Interferometers and properties of laser radiation

Task objective: Gaining experience in the construction of different types of laser interferometers, studying their properties and possible applications.

Measurement objective

1) Build a Michelson interferometer in both "plane wave" and "spherical wave" configurations
2) Measure the number of strips (changes) for different mirror displacements. Determine the wavelength of the laser.
3) Build a Mach-Zehnder interferometer and record the maximum visibility of the interference field.
4) Justify the differences in phase stability of the constructed interferometers.

Task theoretical basis

When two (or more) optical waves occur simultaneously in the same space and time, interference of light occurs when the resulting wave function is the sum of the wave functions of the individual waves. This superposition principle is a consequence of the linearity of the wave equation. The superposition principle applies to the complex amplitudes of optical waves (not their intensities) and thus the phase of the waves plays an important role. Optical interferometers are instruments for very precise measurements, the principle of which is based on the interference of light. Due to the very short wavelength of light, at the level of hundreds of nanometres, extremely small changes in quantities such as length, refractive index and, indirectly, a whole range of other quantities can be resolved by interference. Furthermore, the interference pattern can be macroscopic and phase changes at the fractional % level can be easily converted to stripe shifts of e.g. millimetres or more. Today, interferometers are used to measure lengths (interference comparators), to study different surfaces, to measure the pressure and temperature of gases or plasmas, to determine the refractive indices of gases and liquids (interference refractometers), to determine the structure of spectral lines (interference spectroscopes), to measure electric and magnetic fields, to measure rotational velocity, to measure the angular diameter of stars and as a gravitational wave detector, and many other measurements.

Interferometric measurement is based on the detection of phase differences that appear when two or more waves superpose in the resulting interference field strength. The resulting intensity is generally not the sum of the intensities of the individual beams; the reason for this difference is the interference between the waves.

The aim of this assignment is to learn the basic principles of light interference and the use of two-beam interference for the measurement of certain quantities using interferometers. Interferometers for measurements can be divided, for example, according to the number of interfering waves, into two-beam and multi-beam interferometers. The best known two-beam interferometers are the Michelson interferometer (Figure 1) and the Mach-Zehnder interferometer (Figure 2).

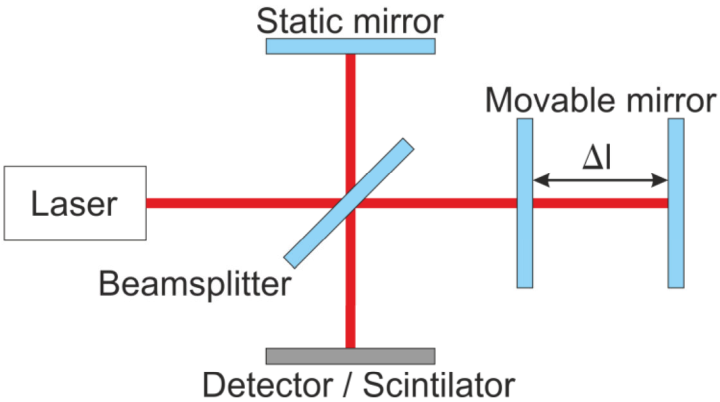

Figure 1: Michelson interferometer arrangement

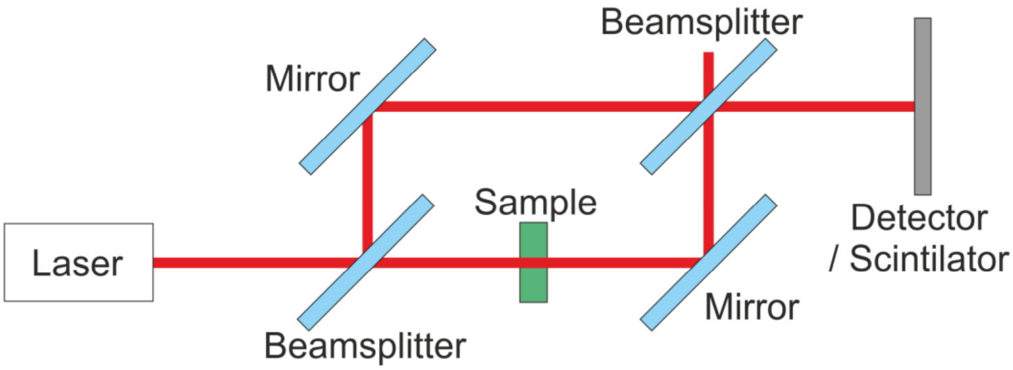

Figure 2: Mach-Zehnder interferometer arrangement

An important parameter of optical radiation is its coherence. The term radiation coherence is often used in connection with two extreme cases that occur when real electromagnetic waves interfere:

1) coherent radiation is said to occur when the phase difference of the interfering waves at a given point in space remains constant in time;

2) interfering waves whose phase difference changes irregularly and sufficiently fast at a given point in space are called incoherent;

In the general case, however, neither of these situations occurs. To mathematically describe the interference of two plane waves, a *complex degree of coherence* is introduced. The intensity of the radiation at the detector depends on the intensity of the plane waves and the degree of coherence:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\ \mathrm{Re}\,\gamma_{12}(\tau) \tag{1}$$

$$\gamma_{12}(\tau) = \frac{\langle E_1(t+\tau)\, E_2^*(t)\rangle}{\sqrt{\langle |E_1|^2\rangle \langle |E_2|^2\rangle}} \tag{2}$$

For fully coherent radiation $\gamma_{12} = 1$, for incoherent radiation $\gamma_{12} = 0$. The complex degree of coherence is a qualitative parameter of the radiation, the waveform of the function $\gamma_{12}(\tau)$ fully determines the behaviour of light during interference.

We also characterize the light source in terms of spatial propagation and temporal stability.

Temporal coherence characterizes the correlation of a wave at two different times, in other words, how well the wave interferes with itself. As a practical parameter, the coherence length is a number that indicates the distance from the source until the radiation maintains a certain degree of coherence, i.e. until when the interference is observed - in the case of a partially coherent source from a certain blanket, the interference is no longer observable.

Spatial coherence gives us the correlation of a wave in two different places, it tells us how uniform the wave is in space. Its parameter is the coherence area, which is, in simple terms, the area where we observe interference on the shield. For a more detailed interpretation of coherence theory, consult the literature (for example: M.Born, E.Wolf - Principles of Optics, E. Hecht, A. Zajac – Optics…).

Laser light sources are advantageously used in optical interferometric measurement systems due to the high degree of coherence of the emitted radiation.

The coherence decay of laser radiation can usually be measured experimentally in two ways.

First way is based on *visibility* of radiation interference measurement:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{3}$$

where I_{max}, I_{min} is maximum resp. minimum intensity of oscillations. Assuming that the intensity of the interfering waves is the same at a given point in space and assuming that the difference in the optical paths of the interfering beams is zero, the visibility value is equivalent to the degree of coherence of the laser radiation

$$V = \gamma_{12}(0) \tag{4}$$

When changing the length of one arm of the interferometer, we change the time shift between the parts of the wave that have been split on the dividing cube. By measuring the visibility for each shift, we get the laser radiation intensity shape. It can be shown that the coherent length of laser radiation can be defined as the difference of the optical paths of the two-beam interferometer at which the visibility of the interference field drops to half.

Second way of coherence measurement lies in utilising corelation of coherent length L_{coh} with the spectral linewidth of the laser radiation Δv,

$$L_{coh} = \frac{c}{\Delta v}, \tag{5}$$

where c is speed of light in vacuum. The coherent radiation length is calculated from the measured spectral width of the laser.

He-Ne lasers typically have a coherence length of ≈ 0.1 m in the multi-frequency regime. In the single-frequency regime (one longitudinal mode), the coherent length of a gas laser can exceed tens of kilometers. Compared to gas lasers, the coherent length of solid-state and semiconductor lasers is usually smaller.

To record the interference pattern a CCD camera or a screen is usually used. It is important to set the controls on the camera correctly. The gain, gamma curve and the number of frames the camera will integrate can be set on the camera. The main problem is to avoid saturating the camera with intense laser light, so it is desirable to use attenuation filters and appropriate settings (minimum gain, single frame integration...). With the right values, a black and white image with the interferogram recording can be obtained, which needs to be evaluated in a relevant way. Matlab can be used for processing, ImageGrab and ImageTool can be used for the task to get a basic idea of the values. Make sure to have appropriate experimental conditions as described in point 2, such as constant ambient lighting for the duration of the experiment.

Measurement procedure

1. Build the Michelson interferometer (Figure 1) in both plane wave and spherical wave configurations as shown in Figure 3. Place one mirror on a micrometre screw to measure the length of the interferometer arm.

Figure 3: Interferometer arrangement with plane wave (left) and spherical wave (right).

2. Estimate the coherence length and spectral width of the radiation of the He-Ne laser used by introducing the path difference into the interferometer arms.
3. Determine the wavelength of the laser. By gently shifting the mirror, the interference pattern is changed so that the maxima gradually shift to the original position of the minima and vice versa. If a slow shift of the moving mirror by a micrometre shift of distance d shifts the maximum by N periods, the following holds:

$$\lambda = \frac{2d}{N} \tag{6}$$

4. Construct the Mach-Zehnder interferometer according to Figures 2. Discuss the properties and possible applications of each interferometer constructed.

Reference:

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