A Guide to Acousto-Optic Modulators

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1 Introduction

Acousto-optic modulators (AOMs) are useful devices which allow the frequency, intensity and direction of a laser beam to be modulated. Within these devices incoming light Bragg diffracts off acoustic wavefronts which propagate through a crystal. Modulation of this incoming light can be achieved by varying the amplitude and frequency of the acoustic waves travelling through the crystal.

2 How do AOMs work?

Sound waves travelling through a crystal can be modelled as crests of increased refractive index alternating with troughs of decreased refractive index. Light incident on gradients in refractive index is scattered, therefore the light scatters from the acoustic wavefronts. In an AOM the light scattered from successive wavefronts interferes constructively. Figure 1 shows two rays of light impinging on two consecutive wavefronts in a crystal. Note that only some of the light is scattered from these wavefronts. The optical and acoustic wavelengths are denoted by λ_L and Λ respectively, while θ_i and θ_d are the angles the incident and scattered light rays make with the acoustic wavefronts respectively. The condition for constructive interference of the scattered light is

$$n\lambda_L = \Lambda(\sin\theta_i + \sin\theta_d), \tag{1}$$

where n is an integer [1]. For an optical wave scattering from sound with a frequency of order 10^8 Hz, it can be shown that the conservation of energy and momentum requires that $\theta_i = \theta_d$ [2], and so we can approximate equation 1 as

$$n\lambda_L = 2\Lambda\sin\theta_d. \tag{2}$$

The Bragg condition would imply that there is only one value of the deflection angle $\Theta = 2\theta_d$ allowed, but this is based on the assumption that the acoustic and optical wavefronts are plane waves (i.e. infinitely wide),
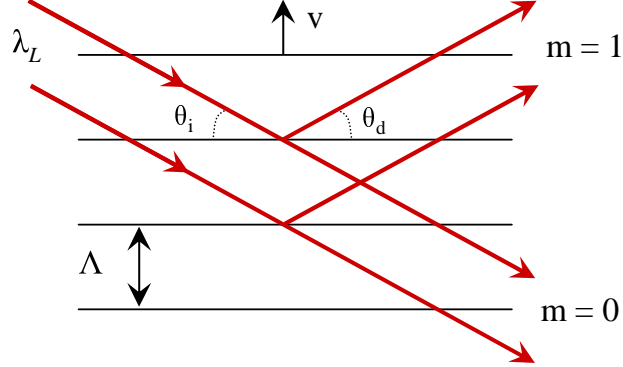
Figure 1: The Bragg construction for identifying ray directions with constructive interference

which is only approximately true in practice. If the acoustic beam is of finite width and the system is optimized for the first order maximum beam power, i.e. for the Bragg condition with $n = 1$, the result will be some light with scattering angle $m\Theta$, where m is the integer corresponding to the other orders[3].

In terms of phonons, scattering into an angle of $m\Theta$ corresponds to the absorption or destruction of m phonons whose momenta contribute to the changed momentum of the light, and whose energies are added to that of the scattered photon. The change in frequency of the input light, Δf, can be written as:

$$\Delta f = \frac{m\ E_{\mathrm{phonon}}}{h}, \tag{3}$$

where E_{phonon} is the phonon energy and h is Planck's constant. Note that if $m < 0$, m phonons are created rather than destroyed and the frequency of the light decreases. In terms of figure 1, this would correspond to the direction of the acoustic waves being reversed.

3 AOM Control

Within an AOM the acoustic wave is provided by a radio frequency (RF) signal to the AOM, controlled by an AOM driver. This driver is made up of three components, a Voltage Controlled Oscillator (VCO); a Voltage Variable Attenuator (VVA); and an amplifier. A schematic diagram of this setup is shown in figure 2.

The VCO provides a RF sine-wave output, the frequency of the RF output is determined by an applied control voltage, and varies approximately linearly with it, see figure 4(a). The VVA attenuates the output from the

VCO, the degree of attenuation is controlled by varying the applied control voltage to the VVA. The amplifier amplifies the output of the VVA, such that the RF output is sufficient to drive the AOM. The response of the AOM varies with the frequency and amplitude of the input RF signal. It is good practise to ensure that the amplifier is separated from the VCO to guard against heating from the amplifier affecting the VCO frequency, whilst ensuring that the cable connecting the amplifier to the AOM is kept as short as possible to minimize any loss of signal or creation of noise.
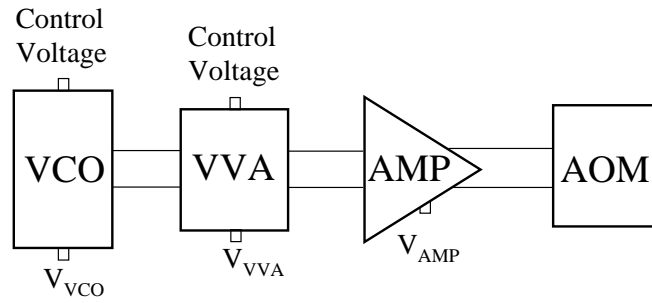

Figure 2: Schematic diagram showing how the VCO, VVA and amplifier are connected to the AOM.

To protect the amplifier when connecting an AOM to a RF signal the order that the three components are connected is crucial. Initially the output load (AOM) must be connected, the DC supply voltage must then be applied and finally the RF input (supply and control voltages to VCO and VVA) must be applied. To safely disconnect an AOM from a RF signal this connecting order is reversed, remove the RF input, remove the DC supply voltage and then remove the output load (AOM).

4 Setting up a double pass AOM

When a laser's frequency is scanned with an AOM, the angle of the first-order diffracted beam shifts as well, since the beam diffraction angle is a function of modulation frequency. For many applications this beam shift is an unwanted side effect and can be effectively eliminated by using the AOM in the double-pass configuration. Here the output of the mth order of the AOM is retroreflected for a second pass through the AOM leading to a frequency offset of $2m\Delta f$ on the double passed beam. In this arrangement changing the frequency of the acoustic wave, Δf, and hence the frequency of the deflected light, does not cause any steering of the first order output of the second pass. The output of the second pass counter-propagates with the

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original input beam. Whilst this is desirable, as it allows the frequency to be changed without any steering of the output beam, it poses the problem of how to separate the path of the output beam from that of the input beam. A $\lambda/4$ wave plate is placed just before the mirror and causes the second pass of the AOM to be orthogonally-linearly polarized with respect to the first pass. This allows the beam paths to be separated using a polarizing beam splitter. The setup for a double passed AOM is shown in figure 3.
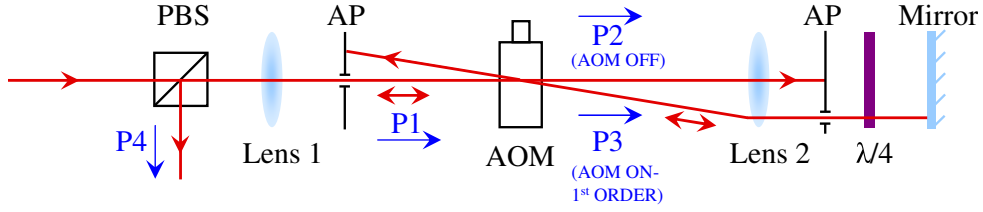

Figure 3: AOM alignment for double passed light, PBS = polarising beam splitter; AP = aperture; AOM = acousto-optic modulator; $\lambda/4$ = quarter wave plate. The labels P1-P4 are beam powers at their specific locations.

Typical properties of the system are defined as:

$$\text{Diffraction Efficiency} = \text{P3/P2} \tag{4}$$

$$\text{Double Pass Efficiency} = \text{P4/P1} \tag{5}$$

$$\text{Single Pass Efficiency} = \text{P3/P1} \tag{6}$$

$$\text{Transmission} = \text{P2/P1} \tag{7}$$

To align the double pass AOM:

1. Ensure that the laser beam passing through the cube is both horizontal and aligned over a row of holes in the optical bench. This will make translating lens 2 easier later.

2. Position lens 1 such that the beam passes through the centre of the lens. This can be tested by observing the position of the beam downstream with and without the lens in place. If the lens is correctly in place there will be no change in the beam position.

3. Locate the focus of the beam. This is done by making knife-edge measurements of the beam at various positions from the lens. Due to the Gaussian profile of the beam it is not sufficient to assume that the

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focus occurs at the focal length of the lens. Now plot the distance the razor blade had to be traversed in order for the beam power to drop from 90% to 10% of the maximum as a function of the distance from the lens. The minimum of this plot corresponds to the beam waist. The beam waist, w_x, can be calculated using:

$$w_x = \frac{X_{10-90}}{1.28},\tag{8}$$

where X_{10-90} is the minimum distance between the points at which the power output is 10% and 90% of the maximum. This equation can be used to calculate the $1/e^2$ radius for any position along the beam path, provided that the X_{10-90} distance for that position is known. Further details on knife-edge measurements can be found in [4].

4. Turn on the AOM and position it at the beam focus, less a small distance to account for the increased optical path length inside the modulator crystal. This increment is of the order of millimeters and can be found on the device data sheet. Align the AOM for maximum diffraction efficiency into the first order. It should be noted that different AOMs have different active acoustic apertures. This results in specific beam waists being needed for different AOMs to achieve optimum transmission and diffraction efficiencies [5]. To obtain the proper optical beam waist diameter, d, stipulated in the device data sheet the following relationship can be used to estimate the required focal length, F, for lens 1

$$d = \frac{1.27\ F\ \lambda}{D},\tag{9}$$

where λ is the light wavelength and D is the $1/e^2$ radius for the input laser beam. Typically d is of the order of 100 μm and F ranges from 160 to 250 mm.

5. Turn off the AOM and insert lens 2 at its focal length from the AOM. Again test that the beam is central on the lens by observing no change in the beam position downstream with and without the lens in position.

6. Insert a $\lambda/4$ waveplate and a zero degree mirror after lens 2, center the $\lambda/4$ waveplate on the zeroth order beam.

7. Place an aperture at the position of the input beam after lens 1 to transmit only the zeroth order light.

8. Retroreflect the zeroth order using the aperture as a guide.

9. Place a power-meter after the cube and fine tune for maximum power using the mirror and by rotating the $\lambda/4$ waveplate.

10. Turn on the AOM and move the $\lambda/4$ waveplate to transmit the first order diffracted beam. Position an aperture between lens 2 and the $\lambda/4$ waveplate to transmit only the first order diffracted light.

11. Final adjustments to maximise the double pass efficiency can be made using the mirror.

12. Optimise the position of lens 2 for minimum beam deflection as the AOM frequency is changed. This is done by looking at the double passed light a known distance downstream. Measure the deflection of the beam for the range of AOM frequencies of interest (typically 110 MHz to 80 MHz) using a knife-edge to find the beam centre. Now plot this deflection as a function lens position. The optimum position for lens 2 corresponds to the point where beam deflection is smallest. The beam deflection is usually given in mrad/MHz.

5   Typical Performance

To test the typical performance of a double pass AOM the setup shown in figure 3 was made. The polarising beam splitting (PBS) cube used was a CASIX PBS0201 cube for 780 nm, both lens' were made by COMAR and had a focal length of 250 mm (250PQ25-AR). A Crystal Technologies AOM (3110-120) and a CASIX $\lambda/4$ waveplate (WPL1210-780) were used in the setup. The mirror used was a high reflection coated zero degree mirror for 740-880 nm. The driver of the AOM consisted of a Minicircuits ZOS-150 Voltage Controlled Oscillator, a Minicircuits ZX73-2500 Voltage Variable Attenuator, and a Minicircuits ZHL-3A Amplifier.

Initially the RF signal was measured before the amplifier. For an attenuator control voltage of 15 ± 0.01 V the signal frequency was measured as a function of VCO control voltage. Then the VCO control voltage was set to 6.31 ± 0.01 V and the peak to peak voltage of the RF signal was measured as a function of attenuator voltage. The results from these tests can be seen in figure 4.

The focus of the beam after lens 1 was then found using the method detailed in part 3 of section 4. The results obtained can be seen in figure 5.

These data clearly show that the focus of the beam occurs at 271 ± 1 mm away from lens 1. This means that the AOM must be positioned at a distance of (271-6) mm from lens 1. This increment of 6 mm accounts for the increased optical path length inside the modulator crystal. This increment varies for different AOMs and can be found on the AOM data sheet. Using
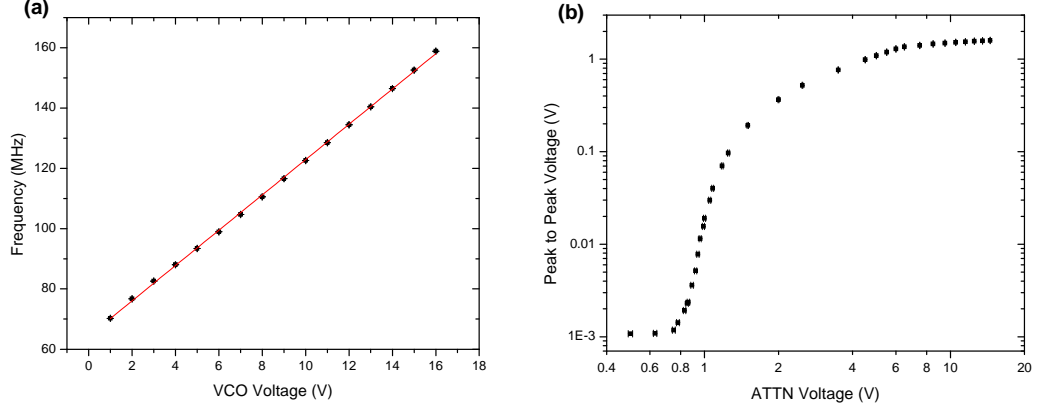
Figure 4: (a) Frequency of the RF output as a function of control voltage to the VCO. A linear fit to the data gives a gradient of 5.86 ± 0.03 MHz V^{-1} and a zero voltage offset of 64.3 ± 0.3 MHz. The reduced χ^2 value for the fit is 2.7, showing that the variation of frequency with control voltage is not simply a linear relationship. (b) Peak to Peak voltage of the RF output as a function of control voltage to the attenuator.
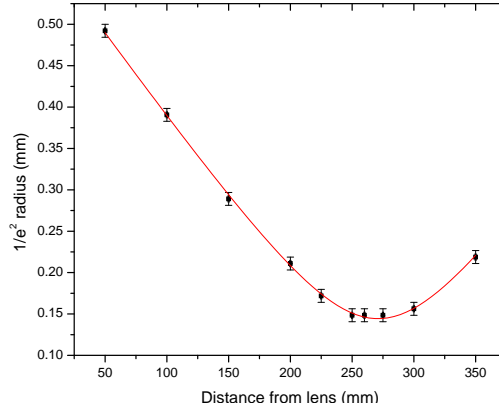

Figure 5: Variation of $1/e^2$ radius as a function of distance from lens 1. These data show that the focus of the beam lies at 271(1) mm away from the lens, of focal length 250 mm. This highlights the importance of measuring the position of the beam focus rather than simply assuming it is at the focal length of the lens. The beam waist was measured to be 0.144(1) mm and the Rayleigh range was 68(1) mm.

the data from figure 5 the M^2 value for the beam can be calculated using

$$M^2 = \frac{\pi w_0^2}{\lambda \; z_{R,\mathrm{real}}}.$$

(10)

The foundations of this equation can be found in [4]. Since real laser beams deviate from the ideal Gaussian, $M^2 > 1$ for a real beam and $M^2 = 1$ for

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an ideal Gaussian beam. Equation 10 gives $M^2 = 1.23(2)$, this is typical for a diode laser.

With the AOM correctly positioned in the setup shown in figure 3, it was aligned for maximum diffraction efficiency into the first order with the AOM frequency set to 110.0(1) MHz. With the AOM switched off the AOM transmission, defined by equation 7, was measured to be 97.6(2)%. The double pass efficiency, defined by equation 5, was measured with the position of lens 2 optimized. Results from these measurements can be seen in figure 6. The diffraction efficiency for the single pass light was then measured as a
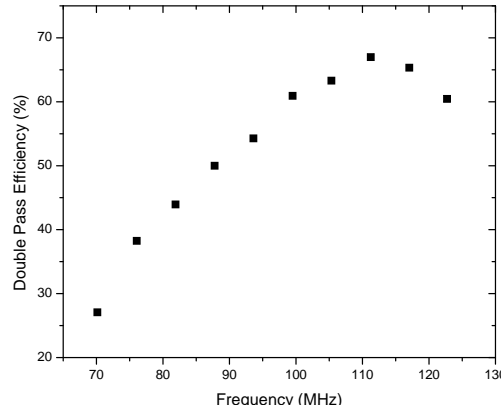

Figure 6: Variation in double pass efficiency as a function of AOM frequency. The double pass efficiency is defined by equation 5.

function of the AOM frequency. Using these data the double pass diffraction efficiency was calculated using the double pass efficiency, equation 5, with the AOM switched off. The double pass efficiency, with the AOM switched off, was measured to be 90.2(2)%. The AOM alone causes a loss of 4.7% so the remaining 5.1% of loss is due to the 16 optical faces the beam passes through. Assuming equal loss at each face the transmission is 99.7% which is in good agreement with typical values for anti-reflection coated optics. The diffraction efficiency for the double passed light was calculated using

$$\text{Diffraction Efficiency} = \sqrt{\frac{\text{P4/P1}}{90.2(2)}}. \tag{11}$$

The data gathered from these measurements and calculations are shown in figure 7.

Figures 6 and 7 show that the diffraction efficiency, and hence the double pass efficiency, of a correctly aligned AOM are not constant as the frequency of the AOM is varied. These data should be remembered when operating
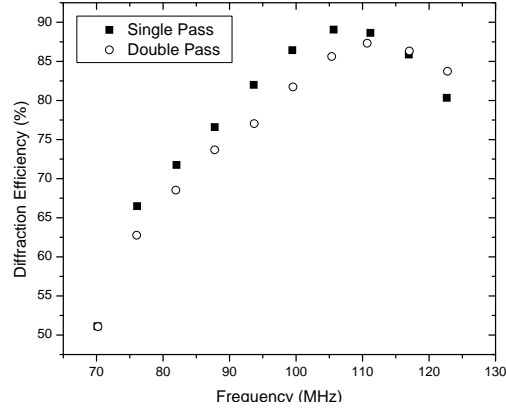
Figure 7: Variation of the diffraction efficiency as a function of AOM frequency. The squares show data for single pass light, the circles show data for double pass light. The error bars on each point are smaller than the shapes used to mark the data points for each plot.

an AOM away from its central frequency.

The method used to optimize the position of lens 2, to minimize beam deflection as a function of frequency, is described in part 12 of section 4. The results gathered using this method, switching the AOM between 110 MHz and 80 MHz, can be seen in figure 8.
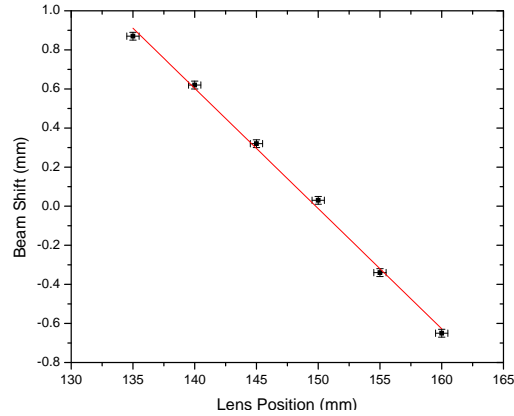

Figure 8: Change in beam deflection as a function of the position of lens 2. The AOM was switched between 110 MHz and 80 MHz. A straight line has been fit to the data. To reduce the error in the intercept the fit has the form $y = m(x - c)$, as this makes the variables independent. These data show that the optimum position for lens 2 is 149.8(2) mm away from an arbitrary point on the optical bench.

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These data show the importance of the position of lens 2, if the lens is positioned 149.8(2) mm away from an arbitrary point on the bench the beam shift can be minimized of even removed. The beam deflection is typically given in mrad/MHz, with lens 2 in the optimum position for this setup a beam deflection of 2×10^{-4} mrad/MHz was measured.

References

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