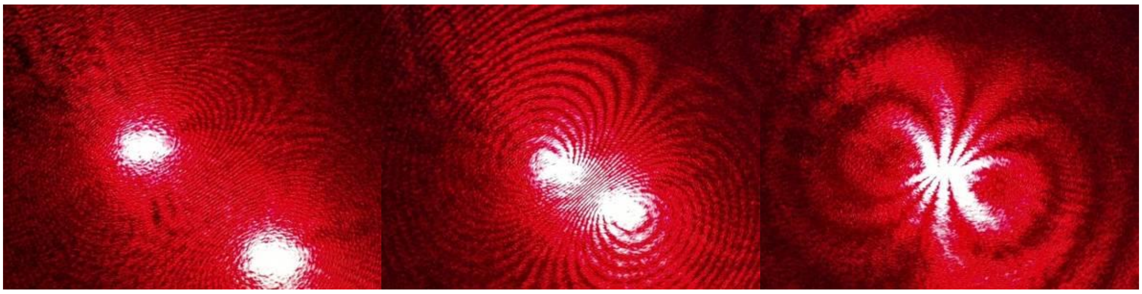
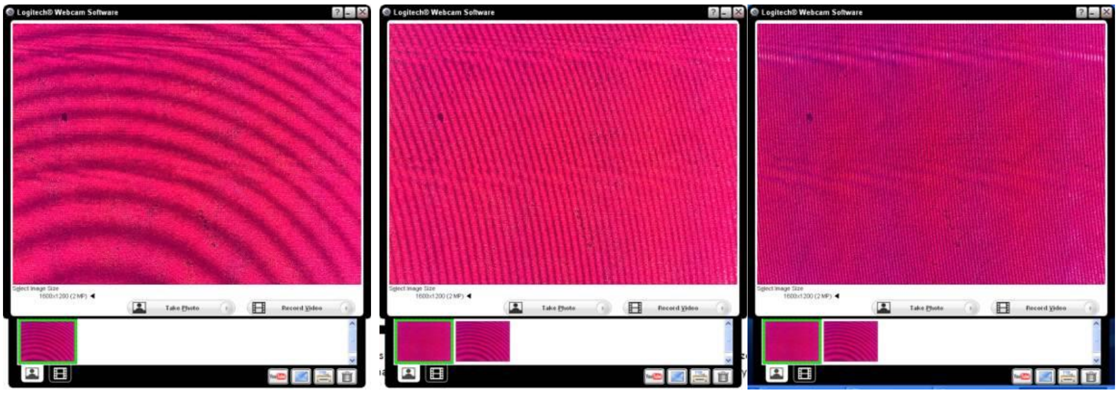


Figure 17. Images of the spots as seen on the detector at different stage of the alignment the two spots have to be superimposed, as seen in the right image.

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

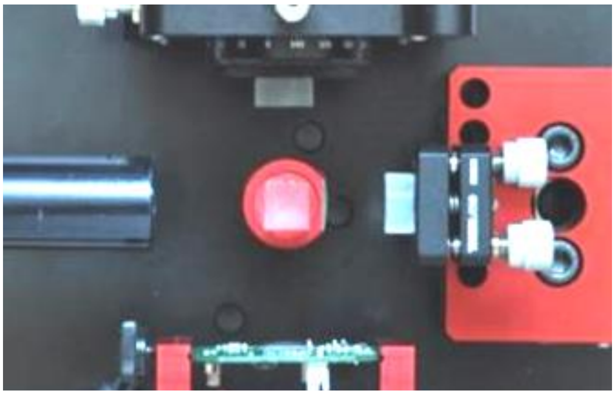
2.2 Zero optical path difference (ZPD) and interferometer alignment

- 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 between the laser and the beam splitter. (The intensity follows a square law with distance). Alternatively, adjust the exposure of the camera.
- Move **VERY 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).

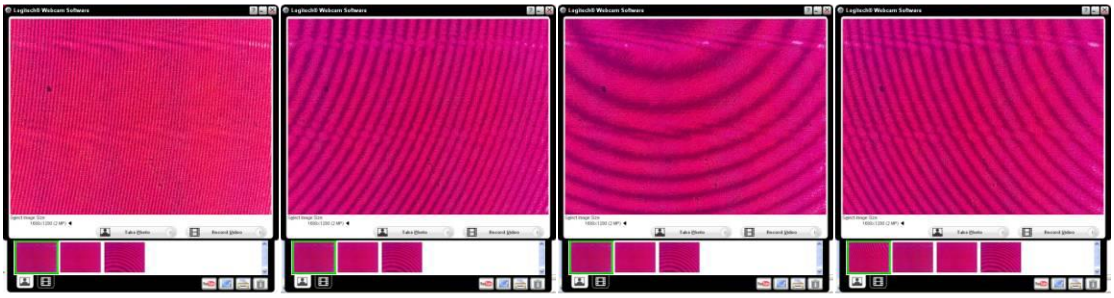
An interferometer can be aligned to its **zero optical path difference (ZPD)** position. That means that the distance between the beam splitter and the mirrors is aligned to a precision of less than a wavelength. In this case, there will be only one fringe (either black or white) on the detector. To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

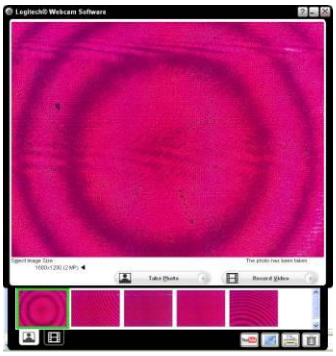
- Turn one knob in the direction of increasing fringe distance.
- At a certain moment, the fringe distance will not increase anymore but the fringes will start to get closer again. Stop and use the other knob.
- Repeat until the result is satisfactory. Follow the indications below.

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 stage** and eventually correct the angular alignment again until you find the position of zero optical path difference (ZPD). At the OPD, the fringes are straight lines and the spacing between them may be very large until one sees only one fringe.

- Move the linear stage until the fringes become 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. Remember: **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 tune the fringe intensity.

4.3 Measurement of laser fringe contrast

The interferometer allows measuring the coherence properties of a laser. In the present case, we 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 displacement of the mirror by using the linear stage.

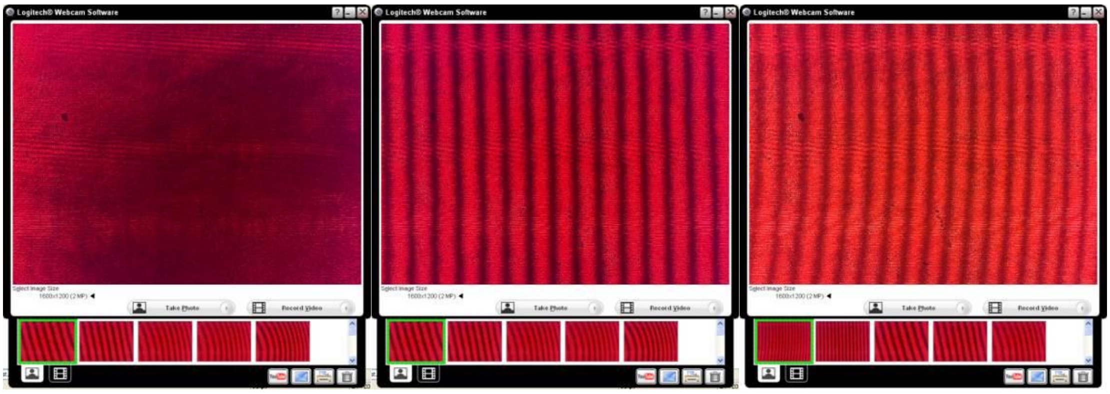
To do so, follow this procedure:

- 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 settings to avoid saturation.
- Move the translation stage and record images for different positions.
- Evaluate the fringe contrast with Matlab.

Remember, the contrast is given as the difference of the maximum and minimum intensity over the sum of maximum and minimum intensity.

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

The 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.

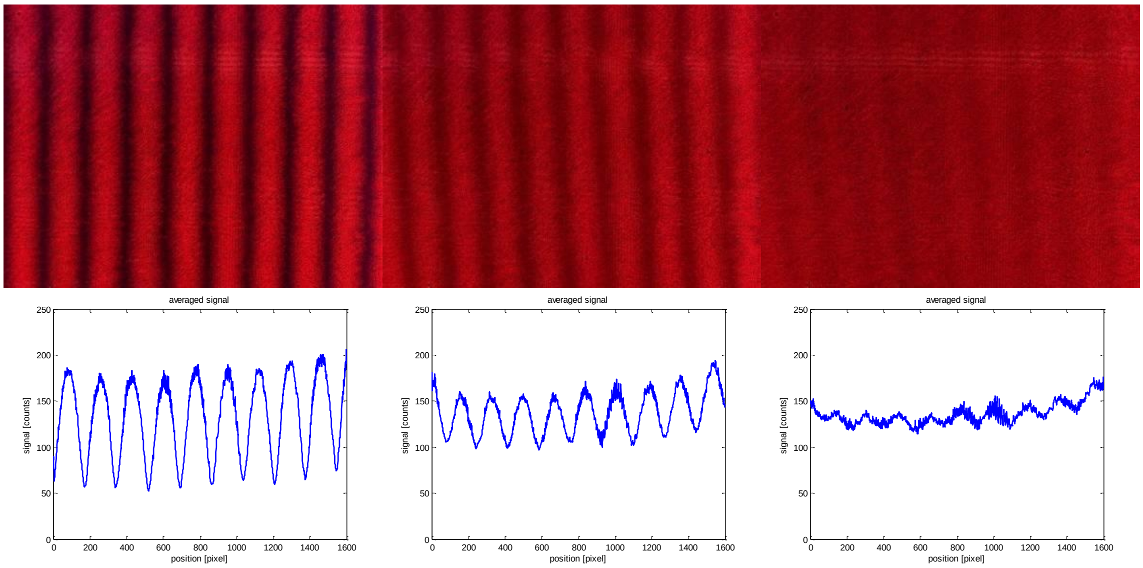


Figure 22. Examples of the fringe contrast obtained at different positions of the linear stage.

Note that the contrast variation between different pictures is highly dependent on the laser and might therefore be difficult to evaluate. The use of (vertical) line averaging in the Matlab script helps in reducing the noise. To apply line averaging, you have to avoid saturation of the image. Moreover, consider that the fringes will become curved as the mirror is displaced with the linear stage. This will impact the quality of your result. To limit this problem, do not average your results in Matlab over too many vertical lines.