Goals of the Lab:

- Learn how acousto-optic modulators work and how they are operated
- Learn the principles behind optical ranging with phase delay detection due to the change of an optical path length
Background: Acousto-optic modulator

The acousto-optic modulator (AOM) consists of a photoelastic material (= material whose index of refraction depends on the strain within the material) connected to a piezoelectric material which produces ultrasound waves in the photoelastic material upon application of a high frequency (HF) oscillation.

As long as the traveling sound waves in the AOM are present, an array of periodically changing layers with alternating dielectric indices of refraction is established. When light passes through the AOM, it can be Bragg reflected of the period $d$ the angle of incidence $\Theta$ of the light (between the incident light in the AOM and the interface between the layers) and the wavelength of the light $\lambda$ fulfill the Bragg condition

$$2d \sin(\Theta) = m\lambda.$$  

For small angles, reflections of the internal beam can therefore be found at angles

The ratio of the intensity $I_{mod}$ of the first order reflection to the incident intensity $I_{in}$ is linear to the sound intensity $I_s$

$$\frac{I_{mod}}{I_{in}} = \left(\frac{\pi l}{\sqrt{2\lambda}}\right)^2 MI_s$$

The light frequency of the deflected beam $\omega_r$ is shifted by the carrier (sound) frequency $\omega_p$

$$\omega_i - \omega_r + \omega_p = 0$$

$\lambda$  light wavelength in AOM
$\lambda_0$  light wavelength outside of AOM
**Background: High frequency phase delay detector**

For lower frequencies one can use a lock-in amplifier in order to determine the phase delay of two harmonic voltage oscillations. At high frequencies that exceed the frequency range of lock-in amplifiers (typically >200MHz) one has to use a high frequency phase delay detector circuit.

\[
\cos(\Delta \omega) \cos(\omega) = \frac{[\cos(\Delta \omega + \omega) + \cos(\Delta \omega - \omega)]}{2} \cos(\Delta \omega - \omega)/2
\]

\[
\cos(\Delta \omega + \phi) \cos(\omega) = \frac{[\cos(\Delta \omega + \omega + \phi) + \cos(\Delta \omega + \phi - \omega)]}{2} \cos(\Delta \omega + \phi - \omega)/2
\]

The high frequency phase delay detector circuit mixes the two signals with a reference signal at \( \omega \) close to the input frequency \( \Delta \omega \). The low frequency components of the two resulting beat oscillations are then filtered out with a low pass. These downconverted signals exhibit the same phase delay as the high frequency signals which can be detected with a lock-in amplifier.
In this lab,

(i) The properties of acousto-optic modulators are explored with regard to the materials properties of the photoelastic material and their influence on the intensity, the maximum intensity angle as well as the frequency shift of the light.

(ii) A two mode laser is used in order to carry out an optical ranging experiment. For this the phase shift of the beat oscillation induced by the displacement of a corner cube which increases the optical path length of one of two different beam paths is measured.
1. **Carry out the following Experiment**

Measure the beam diffraction angle and RF frequency of the drive signal. Use the specifications of the acousto-optic (AO) modulator (index of refraction, speed of sound) to calculate the expected internal and external diffraction angle using Bragg theory and compare your measured value with the experimentally determined value and AO modulator specifications. Note that the specifications include the Bragg angle (which corresponds to half of the full beam deviation angle $\theta_{net}$ shown above. Don’t forget to include refraction at the faces of the acousto-optic modulator. Measure the intensity of the the first order beam as a function of the AOM drive power by recording the intensity as a function the attenuation (3-4 data points). Is the intensity proportional to the AOM drive power? If not, explain differences!
Principal sketch of the experiment (2)

- HeNe laser
- Optical isolator
- AOM driver
- AOM
- Piezo controlled Fabry-Perot interferometer
- Manual translator
- Beam splitter
- Mirror
- Photodiode
- Oscilloscope: Tektronix TDS1012
- Ch1, Ch2 trigger
- Optical spectrum analyzer
- Department of Physics
- University of Utah
2. Carry out the following experiment:

Observation of 80 MHz shift with Fabry-Perot Optical Spectrum Analyzer

With a Fabry-Perot cavity or Optical Spectrum Analyser (OSA), observe and measure the frequency shift produced by the acousto-optic (AO) modulator. To do this, fold the AO diffracted beam back onto the zero order beam and pass both through the OSA. See Slide 6. The two beams have to be aligned to an extremely high degree (as well as in an interferometer), or the Fabry-Perot measurements will give the wrong value. **Explain why this is so. Compare the OSA measured frequency difference with the drive frequency of the AO modulator**, as measured by the oscilloscope. As in the first half of this lab, the OSA is calibrated by using the free spectral range of the OSA. Perform the measurements and explain how you have determined the separation in frequency of the two beams.
Principal sketch of the experiment (3):
Optical ranging

A measurement of the phase change $\phi$ between two detected beat oscillations allows the determination of a displacement $\delta d$.

If $\phi_{res} = 1^\circ$ is phase shift resolution:

$\Rightarrow \Delta d_{res} = c \phi_{res} / 2 \Delta \omega = 0.6 \text{mm}$

Two mode HeNe laser

$\Delta f = 720 \text{MHz}$
(temperature controlled)

Both modes are in one beam
$\Rightarrow$ their electric fields interfere

$\phi = 2 \delta d \Delta \omega / c$

$I(t) \propto 1 + \cos(\Delta \omega t + \phi)$

Phase delay detector

Beam analysis (OSA)

Glass slab splits off small portion of intensity

Corner cube (2 mirrors)

Fast detector D1

Fast detector D2

Beam splitter splits off half of the intensity

If $\phi_{res} = 1^\circ$ is phase shift resolution:

$\Rightarrow \Delta d_{res} = c \phi_{res} / 2 \Delta \omega = 0.6 \text{mm}$

$\phi = 2 \delta d \Delta \omega / c$

$I(t) \propto 1 + \cos(\Delta \omega t + \phi)$

$\Delta \omega = 2 \pi f$
Overview about experiment 3 (optical ranging)

- 2 mode HeNe laser
- fast detector D1 + preamplifier
- fast detector D2 + preamplifier
- lens focuses beam onto detector
- lens focuses beam onto detector
- beam splitter cube
- optical spectrum analyzer
- optical isolator
- glass slab
- track
Explanation of the optical ranging experiment

The output of the laser (two axial modes) provides a built-in power modulation at the frequency difference between the two modes. Observe the beating of the two optical fields on the detector using a fast oscilloscope (if available). This beat signal represents the envelope modulation of the beam at the difference frequency of the modes, caused by the interference of the two fields at different optical frequencies. This signal will be called the reference signal for optical ranging. It will be compared with a time delayed (or phase delayed) measurement signal obtained from beam 2 (B2) by a second detector (D2) after the light has propagated the distance to be measured. The change in the relative phase of the two signals is directly proportional to the change in the measurement distance. The relative phase between the reference and measurement beam will be measured by first mixing both signals down to an intermediate frequency (near 100 kHz), and then detecting the phase difference with a lock-in amplifier as explained on Slide 3 (phase delay detector).
3. Carry out the following experiment:

(a) Place a corner cube or pair of aligned mirrors that act as a corner cube reflector on a stage which is guided by the optical rail along the axis of beam 2 (B2). Position the second detector (D2) so that it collects the light which is reflected from the corner cube. Measure the relative phase delay (using the phase detection circuit) between the signals from the two detectors as a function of path length of beam 2 by translating the stage with the corner cube along the optical rail over a 10 centimeter distance and reading the phase change from the lock-in amplifier. Remember that the optical path length change is twice the distance change of the corner cube, since the beam must travel to and from the mirror(s). Quantitatively compare your measured phase delay with the predictions of the time of flight equation.

(b) Calculate the mirror distance change over which the phase of the signal beam will shift by 360 degrees relative to the reference signal, using the time of flight equation given on Slide 8.

(c) Determine the resolution of the displacement measurement by measuring the lock-in amplifier phase noise.