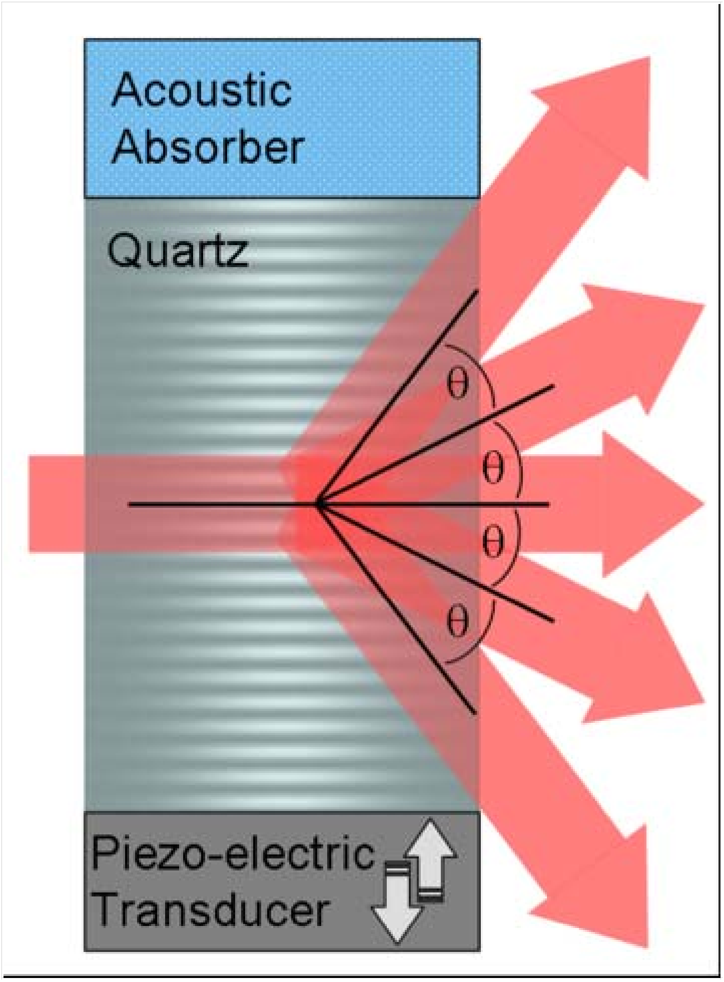
Acousto-optic modulator



An acousto-optic modulator consists of a piezoelectric transducer which creates sound waves in a material like glass or quartz. A light beam is diffracted into several orders. By vibrating the material with a pure sinusoid and tilting the AOM so the light is reflected from the flat sound waves into the first diffraction order, up to 90% deflection efficiency can be achieved.

An **acousto-optic modulator** (AOM), also called a **Bragg cell**, uses the acousto-optic effect to diffract and shift the frequency of light using sound waves (usually at radio-frequency). They are used in lasers for Q-switching, telecommunications for signal modulation, and in spectroscopy for frequency control. A piezoelectric transducer is attached to a material such as glass. An oscillating electric signal drives the transducer to vibrate, which creates sound waves in the glass. These can be thought of as moving periodic planes of expansion and compression that change the index of refraction. Incoming light scatters (see Brillouin scattering) off the resulting periodic index modulation and interference occurs similar to in Bragg diffraction. The interaction can be thought of as four-wave mixing between phonons and photons. The properties of the light exiting the AOM can be controlled in five ways:

1. Deflection

   A diffracted beam emerges at an angle θ that depends on the wavelength of the light λ relative to the wavelength of the sound Λ

   $\sin\theta = \left(\frac{m\lambda}{2\Lambda}\right)$ in the Bragg regime

and

   $\sin\theta = \left(\frac{m\lambda_0}{n\Lambda}\right)$ with the light normal to the sound waves

   where $m = ...-2,-1,0,1,2,...$ is the order of diffraction. Diffraction from a sinusoidal modulation in a thin crystal solely results in the $m = -1,0,+1$ diffraction orders. Cascaded diffraction in medium thickness crystals leads to higher orders of diffraction. In thick crystals with weak modulation, only phasematched orders are diffracted, this is called Bragg diffraction. The angular deflection can range from 1 to 5000 beam widths (the number of resolvable spots). Consequently, the deflection is typically limited to tens of milliradians.

2. Intensity

   The amount of light diffracted by the sound wave depends on the intensity of the sound. Hence, the intensity of the sound can be used to modulate the intensity of the light in the diffracted beam. Typically, the intensity that is diffracted into m=0 order can be varied between 15% to 99% of the input light intensity. Likewise, the intensity of the *m*=1 order can be varied between 0% and 80%.

3. Frequency
   One difference from Bragg diffraction is that the light is scattering from moving planes. A consequence of this is the frequency of the diffracted beam *f* in order *m* will be Doppler-shifted by an amount equal to the frequency of the sound wave *F*.
   $$f \rightarrow f + mF$$

This frequency shift is also required by the fact that energy and momentum (of the photons and phonons) are conserved in the process. A typical frequency shift varies from 27 MHz, for a less-expensive AOM, to 400 MHz, for a state-of-the-art commercial device. In some AOMs, two acoustic waves travel in opposite directions in the material, creating a standing wave. Diffraction from the standing wave does not shift the frequency of the diffracted light.

4. Phase
   In addition, the phase of the diffracted beam will also be shifted by the phase of the sound wave. The phase can be changed by an arbitrary amount.

5. Polarization
   Collinear transverse acoustic waves or perpendicular longitudinal waves can change the polarization. The acoustic waves induce a birefringent phase-shift, much like in a Pockels cell. The acousto-optic tunable filter, especially the dazzler, which can generate variable pulse shapes, is based on this principle.

Acousto-optic modulators are much faster than typical mechanical devices such as tiltable mirrors. The time it takes an AOM to shift the exiting beam in is roughly limited to the transit time of the sound wave across the beam (typically 5 to 100 nanoseconds). This is fast enough to create active modelocking in an ultrafast laser. When faster control is necessary electro-optic modulators are used. However, these require very high voltages (e.g. 10 kilovolts), whereas AOMs offer more deflection range, simple design, and low power consumption (less than 3 watts)

(1) The Acousto-Optic Modulator.

The acousto-optic effect occurs when a light beam passes through a transparent material, such as glass, in which travelling acoustic waves are also present, as depicted in Fig. 1.[2] Acoustic waves are generated in the glass by a piezoelectric transducer that is driven by a RF signal source. The spatially periodic density variations in the glass corresponding to compressions and rarefactions of the travelling acoustic wave are accompanied by corresponding changes in the index of refraction for propagation of light in the medium. These travelling waves of index of refraction variation diffract the incident light much as the atomic planes of a crystal diffract x-rays in Bragg scattering.[2] For acoustic waves of sufficiently high power, most of the light incident on the acousto-optic modulator can be diffracted and therefore deflected from its incident direction.

For acoustic waves of frequency f travelling at the speed of sound in a medium, v_S, the wavelength of the acoustic waves, Λ
, and therefore the spacing between the planes of index of refraction variation, is given by the usual wave relation $v_S = \Lambda$
f. A light beam passing through the acoustically driven medium will be diffracted to angles θ given by

$$\sin\theta = (m\lambda / 2\Lambda) \qquad (1)$$

where m = 0, ±1, ±2, ... is called the diffraction order.[2] In this experiment only the m 0 and m = +1 diffraction orders will be important. Note the similarity of Eq. (1) to the analogous formula for Bragg diffraction of x-rays by atomic planes separated by a distance d:[3]

$$\sin\epsilon = (m\lambda / 2d)$$

From Fig. 1, the angle α between a diffracted beam and the undiffracted beam is given by

$$\begin{aligned}\sin(\alpha / 2) &= (m\lambda / 2\Lambda) \\ &= (m\lambda f / 2v_s) \qquad (2)\end{aligned}$$

At this point it is helpful to consider numerical estimates for these quantities for the IntraAction ADM-40, flint glass, acousto-optic modulator/deflectors used in this experiment. The "40" in the model number signifies that these acousto-optic modulators have been optimized for operation at an acoustic frequency f = 40 MHz, but the manufacturer guarantees good performance over the range 30-50 MHz. Although v_S
for the flint glass material used in the ADM-40 is not given by the manufacturer, an estimate can be made using the speed of sound in clear lead glass, v_S = 3800 m/s, from Ref. 4. The acoustic wavelength Λ will therefore be $\Lambda = v_S/f$ = 9.5 µm. For deflection of a HeNe laser beam, the deflection angle α
for the first order (m = 1) diffracted beam is less than a degree, so that the usual small angle approximation can be made in Eq.(2) to give

$$\alpha = (\lambda f / v_S) = ((6328 \times 10^{-10}\ \mathrm{m})(40 \times 10^{6}\ \mathrm{s}^{-1})/3800\ \mathrm{m/s}) = 6.7 \times 10^{-3}\ \mathrm{rad} = 0.38^{0} \qquad (3)$$

a very small, but useful deflection.

Three common operating modes of the acousto-optic modulator will be described in detail.

(a) Deflection. Under optimal conditions, the ADM-40 can diffract nearly 85-90% of the incident light into the first order diffracted beam.[5]
By simply turning the acoustic energy source on and off, the acousto-optic modulator can act as a rapid light deflector. The switching of the incident light beam to the first order diffracted beam can occur in a very short period of time (< 5 μs) depending only on how rapidly the acoustic wave field can be turned on and off in the volume of the flint glass traversed by the laser beam. From Eq. (3) it can be seen that an acousto-optic modulator can deflect a laser beam to different angles α by simply varying the acousto-optic modulator frequency f. The diffracted beam emerging from the ADM-40 can be swept through an angular range of 3.3 mrad when the acoustic driver frequency is swept from 30 to 50 MHz. This property can be used to move a laser beam rapidly in space - without moving parts - in such applications as the laser printer and direct laser display devices.

From Eq. (3) it can be seen that the deflection angle α depends on the wavelength λ of the incident light beam. The acousto-optic modulator can therefore be used to deflect beams of polychromatic light into component colors or wavelengths, in a manner reminiscent of the dispersive prism.

(b) Modulation. The amount of laser light diffracted to the first order beam depends on the amplitude of the acoustic waves that diffract the incident laser beam, and therefore, by modulating the power level of the acoustic wave source, the intensity of the diffracted light beam can be modulated. By this means an electrical signal containing voice, music, or television can modulate the intensity of a light beam as part of an optical communications system.

(c) Frequency shifting. This is one of the most useful properties of the acousto-optic modulator. The ability of the acousto-optic modulator to shift the frequency of a laser light beam by a precise and stable amount is crucial to production of a beat note from two light beams in this experiment. The similarity of Eq. (1) for the acousto-optic effect to Eq. (2) for Bragg diffraction of x-rays belies an important difference between the two diffraction situations. Bragg diffraction of x-rays occurs for atomic planes that are at rest in the laboratory, while acousto-optic diffraction occurs from acoustic wave planes that travel at the relatively high speed v_S with respect to the laboratory. The fact that the diffracting acoustic planes move with respect to the laboratory leads to a Doppler shift of the frequency of the diffracted beams. Although a derivation of the Doppler effect expected for this case will not be given here, the answer for the Doppler shifted frequency of the diffracted beam is very simple to state: the frequency of the first order diffracted beam is shifted by an amount *exactly* equal to the acousto-optic modulator frequency f. If ν_0 is the frequency of the light incident on the acousto-optic modulator, the frequency of the first order beam will be upshifted to ν_0+f in the case that the acoustic planes have a component of motion toward the incident light beam, as in the configuration of Fig. 2(a), and downshifted to ν_0-f when the acoustic planes have a component of motion away from the incident light beam, as in Fig. 2(b).

The frequency shift produced by an acousto-optic modulator can be used to transform a fixed frequency laser like the HeNe laser, into a tunable laser, although only over the small range of frequencies (20 MHz for the ADM-40) over which the acousto-optic modulator can be operated.

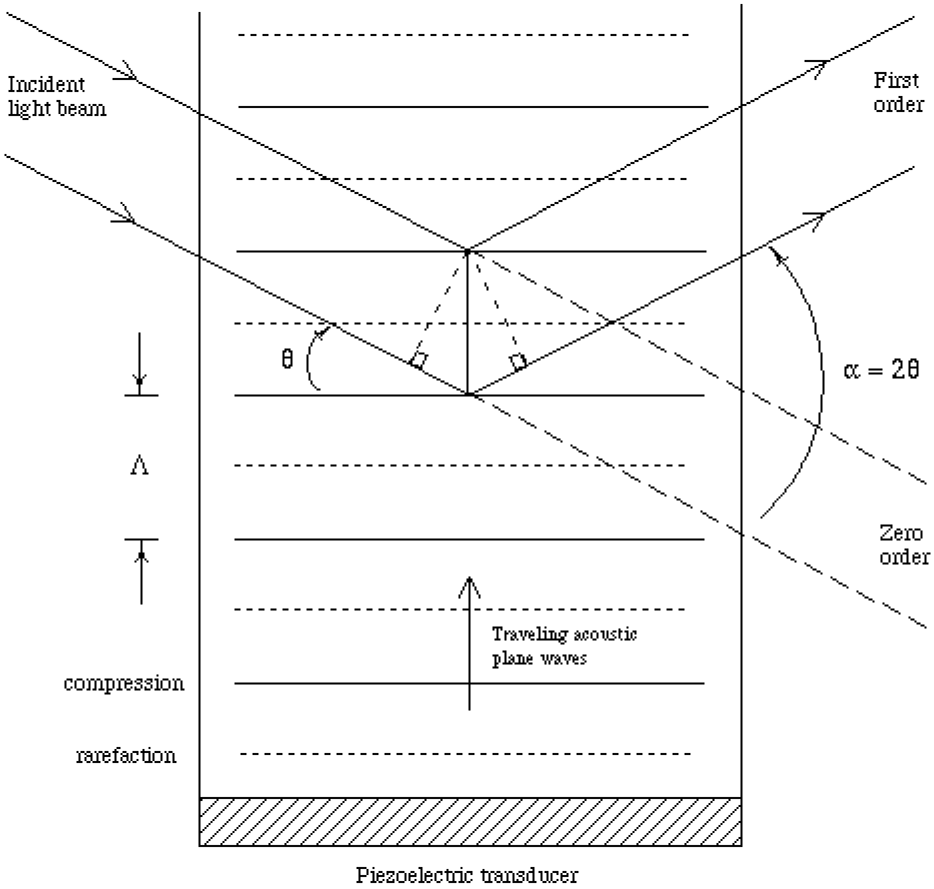


FIG. 1. Diffraction of a light beam by traveling acoustic plane waves in an acousto-optic modulator. The refraction of light at the air-glass boundaries is not shown.