O - 2. INTERFEROMETER. COHERENCE.

This laboratory exercise concentrates on the Michelson interferometer, which is excellently suited to demonstrate different aspects of optical interferometry and coherence. The principle of the Michelson interferometer is also extensively used in optical metrology and communicaton.

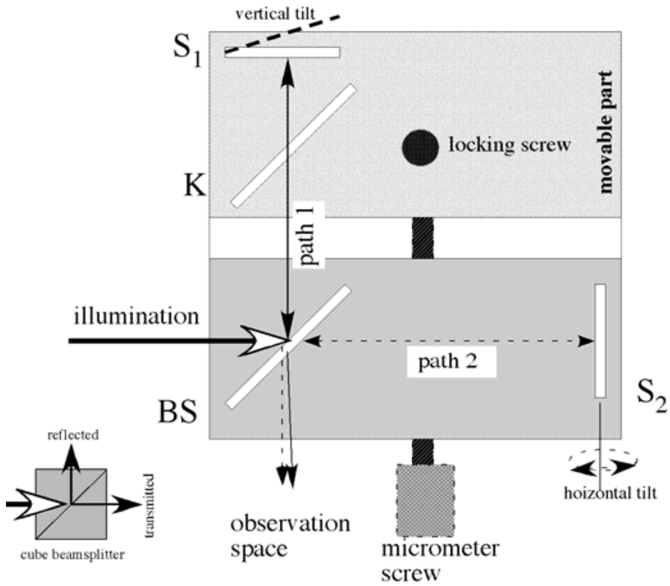

Figure 1. The Michelson interferometer

Principle and construction of the interferometer
The key parts of the interferometer is shown on the left of figure 1. The illumination wave (here we will use laser, lightbulb and finally a sodium spectrallamp) is split into two separate paths by a 50% reflection from- and a 50% transmission through -the partly reflecting mirror or the beamsplitter BS.
The wave **reflected** from BS passes first through the so-called compensator –plate K. This plate is an exact replica of the beamsplitter plate both in thickness and surface quality, but is coated for maximum transmission. The purpose of this plate is to ensure equal optical paths in glass as the reflection takes place in the front surface of the beamsplitter (one of the interferometer has a cube beamsplitter shown on lower left where the glass paths are automatically compensated). The lightwave is thereafter reflected from mirror S_1 back through K, hits the beamsplitter again where half of it is transmitted into observation space. The light wave originally **transmitted** through BS is reflected from S_2 and sent into the observation space after reflection from the beamsplitter. In observation space we therefore have the superposition of two waves which have travelled two separate paths - 1 and 2. If the coherence conditions for interference are fulfilled we observe the interference phenomena here.

Fringe observation
When we use the laser or a small light source the interference pattern can be observed on a diffusing screen or simply a paper in the observation space. For extended sources like a light bulb we place the screen at the entrance of the interferometer - this is mainly done to obtain a more even illumination.
To observe the interference patterns we have to adjust the mirrors so that the eye can resolve the fringes either on the screen or directly when an extended source is used. To find the necessary angle of alignment we can use the equation for fringe distance d when two coherent plane waves with wavelength λ interfere at angle:

$$d = \lambda/2 \sin(\phi/2) \approx \lambda/\phi \text{ (for small angles)} \qquad (1)$$

This gives the fringe spacing in a plane normal to half angle between the waves. Note that equation (1) is a general equation which can be used even for spherical waves to find the local fringe period at certain location.

Mirror alignment
The angles between waves 1 and 2 can be adjusted by tilting mirror 1 and 2 around vertical and horizontal axes as indicated by figure 1.
For a coarse adjustment of the interferometer, we may place for example a pencil in the illumination entrance. If the mirrors are out of adjustment we see two images of the pencil looking into the interferometer. (Due multiple reflections we probably see several images but the two main images are much stronger). We adjust the mirrors until the images coincide. If we now use the laser with a lens attached (effectively producing a spherical wave) we should see an interference pattern which can be optimised further by adjusting the mirrors and the path length.

Path adjustment
The light path of wave 1 can be changed in a controlled way by moving the part of the interfero-meter table where K and S_1 are fastened - the moving unit is usually called the wagon.
The distance between the mirrors can be varied by a **coarse** and a **fine** adjustment:
For **coars**e adjustment we unlock the screw on top of the interferometer whereby the back part of the interferometer (the wagon) can be moved manually.
For **fine** adjustment the screw is locked. The micrometer screw and an internal mechanical construction now enable us to change and control path 1 with submicrometer accuracy
NB! The internal mechanism reduces the movement as read by the micrometer by a factor of 1: 50

1. Ideal (laser) interference. Wavefront curvature.

Two spherical waves originating from the same monochromatic source will interfere **wherever** they overlap. Note that the plane wave is only a special case of a spherical wave with infinite radius. A laser can be considered such an ideal point source provided it operates in a single transversal mode. By interference between two spherical waves the resulting interference pattern that is the surfaces for light maxima and minima will be hyperboloids in space. When we place a screen in this volume of overlap, the pattern observed on the screen will depend on how the hyperboloids cut through the screen.
We have two important special cases:
1.1. **The interferometer is adjusted to make the point sources lined up in the direction of propagation** like shown to the left on figure 2.
The observed pattern will here be a circular structure where the circles grows increasingly closer as we move out from the centre – this pattern is often called a zone plate structure. The scale of the pattern will be dependent on the relative curvature between the two waves.
At **zero pathlenght difference** we will observe only one interference fringe independent of the curvature of the illumination wave. One interference fringe in this connection means that we will observe a uniform intensity over the screen – the absolute intensity of the fringe will be depending on the absolute phase difference between the two waves. As the optics in our interferometers are not perfect we will not get a complete uniform intensity. The total wavefront error is in the order of 1 - 2 λ, mostly at the edges of the field.
We can use this property to determine where we are close to zero path length difference in the interferometer and thus where we should start searching for absolute zero difference or white light interference.
When the illumination is a plane wave (or the light source is located in infinity), we will always get no fringe or straight fringes regardless of the pathlength difference in the interferometer. This property can be used to check the collimation of laserbeams.

2. Coherent (point) sources transversally separated.

Shown to the right on figure 2. This wave configuration is similar to the classical Young´s Double Slit experiment. When we are working with small angles between the interference sources the resulting pattern consists of straight fringes –often called tilt fringes. Such tilt fringes are often used as reference fringes where the wavefront deviations we want to measure results in departure from the straight fringe pattern.

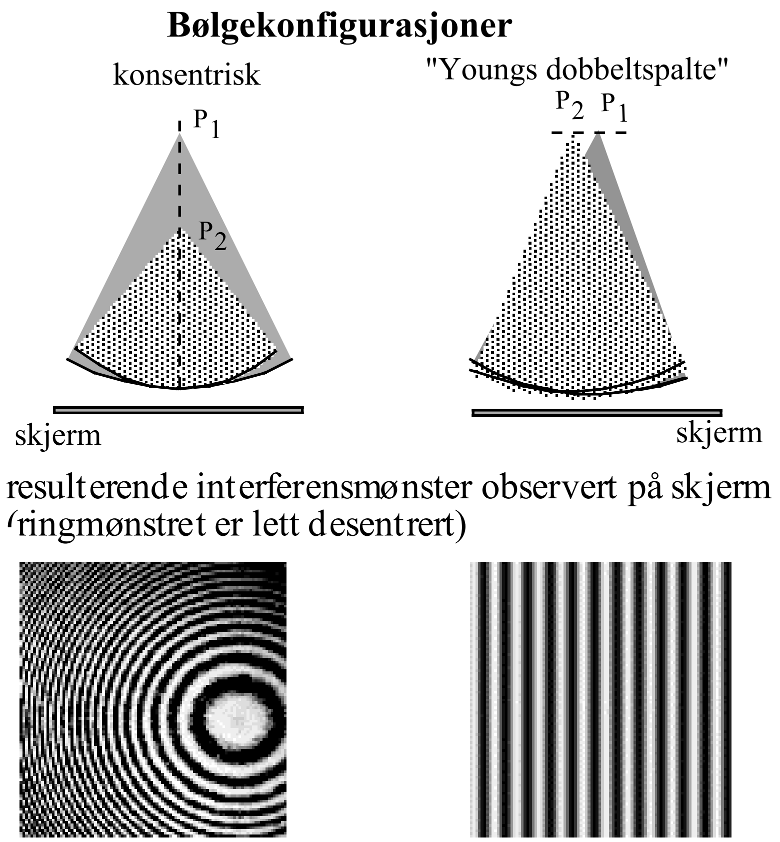

Figure 2.
Resulterende...- resulting interference pattern as observed on the screen (the ring pattern is slightly decentered)

EXPERIMENTS

Equipment to be used
* Michelson interferometer
* He-Ne laser where a microscopic lens has been attached to generate a spherical wave
* Matte screen
* 2 polarizers
* Plate with small apertures

Make a rough adjustment of the interferometer using an aiming pin (e.g.: a pencil). Send the spherical wave into the interferometer and observe the pattern on the screen. Adjust the mirrors to center the pattern. Vary the distances between the mirrors and observe changes in the pattern.
Move the interferometer wagon until maximum distance between the mirrors. Collimate the spherical wave into a plane wave by using the large lens and observe how the pattern grows coarser and finally fills the entire aperture by perfect collimation (a plane wave). By perfect collimation the interference pattern is independent of the pathlength difference.

1.3. Polarisation vs. interference
Adjust the interferometer using a spherical wave until you have a minimum number of fringe across the field. Place a polarizer in each path of the interferometer and convince yourself that orthogonal states of polarisation do not interfere
It might be necessary to adjust the mirrors slightly after putting in the polarizers to get a coarser fringe patterns as the polarizers are not plane-parallell. The interference pattern observed with one polarizer in the path is, by the way, a map of the thickness variations of the polarizer with a equidistance given by the laser wavelength.

1.4. Laserspeckle
Remove the polarizers and place the matte screen in the laser illumination in the entrance of the interferometers – alternatively look directly at the screen.

Notice the coarse intensity variations -speckles - in the light. You can observe the speckles growing larger by looking through smaller holes in the "rotating" disk.
The speckle pattern is an interference phenomena which is present whenever coherent light is reflected – or transmitted by a non-plane surface. The rough surface changes the smooth wave into a complicated wavefront with great phase-variations which by interference is transformed into random intensity variations – speckles. When you limit the field of view the speckles get coarser according to equation 1.

2. Longitudinal and spatial coherence.
White light interference. Fourier Transform Interferometry.

For optimum contrast in the interference pattern the light source should be a point source and emit light at only one wavelength (monochromatic). Again, certain lasers are very good approximations to a monochromatic point source, while most non-laser sources can be considered as a distribution of polychromatic point sources where each microscopic point source is decoupled in their emission. The result is spatial and spectral incoherent light, which will reduce the contrast of the interference pattern.

Size of source (spatial coherence).
When the lightsource is an incoherent, extended source, each point of the source interferes only with itself. The interference patterns from all the sources will add together intensitywise and the result is a pattern with reduced or zero contrast. As to be shown in the lectures there is a Fourier relation between the angular size of the source and the contrast. In practise, when we are using an angular large source like for example a gas discharge or a frosted light bulb close to the interferometer we can observe the interference pattern only in the image of the source where the waves from the point sources becomes separate points again.

Spectral distribution (longitudinal coherence)
Practical light sources (including most lasers) emit light containing several discrete frequencies (wavelengths) or a continuos frequency spectrum. What happens to the interference pattern can be briefly explained as follows:
To get a "stable" interference pattern, each frequency component has to interfere only with itself. Interference between different frequencies (wavelengths) take place, but the resulting interference pattern moves so fast that it can only be observed by fast detectors.
Therefore, working with only **one** frequency, like from a single mode laser, everything is very easy - regardless of the pathlength difference between the mirrors we will always observe the interference pattern with full contrast. For a single mode laser pathlength difference in the kilometre range is possible.
If we have **two** frequencies, each frequency gives an interference pattern with different distance between the fringes. Starting with zero pathlength difference the two patterns coincide in the beginning and we observe full contrast. As the distance increases, one pattern will be lagging more and more compared to the other one, and the resulting pattern loses contrast. When the two patterns are complementary (the trough in one pattern coincides with the crest in the other), the resulting pattern have minimum contrast – zero contrast if the intensity of the two patterns are the same.
This phenomenon will repeat itself as we increase the distance between the mirrors and can be considered to be an optical variation of the beat phenomena best known from acoustics.
This argument can be carried on with more and more frequencies until we have a continuos frequency spectrum. A white light source like a thermal light bulb represents a typical continuos spectrum – here the contrast of the interference pattern will decrease rapidly and only a few fringes will be seen. Again the lectures will show that there is a Fourier transformation-relation between the spectrum of the light source and the contrast of the fringe pattern as we change the optical path length. This is used to determine the spectrum of unknown sources especially in the infrared region.

EXPERIMENTS

Equipment
*** Laser with microscopic lens:**
*** Ordinary lamp**
*** Sodium spectral lamp**

First adjust the micrometer screw to the 12 mm reading.
Place the laser w/lens close to the interferometer. Adjust the distance between the mirrors until the circular structure is gone. You are now very close to zero pathlength difference

Replace the laser with the table lamp with the matte screen in front and look into the interferometer. Adjust the micrometer screw carefully in both directions while staring into the interferometer – and suddenly, a beautiful coloured fringe pattern will appear.
How many fringes can you detect?
What pathlength difference does this correspond to? (the visible spectrum is centred at about 550 nm)
Are you able to project this pattern on the screen? If not, you might try to make the source smaller by holding the hands in front of the source.
Why do we see a much better fringe pattern directly than by projection on a screen?

Replace the white light source with the Sodium spectral lamp (the lamp needs a couple of minutes to heat up). The sodium line (λ_m = 589.3 nm) consists of two wavelengths λ_1 and λ_2 which are very close together. We can determine the separation of these two lines by measuring the beat-period as we change the pathlength difference in the interferometer. We do this by turning the micrometer screw and measuring the positions where the interferogram has minimum contrast. Unfortunately the two wavelengths are not equally strong which does not make the interference pattern reach zero contrast, but it is still possible to detect the position of the minimum. Figure 3 shows approximately how the contrast will diminish in the experiment.

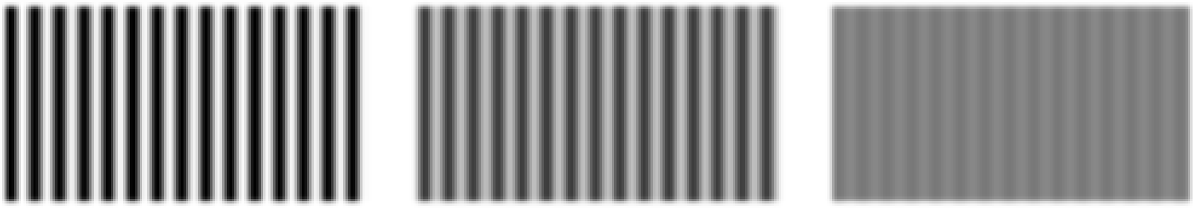

Figure 3
Interference pattern at 100, 50 and 7 % modulation

Find the wavelength difference $\Delta\lambda$ by measuring the distance d between the contrast minima and using the relation.

$$\Delta\lambda = \frac{\lambda_m^2}{2\,\Delta d} \qquad (2)$$

The disadvantage of this technique used in a Michelson interferometer is a rather large uncertainty in determining the minima of a sinusfunction, which has very broad troughs and peaks. As will be explained in the lectures a Fabry-Perot interferometer, which is based on multiple interference with resulting sharp peaks, would be much better suited.

Demonstrations of interference by Moire patterns.
At the lab. you will get one transparent and one reflective sheet , which each contains two linear patterns, two circular with constant circle distance and 3 circular where the distance between the circles increases linearly from the center – i.e a zone plate structure. You can use these sheets to vizualize interference between plane - and spherical waves
The **linear** pattern(s) represents a cross-section in the direction of propagation to a plane wave – the lines represent phase-fronts. One pattern is slightly demagnified which then corresponds to a shorter wavelength. In the same wave the **circular** patterns represents the phase-front of a spherical wave expanding out from the center. The three **zoneplates** represent phase fronts in plane <u>normal</u> to the direction of propagation. Here a demagnification means that the curvature of the phase front has increased which means that the centre of wave has come closer.
When we put a transparent pattern on top of the reflective a new secondary pattern appears which is called a Moire pattern. We often see such patterns on TV when a person wears a jacket with a periodic weaving – a beat occurs between this patterns and the TV-picture lines.
What is interesting for us is that the Moire between these simple patterns will yield secondary patterns similar to those obtained by real interference.

Interference between plane waves. Beats.
When the identical **linear** patterns are combined at a small angle the secondary pattern is also linear directed at the half angle. This now represents plane wave interference in space. As given by equation 1 we see that a smaller angle gives a coarser secondary pattern (due to drawing and printing inaccuracies the secondary patterns might not be completely straight).

If several transparancies are put on top of each other we can simulate multiple wave interference. When you align the coarser pattern on top the finer pattern we get the Beating.

Interference between spherical waves.
Displacement of two identical **spherical** patterns shows the interference in space between two spherical waves where the two special cases in figure 2 are easily seen. Again we see that a longer displacement gives a finer pattern- again also according to equation 1.
Notice that along the connecting lines between the two sources we will have a standing wave pattern which is locally plane – this is not directly evident on the Moire pattern.
By placing the linear pattern over a circular (the wavelength should be matched for the patterns but again small mismatches might evident), we get the interference between a spherical wave and a plane wave. We get a zoneplate structure in space.
If you put the **zoneplate**s on top of each other you get the same patterns as mentioned in 1.1 and 1.2. Two identical zoneplates slightly displaced give straight fringes around the axis, two zoneplates representing different curvatures gives a new coarse zoneplate etc.