Free-Space EO Modulators

- Thorlabs' Free-space electro-optic (EO) modulators provide either phase or amplitude modulation of a laser beam by applying an electrical control signal.
- EO Modulators (EOMs) require drive voltages on the order of hundreds of volts requiring both a function generator and high voltage amplifier.
- Amplitude modulators require an output polarizer and a larger V_{π}, but using a quarter-wave plate on the input provides the means to increase the usable voltage range of the high voltage amplifier.

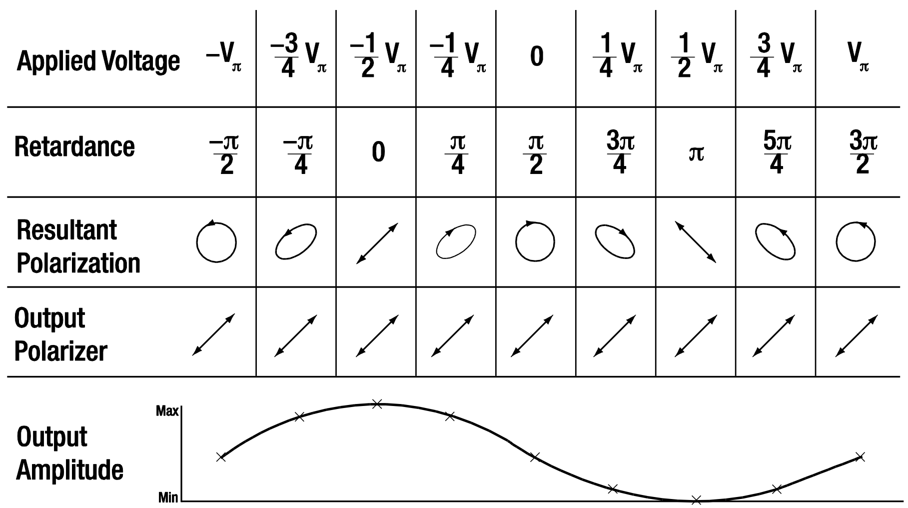

Figure 1: Amplitude modulation of a signal through an EOM

Background

- Electro-optic (EO) modulators apply a time-varying voltage *V(t)* along the Z-cut axis of a nonlinear crystal (such as $LiNbO_3$) to change the refractive index along the Z-cut axis proportional to *V(t)*.
- Phase modulators use light polarized parallel to the Z-cut axis to ensure all light undergoes a phase shift as shown in Figure 2. The time dependency of this phase shift is due to the time-dependent change of the optical path length through the crystal (which is proportional to *V(t)*).
- Amplitude modulators use light polarized at 45° with respect to the Z-cut axis to create retardance, $\Gamma(t)$, between polarization components parallel to and perpendicular to the Z-cut axis based on *V(t)*, as shown in Figure 3. This $\Gamma(t)$ corresponds to a change in polarization, leading to amplitude modulation when passed through a linear polarizer.
- In this presentation we will demonstrate how to obtain the largest operating voltage range for driving free-space amplitude EO modulators using Thorlabs' HVA200 High Voltage Amplifier.

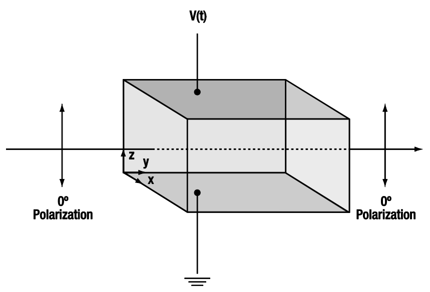

Figure 2: Phase modulator diagram with the input polarization aligned to *Z*-cut axis, which is parallel to the applied voltage *V(t)*.

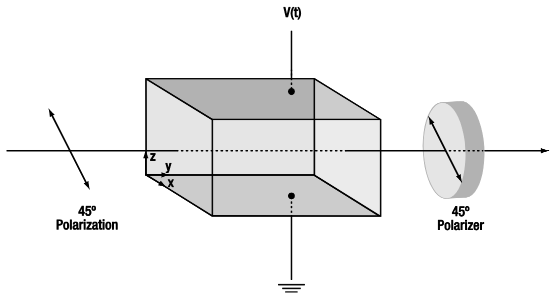

Figure 3: Amplitude modulator diagram showing the input polarization aligned 45° to the *Z*-cut axis and voltage *V(t)*. A polarizer modulates the output based on the polarization change.

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Phase Modulators (PM)

- Linearly polarized light, parallel to the Z-cut crystal axis, propagates through the phase modulator. An applied voltage to the Z-cut axis creates a linear change in refractive index, thus changing the optical path length through the crystal. This path length change results in a phase shift with respect to the input light.
- Half-wave voltage (V_π) is the voltage required to shift the output phase by π radians. The phase shift changes linearly with applied voltage, as show in Figure 4. Modulating the applied voltage with a peak-to-peak amplitude $V_{pp} = 2V_\pi$ results in a sinusoidal modulation of the phase.
- In many applications, a phase shift of only π radians is needed making the HVA200 high voltage amplifier a suitable choice. However, a third-party amplifier would be required to provide the full 2π phase shift for operating wavelengths above approximately 900 nm.

Applied Voltage	$-V_\pi$	$\frac{-3}{4}V_\pi$	$\frac{-1}{2}V_\pi$	$\frac{-1}{4}V_\pi$	0	$\frac{1}{4}V_\pi$	$\frac{1}{2}V_\pi$	$\frac{3}{4}V_\pi$	V_π
Phase Shift	$-\pi$	$\frac{-3\pi}{4}$	$\frac{-\pi}{2}$	$\frac{-\pi}{4}$	0	$\frac{\pi}{4}$	$\frac{\pi}{2}$	$\frac{3\pi}{4}$	π

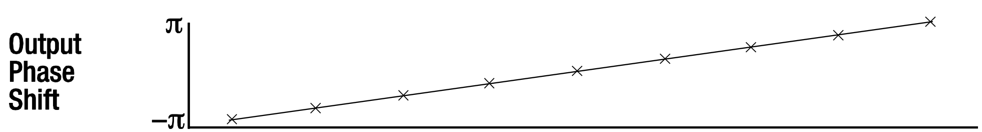

Figure 4: Phase modulator diagram relating the phase shift to applied voltage.

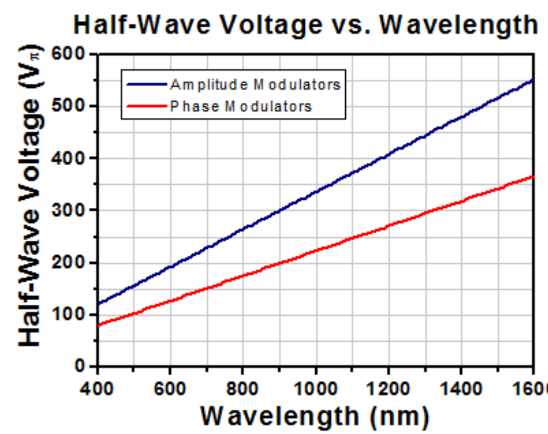

Figure 5: Plot of half-wave voltage (V_π) for Thorlabs' amplitude and phase modulators with respect to operating wavelength.

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Amplitude Modulators (AM)

- Light linearly polarized at 45° (with respect to the Z-cut crystal axis) is made up of equal amounts of the two orthogonal polarization components aligned with the X and Z crystal axes shown in Figure 2.[1] Voltage applied to the Z-cut axis retards the light polarized in the Z-axis with respect to the X-axis. It is important to note that the Z-axis has been aligned to the Z-cut axis of the crystal, which does not correspond to the direction of travel.
- Retarding light of one polarization axis with respect to the other changes the polarization state as shown in Figure 6.
- A polarizer at the output modulates the amplitude of the light as the polarization changes.
- Half-wave voltage (V_π) for an amplitude modulator is the voltage required to shift the retardance (polarization state) of the output light by π radians.
- Typical use of an amplitude modulator utilizes a triangle wave with $V_{pp} = V_\pi$ and electrical bias of $V_\pi/2$ for full sinusoidal modulation.

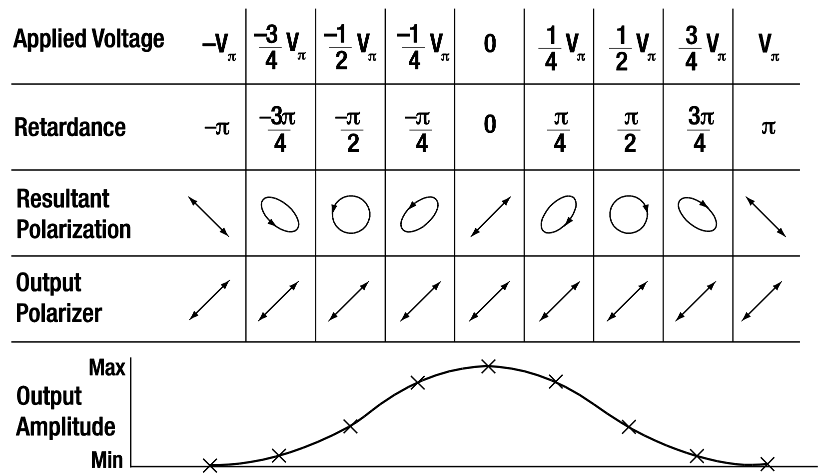

Figure 6: DC bias diagram visualizing the retardance and change in output polarization from the crystal with applied voltage. Passing the output through a polarizer results in a sinusoidal amplitude modulation when cycling the voltage from 0 - V_π and applying bias of $V_\pi/2$.

[1] In Thorlabs' free-space EO Amplitude Modulators, the crystal has been rotated by 45° so that the light can be vertically polarized in the lab frame. For this presentation, we use the crystal axes as the frame of reference.

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QWP Technique

- Typical V_π for non-resonant free-space EO modulators is 100 – 600 V, which is dependent on wavelength as seen in Figure 5.
- When using electrical DC bias alone, V_π is limited by the maximum output voltage of the high voltage amplifier. This corresponds to a maximum operating wavelength of approximately 600 nm with the HVA200.
- However, we can shift the bias optically by inserting a quarter-wave plate (QWP) prior to the modulator such that the input polarization state is circular in Figures 7 and 8. This eliminates the need for an electrical bias, which increases the usable V_π to the entire range of the HVA200. The 400 V operating range of the HVA200 (±200 V) corresponds to a maximum operating wavelength of approximately 1000 nm.

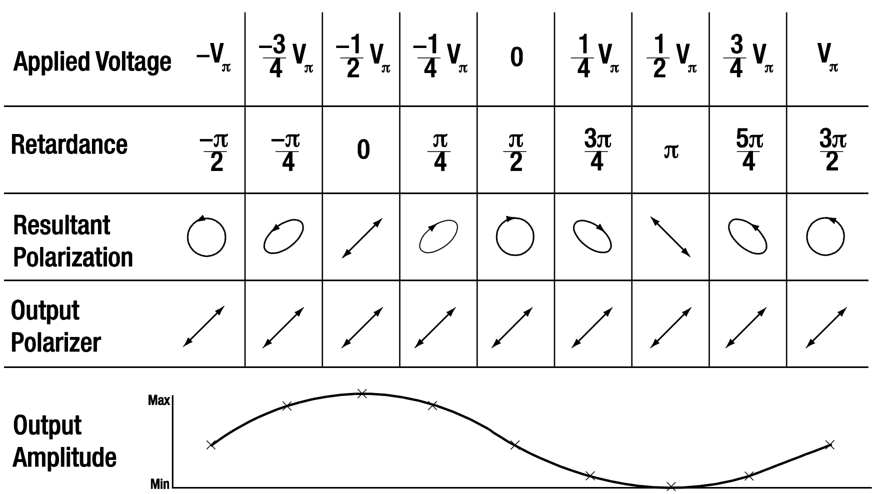


Figure 7: QWP Method diagram relating the retardance and change in output polarization to the applied voltage. Inputting circularly polarized light to the crystal removes the need for an electrical bias; sinusoidal amplitude modulation results from cycling the voltage between $\pm V_\pi$.

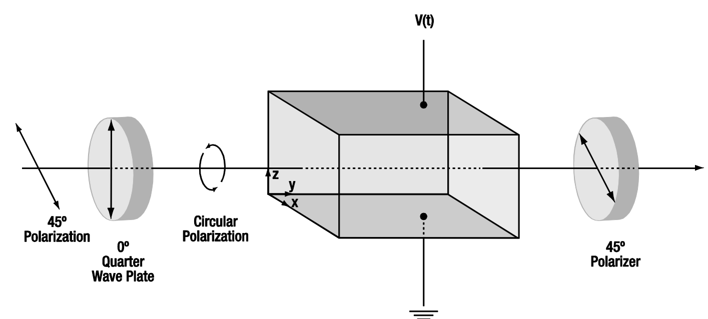
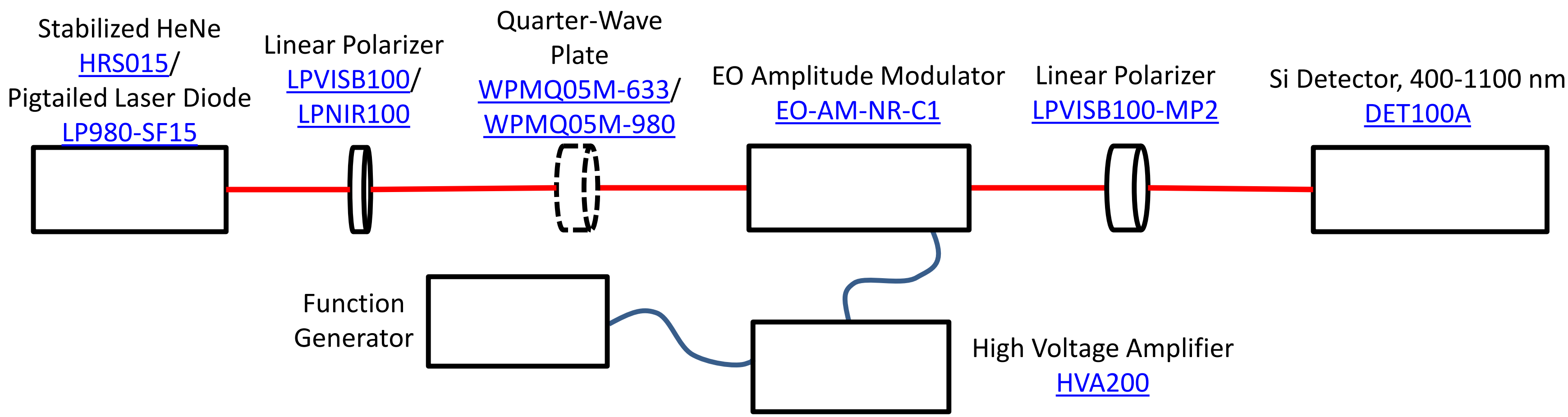


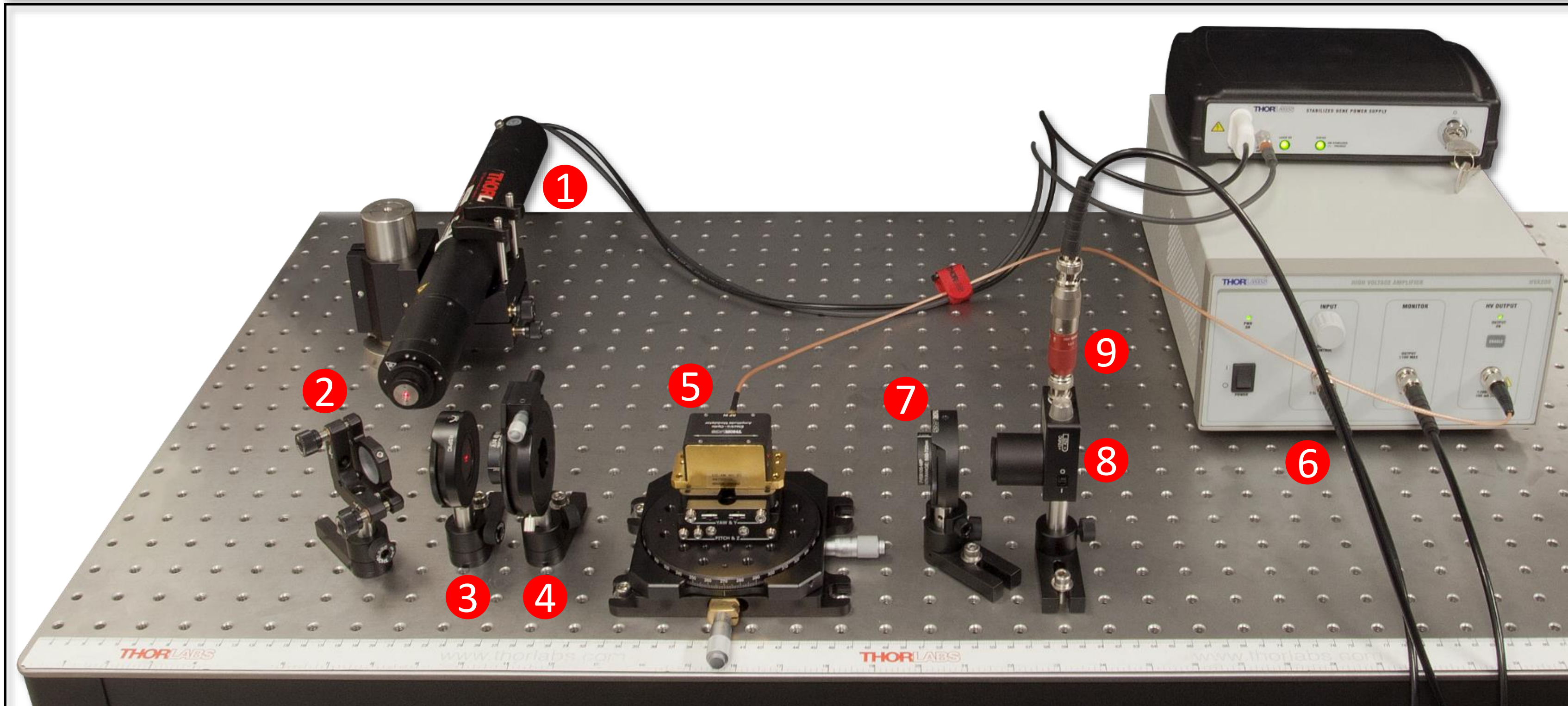
Figure 8: A quarter-wave plate adds a quarter wave offset to the polarization before it passes into the EO Amplitude Modulator. A polarizer modulates the output based on the polarization change.

Experimental Design

- A stabilized 633 nm HeNe laser (HRS015) or 980 nm laser (LP980-SF15) output was polarized vertical to the table surface using a linear polarizer (LPVISB100/LPNIR100) and was incident upon a free-space amplitude modulator (EO-AM-NR-C1).
- A second linear polarizer (LPVISB100-MP2) was aligned parallel to the input polarizer and positioned after the EO amplitude modulator.
- The modulated output signal from the EO amplitude modulator was measured with a detector (DET100A) and sent to an oscilloscope with a 50 Ω terminator.
- A 100 kHz ramp signal from a function generator was amplified by a high voltage amplifier HVA200 and then applied to the EO amplitude modulator.
- An optional quarter-wave plate (WPMQ05M-633/WPMQ05M-980) with the fast axis aligned at 45˚ with respect to the input polarizer was placed immediately prior to the EO amplitude modulator to introduce a fixed quarter-wave optical retardance and to demonstrate the use of the HVA200's full voltage range.



Experimental Setup



1. Stabilized HeNe Laser: HRS015 or
   Pigtailed Laser Diode: LP980-SF15
2. Optical Isolator: IO-3D-633-VLP
3. Unmounted Linear Polarizer: LPVISB100 or
   Unmounted Linear Polarizer: LPNIR100
4. Quarter-Wave Plate: WPMQ05M-633 or
   Quarter-Wave Plate: WPMQ05M-980
5. EO Amplitude Modulator: EO-AM-NR-C1
6. High Voltage Amplifier: HVA200
7. Mounted Linear Polarizer: LPVISB100-MP2
8. Si Detector, 400 - 1100 nm: DET100A
9. Variable BNC Terminator: VT1

Results: Measuring V_π at 633 nm

- The most common method to measure V_π is to supply a V_{pp} greater than V_π (overmodulating) such that a clear minimum and maximum throughput can be observed during one ramp of the drive voltage.
- Figure 9 shows the modulation signal (red) overlaid with the HVA200 voltage (blue).

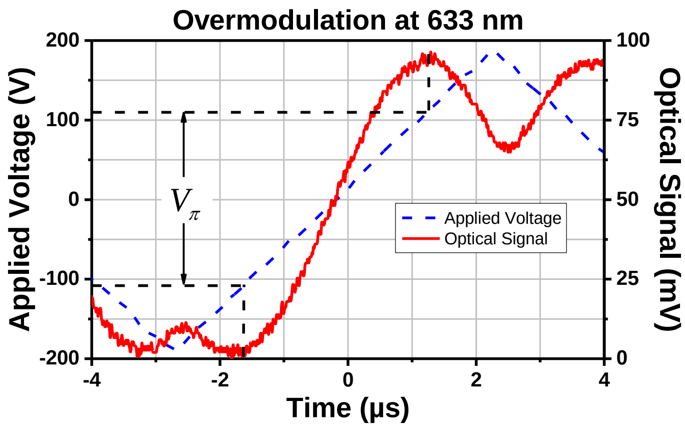


Figure 9: Measuring V_π by overmodulating the output signal and recording the HVA200 voltages for the minimum and maximum modulation time points.

- V_π was measured by taking the difference of the HVA200 voltages at the time points corresponding to the minimum and maximum modulation points.
- In this case:
  - HVA200 voltage at minimum transmission: V_{min} = -108 V
  - HVA200 voltage at maximum transmission: V_{max} = +112 V
  - $V_\pi = V_{max} - V_{min}$ = 220 V

- The output monitor of the HVA200 produces a voltage signal that is 1/20th the operating voltage, *V(t)*. We set our oscilloscope attenuation to -20X to compensate for this in Figure 9.
- It is important to note that V_π corresponds to the voltage required to modulate the light output from the crystal by π radians, which is dependent on the optical path length through the crystal. As a result, it is important for the user to measure V_π for the setup as misalignment of the crystal from normal incidence can result in a smaller value for V_π.

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Results: DC Bias vs. QWP at 633 nm

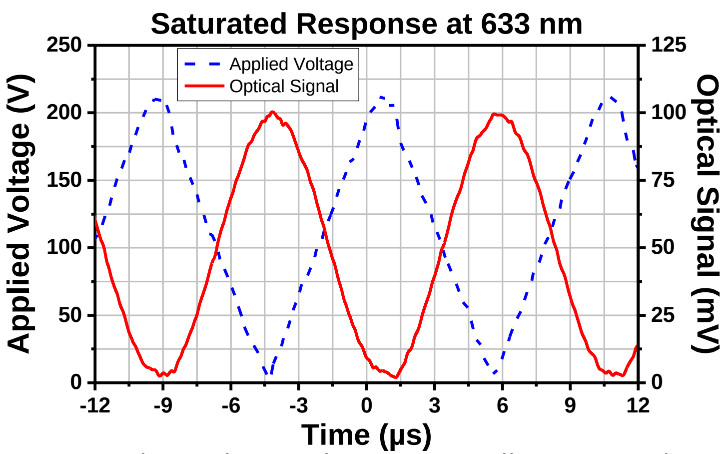

Figure 10: The DC bias technique uses all positive voltage from HVA200. Optical signal phase shifted 90° with respect to HVA200 output post processing to visualize discontinuities when HVA200 is unable to reach V_π.

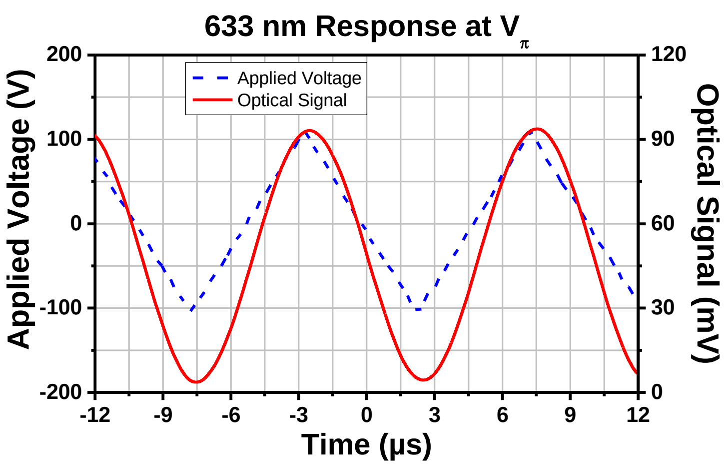

Figure 11: The QWP technique is used to create an initial input retardance and, thus, is able to use the full voltage range of the HVA200, allowing for full depth of modulation at 633 nm.

- DC Bias Technique: We provided all positive voltage to the EO modulator with a 11 V_{pp} input to the HVA200 (to apply a 200 V_{pp} signal) and a 110 V bias (knowing V_π = 220 V from the previous slide).
- Because V_π was greater than 200 V, the HVA200 output saturated at the upper limit, thereby creating a distortion in the modulation during the minima in Figure 10.
- Quarter-Wave Plate (QWP) Technique: We provided both positive and negative voltage by inserting a QWP to provide circular polarization into the crystal with the same 11 V_{pp} input to the HVA200 but with a 0 V bias.
- Now the HVA200 signal was not saturated and we were able to obtain a smooth sinusoidal modulation in Figure 11.
- This result demonstrates that we can use a QWP to create an initial retardance offset to reduce the voltage bias and utilize the negative voltage range of the HVA200 output.

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Results: Modulation at 980 nm

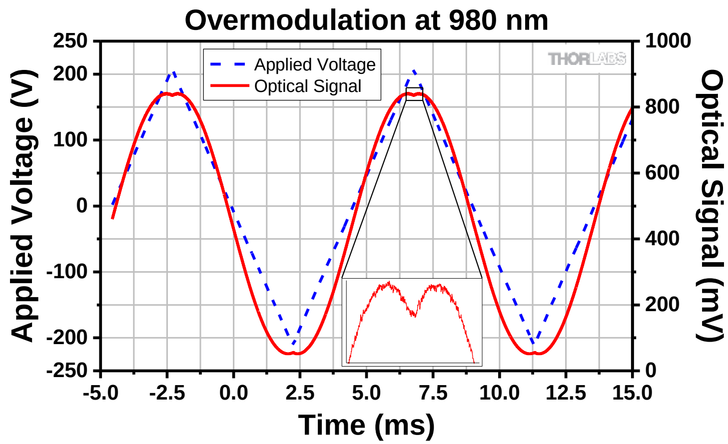

Figure 12: Measuring V_π by overmodulating the output signal and recording the HVA200 voltages for the minimum and maximum modulation time points.

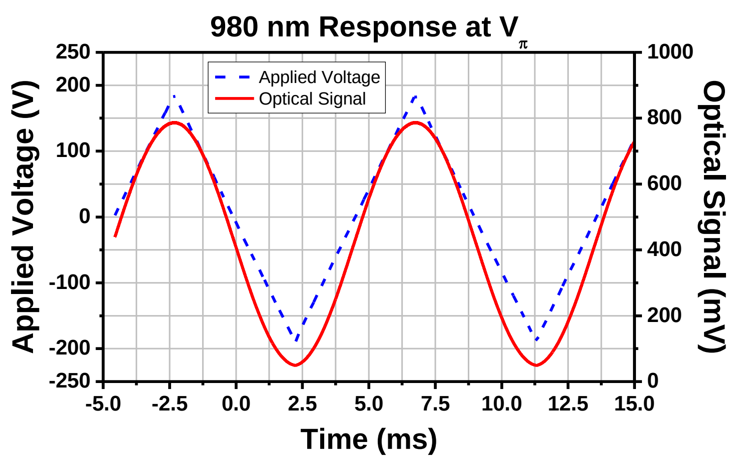

Figure 13: The QWP technique is used to create an initial input retardance and, thus, is able to use the full voltage range of the HVA200, allowing for full depth of modulation at 980 nm.

- To demonstrate the upper limit for the QWP technique, we also used a 980 nm laser diode source in our system.
- Using the QWP and the overmodulation technique, we measured a V_π = 368.8 V for the 980 nm source (see Figure 12).
- Using a QWP to input circular polarization into the EO modulator with a 368.8 V_{pp} signal and 0 V DC offset, we demonstrated smooth, sinusoidal modulation of the laser (see Figure 13).
- It is important to note that a full depth of modulation could be obtained with longer wavelengths, such as 1064 nm, but the overmodulation will become difficult to resolve.

Experimental Limitations

- We only demonstrated the technique with a modulation of 100 kHz. We do not expect any changes with lower or higher frequency, but it is important to note that the output frequency of the HVA200 cannot exceed 1 MHz.
- The input beam was aligned to fit within the aperture of the EO amplitude modulator but was not necessarily at normal incidence exactly. Deviation of tip/tilt from normal incidence can increase the optical path length through the crystal, effectively reducing V_π. As a result the user should measure V_π for the setup prior to fixing the voltage parameters of the amplifier.
- V_π for the EO-AM-NR-C1 modulator was successfully measured for 633 nm and 980 nm. Overmodulation was not resolved with a 1064 nm input, which prevented us from accurately measuring V_π at 1064 nm. However, V_π is expected to be less than 400 V at 1064 nm.
- Even with a QWP, the 400 V range of the HVA200 cannot drive modulators within the 1100 - 1600 nm wavelength range. For these wavelengths, the user is currently required to use a third-party high-voltage amplifier when using Thorlabs' free-space modulators. Alternatively, a fiber-coupled EO modulator with a lower V_π can be used.

Summary

- Free-Space EO phase and amplitude modulators use the same operating principle but with different input polarization alignment.
- The HVA200 amplifies a modulated input up to ±200 V to drive Thorlabs' free-space EO modulators. While this range covers all the phase modulators, it limits the amplitude modulators to an operating wavelength of approximately 600 nm when using the DC bias method.
- Adding a quarter-wave plate prior to the EO modulator inputs circular polarization to remove the need for an electrical bias, which increases the operating wavelength of the HVA200 to approximately 1000 nm for an amplitude modulator.

Standard DC Bias Method

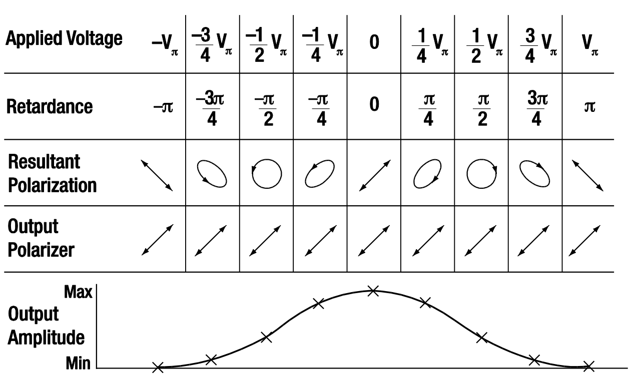

Figure 14: DC bias method producing sinusoidal amplitude modulation when cycling the voltage from 0 - V_π and applying bias of $V_\pi/2$.

Quarter Wave Plate Method

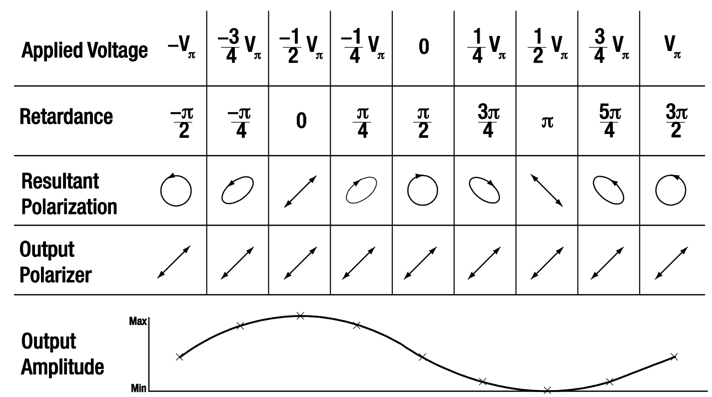

Figure 15: QWP Method producing sinusoidal amplitude modulation results from cycling the voltage between $\pm V_\pi$.

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