Lab #7

Optical Modulators

(2 weeks)

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1. Set up a Mach-Zehnder interferometer with a Lithium Niobate phase modulator in one arm and observe the phase modulation as a function of drive amplitude.
2. Estimate the half wave voltage for the phase modulator.
3. Observe the effect of polarization on the phase modulation.
4. Construct an electrooptic variable retarder amplitude modulator, and measure its half wave voltage.

Acoustooptic Modulator

5. Measure the diffraction angle and identify the AO modulator material.
6. Measure the transmission of the 0^{th} and 1^{st} order beams as a function of the amplitude of the applied voltage.
7. Measure the "acceptance angle", which is the FWHM angular range for Bragg diffraction.
8. Experiment with a modulated voltage waveform, and observe the effect on the diffracted spot pattern, looking for a Fourier transform relationship.

2. Introduction

In this lab you will experiment with two important optical modulators – the electrooptic modulator and the acoustooptic Bragg modulator. These two classes of devices are widely used in photonic devices and instruments, and can be used to impress information on laser beams from a wide variety of sources. For many lasers, direct modulation of the output is very difficult, or can introduce unwanted artifacts, therefore an external modulator is required. You will build both an electrooptic phase modulator and electrooptic amplitude modulator, and experiment with the properties of an acoustooptic amplitude modulator.

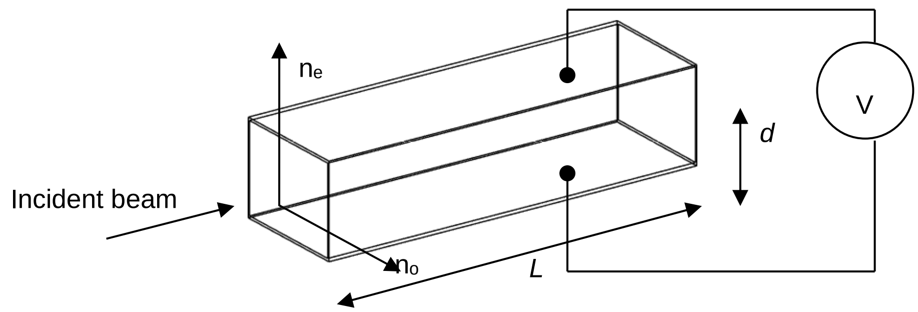
3. Electrooptic Modulator

An electro-optic medium is characterized by an index of refraction that is dependent upon an applied electric field, $n = n(E)$. The effect is usually small, and it is possible to write an expression for the index of refraction as a Taylor series expansion in terms of electric field about the value with zero applied field

$$n(E) = n - \frac{1}{2} r n^3 E - \frac{1}{2} s n^3 E^2 + \cdots .$$

When the dominant effect involves the first term of the expansion, we speak of the *linear electrooptic effect*, which is also called the Pockel's effect. The coefficient r is called the Pockel's coeffecient. Only certain materials exhibit the linear electrooptic effect. Isotropic materials that possess inversion symmetry (centrosymmetry) do not. Examples of useful, non-centrosymmetric crystals that exhibit a linear electrooptic effect include GaAs, CdTe (cubic crystals), KDP, ADP (tetragonal), $LiNbO_3$ and $LiTaO_3$ (trigonal). Several considerations go into selecting a material for a practical modulator, but among them are the size of the Pockel's coeffecient and the stability, availability and cost of the crystal material. Lithium Niobate ($LiNbO_3$) has a sizeable Pockel's coeffecient and is widely available as a high quality, reasonable cost crystal material. You will be using a magnesium doped lithium niobate electrooptic modulator for your experiments.

The details of the interaction between the electric field and the index of refraction of the crystal can be rather messy (see the treatment in Saleh, or classic references such as Yariv and Yeh). However, for our modulator we can use the following description.



The electric field is applied along the vertical axis, which is the extraordinary axis of the crystal. In this case we can write for the ordinary and extraordinary indices of refraction:

$$n_o(E) = n_o - \frac{1}{2} r_{13} n_o{}^3 E \qquad \text{where} \qquad \left.\begin{array}{ll} \mathrm{r}_{13} = 9.6 \quad \mathrm{pm/V} & \mathrm{n_o} = 2.3 \\ \mathrm{r}_{33} = 30.9 \quad \mathrm{pm/V} & \mathrm{n_e} = 2.2 \end{array}\right\} \; \lambda = 678 \text{ nm}$$

$$n_e(E) = n_e - \frac{1}{2} r_{33} n_e{}^3 E$$

Phase modulator

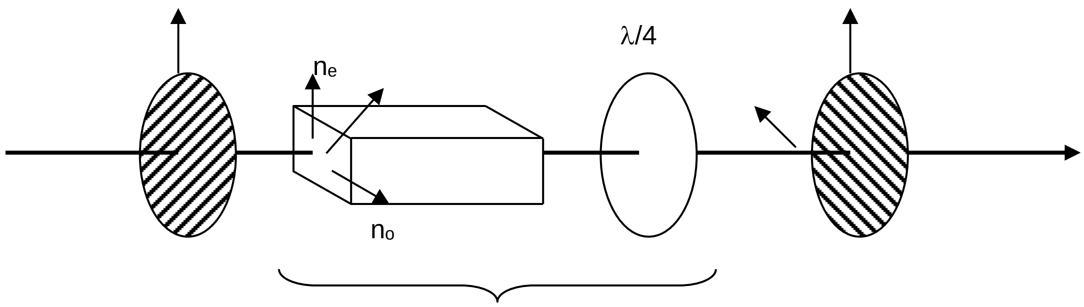
Light passing through the crystal propagates according to $e^{-jk_o n(E)L} = e^{-jk_o nL + jk_o \frac{1}{2} n^3 rEL} = e^{-j\phi}$, where $\phi = \phi_o - \pi \frac{V}{V_\pi}$, $\phi_o = k_o nL = \frac{2\pi nL}{\lambda_o}$, $V_\pi = \frac{\lambda_o d}{n^3 rL}$. The electrically controlled phase term is characterized for a particular device by its V_π, or the voltage required for a π phase shift. Inspection of the parameter values listed above shows that the smallest V_π for the electrooptic modulator should occur with vertical polarization, that is, for the extraordinary wave. Using approximate crystal dimensions for the New Focus electrooptic modulator as L = 40 mm and d = 2 mm yields **V_π for the vertically polarized beam of approximately 96 volts**, and approximately 270 volts for the horizontally polarized beam.

The New Focus model 4001 phase modulator is a resonant device, meaning that a tank circuit has been used to increase the voltage across the crystal when driven at the resonant frequency of the circuit. The resonant frequency of your modulator is approximately 12 MHz. The voltage enhancement is approximately a factor of 10, so that you should observe a π phase shift with less than 10 volts applied to the device, when driven at resonance.

a) Using a 678nm diode laser (or the HeNe), construct a Mach-Zehnder interferometer with the electrooptic modulator in one arm of the interferometer. Adjust for maximum fringe contrast, and then focus the light from the interferometer into the New Focus 125 MHz low noise detector. Connect the SRS function generator to the modulator, and observe the output from the interferometer. The interferometer converts a phase delay in one arm into an observable amplitude modulation.
b) Measure the bandwidth of the modulator.
c) Estimate V_π for the modulator (on resonance) by observing the shape of the intensity waveform, and adjusting the function generator amplitude until the interference waveform corresponds to a full π phase modulation (peak to peak – the voltage sinewave amplitude corresponds to $\pi/2$). How does your measured value compare to the theoretical value given above? Can you estimate the resonant enhancement of the tank circuit?
d) Use the FFT function on your oscilloscope to measure the amplitude of the phase modulation sidebands as a function of applied voltage. This is a common way to accurately measure V_π for a phase modulator. (see appendix for description of Bessel function dependence for sideband amplitude of phase modulated signals)
e) Investigate the effect of input beam polarization on the observed modulation depth. For a fixed modulation voltage, estimate the difference in phase modulation between vertically and horizontally polarized beams. Do your results agree with the predicted ratio of r_{33} to r_{13}?

Intensity modulator

Because the Pockel's coeffecients are different for the ordinary and extraordinary polarizations, the electrooptic modulator also functions as a voltage controlled variable wave retarder. Use this effect to construct an electrooptic amplitude modulator that does not require an interferometer. Place the modulator between crossed polarizers, with the incident beam polarized at 45^o to the modulator axes. You should also include a $\lambda/4$ wave plate in series with the modulator, since there will be a static retardation for the lithium niobate crystal with no applied voltage. You should be able to adjust the $\lambda/4$ wave plate to approximately cancel this residual retardation.



$$\begin{bmatrix}1 & 0\\ 0 & e^{-j\Gamma}\end{bmatrix},\quad \Gamma=\Gamma_o-\pi\frac{V}{V_\pi}\quad,\quad V_\pi=\frac{(d/L)\lambda_o}{n_o^{\,3}r_{13}-n_e^{\,3}r_{33}}$$

f) What intensity modulation depth can you obtain with your electrooptic modulator? Define the modulation depth as $(P_{max} - P_{min})/(P_{max} + P_{min})$.
g) Try to estimate V_π, if the signal generator has sufficient amplitude.
h) Measure output power vs. modulator drive voltage. Write the Jones matrix for your system, and from it obtain a theoretical expression for output power vs. drive voltage. What value for V_π gives you reasonable agreement between your data and the theory? Does this value agree with your measurement in part (g)?

4. Acoustooptic modulator

The acoustooptic modulator operates on the principle of light being diffracted by sound. Sound waves (in this case, ultrasound) propagate through a crystal as a wave of alternating denser and rarer regions. Associated with this local change in density of the material is a local change in the dielectric permittivity and index of refraction. The sound wave is a moving, spatially periodic phase grating that will diffract the light beam.

When the length of the interaction between the light and sound is long, the grating may be thought of as thick, and the energy can be efficiently diffracted into a single order. This is called Bragg diffraction, and efficient coupling of energy into the diffracted order requires that the angles of incidence and diffraction be equal, and they must furthermore satisfy the diffraction equation. The Bragg angle θ_B is then given by

$\sin(\theta_B)=\lambda/2\Lambda$

where λ is the optical wavelength and Λ is the acoustic wavelength. If the grating is not thick compared to the light beam, then more than one diffracted order is typically present, and the acoustic wave looks like a thin grating. This is called the Raman-Nath diffraction regime. The Bragg and Raman-Nath regimes may be distinguished by the Raman-Nath parameter Q defined as

$Q = k_a^2 w/k_o$

Where k_a is the wavenumber of the acoustic wave, k_o is the wavenumber of the optic wave and w is the diameter of the acoustic wave. When Q is small compared to unity the modulator is in the Raman-Nath regime. When Q is large compared to unity the modulator operates in the Bragg regime.

The acoustooptic modulator used for this experiment has a center frequency of 80 MHz. Mount the modulator so that you can conveniently adjust the angle between the beam and the modulator.

a) Use a “T” connector to connect the RF output port of the AO modulator driver to both the AO modulator and the oscilloscope. The oscilloscope input should be 1 MOhm input impedance (the AO Modulator is approximately 50 ohm input impedance). Make these connections **first**, **then** supply the AO modulator driver with +24 Vdc. Disable the output from the Sony/Tektronix function generator, then connect it to the MOD input (a 50 ohm input) on the AO modulator driver. Set the FUNCtion for the function generator to DC and set it to 0V. Enable the output, and observe the diffraction pattern that results when you increase the DC voltage of the function generator from 0 to 1 volt.

b) Measure the diffraction angle of the 1^{st} order spot. Calculate the wavelength of sound in the crystal. What is the speed of sound for this material? From the chart of AO materials, can you identify a likely candidate from which this device was made? What value of refractive index should be used for this device?

c) From inspection of the crystal dimensions and assuming that the acoustic beam comes close to filling the crystal, calculate the Raman-Nath parameter for your modulator. In which regime do you expect to find your device?

d) Use the optical power meter to measure the power in the laser beam (before passing through the A-O modulator). Then, with the laser beam again passing through the A-O modulator, use the optical power meter with a variable iris on the detector head to measure the power in the zero- and first-order spots (set the iris diameter so that you measure only one spot at a time). Adjust the angle of the modulator until the power in the 0th order beam is minimized and the power in the diffracted beam is maximized (the Bragg angle).

e) Using the function generator to control the amplitude of the drive signal (the MOD input), measure the power in the 0^{th} and 1^{st} order beams as a function of amplitude of the RF signal applied to the device. Use the oscilloscope to monitor the RF signal. Plot the 0th and 1st-order spot powers as a function of RF signal amplitude. Plot the diffraction efficiency as a function of RF drive signal amplitude. Explain both plots.

f) Measure the power in the 1^{st} order diffracted beam as a function of beam incidence angle. What is the angular acceptance of the grating? (You may have to use backreflection or some other means to accurately measure these small angles.)

g) Adjust the function generator for 0.5 Vdc offset plus 1.0Vpp ac amplitude sine wave at 8 MHz. What is the effect on the diffraction pattern? Measure the location/diffraction angle of the diffraction spots. What is a mathematical description of the drive waveform that is reaching the AO crystal? Sketch a few cycles of the drive waveform.

h) What is the effect of modulating at 4 MHz? At 16 MHz? What happens if you select the square wave on the function generator? Comment on the Fourier transform properties of the AO modulator.

5. References

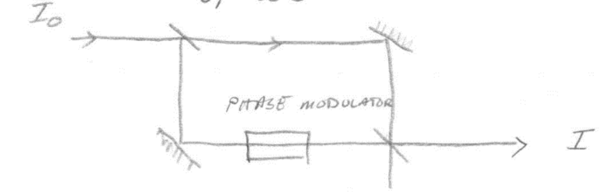
1. This lab write-up has been written with liberal use of Marty Fejer's lab notes for Applied Physics 305, Spring 1991, Stanford University.

2. Bahaa E. A. Saleh and Malvin Carl Teich, "Fundamentals of Photonics", Wiley, 1991.

LAB 5 – MODULATORS
APPENDIX

PHASE MODULATOR MEASUREMENTS IN THE MACH-ZEHNDER INTERFEROMETER

$$U_1 = a e^{j(\omega t - kL_1)}$$



$$U_2 = b e^{j(\omega t - kL_2 + \phi(t))}$$

$$I = \langle |U_1 + U_2|^2 \rangle = a^2 + b^2 + 2ab\cos(k\Delta L(t) + \phi(t))$$

$$= a^2 + b^2 + 2ab\left(\cos(k\Delta L(t))\cos\phi(t) - \sin(k\Delta L(t))\sin\phi(t)\right)$$

$$\phi(t) = \phi_o \sin\omega_m t \quad \text{(modulated phase delay)}$$

We know that

$$\cos\phi(t) = \cos(\phi_o \sin\omega_m t) = J_0(\phi_o) + 2J_2(\phi_o)\cos(2\omega_m t) + 2J_4(\phi_o)\cos(4\omega_m t)\ldots$$

$$\sin\phi(t) = \sin(\phi_o \sin\omega_m t) = 2J_1(\phi_o)\sin(\omega_m t) + 2J_3(\phi_o)\sin(3\omega_m t)$$

$$\therefore\ I = a^2 + b^2 + 2ab\cos(k\Delta L(t))\,J_0(\phi_o) \quad (\text{DC term}, I_{dc})$$

$$-4ab\sin(k\Delta L(t))\,J_1(\phi_o)\sin(\omega_m t) \quad (\omega_m \text{ term}, I_{\omega_m})$$

$$+4ab\cos(k\Delta L(t))\,J_2(\phi_o)\cos(2\omega_m t) \quad (2\omega_m \text{ term}, I_{2\omega_m})$$

$$-4ab\sin(k\Delta L(t))\,J_3(\phi_o)\sin(3\omega_m t) \quad (3\omega_m \text{ term}, I_{3\omega_m})$$

$$+4ab\cos(k\Delta L(t))\,J_4(\phi_o)\cos(4\omega_m t) \quad (4\omega_m \text{ term}, I_{4\omega_m})$$

$$\vdots$$

Note that $\Delta L(t)$ is the slow random drift of the relative lengths of the two interferometer paths. This drift causes the side lobe amplitudes to shrink & grow.

APPENDIX, CONT. 2

A couple of approaches could be used to eliminate the variation due to the random $\Delta L(t)$.

1) Monitor the spectrum & wait for each sidelobe to max before measuring its amplitude. Then the coeffs $\cos(k\Delta L(t))$ or $\sin(k\Delta L(t))$ go to unity, allowing side lobe relative intensities to be compared.

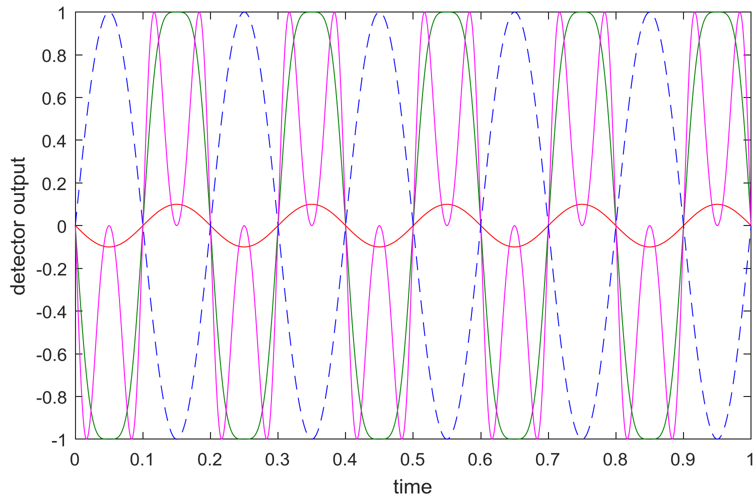
   This approach may take a while, and is subject to some error.

2) Monitor the spectrum until the 1st & 3rd harmonic are large, then freeze the image & measure $I_{3\omega_m}/I_{\omega_m}$. (Remember the FFT function gives the output in dB, so the difference in height of the two sidelobes is their relative intensity in dB.) Next, wait until the 2nd & 4th sidelobes are large & freeze the image & measure $I_{4\omega_m}/I_{2\omega_m}$. These power ratios depend on the phase modulation depth ϕ_0 according to:

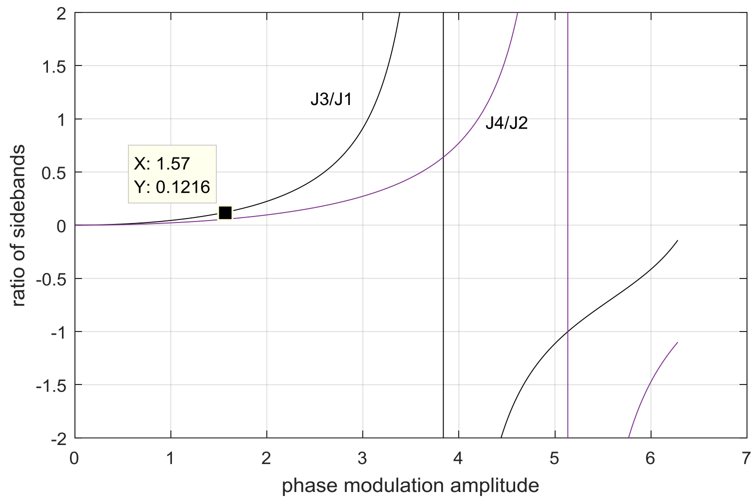
$$\frac{I_{3\omega_m}}{I_{\omega_m}} = \frac{J_3(\phi_0)}{J_1(\phi_0)}$$

$$\frac{I_{4\omega_m}}{I_{2\omega_m}} = \frac{J_4(\phi_0)}{J_2(\phi_0)}$$

The graph on the next page shows the variation of these ratios vs. ϕ_0.



Detected waveform for different modulation depths. Blue dashed is the underlying sin(ωt); solid lines plot cos(A*sin(ωt)+π/2);
Red: A=.1
Green: A=π/2
Magenta: A=π



After doing an FFT of the waveform, compare the strength of the 3rd harmonic to the 1st (J3/J1), or the fourth to the second (J4/J2). Peak-to-peak modulation of the phase by π radians corresponds to an amplitude A=π/2 (green curve in the graph above). This is where the marker is on this graph and the graph below.

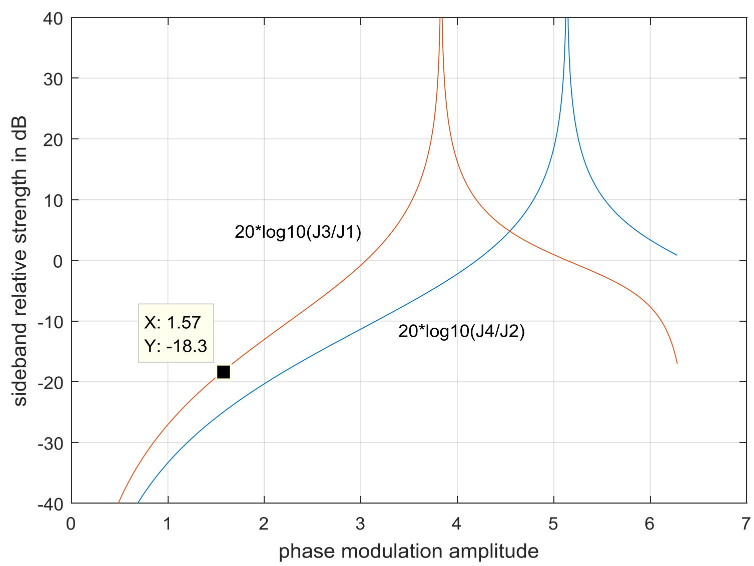


Table 12-1 A List of Some Materials Commonly Used in the Diffraction of Light by Sound and Some of Their Relevant Properties. ρ is the Density, v_s the Velocity of Sound, n the Index of Refraction, p the Photoelastic Constant as Defined by Equation (12.3-9), and M_ω is the Relative Diffraction Constant Defined Above. (After Reference [4].)

Material	ρ (mg/m^3)	v_s (km/s)	n	p	M_ω
Water	1.0	1.5	1.33	0.31	1.0
Extra-dense flint glass	6.3	3.1	1.92	0.25	0.12
Fused quartz (SiO_2)	2.2	5.97	1.46	0.20	0.006
Polystyrene	1.06	2.35	1.59	0.31	0.8
KRS-5	7.4	2.11	2.60	0.21	1.6
Lithium niobate ($LiNbO_3$)	4.7	7.40	2.25	0.15	0.012
Lithium fluoride (LiF)	2.6	6.00	1.39	0.13	0.001
Rutile (TiO_2)	4.26	10.30	2.60	0.05	0.001
Sapphire (Al_2O_3)	4.0	11.00	1.76	0.17	0.001
Lead molybdate ($PbMO_4$)	6.95	3.75	2.30	0.28	0.22
Alpha iodic acid (HIO_3)	4.63	2.44	1.90	0.41	0.5
Tellurium dioxide (TeO_2) (Slow shear wave)	5.99	0.617	2.35	0.09	5.0

Table 12-2 A List of Materials Commonly Used in Acoustooptic Interactions and Some of Their Relevant Properties. $M = n^6p^2/\rho v_s^3$ is the Figure of Merit, Defined by (12.3-20) and is Given in MKS Units. (After Reference [6].)

Material	$\lambda(\mu m)$	n	ρ(g/cm^3)	Acoustic wave polarization and direction	v_s(10^5 cm/s)	Optical wave polarization and direction*	$M = n^6p^2/\rho v_s^3$
Fused quartz	0.63	1.46	2.2	long.	5.95	⊥	1.51×10^{-15}
Fused quartz	0.63			trans.	3.76	∥ or ⊥	0.467
GaP	0.63	3.31	4.13	long. in [110]	6.32	∥	44.6
GaP	0.63			trans. in [100]	4.13	∥ or ⊥ in [010]	24.1
GaAs	1.15	3.37	5.34	long. in [110]	5.15	∥	104
GaAs	1.15			trans. in [100]	3.32	∥ or ⊥ in [010]	46.3
TiO_2	0.63	2.58	4.6	long. in [11–20]	7.86	⊥ in [001]	3.93
$LiNbO_3$	0.63	2.20	4.7	long. in [11–20]	6.57		6.99
YAG	0.63	1.83	4.2	long. in [100]	8.53	∥	0.012
YAG	0.63			long. in [110]	8.60	⊥	0.073
YIG	1.15	2.22	5.17	long. in [100]	7.21	⊥	0.33
$LiTaO_3$	0.63	2.18	7.45	long. in [001]	6.19	∥	1.37
As_2S_3	0.63	2.61	3.20	long.	2.6	⊥	433
As_2S_3	1.15	2.46		long.		∥	347
SF-4	0.63	1.616	3.59	long.	3.63	⊥	4.51
β-ZnS	0.63	2.35	4.10	long. in [110]	5.51	∥ in [001]	3.41
β-ZnS	0.63			trans. in [110]	2.165	∥ or ⊥ in [001]	0.57
α-Al_2O_3	0.63	1.76	4.0	long. in [001]	11.15	∥ in [11–20]	0.34
CdS	0.63	2.44	4.82	long. in [11–20]	4.17	∥	12.1
ADP	0.63	1.58	1.803	long. in [100]	6.15	∥ in [010]	2.78
ADP	0.63			trans. in [100]	1.83	∥ or ⊥ in [001]	6.43
KDP	0.63	1.51	2.34	long. in [100]	5.50	∥ in [010]	1.91
KDP	0.63			trans. in [100]		∥ or ⊥ in [001]	3.83
H_2O	0.63	1.33	1.0	long.	1.5		160
Te	10.6	4.8	6.24	long. in [11–20]	2.2	∥ in [0001]	4400
$PbMO_4$ [14]	0.63	2.4		long. ∥ c axis	3.75	∥ or ⊥	73

*The optical-beam direction actually differs from that indicated by the magnitude of the Bragg angle. The polarization is defined as parallel or perpendicular to the scattering plane formed by the acoustic and optical k vectors.