6. Experiments

6.1 Observe the interference of focused polarized light in crystal

1. Refer Figure 5 to do system alignment.

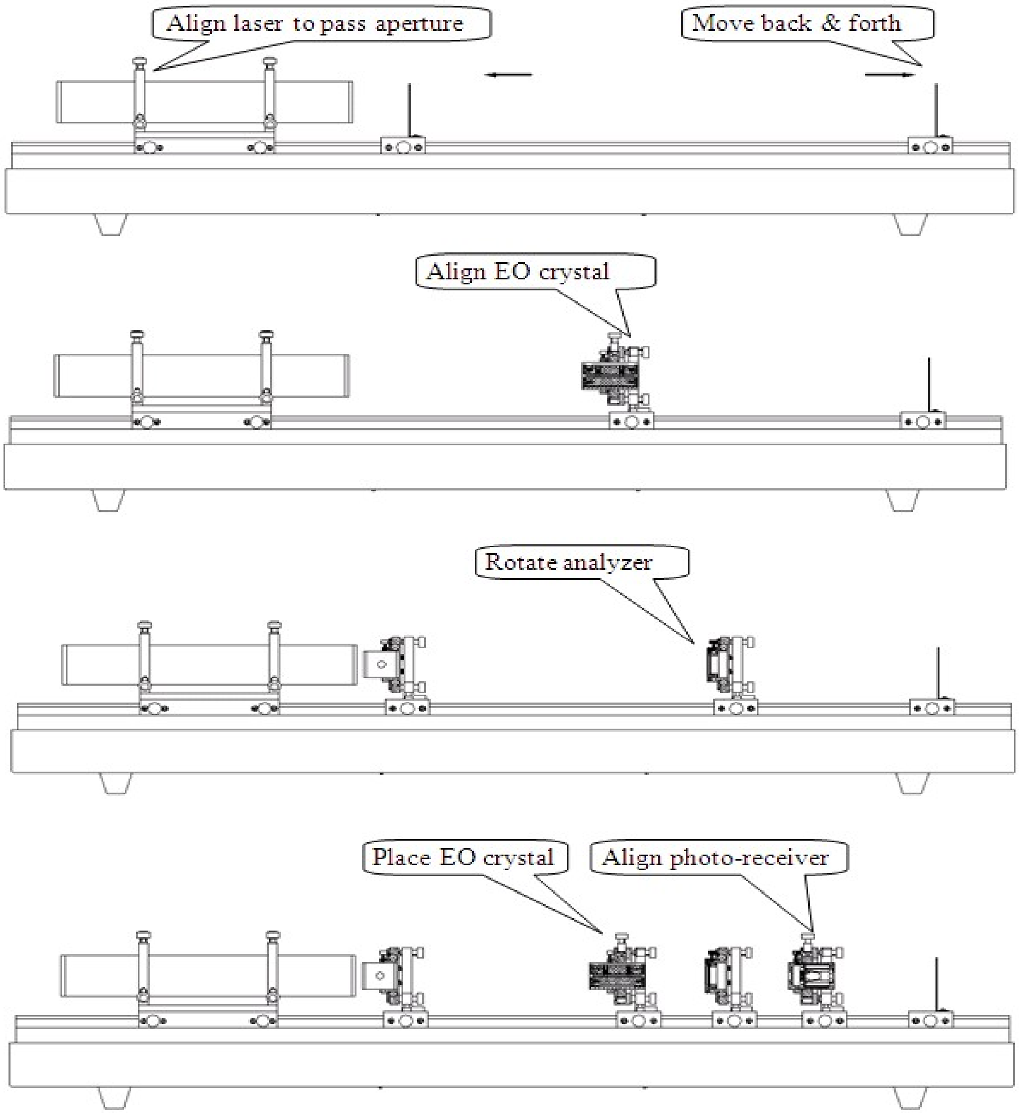


Figure 5 Alignment sequences of components

a) Mount the He-Ne laser head at the left end of the rail. Turn on the laser. With the assistance of the polarizer whose polarization direction is marked on its mount, set the polarization direction of the laser beam to vertical direction by rotating the laser tube. At this time, the laser intensity passing through the polarizer is maximized when the polarization direction of the polarizer is placed in vertical direction.

b) Align the He-Ne laser beam: move back and forth of the alignment aperture to let the beam pass through the small aperture hole by carefully adjusting the six screws of the laser tube holder.

c) Align the EO crystal: adjust the 4-D adjustable holder, let the beam illuminate at the center of the crystal front surface and let the reflected beam return back to the laser exit on the laser head.

d) Refer Fig. 2 to do setup: firstly remove the EO crystal, place the Glan prism (Polarizer) and the other polarizer (Analyser) on the rail, rotate the Glan prism and the polarizer so that their polarizations are perpendicular to each other, but parallel to *x*-(vertical) and *y*-(horizontal) axis, respectively.

e) Place the E-O crystal in between the Glan lens (Polarizer) and the Analyser, interference pattern will be generated. To view the interference pattern, place a piece of lens tissue in front of the crystal or attach the provided ground glass in front of the EO crystal entrance (may use a piece of tape to attach the ground glass) and then the interference pattern shown in Fig. 6 can be observed on a white screen behind the polarizer.

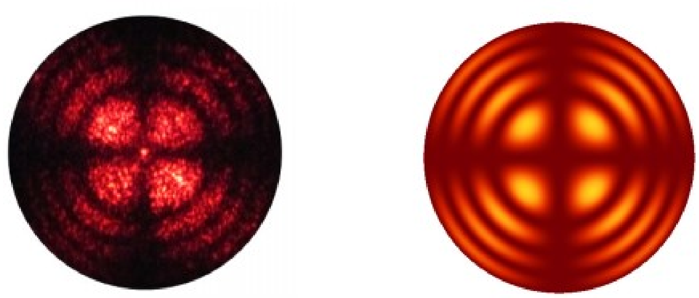


Figure 6 Interference pattern of polarized light in uniaxial crystal in comparison to computer simulation

As seen in Figure 6, such interference pattern contains a dark cross surrounded by alternative dark and bright interference rings. The center of the cross, also the center of the interference rings, corresponds to the optical axis of the crystal while the cross corresponds to the polarization directions of the two polarizers. To align the crystal, make the center of the cross overlap with the center of the interference rings, and the interference pattern as symmetric and complete as possible. Make sure the laser beam gets transmitted from the center of the crystal and one line of the cross is parallel to the *x*-axis. Note: the crystal can be rotated along the optical axis (*z*-axis) by releasing the two fixing screws on the mount. In this experiment, let the short side of the rectangular cross-section parallel to *x*-axis.

Note, without DC bias voltage applied, the dark cross interference pattern may not be symmetric. This is due to the residual biaxiality of the crystal. It is hard to make a perfectly uniaxial crystal of this length. It could be corrected by applying certain of DC bias voltage.

2. Connect the cable of the crystal to the “Modulation Voltage” (on the back panel of the driver control box). Apply dc voltage bias to the $LiNbO_3$ crystal and observe the interference pattern of polarized light in the biaxial crystal, as now the uniaxial crystal becomes a biaxial crystal under an electric field.

3. The interference patterns are complimentary with parallel and orthogonal polarizers.

4. By varying the dc bias voltage, the separation between the hyperbolae varies, however, the interference pattern does not rotate. This means that the applied electric field only changes the principal index of refraction of the crystal along its principal axis while the rotation angle of the refractive index ellipsoid is independent of the electric field applied.

6.2 Derive the half-wave voltage and the electro-optic coefficient of $LiNbO_3$ crystal by measuring its transmittance curve (*T~U* curve)

There are two methods to measure the half-wave voltage of a $LiNbO_3$ crystal, the extremum method and the modulation method.

1. The extremum method

Connect the photo detector to "Receiving Light Intensity" on the back panel of the control box. Zero the meter of the light intensity by blocking the photo receiver and adjusting the Zeroing knob. Align the photo-receiver to let the output laser spot hit the active area of the photo receiver (at this time, the lens tissue or ground glass applied in previous experiment is removed from the optical path). Set the signal selection switch on the front panel of the control box to "Extreme Value". Only dc voltage (i.e. turning the knob of "Modulation Amplitude" to minimum) is applied to the $LiNbO_3$ crystal and is increased gradually. Correspondingly, maximum and minimum output optical intensities will be observed from the meter. The difference between the voltages corresponding to adjacent maximum and minimum output intensities is the half-wave voltage of the crystal, U_π.

Change the dc bias voltage applied to the crystal from zero to maximum, and then back to zero while monitoring the intensity reading of the output laser signal. If the intensity reading does not exceed 200 mV (i.e. no saturation of the light intensity meter), then measure the *T~U* (*T~U_0*) data in step of 10 V from 0 V to the maximum range.

Note: the first minimum of the *T~U* curve may not be located at 0 V, as caused by the residual biaxiality of the crystal. Hence, the voltage should be finely tuned to precisely locate the first minimum of the *T~U* curve.

Use the measured data to plot the *T~U* (*T~U_0*) curve and determine the half-wave voltage of crystal, U_π between the voltages of adjacent minimum valley and maximum peak ($U_\pi \cong 170$ V as shown in Figure 7). Finally, calculate the electro-optic coefficient of the crystal using Eq. (17) with the parameters as thickness of crystal d=2.5 mm; length of crystal L=60 mm; refractive index of crystal: n_0=2.289; laser wavelength: λ=632.8 nm ($\gamma_{22} \cong 6.5$ pm/V can be derived), and compare the result with the well-recognized value of 6.8 pm/V (please note Figure 7 is just for example as the actual measurement error may vary from apparatus to apparatus).

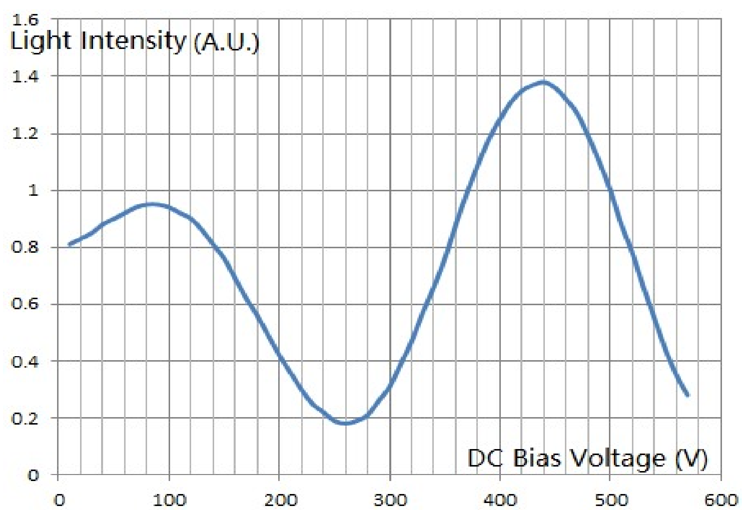


Figure 7 Typical *T~U_0* curve

2. The modulation method

Apply both dc (DC Bias) and ac (set "Modulation Amplitude" at small level) voltages to the crystal and increase the dc voltage gradually while observing maximum and minimum output intensities when the output signal waveform suffers from frequency distortion. Similarly, the difference between the dc voltages corresponding to adjacent output signals with frequency distortion is the half-wave voltage of the crystal, U_{π}.

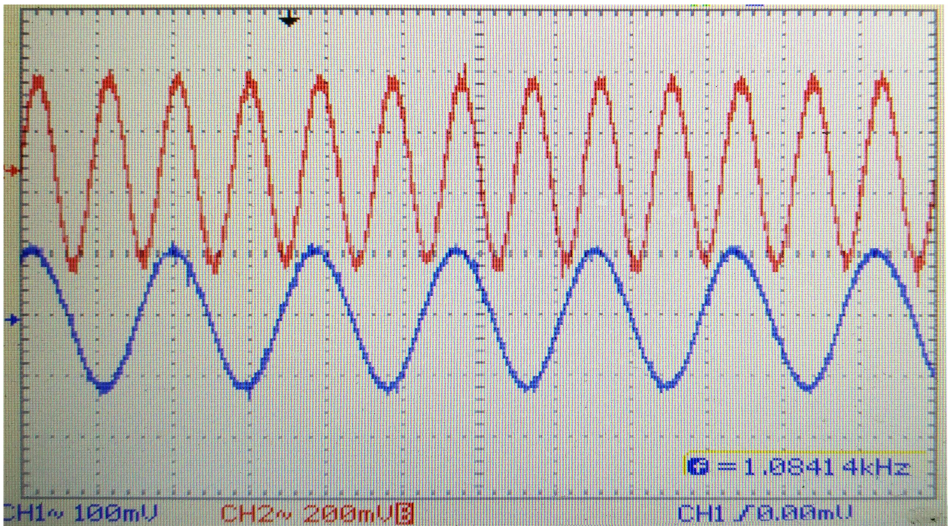


Figure 8 Modulation signal and frequency doubled signal observed on oscilloscope

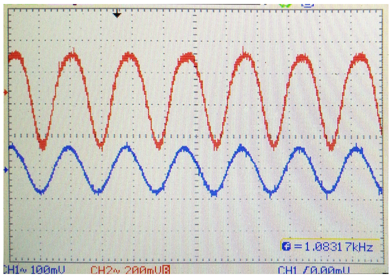
To use the modulation method, first set the signal selection switch on the front panel of the modulation driver to "Modulation", and then connect the output of the "Modulation Signal" from the front panel of the driver to one channel of the oscilloscope while connecting the "Light Intensity Signal" to the other channel of the oscilloscope. Compare the two waveforms on the oscilloscope while adjusting the dc voltage bias. When the dc bias voltage is increased to a certain value U_1, the output optical waveform suffers from frequency-doubling distortion (see Figure 8); continue to increase the dc bias voltage to another value U_2 until frequency-doubling distortion is observed again for the output optical signal. The difference between the two dc bias voltages is the half-wave voltage of the crystal ($U_{\pi} = U_2 - U_1$).

Note, during the process of measuring the serials of maximum/minimum light intensity points to acquire corresponding DC voltages, the ac "Modulation amplitude" should be fixed, since the reading of DC voltage on the meter is the summation of the actual DC bias and the offset of ac modulation. The difference of two readings (i.e. U_2-U_1) will eliminate the influence of ac offset.

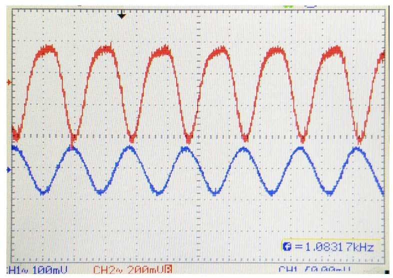
The modulation method is more precise than the extremum method because the maximum and minimum intensities cannot be precisely located from a $T \sim U$ curve. However, the modulation method comes with its own challenge, which imposes strict requirement on optical alignments. If frequency-doubling distortion is not observed, then the whole system needs to be realigned until a satisfactory interference pattern, as shown in Figure 6, is observed.

3. Observe the modulation characteristic of sinusoidal waveform at various dc bias voltages

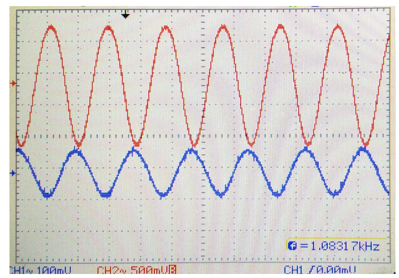
Set the signal selection switch on the front panel of the modulation driver to "Modulation", and apply the built-in sinusoidal waveform to the crystal. In the meantime, connect this "Modulation Signal" to one channel of the oscilloscope via the output port on the front panel of the modulation driver. Connect the output of the "Light Intensity Signal" to the other channel of the oscilloscope to simultaneously monitor the waveforms of both output and modulation signals. Compare the two waveforms on the oscilloscope at five "DC Bias Voltages" of 40 V, 80 V, 120 V, 160 V, and 200 V as shown in Figure 9.



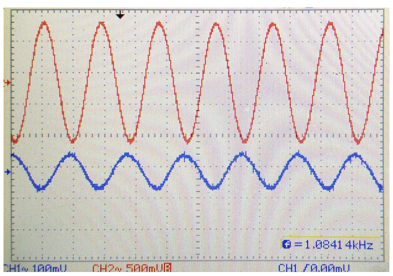
DC 40V



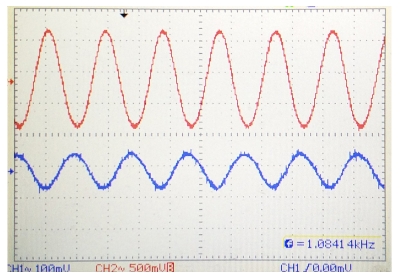
DC 80V



DC 120V



DC 160V



DC 200V

Figure 9 Modulation waveform and modulated waveform under different DC voltages

If the dc bias voltage is located in the linear portion of the *T*~*U* curve, when $U_0=U_\pi/2$, a linear modulation is achieved; if the dc bias voltage is selected near a maximum or minimum location of the *T*~*U* curve, the output signal suffers from distortion. In the latter case, the amplitude of the modulation signal should not be made too big, as otherwise the modulation signal would suffers from distortion and therefore the true cause for output signal distortion would not be determined. Thus, the amplitude of the modulation signal (adjusted by knob "Modulation Amplitude"), the intensity of the input optical signal, the output of the power amplifier, and the gain or attenuation of the oscilloscope must be properly adjusted.

4. Observe the modulation characteristic of sinusoidal waveform with a λ/4 wave plate

In the above experiment, remove the dc bias voltage applied to the crystal (the "DC Bias Voltage" is reduced to 0 V), and then insert a λ/4 wave plate between the Polarizer and the crystal. The waveform of the output signal changes when the λ/4 wave plate is rotated. When the fast and slow axes of the λ/4 wave plate are parallel to the inductive *x*'- and *y*'-axes of the crystal, linear modulation is achieved; when the fast and slow axes of the λ/4 wave plate are parallel to the principal *x*- and *y*-axes of the crystal, frequency-doubling distortion is observed for the output signal. If the λ/4 wave plate is rotated for one circle, linear modulation and frequency-doubling distortion can be each observed four times for the output signal.

5. Demonstrate optical communication with electro-optic modulation

Set the signal selection switch on the front panel of the modulation driver to "Audio Frequency" and now the built-in sinusoidal signal is turned off. Connect the "Audio Output" signal on the back panel of the modulation driver to a speaker and hence music will be heard. By varying the dc bias voltage applied to the crystal, the quality of the music played from the speaker changes, indicating fidelity and infidelity of the music played. If an opaque plate is inserted between the laser and the crystal to block the laser beam from entering the crystal, then no music will be heard from the speaker; if the opaque plate is removed, then music will be heard again from the speaker. This indicates that the laser beam can carry an audio signal for optical communication. If the audio signal is sent to the oscilloscope, its waveform can be observed, as the superposition of sinusoidal waves of identical amplitude but with different frequencies.

Note: Since the laser beam exiting from the laser tube is polarized, to achieve maximum light transmittance from the Glan prism (polarizer), the laser tube may be rotated.