Australia's Global University

UNSW SYDNEY

Acousto-Optics

Student Notes

1 Experimental Aim

To study the operation of an acousto-optic deflector and of a modulator and hence to gain an understanding of acousto-optic devices and the differences between Bragg and Raman-Nath Diffraction.

2 Introduction

In 1922, the interaction between light and acoustic sound waves in a transparent medium was theorised by Brillouin. He found that light would scatter from thermally excited elastic waves in a crystal which would be diffracted in both solids and liquids. He predicted that an interference pattern with its maximum peak intensities at specific angles known as Bragg Angles, similar to Bragg's Law and **Bragg Diffraction** with X-rays in crystals.

This phenomenon was successfully demonstrated by Debye and Sears' experiment in 1932 using artificially generated elastic waves. This allowed them to precisely control the acoustic waves, which in turn allowed them to control and modulate the transmitted light at specific frequencies, amplitude and the direction.

However, when varying the parameters, higher order diffractions appeared with different intensities which could not be explained by Brillouin's theory. It wasn't until 1937 that Raman and Nath produced their theory explaining the intensities distribution in higher order diffractions - now known as **Raman-Nath Diffraction**.

With the advancement of lasers, crystal growing techniques and high frequency piezoelectric transducers, modern acousto-optic devices allow precise control of **optical deflection**, **modulation**, frequency shifting and much more. Hence, they are commonly used in applications such as civil and biomedicine for structural monitoring, Q-switching in pulsed operating lasers and signal processing in optical fibres.

3 Theory

Acousto-Optics (AO) is a branch of physics where light interacts with acoustic sound waves in a transparent medium due to the photoelastic effect.

It begins by using a piezo-electric transducer that converts electrical energy into mechanical vibrations which sends compression waves through the transparent medium equal to the input RF frequency and proportional to the amplitude. The travelling periodic acoustic waves cause mechanical strains within the lattice of the crystal, resulting in varying periodic densities equal to that of the acoustic wavelength. The varying densities signifies high refractive index at the acoustic peaks (compression) and low refractive index at the troughs (rarefaction) as shown in [Fig 1].

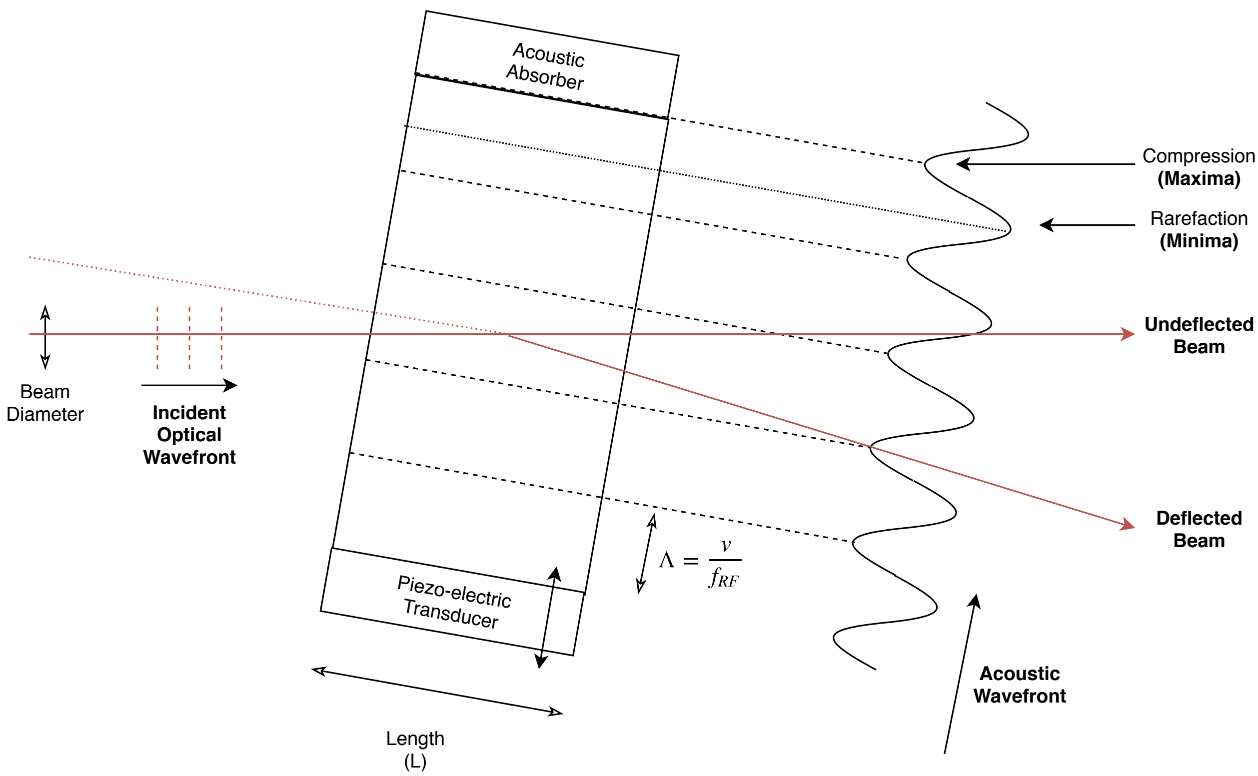

Figure 1: *An acousto-optic device schematic with periodic acoustic wavelengths peaks at maximum density and refractive index.*

Although the exact relationship between refractive index and mechanical strain are complicated due to the moving periodic acoustic waves, calculations may be simplified by approximating it as a standing wave of compression and rarefaction since the velocity of light is much greater than the velocity of the acoustic wave.

Therefore, these periodic refractive indices acts similar to diffraction gratings as the light interferes after the variation in change in phases, resulting in the observed diffraction signifying constructive interference at peak intensities.

Two types of diffraction may be observed:

- **Bragg diffraction**
- **Raman-Nath diffraction**

Both types of diffraction occurs simultaneously as there is no well-defined boundary between the two diffraction regimes. However, the Q-Factor (Quality Factor) - also known as Klein-Cook's parameter - may be used to determine the regime of the dominant diffraction.

$$Q = \frac{2\pi\lambda L}{n\Lambda^2} \tag{1}$$

Q = Q-Factor
λ = Laser wavelength (m)
L = Length of interaction (m)
n = Refractive index
Λ = Acoustic wavelength (m)

$Q >> 1$ = Bragg regime
$Q << 1$ = Raman-Nath regime

Bragg Diffraction

The physical basis of Bragg regime is that the light diffracted from the incident beam is extensively re-diffracted before leaving the acoustic field. Hence, it acts similar to 'thick' diffraction gratings that is made up of planes rather than lines. Therefore, the diffraction angle can be derived using similar method that of Bragg diffraction of a crystal using X-rays in the planes of atoms in a crystal [Fig 2].

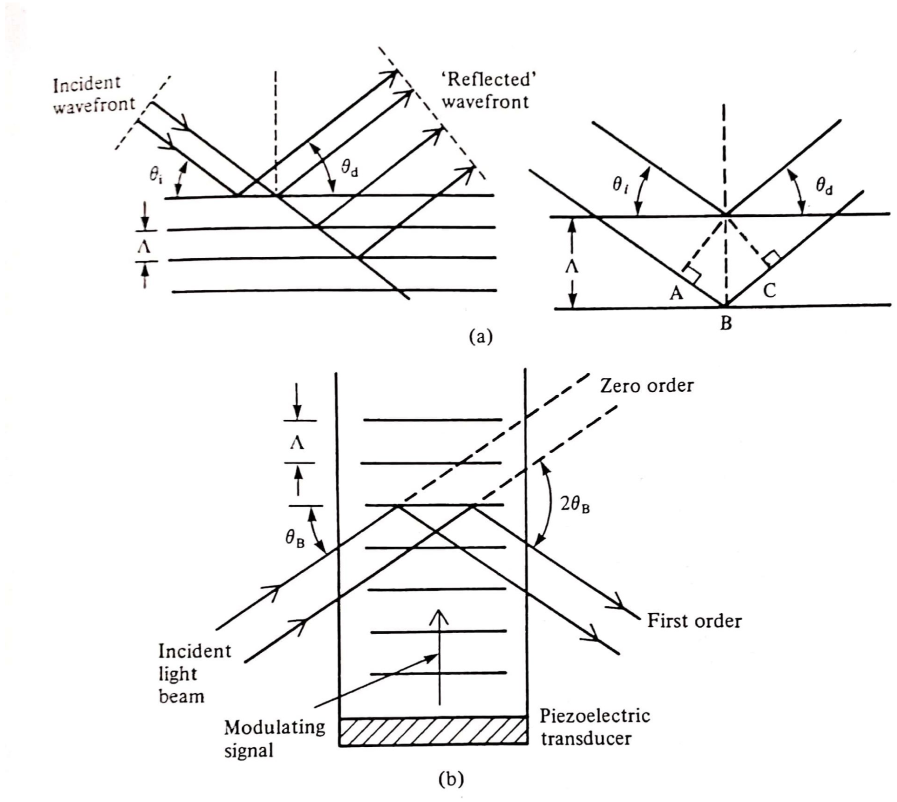

Figure 2: *Geometry for Bragg acousto-optic diffraction grating: (a) incident rays being scattered from successive layers - for constructive interference the path difference AB + BC must equal an integral number of wavelength $m\lambda$; (b) the amount of light 'reflected' into the first order depends on the amplitude of the modulating signal (refraction of light beam at boundaries of the acousto-optic crystal has been omitted for simplicity).*

As shown in [Fig 2] angle of incidence = angle deflected,

$$\theta_i = \theta_d \tag{2}$$

The total path difference travelled at constructive inteference wher m must be an integer:

$$\sin\theta_i + \sin\theta_d = \frac{m\lambda}{\Lambda} \tag{3}$$

Simplifying to,

$$2\sin\theta_B = \frac{m\lambda}{\Lambda} \tag{4}$$

And since angles are relatively small, we can approximate:

$$\sin\theta \approx \theta \tag{5}$$

Since scattering is not from discrete planes but rather from a continuous medium, it is shown that scattering only takes place when **m = 1**.

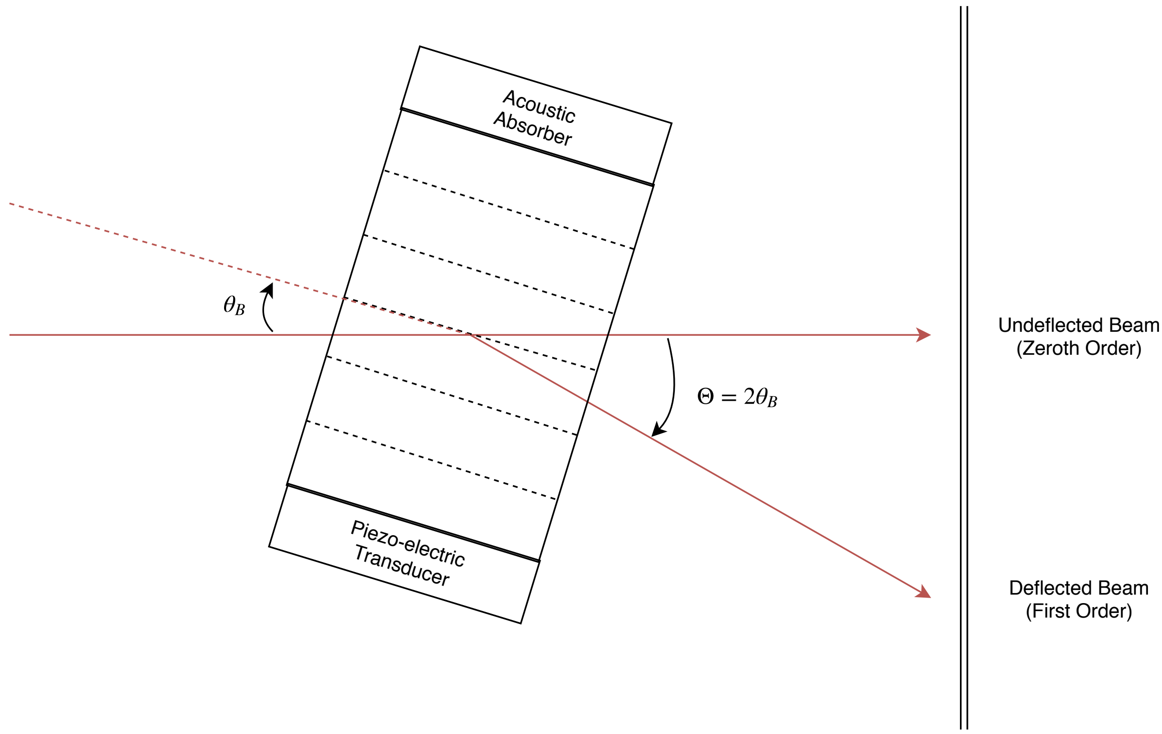

Figure 3: *Bragg diffraction using a deflector with its peaks corresponding to Bragg Angles.*

And finally since,

$$\Lambda = \frac{v}{f_{RF}} \tag{6}$$

$$\Theta = 2\theta_B = \frac{\lambda}{\Lambda} = \frac{\lambda f_{RF}}{v} \tag{7}$$

Θ = Zeroth and First Order maxima angle (rad)
θ_B = Bragg angle (rad)
λ = Light wavelength (m)
Λ = Acoustic wavelength (m)
f_{RF} = Generator frequency (Hz)
v = Acoustic velocity (m/s)

Raman-Nath Diffraction

In **Raman-Nath (R-N) diffraction** the width of the acoustic beam is so small that the diffracted light suffers no further redistribution before leaving the modulator. Thus multiple orders will be seen with its intensity distribution corresponding to the **Bessel Function**.

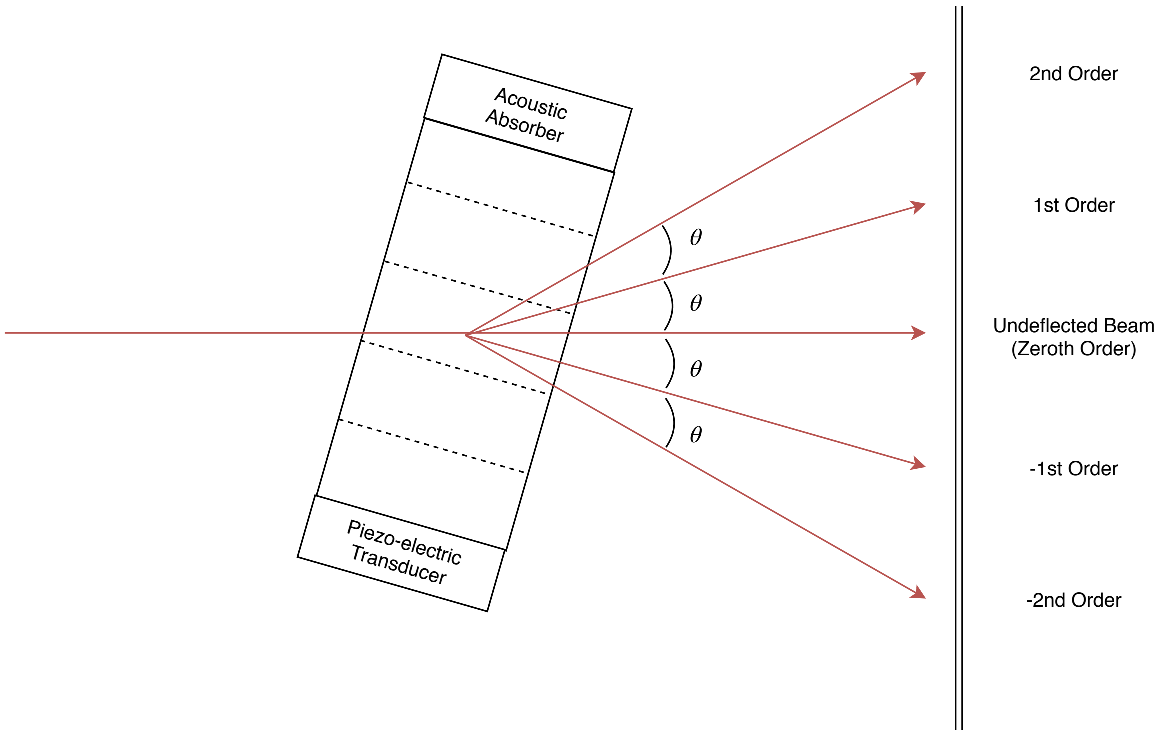

Figure 4: *Raman-Nath diffraction at multiple orders with its intensity distribution corresponding to Bessel Function due to its smaller interaction length relative to Bragg diffraction.*

Therefore, the light is simply diffracted from a simple plane grating such that:

$$\sin\theta_m = \frac{m\lambda}{\Lambda} \tag{8}$$

θ_m = Angle from Zeroth Order (rad)
m = Order $(0, \pm 1, \pm 2, ...)$
λ = Light wavelength (m)
Λ = Acoustic wavelength (m)

4 Experimental Instructions

In this experiment we look at two devices, an **AO Deflector** made of Dense Flint Glass **(IntraAction-AOD-70)** that is used for the **Bragg regime** and a Lead Molybdate ($PbMoO_4$), an **AO modulator (ISOMET-1260C)** used for the **R-N regime**.

A deflector simply deflects the beam into 1st orders in accordance to Bragg Angles, whilst a modulator is able modulate using **amplitude modulation (AM)** - see [Fig 5], similar to that used in radio waves.

The modulation occurs to the transmitted light that varies its intensity at the peaks proportional to modulated signal which is a combination of both **110 MHz carrier signal** from the AO Modulation Driver and the input signal from the signal function generator (SFG). This enables information to be 'encoded' and transmitted in the laser.

Although of these devices are able to deflect and modulate the beam, but are best designed for the specific regimes.

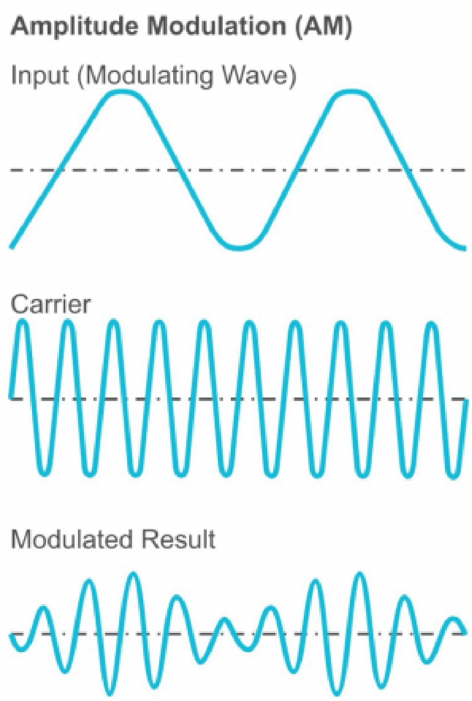

Figure 5: *Resultant amplitude modulation given a carrier signal and input signal.*

Many measurements in this experiment can be made using a white screen and a meter ruler. To make quantitative measurements of light intensity, there are two photodiodes that are used in its photovoltaic mode. It has a DC output sensitivity of **6V/mW** with a current conversion rate of **15V/mA**. The signal can be observed using the Digital Oscilloscope (DSO) and the image can be captured using 'OpenChoice Desktop' application on the computer.

Experimental Precautions

- The light source in this experiment is a low power **1 mW Helium-Neon (HeNe)** laser which, nevertheless, is capable of delivering power densities high enough to damage the retina. Therefore, wear the safety googles and never directly view the laser beam or its reflection from a shiny surface. Leave the room lights on whenever possible during the experiment and take care not to endanger other people's eyes with stray reflections of the beam.
- The deflector and modulator are expensive devices which can be easily damaged. Do not drop or bump them and always switch the power supply off when connecting / disconnecting any part of the circuit.
- **REMEMBER** to **DISCONNECT** the photodiode after the experiment to prevent battery drainage.

4.1 Bragg Diffraction using a Deflector

Experimental Setup for 'IntraAction' AOD-70 Deflector

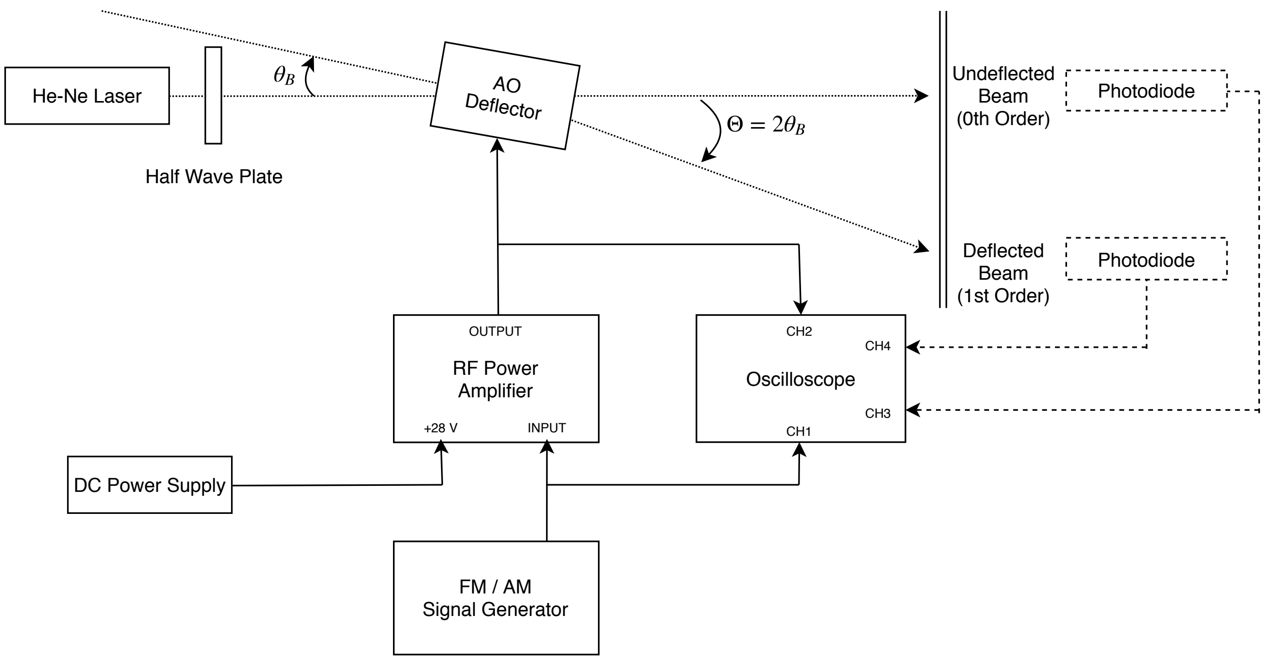

Figure 6: *Schematic of the AOD-70 circuit. (the dotted equipment is used for the optional part of the experiment)*

POWER SUPPLY	VOLTAGE:	28 V
FUNCTION GENERATOR	MODULATION: FREQUENCY: LEVEL:	OFF 70 MHz 99 dB
OSCILLISCOPE / DSO	Press AUTOSET and MEASURE	

Table 1: *Conditions for Bragg diffraction - Equipment settings for deflector*

INSTRUCTIONS:

1. Connect the circuit as shown in the schematic - [Fig 6].
2. Switch on all the devices needed for the experiment and adjust the settings as shown in - [Table 1].
3. Align the laser correctly (it should already be aligned) - if you are having difficulty ask for demonstrator's help.
4. Switch the computer on and login to use the program 'OpenChoice Desktop' to get the to get the current picture of the DSO. Save the image.
5. Record V_{pk-pk} for both, the Signal Generator and the Amplified Signal. Then calculate approximate gain of the RF Power Amplifier.

$$Gain = \frac{V_{output}}{V_{input}}$$

   Press "MEASURE" on the DSO and then any of the button in the tab showing "CH-X" on the screen. Cycle through "TYPE" to measure the pk-pk voltage.

6. Orient the deflector so that you get a through beam and the reflected laser beam goes back directly back into the laser. Then maximise the intensity of the diffracted beam at the scaled screen by adjusting he deflector orientation carefully.
7. Using the screen and a ruler, measure the distance between the 0th and 1st maxima as well as the distance from the deflector to the screen. Then calculate the angle of deflection and hence the Bragg angle.
8. Rotate the deflector so that it gives a diffracted spot on the other side of the undeflected beam, repeat and measure the angle of deflection and find the Bragg angle for the other side.
9. Compare the calculated values in the experiment to the manufacturer's specification of the device. Does it agree with what you might expect? (refer to reference manual for documentation).
10. Measure the Bragg angle as a function of the acoustic frequency in the range 60 to 100 MHz and draw a quick plot (<= 10 points) of your results to predict the relationship between the frequency and the Bragg angle. Then hence determine the velocity of the ultrasound.

RF Frequency (MHz)	Distance (mm)	Deflection Angle (mrad)	Bragg Angle (mrad)
50			
..			
110			

11. Now vary the frequency in range 20 to 40 MHz. Note and explain what you observe.

OPTIONAL:

12. Add the photodiode as shown in [Fig 6] and set the frequency of the generator at 70 MHz.

13. Using the oscilloscope check how the diffracted intensity varies with the direction of the polarisation of the laser beam and try to explain what you see. - the laser beam is linearly polarised and the direction of polarisation can be varied by rotating the half-wave plate polariser. - the half-wave plate simply rotates the polarisation of beam by two times the actual angle rotated. (e.g 45° rotation of the polariser results in 90° polarisation rotation of the beam)

4.2 R-N Diffraction using a Modulator

Experimental Setup for 'ISOMET-1206C' Modulator

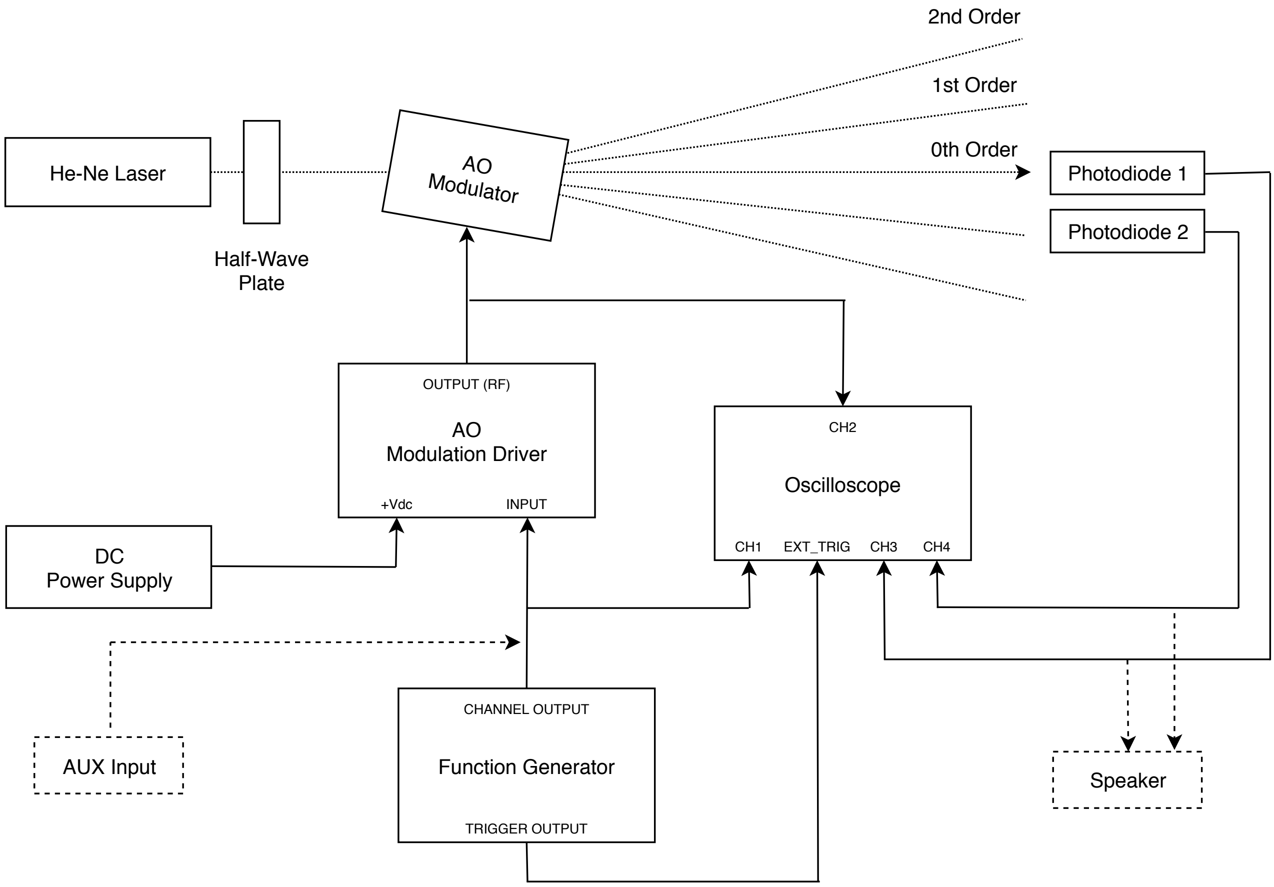

Figure 7: *Schematic of the AOM (ISOMET-1206C) circuit.*

POWER SUPPLY	VOLTAGE:	28 V
SFG	FREQUENCY: AMPLITUDE: OFFSET:	400 Hz MAX 0V
OSCILLISCOPE / DSO	Press AUTOSET and MEASURE	

Table 2: Conditions for Raman-Nath diffraction - Equipment settings for modulator

INSTRUCTIONS:

1. Connect the circuit as shown in the schematic - [Fig 7].
2. Switch on all the devices for the experiment and adjust the settings as shown in - [Table 2].
3. Check that the photodiode is calibrated by measuring the DC voltage output using the multimeter by placing the photodiode in front of the laser (without any equipment). Since the laser is approx 1 mW, you should get a similar reading for voltage given the conversion rate of the photodiode 6V 1 mW.
4. Orient the modulator crystal approximately perpendicular to the incident beam (use back reflection), then maximise the intensity of the diffracted beams by slightly rotating the modulator. You should be able to see at least 1 diffracted beam on each side of the main beam (two if the laser is aligned well).
5. Try rotating the modulator to give diffracted beams on the other side of the undeflected beam. Can you do this? Explain. Can you see the signal from the SFG on DSO CH1 (yellow) and the amplified signal which is driving the modulator on CH2 (blue)? If not, see the demonstrator.
6. Measure the angles between adjacent beams and hence calculate the velocity of the acoustic wave. Compare values with given ref.
7. Position one photodiode so that the first order diffracted beam strikes it centrally and the other photodiode to collect the main beam.
8. Plug the 0th order (undeflected beam) to CH3 and the 1st order to CH4
9. Check if the modulation works by setting the SFG to frequency of 2-5 Hz, and you should be able to see the diffraction pattern "blink" relative to the corresponding frequency.

   To observe AC modulation set the DSO to "AC" Coupling by pressing "CH-X MENU" button and similarly with DC if you want to measure the DC current.

10. For modulation set the SFG to sine wave at 400Hz and amplitude to $0.4V_{pk-pk}$. Check if you have got diffracted beams on each side of the main beam with approximately the same intensity. Observe the DSO and how it changes the modulated signal. - To get a successful quality of modulation make sure not to over modulate the signal, otherwise the signal may become distorted. [Fig 8]

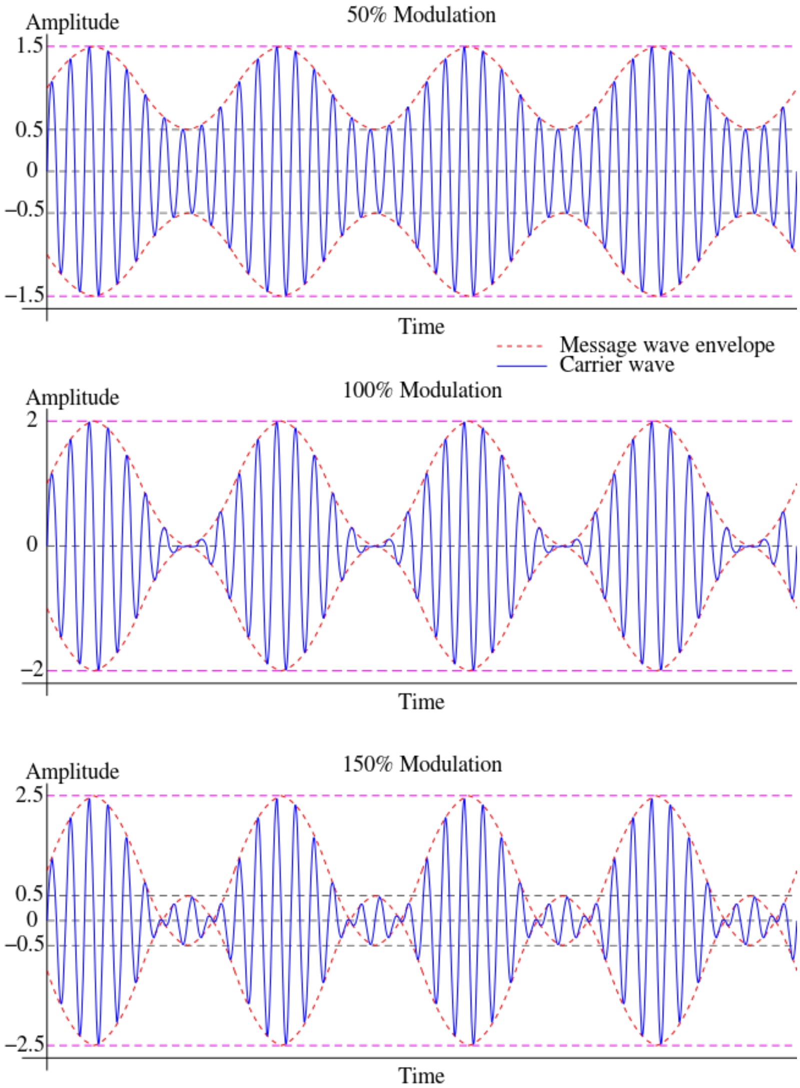

Figure 8: *Under, Full and Over modulation of a signal*

11. Increase the OFFSET at the AFG and observe at what voltage the 400Hz signal is first detected by the photodiode. Increase OFFSET further to find the higher voltage limit at which the signal is still detected.

    If the modulation is not steady press "TRIG MENU" on the DSO and make sure the source is configured to "EXT". If this does not help press "AUTOSET", similarly set the SFG to "TTL".

12. Try placing the photodiode in other orders to observe and record any interesting effects - *Resolution may need to be increased on the DSO to see the 2nd order.*

13. Insert the speaker as shown in [Fig 7], find and note the maximum amplitude and

best DC level for 400 Hz audio signal transmission before appreciable distortion of the signal occurs.

14. Wind up the frequency and find your own and your partner's maximum frequency response of your ears.

15. Check the phases of the main beam relative to the signal at the input of the modulator driver as well as the phases of 1st and 2nd orders. Are the relative phases as you would expect? Explain.

16. Measure the V_{mean} of the DC voltage from the photodiode and calculate the power. - *try to keep the lights off if possible to reduce background light.*

	Background (no laser)	Full Modulation	No Modulation
0°			
1° (left)			
1° (right)			

17. Now measure the signal modulation $V_{peak-peak}$ (AC) and V_{mean} (DC) from the photodiode to calculate signal to mean value ratio.

	V_{pp} (AC)	V_{mean} (DC)	SMVR
0°			
1° (left)			
1° (right)			

18. Use the AUX input [Fig 7] to transmit music on the laser beam and play back out the amplified speaker. Record and detail observations of quality in different order beams and compare it to the SMV ratio.

19. Try transmitting various forms of waveforms, frequencies, offset, amplitudes and note any interesting effects. Use "OpenChoice Desktop" to copy and save the picture of the DSO.

20. When complete, make sure to **DISCONNECT** the cables from the **PHOTODIODE** to prevent battery drainage.

5 Questions

1. Describe the acousto-optic principle.
2. Distinguish the difference between Bragg and Raman-Nath diffraction.
3. Show that the deflector is in Bragg regime and Raman-Nath is in diffraction regime using the Q-Factor (refer to references for unknown parameters).
4. What determines the intensity of the diffracted beams?
5. Give some applications for AO and deflectors and modulators.

References

[1] *Wilson J. and Hawkes J.F.B, "Optoelectronics: An Introduction" (1983) - '3.8.*

[2] *Main R.P., Lasers and Applications, June 1984, pp111-116.*

[3] *'IntraAction' AO Light Deflector Instruction Manual.*

[4] *'ISOMET' AO Modulator Instruction Manual.*

[5] *Pierce D.T and Byer R.L., American Journal of Physics 41, 314-325 (1973).*

[6] *http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/imgqua/Bragglaw.gif*

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