Title: Acousto-Optic Modulators

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Abstract:

Manipulation of a laser beam and its propagation are essential for many physics experiments. Any experiment where it is critical to have special beam properties such as phase, temporal or spacial distributions, or frequency control, beam manipulation is required. Acousto-optic modulators (AOM) are devices that use standing acoustic waves in a crystalline media to diffract the incident light. This paper will study and characterize the acoustic waves in the media and show two techniques of beam manipulation unique to the AOM: CW to pulsed laser, and frequency changing.

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Introduction:

Optical manipulation of a laser beam and its propagation are very important for many optics experiments. One technique is using an acousto-optic modulator (AOM) that uses sound waves to modify the original beam. Using radio frequency (RF) waves we set up standing acoustic waves in the AOM media that act as a moving diffraction grating for the incident light. The output of the AOM on a screen shows an interference pattern with brightest fringes in the zeroth and first order. The zeroth being the non-deflected beam, and the first being the brightest deflected beam. This coupling between photons and acoustic phonons forms the basis for all sound-light interactions and can be easily exploited to gain unprecedented beam control in the spacial, temporal, and frequency domain.

The AOM uses a piezo-electric driver to generate an acoustic standing wave inside a transparent crystal and can be based on bulk acoustic waves, like ours, traveling through a three-dimensional crystal, or alternatively those based on surface acoustic waves (SAW devices) [de lima]. The diffraction grating arises from spatially periodic refractive index modulations that accompany the density variations present in acoustic waves. The crystal becomes a dynamic graded-index medium—an inhomogeneous medium with time-varying refractive index [Saleh]. Since these acoustic waves are traveling in the media, they act as a sort of moving diffraction grating, so higher diffracted orders experience a Doppler shift at the acoustic frequency, or multiples of it [Donley, Saleh]. There is even proof 100% conversion efficiency into the deflected beam can be achieved at a special Bragg's reflection [Donley].

This frequency shift from AOM modulators are widely used for laser cooling and trapping experiments. Many require a shift and/or sweep in laser frequency at the end of a cooling cycle to adiabatically cool the atoms in low temperature experiments and this means the use of a single source laser [Donley]. AOMs can be utilized in many devices such as spectrum analyzers, interferometers, and optical switches [Saleh]. Other uses include probing molecular or chemical processes using short laser pulses on time scales shorter than 1 ms, where we get a slideshow of how these events happen over time. These devices are very flexible and have a wide range of uses in both the temporal and frequency domain. The main appeal is laser beam control in these domains using a device much smaller and cheaper than tunable or pulsed laser systems. Using relatively cheap materials, pulsed laser systems with high pulse frequency, as well as frequency control can be achieved.

In this paper, we will characterize our AOM and the diffracted first-order beam to study the efficiency, study operation of the laser in pulsed mode, and finally, study the change in frequency caused by the Doppler shift of the acoustic wave in the AOM crystal.

Background:

By controlling the amplitude and frequency of the acoustic waves in the AOM, one can control the amplitude and frequency of the deflected beams. This enables a high level of temporal beam control as the direct manipulation of the acoustic waves using a function generator can influence the laser and deflected beams.

The characterization of the AOM crystal starts by creating a standing acoustic wave produced by an RF power amplifier and measuring the angle deflection angle of the first order. In our experiment, we used a Newport N24080 AOM and an IntraAction Model ME RF source measured at $v = 80.65 \pm 0.01\ MHz$ to set up an acoustic standing wave inside the crystal of the AOM. From our understanding of multiple slit diffraction gratings, we know that bright fringes appear at path lengths of integer multiples of the wavelength and dark fringes at half multiples of the wavelength. As given by the Bragg's relations, for slit spacing a, and deflection angle θ, we have that,

$$\sin(\theta) = \frac{\lambda}{2a}$$

Gives the location where the first-order maximum occurs. Slit spacing in this case, correspond to the acoustic wavelength inside the AOM crystal.

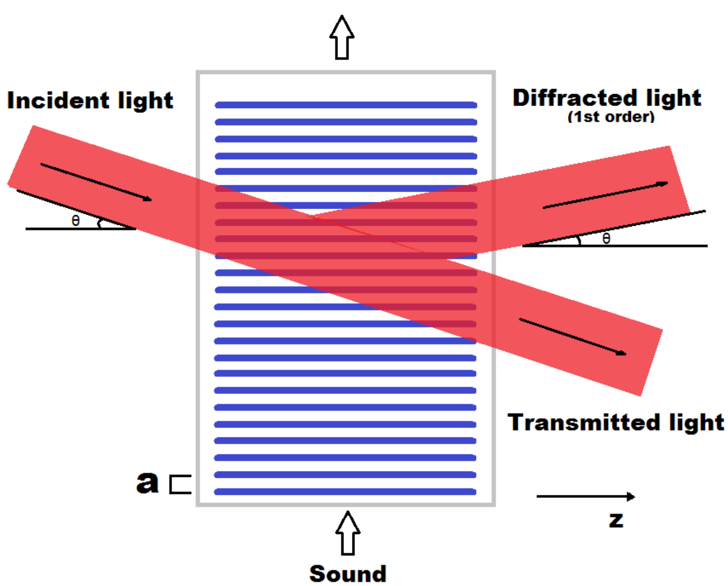


Figure 1: The acoustic wave inside the AOM diffracts incident light per the Bragg's relation.

From the first-order fringe deflection angle and the wavelength of light, we can determine the speed of sound in the AOM crystal:

$$V_{AOM} = a * v_{acous} = \frac{\lambda\, v_{acous}}{2\sin(\theta)}$$

Where the speed of sound in air is $V_{air} = 343\ m/s$ and $v_{acous} = 80\ MHz$.

As discussed above, the direct manipulation of the acoustic waves using a function generator can modulate the laser in the temporal domain, allowing ramp or pulsed laser operation. Modulating the acoustic wave with a square wave allows a continuous wave (CW) laser to operate in pulsed mode with the frequency of modulation being the pulse frequency. The limit on pulse frequency, when pulses start to degrade, is limited by the laser waist inside the AOM crystal. As the acoustic waves propagate at a fixed velocity, the shorter the path length across the transverse Gaussian profile of the laser, the faster the pulse frequency. When pulse wavelength is less than the laser's waist, pulse shape starts to deteriorate. Our goal in this lab was to obtain the shortest pulses possible. This means maximizing the modulation frequency and minimizing the laser waist.

The standing waves in the AOM act as a sort of moving diffraction grating and as such, scattering events provide a Doppler shift to the incident light at the acoustic frequency. This is due to the momentum increase of the incident photons through a photon/phonon interaction inside the crystal. This frequency shift occurs only for the higher order fringes and must be a multiple of the acoustic frequency. The shift can be observed by interfering the zeroth-order and first order and observing the beat frequency. The beat frequency will be the difference between the frequencies of the two beams,

$$v_{beat} = |v_{0th} - v_{1st}|$$

$$v_{1st} = v_{0th} + \Omega$$

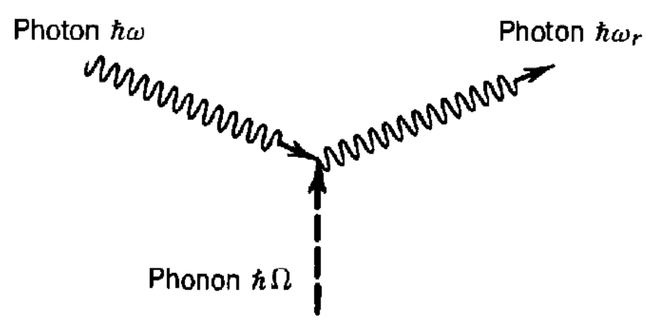


Figure 2: The photon/phonon interaction create a new photon of differing frequency and momentum [Source: Saleh]

Where the zeroth is at the original wavelength, $\lambda = 633nm$, and the first order is upshifted by the acoustic wave of $\Omega = 80\ MHz$, we expect our $v_{beat} = \Omega = 80\ MHz$.

Data:

In these first experiments, we needed to characterize the AOM and the first deflected beam to satisfy the Bragg's condition. We measured the distance between the zeroth and first order fringes to be $y = 15 \pm 1\ mm$ at a distance $z = 1\ m$ away, and got a Bragg's angle of $\theta = 0.859 \pm 0.001°$. Using the Bragg's condition, the acoustic wavelength in the crystal is $a = 21 \pm 1\ \mu m$. This gives the speed of sound in the crystal to be $V_{AOM} = 1690 \pm 80\ m/s$, or $\frac{V_{AOM}}{V_{air}} = 4.9 \pm 0.2$ times the speed of sound in air.

As many uses of an AOM involve the first deflected beam and its frequency/temporal modification, sometimes the zeroth order is blocked from propagating using a beam stop [Donley]. As such, having the highest coupling efficiency into the first order is many times the most convenient. Using a photodetector to check the coupling efficiency, we measured 30% of the incident laser power getting coupled to the first order, with the rest mostly contained within the zeroth order.

Next, using a function generator to modulate the RF acoustic wave with a square wave in the MHz range, the AOM can create laser pulses at the generated frequency. To characterize these pulses, study of the Gaussian beam propagating inside the crystal and the dependence on spot size must be understood. Letting the laser diverge into the AOM, the waist is 1.5 mm, and with two focusing lenses of f=200mm and 100mm, we obtained waists of 27μm and 14μm respectively. For each waist, we increased the modulation frequency until laser pulses started to degrade. Data is presented in Table 1.

	Waist, ω_0 (μm) :	Maximum pulse frequency (MHz)
Unfocused laser	1500 ± 100	1.4 ± 0.1
F=200mm	27 ± 1	5.0 ± 0.1
F=100mm	14 ± 1	7.0 ± 0.1

Table 1: Maximum laser pulse frequency for a given Gaussian waist, ω_0.

Care must be taken to find the maximum pulse frequency, since in experiments that utilize this technique, the pulse must have the correct shape. Since we are using a generated square wave, the laser pulse must approximate this shape. Figures 3a and 3b shows the pulse for two frequencies above and below the maximum for a waist, $\omega_0 = 27 \pm 1\ \mu m$. Above the maximum you can see how the resemblance is more of a sine wave shape. Figure 3a is what pulses should look like, not 3b.

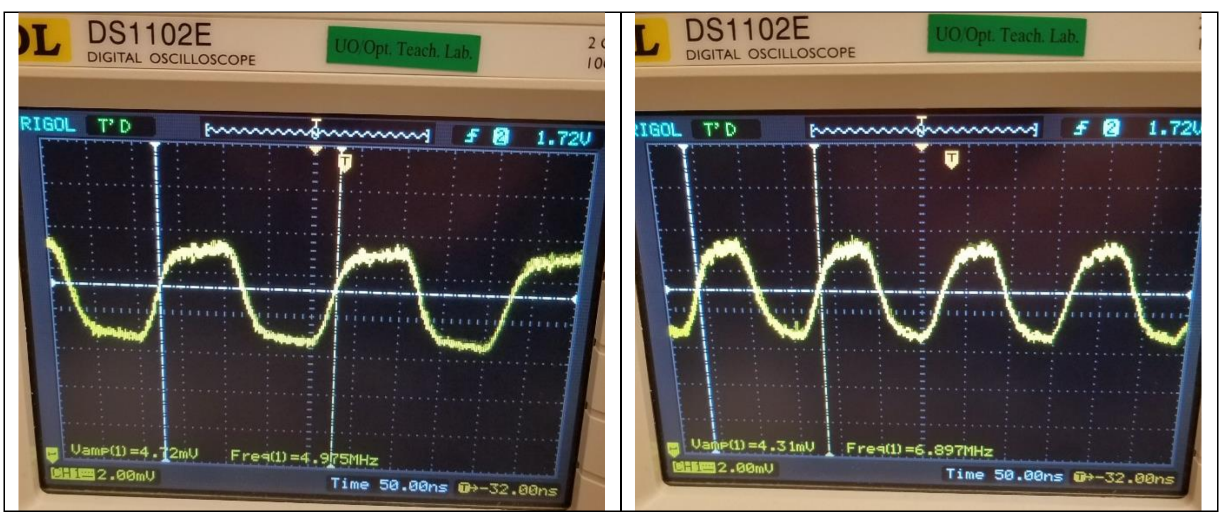


Figure 3a (left): Nice pulse shape. Figure 3b (right): The pulse degrades at high modulation frequencies (F=200mm)

The final experiment is using the difference in frequency between the zeroth and first order to observe a beat frequency when the two are interfered together. The deflected beam should be Doppler shifted in the AOM because of the photon/phonon interaction of the light and sound waves. The extra momentum "kick" the light receives should be at the acoustic frequency and the deflected beam receives this extra momentum by shifting wavelength slightly. Interfering the two gives us the difference in frequency between beams that manifests itself in a change in intensity over time.

The first order beam was deflected and then recombined along the zeroth order optical path using beam splitters into a single mode fiber. Optimization of both beams was necessary to get both beams to have similar amplitude. A diagram of the optical setup is presented in figure 4.

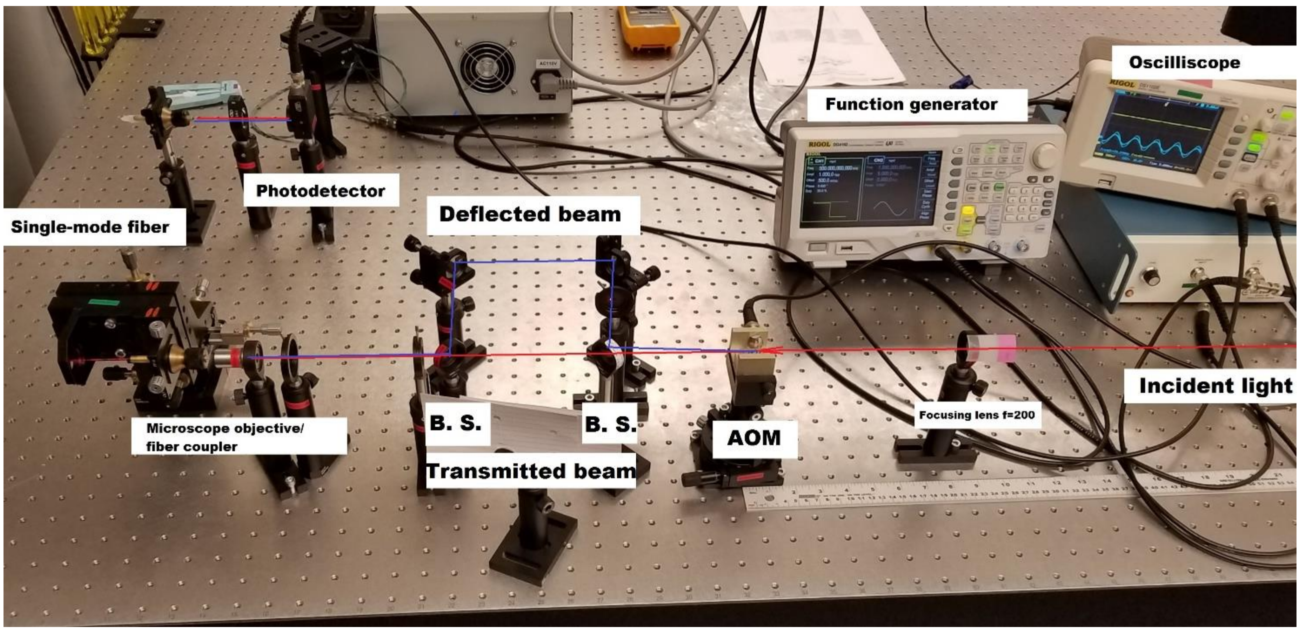


Figure 4: Optical setup for observing the beat frequency.

Error:

The propagation of errors on the speed of sound in the crystal is given by,

$$\delta V_{acous} = \left|\frac{dV_{acous}}{d\theta}\right| \delta\theta$$

Where $\delta\theta = \left|\frac{d\theta}{dy}\right| \delta y$. We measured the offset of the first order as $y = 15 \pm 1\ mm$ at $x = 1\ m$. So,

$$\delta\theta = \left|\frac{d\theta}{dy}\right| \delta y = \left|\frac{d}{dy}\left(\arctan\left(\frac{y}{x}\right)\right)\right| \delta y = \frac{1}{1+y^2}\delta y = 0.001°$$

And,

$$\delta V_{acous} = \left|\frac{dV_{acous}}{d\theta}\right| \delta\theta = \frac{\lambda}{2} sin^{-2}(\theta)\cos(\theta)\,\delta\theta = 80\ m/s$$

Therefore,

$$\delta \frac{V_{acous}}{V_{air}} = |V_{air}| \delta V_{acous} = 0.2$$

is the error on the ratio of the speed of sound in the AOM crystal to the speed of sound in air.

Analysis:

We characterized our AOM device to have the following properties: the speed of sound in the crystal was found to be $1690 \pm 80\ m/s$, or 4.9 ± 0.2 times the speed in air, with a deflection angle of $\theta = 0.860 \pm 0.001°$. On the AOM crystal the speed of sound is given to be 4.929 times that in air and is identical to the value obtained.

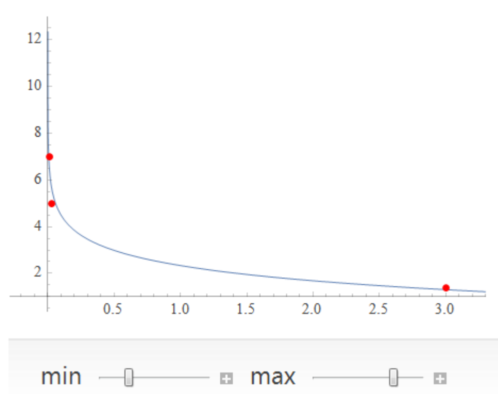
The maximum efficiency of the deflected beam is 30% of the incident beam for our AOM. This is a noticeable amount, however reports of special configurations have achieve deflected efficiencies up to 100%. Higher efficiency come from careful amplitude modulation of the acoustic wave inside the crystal, with multiple acoustic sources having the best results [Wang].

We achieved the highest pulse frequency of $7.0 \pm 0.1\ MHz$ from the smallest waist of $\omega_0 = 14 \pm 1\ \mu m$, as to be expected. The pulse has a finite transit time across the transverse Gaussian profile of the laser and the shorter the distance, the faster the pulse that can be achieved. Pulse shape degrades at high modulation frequencies and using the three data points we found a logarithmic fit that gives the maximum pulse frequency for a given Gaussian waist in meters,

$$v_{pulse}(\omega_0) = -0.937 \log(82.6\ \omega_0)\ \times 10^6\ Hz$$

And we can see that as laser spot size goes to zero, maximum pulse frequency goes to infinity.

Plot of the least–squares fit:



Fit diagnostics:

AIC	BIC	R^2	adjusted R^2
12.2789	9.57475	0.987826	0.963478

Figure 5: Best fit for maximum pulse frequency (MHz) as a function of laser waist (mm) [Source: Wolfram Alpha].

Finally, in the experiment to find the beat frequency, we were successful in creating the optical setup, but never observed the beat frequency. The amplitudes of the two beams were matched and the modulation frequency was clearly interfering equally between the two, but no beat frequency was apparent on the oscilloscope. One possibility was our detector did not have the response needed to achieve a temporal resolution of 80 MHz and the oscilloscope only showed some sort of time average. While we had another high frequency detector, we had no luck getting it to work in our experiment. At 80 MHz, the temporal frequency is too high to observe on a simple screen, so a photodetector must be used with a fast response. Unfortunately, we reached the limit of our detector and could not quantitatively take measurements of the beat frequency.

Conclusion:

There are many ways to modify light in the frequency and temporal domain and an acousto-optic modulator is a great tool to modulate light in both. These devices are used in many trapping, cooling, and interferometry physics experiments since size and costs are minimal compared to tunable and pulsed laser systems. In this lab, we have shown how to characterize the acoustic wave and the deflected beam, as well as modulation techniques to achieve the fastest laser pulses. The ability to convert continuous-wave lasers into pulsed operation alone is an extremely useful technique that can be integrated into many optical setups. We measured an acoustic wave velocity of 4.9 ± 0.2 times that in air and a maximum pulse frequency of $7.0 \pm 0.1\ MHz$ through an f=100 mm lens for our AOM.

The deflected beam conversion efficiency of 30% was standard for most AOM devices, but some experimenters have shown conversion up to 100% for the deflected beam. This shows how acousto-optic devices can be used in high performance optical setups since there is no energy wasted in the zeroth order transmitted beam. These, and many other reasons are why AOM devices are a commonplace among optical experiments where temporal and frequency modulation is needed. They allow substantial beam control in a small package, with some devices on the order of microns [de Lima], and others using multiple AOMs or multiple passes through the same [Donley]. In all, acousto-optic modulators are an extremely useful tool to experimentalists that need unprecedented beam control through simple electronic modulation.

References:

E. A. Donley, T. P. Heavner, F. Levi, M. O. Tataw, and S. R. Jefferts. “Double-pass acousto-optic modulator system”. Review of Scientific Instruments **76**, 063112 (2005); doi: 10.1063/1.1930095.

M. M. de Lima Jr., M. Beck, R. Hey, and P. V. Santos. “Compact Mach-Zehnder acousto-optic modulator”. Appl. Phys. Lett. **89**, 121104 (2006); doi: 10.1063/1.2354411.

B. E. A. Saleh. “Fundamentals of Photonics”. John Wiley & Sons, Inc. 1991.

Tiansi Wang, Chong Zhang, Aleksandar Aleksov, Islam Salama, Aravinda Kar. “Effect of large deflection angle on the laser intensity profile produced by acousto-optic deflector scanners in high precision manufacturing”. Citation: J. Laser Appl. 28, 012012 (2016); doi: 10.2351/1.4937174