Goals of the lab:

• Understand interference, interferometry and the heterodyne interferometer

• Understand how interference depends on beam overlap and wave front angles

• Learn how to operate: oscilloscope, motor- and manual-micrometers, photodetectors, laser, acousto-optic modulator, attenuator, beam splitters
Background:

If two coherent light sources with different intensities $P_1$, $P_2$ (and therefore different electric fields $E_1$, $E_2$) and different frequencies $\omega_1$, $\omega_2$ overlap, the power of the interfering light is

$$P(t) \propto \frac{|E_1|^2}{2} + \frac{|E_2|^2}{2} + |E_1 E_2| \cos [(\omega_1 - \omega_2)t - \phi]$$

In order to relate the maximum and the minimum power of the interfering beams we define the visibility

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{2\sqrt{P_1 P_2}}{P_1 + P_2}$$

or modulation depth.

The heterodyning power $|E_1 E_2|$ depends on how well the two light beams overlap. If two Gaussian beams interfere, an offset between the beams axes causes the heterodyning power to become

$$P_{\text{het}} \propto E_1 E_2 \frac{\pi w^2}{2} e^{-\frac{\Delta x^2}{2w^2}}$$

If the wave fronts of the beams are not parallel, the heterodyning power becomes (assume L to be beam width)

$$P_{\text{het}} \propto E_1 E_2 L^2 \text{sinc} \left( \frac{\theta L}{\lambda} \right)$$
In this lab, the interference of two coherent laser beams with different frequency (color) is measured in a Mach-Zehnder interferometer as a function of

- The transverse displacement of the two beams
- The angle between the beams axes (= angle between wave fronts)
- The power and the ratio of the power between the two beams
Heterodyne Interferometer

Principal sketch of the Mach-Zehnder Heterodyne-Interferometer

\[ P_{het} = |E_1E_2|, \phi \]

Familiarize yourself with display (unit is micrometer, note decimal point before last digit) and operation.
Explanation of the experimental setup:

The laser can be considered a single mode laser (spacing between its longitudinal modes can be neglected). The laser light is split into two beams with equal intensity by beam splitter 1 (BS1). One of the two beams is modulated by an $f = 80$MHz acousto-optic modulator (AOM) which shifts its color by $\omega_s = 2\pi f$. The two beams are then aligned on top of each other by means of beam splitter 2 (BS2). This setup is a heterodyne Mach-Zehnder interferometer.

Note that in order to align the beams on top of each other, one needs to align the rotation axis of BS2 which aligns the angle between the wave fronts and the axes of the interfering beams, and the lateral position of mirror 2 (M2) which aligns the transverse displacement between the two beams.

The AOM power, and, therefore the intensity of the modulated beam can be adjusted with an attenuator. Thus, the setup allows the measurement of the modulation depth as a function of wave front angle and transverse beam displacement. All functions are measured by observing the visibility of the interference beat oscillation.

The beat oscillation is measured with an oscilloscope which displays the power detected with a photodiode detector as a function of time. One can interpret the observed power by means of the equations given in Slide 2.
Overview about experiment
1.) Align the heterodyne Interferometer

Make sure that the AOM is adjusted for maximum diffraction efficiency. Verify that you have a diffraction efficiency near 85%. Measure the efficiency by comparing transmitted beam power with the RF power supply turned off with the diffracted beam power with the RF power supply turned on.

To align the interferometer, place BS2 in a position where the frequency shifted beam (diffracted) hits BS2 in the middle of the cube. Adjust M2 so that the beam from the other path also hits BS2 in the middle. Carefully adjust M2 while observing the spot at the interface of the two halves of BS2 until they overlap. Once overlap has been achieved, adjust the tilt and rotation angle of BS2 until the two beams overlap on the wall. You may have to do this a couple of times to find this condition. This will produce 2 beams that are spatially overlapped and parallel. Both conditions are necessary for good interference.

Place a fast photo-detector (better than 80 MHz) in the path of the two aligned beams and display the photocurrent versus time. The time base should be set to see an 80 MHz signal. The 80 MHz RF drive signal is also used to trigger the oscilloscope. If the two beams are aligned, you will see an 80 MHz modulation on the photocurrent. Adjust the tilt and rotation angle of BS2 to maximize the size of the 80 MHz modulation of the photocurrent. If you block either of the interferometer beams, the 80 MHz modulation will disappear and you will measure the average power of the unblocked beam. Measure the modulation depth of the heterodyne photocurrent signal. It should be above 70%, if the intensities of the 2 beams are equal. If the modulation depth is not good, run through the alignment procedure again. It may require a 2 dimensional search to find the optimal interference condition (overlap, parallelism). If the interferometer is not aligned in 30 minutes, have the lab assistant make the alignment.
2.) Carry out **Metrology measurements**

a.) Use the motorized micrometer and translator on M2 to observe the movement of the 80 MHz heterodyne photocurrent fringes as the position of M2 is changed. Each time a fringe shift occurs (by one fringe spacing), the path length difference in the interferometer has changed by exactly 1 wavelength (633nm). Adjust the motorized micrometer speed until you can easily see the movement of the fringes on the oscilloscope. Use the pulse mode of the motorized micrometer to observe sub-micrometer changes in the position of M2 (sub-fringe shift). As M2 is translated over large distances (hundreds of fringes), you will observe that the modulation depth decreases. This is due to the displacement of the 2 interfering beams. Reverse the direction of the micrometer motor and you can bring the heterodyne signal back to maximum modulation depth.

b.) Measure the beam width using the heterodyne signal. Align the interferometer as best you can. As M2 is translated, the 2 interfering beams are separated, while maintaining their parallelism. This walk off reduces the interference signal. It can be used to measure the width of the two beams. Use the mechanical micrometer (by hand) to measure the M2 translation distance required to reduce the 80 MHz heterodyne signal to 60% of its maximum value. This distance should be the same on either side of the maximum. Use the equation provided on Slide 2 to determine the beam width at the detector based on your measurements. Compare your answer with the known laser beam width at the laser output aperture including the effects of propagation to the detector (see Gaussian beam diffraction formulas). You may assume that the beam waist is at the laser output aperture.
2.) Carry out **Metrology measurements**

c.) Calibrate the movement of a piezoelectric disk provided. Measure the absolute displacement as a function of applied voltage to the disk. Use the fringes on the oscilloscope to determine the displacement. Graph the absolute displacement versus applied voltage and determine the average sensitivity of the piezo element (in nanometers/volt). You may want to measure a large displacement (many fringes) to minimize the effect of random noise in the interferometer.

3.) Carry out **angular tolerance on interference condition measurements**

With the interferometer aligned for maximum interference, place the detector very close to BS2 (within 1.5 cm). Use the micrometer adjustment to rotate BS2 and measure the full angle over which the 80 MHz RF heterodyne signal drops to half of its maximum value, on either side of the maximum. Compare the measured angle with the theory presented in class and the formula on Slide 2, using the beam width determined in part 2b.
4.) Measure **RF power dependence on diffracted power and heterodyne power**

Block the beam which passes through BS1 and hits M2. Measure the average optical power of the acousto-optically diffracted beam in the other arm of the interferometer as a function of RF power, using the RF attenuator to change the magnitude of the RF signal to the AOM. Remember, 6 db of attenuation is equivalent to reducing the RF power by a factor of 4 (RF voltage or amplitude changes by factor of 2). Graph on a log-log scale the detected DC photocurrent on the oscilloscope versus the relative RF power at the AOM. Now unblock the other interferometer arm. Make sure that the interferometer is well aligned. Measure the relative magnitude of the heterodyne (RF) photo-current as a function of RF power to the AOM. Plot both of these results on the same graph. Explain why the two measurements depend differently on RF power.

With the interferometer aligned and balanced, measure the modulation depth of the heterodyne signal and the DC photo-current from each arm of the interferometer separately. Reduce the RF power to the AOM by 6 db and re-measure all 3 quantities again (photocurrent from each arm separately and modulation depth of the heterodyne signal with both beams present). Calculate what the modulation depth should be for both cases and compare with your measurements. Explain discrepancies.