

Electro-Optic Devices in Review

The Linear Electro-Optic (Pockels) Effect Forms the Basis for a Family of Active Devices

by Robert Goldstein

Electro-optic light modulators control the polarization of light passing through a crystal subjected to an electrical driving signal. The effect was first described by F. Pockels in 1893; hence, the devices are known as Pockels cells. The phenomenon is also called the linear electro-optic effect, because phase retardation of light transiting the crystal is directly proportional to the applied electric field. Early attempts to use Pockels cells were not overly successful, in the absence of a source of well-collimated, monochromatic light. The advent of the laser opened the field for a variety of Pockels-effect devices.

The most commonly used crystals for e-o light modulators constrain the vibrations of propagating light waves in two mutually perpendicular planes of polarization determined by the symmetry axes of the crystal. Crystals of this class are optically uni-axial — for only one direction through the crystal will the wave velocity be the same for both planes of polarization. That direction is the optic axis, which is parallel to the crystallographic z axis. For waves propagating in the z direction, the associated vibrations occur in the

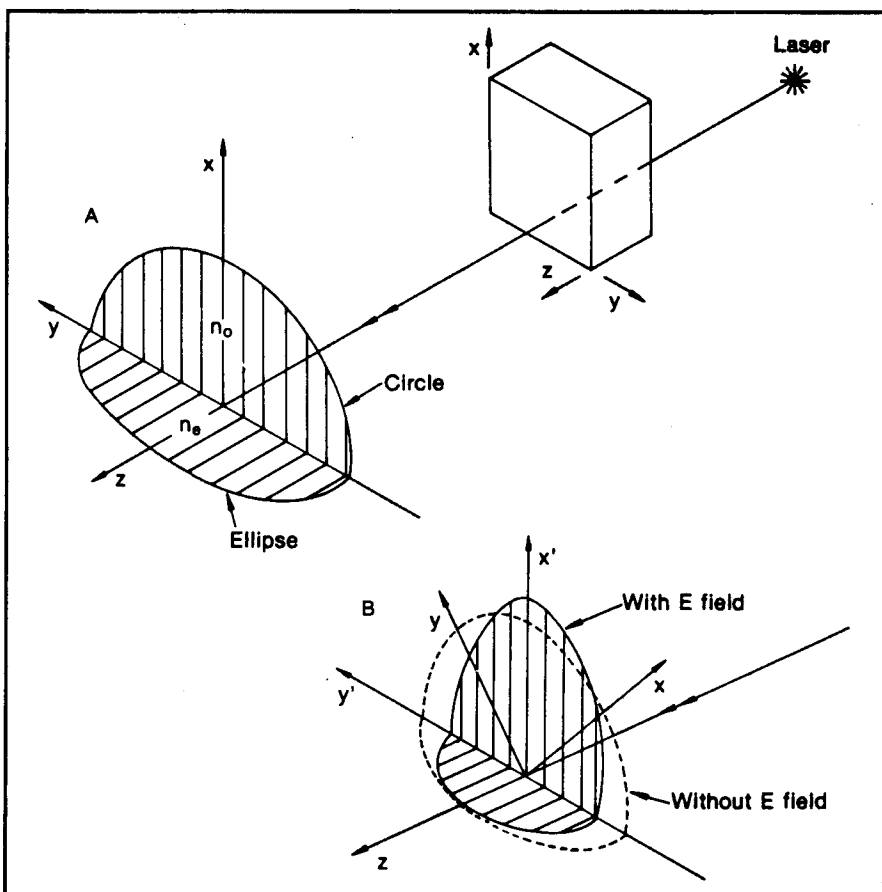


Figure 1. A) Projection of the index ellipsoid of a uni-axial crystal, sectional view. B) Projection of index ellipsoid with electric field applied parallel to the optic (z) axis. Induced axes are 45° from crystallographic axes.

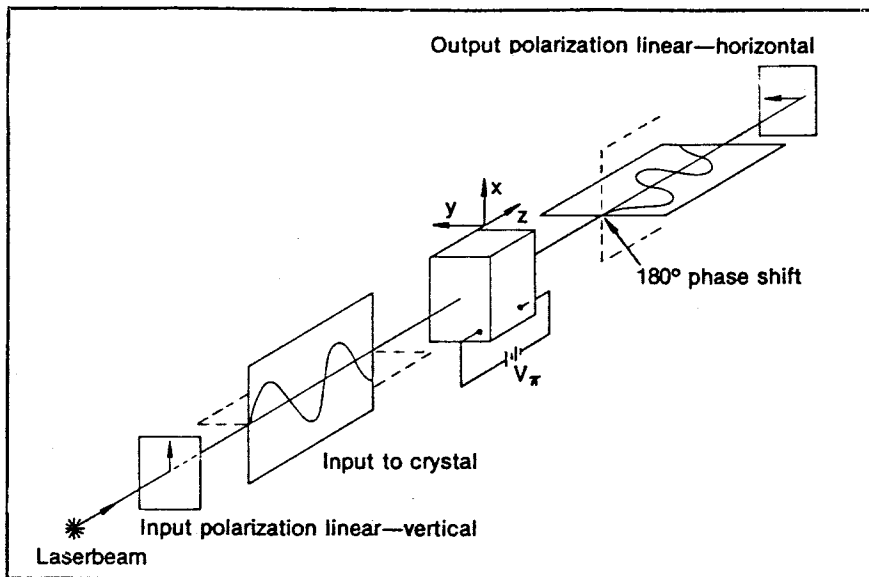


Figure 2. 180° phase shift and 90° rotation of plane of polarization induced by voltage applied to Pockels cell crystal.

orthogonal x and y axes of the crystal. All modulator geometries make use of the fact that the refractive indices associated with the x and y axes (and therefore the vibration amplitudes) are voltage sensitive.

Polarization Effects

The indices of refraction are a measure of the speed of light in a

particular direction within the crystal. A difference in speed between two rays implies a difference in phase. The change of refractive index with direction of propagation or by application of an electric field may be illustrated by defining an index ellipsoid or indicatrix (Figure 1a). For waves propagating along the optic axis, the magnitude of the orthogonal vibrations can be shown

as radius vectors, proportional to the indices. As indicated, the beam traverses the crystal parallel to the optic axis while the vibrations lie in the x-y plane. With no electric field applied, the indicatrix projects as a circle, and the indices (n_o) in the x and y directions are equal. The emergent rays (vibrations) will be unchanged in amplitude and relative phase.

When an electric field is applied to a uni-axial crystal parallel to its optic axis, the indicatrix is deformed into an ellipse (Figure 1b), and the indices are no longer equal. Since the indices are not equal, the vibrations do not have equal velocity (or amplitude), and a phase difference or retardation now exists. By definition, unequal indices produce elliptically polarized light. Also by definition, linear and circular polarizations are special forms of elliptical polarization.

The ellipticity of the indicatrix is dependent on the electric field strength and an electro-optic coefficient associated with the particular crystal material. By increasing or decreasing the voltage applied to the crystal, the phase shift between the two components can be varied to produce differences between 0° and any value up to the voltage breakdown limit of the crystal. Practically, values between 0°, 90°, and 180° are most useful. Figure 2 shows the phase shift induced by applying halfwave voltage.

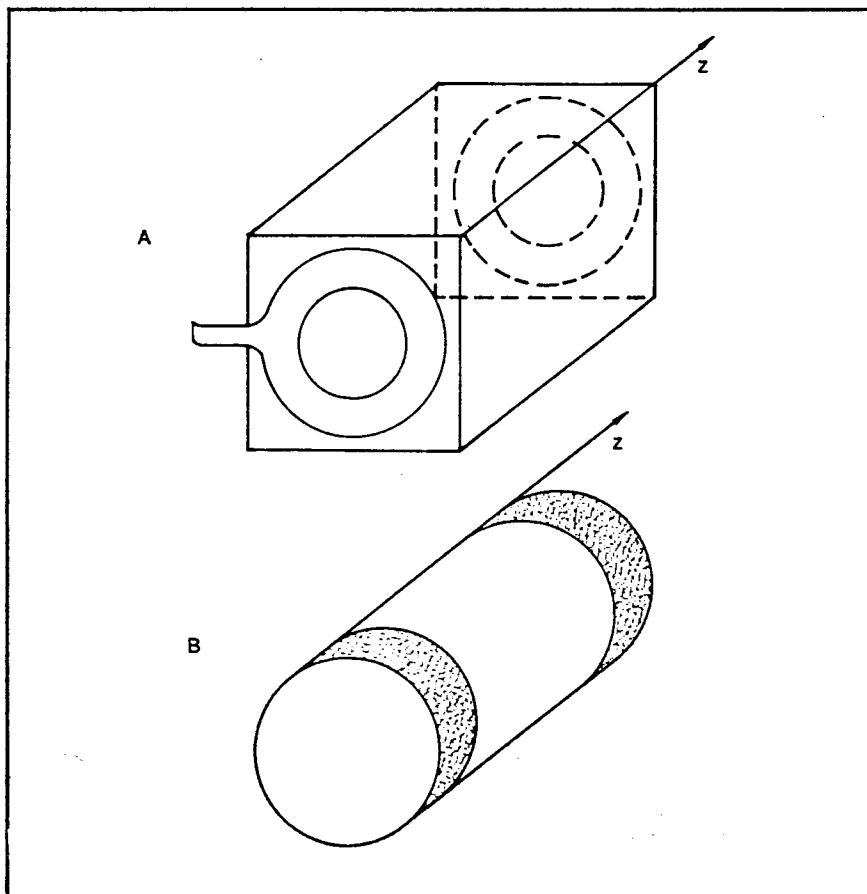


Figure 3. Typical electrode configurations: A) washer electrodes and B) cylindrical band electrodes.

The Pockels Cell as Dynamic Retarder

Pockels cells can be thought of as dynamic optical retarders. A quarterwave plate, for instance, induces a quarterwavelength retardation or 90° phase shift between the ordinary and extraordinary rays of a linearly polarized beam transiting the plate. In terms of polarization forms, the linearly polarized input beam is converted to a circularly polarized beam. Similarly, a halfwave retarder will produce a 180° phase shift between o and e rays. This corresponds to a linearly polarized beam, rotated 90° from the input direction. These retarders are static devices, their retardation fixed by physical dimensions and wavelength. In contrast, Pockels cells are not so limited; the degree of phase shift is determined only by the applied voltage. However, phase shifts other than 90° and 180° will produce elliptically polarized light. The Pockels cell is a polarization rotator only at the 0° and 180° phase shift points.

The simplest form of Pockels cell

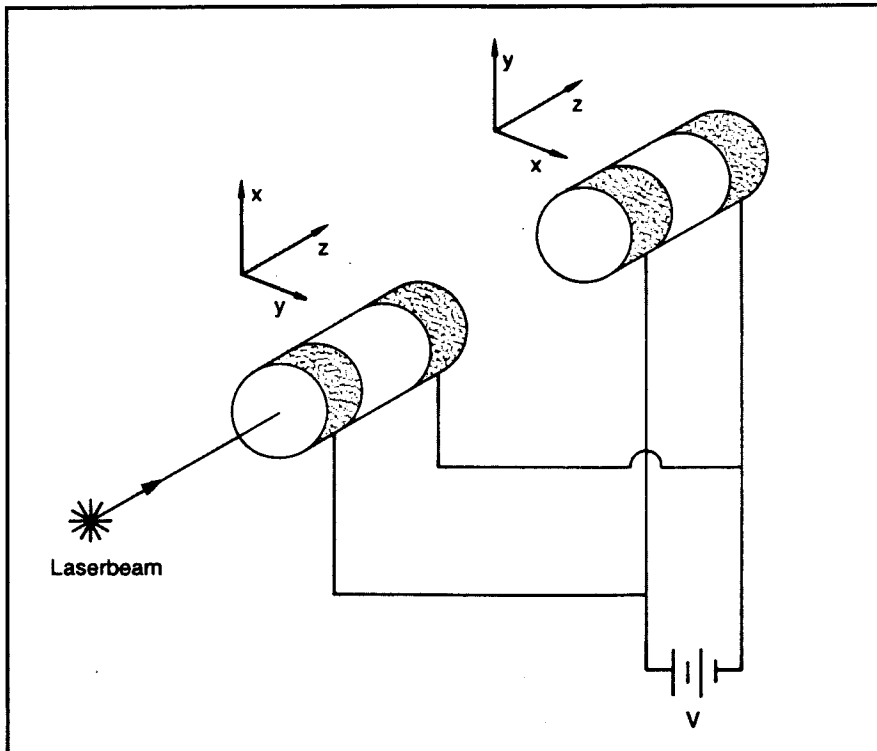


Figure 4. Connecting two crystals, optically in series and electrically in parallel, reduces required voltage by a factor of two.

is a crystal with electrodes fixed to two polished faces perpendicular to the optic axis (Figure 3a). In this case the electrodes are washers. The laserbeam passes through the central aperture while the electric field is applied in the same direction. A more modern approach is to machine the crystal into a solid cylinder and apply the electrodes as bands on the circumference of the barrel (Figure 3b).

Electro-optic switches with clear apertures exceeding 75 millimeters have been built in this configuration. The cylindrical arrangement of crystal and electrodes produces a more uniform electric field within the crystal and thus more uniform retardation across the clear aperture. When the electric field is in a direction parallel to the light passing through the crystal, the device is called a longitudinal field modulator (LFM). Another configuration boasts the electric field applied orthogonally to the direction of the light beam. This arrangement is called a transverse field modulator (TFM); in a TFM, the light beam need not propagate in the direction of the optic axis.

For a typical longitudinal device, the relative retardation of the *o* and *e* waves is:

$$\Gamma = 2\pi n_o^3 V r_{ij} / \lambda \quad (1)$$

where Γ is the relative phase shift between *o* and *e* ray vibrations [measured in radians], n_o is the ordinary refractive index, r_{ij} is the

electro-optic coefficient [micrometers per volt], V is the applied voltage [V], and λ is the wavelength [μm].

Halfwave Voltage

The voltage at which halfwave retardation occurs for a given wavelength is a useful figure of merit for comparing devices. In many applications it is the limiting factor on the types of electronic drivers available. If the retardation in Equation 1 is

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180° (π radians), we may then rearrange the equation and solve it for the voltage required. The value V is defined as the halfwave retardation voltage or, simply, halfwave voltage:

$$V_{\pi} = \lambda / 2r_{ij}n_o^3. \quad (2)$$

In the longitudinal configuration, the halfwave voltage is independent of dimensions and directly proportional to wavelength. At longer wavelengths, higher voltages are needed to reach the halfwave point.

The *e-o* coefficients for available crystals are quite small. Thus, halfwave voltages lie in the kilovolt region.⁵ Several techniques will reduce the required voltage. For the longitudinal mode, crystals may be

stacked optically in series and electrically in parallel (Figure 4). Some compensation for thermal variations in the crystals can be obtained by rotating the second crystal 90° around the optic axis. The net voltage required to produce halfwave retardation will be reduced by a factor of two for a two-crystal stack. Modulators have been built with as many as six stacked crystals, but when three or more are used optical performance suffers.

Halfwave voltages can be reduced to less than 100 V by use of the TFM configurations depicted in Figure 5. In these arrangements, the crystals are in the form of long, thin rods; halfwave voltage is a function of the crystal dimensions. Depending on the type of crystal used, the modulator may contain a single crystal or multiples of two. Each combination has advantages and limitations related to the crystal materials.

In general, for a given crystal thickness between electrodes, the halfwave voltage is related to length. It is not uncommon to see a total crystal pathlength of 200 mm and thickness of 3 mm in devices that use ammonium dihydrogen phosphate (ADP) or deuterated potassium dihydrogen phosphate (D-KDP or KD*P) in the TFM configuration. Only the availability of extremely high optical quality crystals permit such lengths. Devices manufactured with cadmium telluride, lithium niobate, and lithium tantalate crystals, which are grown at high temperatures, do not exhibit such high degrees of crystal quality and are generally limited to maximum lengths of about 50 mm.

The layout of a four-crystal ADP TFM is shown in Figure 5b. This arrangement also applies to D-ADP. Light propagates at 45° to the optic axis, making the crystal appear birefringent. The natural birefringence causes the incoming beam to be split into *o* and *e* rays separated by an angle of $1^\circ 47'$. Crystals must be used in pairs and are oriented with the second crystal rotated 180° around the propagation axis. This causes an interchange of the *o* and *e* rays, provides thermal compensation, and recombines the *o* and *e* rays. However, after transiting the first pair of crystals, the beam will be offset. The second pair of crystals compensates for beam offset and brings the beam back to the original optical path.

Multiple-crystal TFMs fabricated from D-KDP crystals offer low voltages similar to the ADP types, with somewhat less constructional complexity. In this form, the *o* and *e* rays do not separate, but thermal compensation is still obtained by

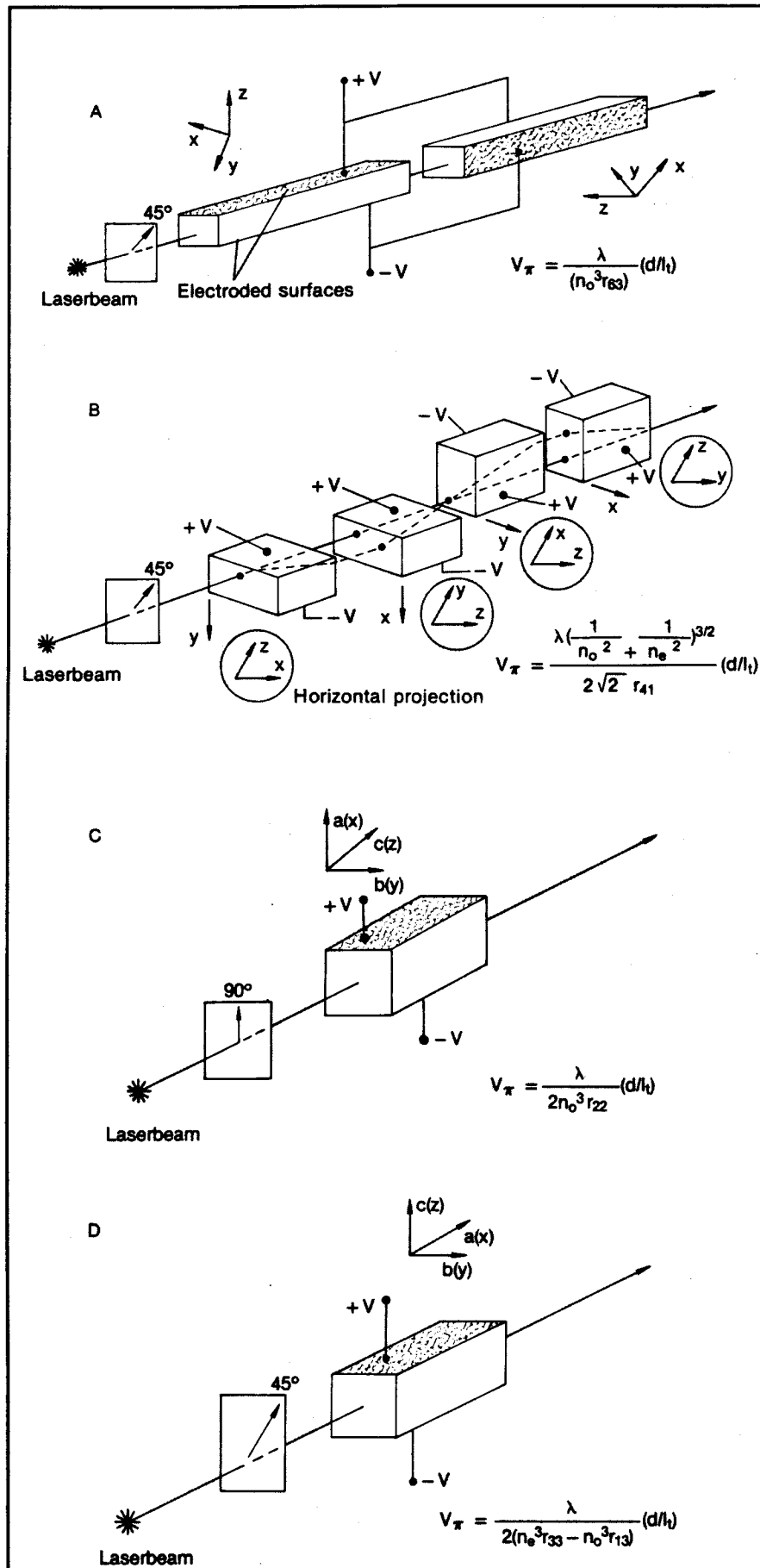


Figure 5. Some representative modulator configurations: A) a dual-crystal D-KDP transverse field modulator, B) a four-crystal ADP transverse field modulator, C) a LiNbO_3 transverse field modulator used as a Q switch, and D) a LiTaO_3 transverse field modulator. In all cases, d = the dimension between the electrodes and l_1 = the total crystal length.

rotating (in this case 90°) each second crystal.

The advantage of D-KDP over ADP in a long-crystal array is the ease with which a transmission-line-type modulator may be built. D-KDP lends itself to a continuous stripline structure, while ADP requires a separation between the two pairs. On the other hand, the crystal orientation of an ADP TFM is such that the piezoelectric constants approach zero, and the devices are essentially resonance-free.

Materials

Many crystalline materials exhibit an electro-optic effect. The characteristics that make some materials more useful than others are large e-o coefficient, high transparency, good optical quality, and availability. The

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most commonly used e-o crystals are ADP, D-ADP, KDP, D-KDP, LiNbO_3 , LiTaO_3 , and CdTe . Other crystals are available, many of them chemical modifications of the ones listed above. But these lesser-used crystals generally do not provide performance advantages commensurate with their higher cost. Alas, no one crystal provides a universal solution for controlling light across a broad range of the ultraviolet through near infrared.

Crystals in the ADP and KDP family are grown from aqueous or heavy water (deuterated) solutions and generally exhibit a high degree of optical uniformity. The major disadvantage of these solution-grown materials is that they are water soluble and must be protected from moisture. Protection is normally accomplished by sealing the crystal in a hermetic container with transparent glass or quartz windows.

Niobates, tantalates, and tellurides are grown at very high temperatures from a melt or vapor. Because of included strain and crystal nonuniformities, they do not exhibit the optical quality of water-grown crystals. They are, however, insoluble in water; except for dust protection, they can be used in open air without protective packaging.

In selecting a material for a particular application, other properties may come to the fore: optical damage threshold (for Q switching), loss tangent (for high frequency modula-

tion), piezoelectric effects, crystal configuration, and wavelength of operation. End users should have frank discussions with device manufacturers early on.

Modulators

The Pockels cell by itself does not produce intensity modulation of the light passing through it. However, the elliptically polarized light induced can be converted into intensity variations by use of static polarizing devices such as Glan-Thompson prisms or polarizing films. Figure 6 represents a simple intensity modulation scheme. If the input polarizer is aligned as shown with its polarizing axis parallel to the crystal x (or y) axis and the analyzing polarizer is rotated by 90° (crossed polarizers), the combination will produce an intensity minimum with no voltage applied to the crystal. When halfwave voltage is applied, the intensity becomes maximum, following a \sin^2 relation to the voltage (Figure 7). The quarterwave retardation voltage corresponds to the 50% transmission level. The equation governing the relative transmission, normalized with respect to the half-wave level, is:

$$T = \sin^2 (\pi V/2V_{\lambda/2}) \quad (3)$$

Figure 7 represents the general transfer characteristic of all e-o modulators operating between crossed polarizers when no optical or electrical bias is present. A critical feature of the characteristic in terms of modulator performance occurs at the minimum or null transmission level. The null value is the controlling factor on contrast ratio (CR, which is also called the extinction ratio), a quantity similar to signal-to-noise ratio.

$$CR = I_{\max}/I_{\min} \quad (4)$$

where I_{\max} and I_{\min} are the maximum and minimum output intensities, respectively.

Electro-optic modulators can also be operated between parallel polarizers, so that maximum transmission occurs when no voltage is applied. In this case, intensity follows a \cos^2 function, and the null must be obtained with halfwave voltage across the crystal. Usually, the contrast ratios attainable are not as large as those obtained in the crossed-polarizer configuration. Either way, an operating point anywhere on the transfer characteristic may be chosen by application of an electrical bias to the crystal (Figure 8). In many applications, equal excursions of light intensity around a middle level are required. This performance can be

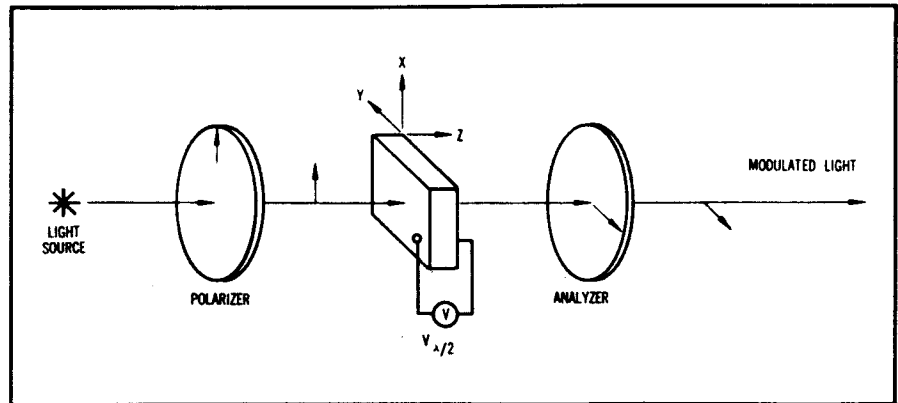


Figure 6. Intensity modulation with an e-o modulator located between crossed polarizers.

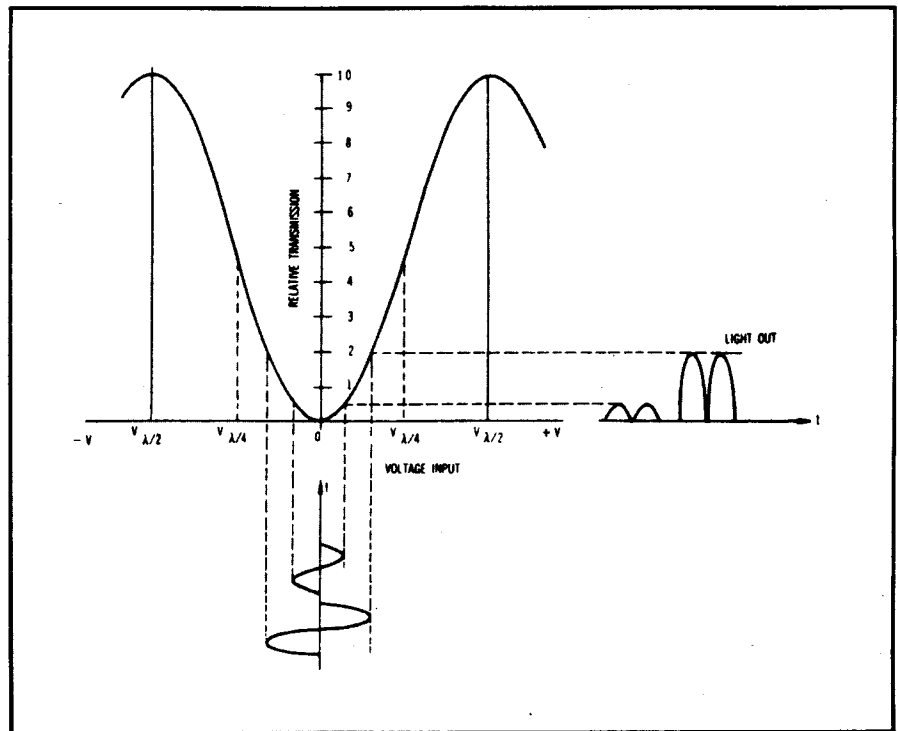


Figure 7. Transfer function for a longitudinal e-o modulator and crossed polarizers.

attained, along with reasonable linearity, by electrically or optically (with a quarterwave plate) biasing the operating point to the 50% transmission level. Intensity swings about this point will be equal for equal

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positive or negative voltage signals. Maximum transmission is limited only by the fixed reflection, absorption, and scattering losses of the optical elements. The null value is sensitive to optical alignment of the input beam with respect to the optic axis, the orientation of the plane of polarization, and the positioning accuracy of the crossed polarizers. The

null value can easily change the CR by orders of magnitude. The general rule is that longer crystals correspond to lower voltages and contrast ratios. LFMs with single crystals and apertures of about 6-mm diameter can have CRs as high as 10,000:1. Two-crystal LFMs usually do not have CRs in excess of 1,000:1, while CRs for three-crystal devices rarely exceed 300:1.

A poor null leaks light, which can be a serious limitation in low light applications where a sensitive detector or film emulsion is used. In addition to alignment accuracy, many factors can affect the null — crystal quality, pathlength, strain birefringence caused by simply holding the crystals in place, thermal effects from ambient changes, absorption of laser energy, and high frequency electrical heating of the crystal and its electrodes.

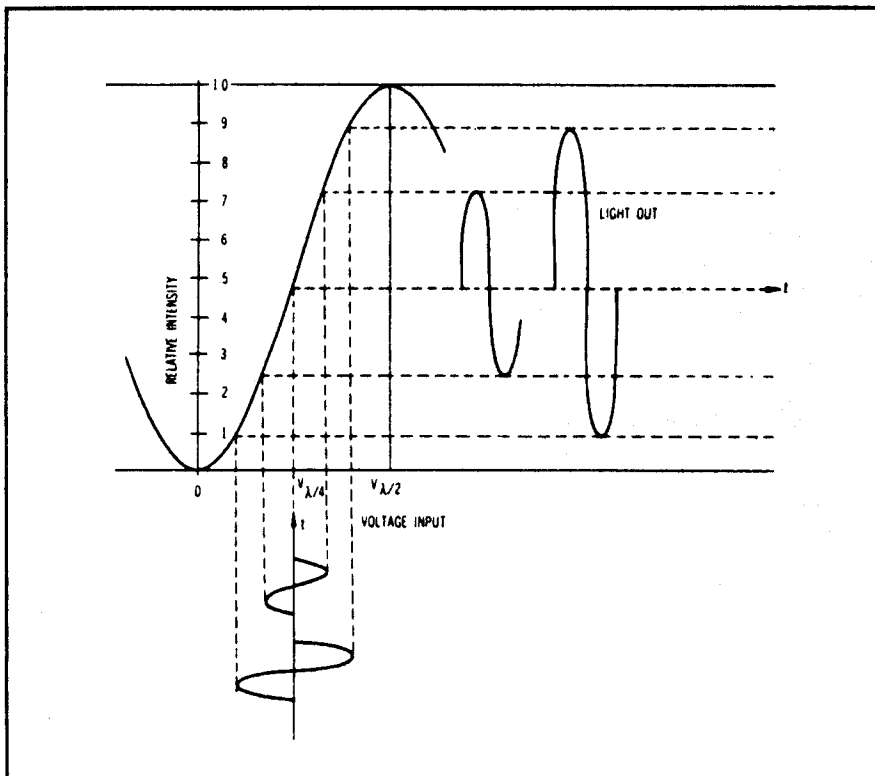


Figure 8. Transfer function for a longitudinal e-o modulator and crossed polarizers, with quarterwave bias.

Electro-optic modulators have produced modulated light at gigahertz frequencies. Several commercial instruments containing LFM's routinely operate at 250 megahertz. Many applications do not demand 100% depth of modulation, which would require generating halfwave voltage at an impossibly high frequency. Voltages in the range of 50 to 100 V peak-to-peak are available from high frequency signal generators. This voltage yields modulation depths of up to 10% with a 10-mm-aperture, two-crystal D-KDP LFM.

High frequency TFM's fabricated from D-KDP or ADP are in general use as video signal modulators and have a useful upper limit of 100 MHz. The limiting factors are the physical dimensions of the crystals (large capacitance) and the power dissipation in electrodes and crystals. High frequency data rates in the vicinity of 500 megabits per second have been attained with LiTaO₃ TFM's. The usual aperture size for this type of device is about 0.050 in. In most instances, high frequency performance is limited by the availability of a signal source with adequate voltage.

Other Applications

Optical pulse rise time is of great interest to those who must turn a laserbeam on or off at speeds in the picosecond region. Most such applications require repetition rates of less than 100 pulses per second, well

within the range of available electronic drivers. The fundamental limit on how fast a modulator will switch is the speed at which the electrical signal field can fill the clear aperture. Given an optimized crystal and electrode geometry and a fixed crystal dielectric constant (i.e., a "good" crystal), the only variable is the aperture size. Typical modulators have a cylindrical LFM configuration with the crystal embedded in an impedance-matched transmission-line housing. A modulator with a 3-mm aperture exhibits a 40-ps rise time, while a device with a 6.5-mm aperture is limited to a rise time of about 150 ps. In comparison, the typical LFM Q-switch with a 10-mm aperture will have a rise time in the 500-ps range.

Perhaps the broadest usage of Pockels cells is in Q switching solid-state lasers. D-KDP and LiNbO₃ are the most common Q-switch materials for Nd:YAG lasers. LiNbO₃ is used in many high repetition rate, low peak power laser systems, particularly in rangefinders and target designators. Because LiNbO₃ has a relatively low optical damage threshold, its use is limited to maximum peak power density levels of about 50 megawatts per square centimeter. D-KDP is used in Q switching with peak power densities up to 800 MW/cm². In optical pulse gating systems, D-KDP devices have tolerated peak power densities as high as 30 gigawatts per square centimeter

with an incident optical pulse width of 100 ps. Carbon-dioxide lasers are Q switched and modulated almost exclusively with CdTe devices. CdTe is used in the TFM mode and has found application as an intensity and frequency modulator for many types of lasers operating between 2.7 and 10.6 μ m.

Both phase and frequency modulation can be accomplished by introducing an optical element having a pathlength dependent on an applied electric field. Phase modulators find limited application, because the resultant modulation can be detected only by optical homodyne or heterodyne techniques. Frequency modulation has found application in widely diverse fields such as optical communications and spectroscopy. A frequency modulator can be made from an appropriately oriented LFM or TFM, preferably with the shortest crystals possible.

Intracavity frequency modulators can change the wavelength of a dye laser by changing the effective length of the optical cavity in response to an electrical signal. An ac signal will cause some portion of the dye emission spectrum to be scanned repetitively. Extracavity frequency modulation may be performed by introducing a Doppler shift in the optical beam as it transits the crystal. Applying a fast-rise-time pulse with its leading edge approximating a ramp will produce a "chirp" at optical frequencies.

Frequency modulators are generally available in ADP, D-ADP, and LiTaO₃. Both ADP and D-ADP can be used in intra- and extracavity operation. LiTaO₃ is usually applied outside the laser cavity because of its absorption losses. Its advantage lies in its favorable high frequency characteristics and its solderability. The latter factor allows good thermal transfer from the electrodes to a metallic substrate.

Summary

Electro-optic modulators have been refined over the past 25 years and have kept pace with the development of improved lasers. New materials and configurations offer the system designer multiple ways to achieve design goals. However, the application of a particular modulator type should be made only after research into its operational characteristics. Most problems arise because the system designer mistakenly assumes it to be a simple optical switch or intensity control that can be added at the last minute. Early consideration in the design process will produce more satisfactory results and a more satisfied designer.