# Pockels Cell Primer

by ROBERT GOLDSTEIN

*Introduction of low-cost Pockels cells has made it possible to use high-performance, reliable light modulators in a wide variety of applications. This article is designed to acquaint lasermen with how the device works and what it can be used for.*

Modulation of light has become increasingly important as new laser applications are developed. Recently, Pockels effect modulators have been receiving a considerable amount of attention because they offer price, performance and reliability advantages. With the introduction of several low-cost modulator models, it is expected that these devices will be incorporated in applications where Pockels cells were once prohibitively expensive. One area in which the use of Pockels cells will grow is expected to be optical test instrumentation where, for example, electronically-variable retarders and light choppers will supplement or replace the various forms now in use. The new modulators are already being used in prototypes of commercial printing and display equipment.

### Advantages of Pockels Cells

Pockels' electro-optic effect describes the phase changes produced in polarized light passing through certain uniaxial crystal materials which are under the stress of an electric field. The effect is a linear function of the voltage which is applied parallel to the crystal optical axis in the same direction as the incident light, as shown in Figure 1A. Light modulators using this geometry are referred to as longitudinal modulators.

The Kerr effect is similar to the Pockels effect except that the field is applied perpendicular (transversely) to the incident light, as shown in Figure 1B, and a liquid medium is used rather than a crystal. In Kerr cell modulators, the electro- optic effect is a function of the square of the *E* field. However, Kerr cells require between five to ten times the voltage a Pockels cell would need to obtain the same optical effect. For this reason, as well as the fact that the liquids used in Kerr cells are toxic, Pockels effect devices have replaced Kerr cells in most laser applications.

ROBERT GOLDSTEIN *is Manager of Engineering of Crystalab Products Corp. (Rochelle Park, N.J.). He has been engaged in laser systems development since 1963. Since joining Crystalab, he has been responsible for developing electro-optic light modulators. His most recent effort involved establishing advanced fabrication techniques which have resulted in a new generation of low cost light modulators. Mr. Goldstein received a BS in electrical engineering from Newark College of Engineering.*

Some applications that involve the use of Pockels effect devices include:

- Light modulation from d-c to more than 30 gigahertz.
- Multiple-color tv-type displays.
- Q-switching of lasers producing up to 500 megawatts/cm$^2$.
- Digital beam deflection.
- Electronically controlled linear retarders.
- Ultra fast optical shutters.
- Optical data processing.

A typical light modulator assembly is shown in Figure 2.

### Longitudinal Electro-Optic Effect

The effect of a Pockels' electro-optic modulator (EOM) on polarized light is similar to the effect obtained with optical retarders such as 1/4- or 1/2-wave retardation plates. A retardation plate, operating with light of a given wavelength, introduces a fixed phase shift between the ordinary *(0)* and extraordinary *(E)* light rays passing through the plate. The electric vectors of the light wave undergo a corresponding change—that is, they experience a rotation which is fixed by the thickness of the plate and the birefringence of the material. EOM's operate on light in an analogous manner except that the value of birefringence can be controlled electronically to produce a desired optical retardation.

The crystal materials used for longitudinal electro-optic modulators are normally uniaxial in the absence of an electric field—that is, there is ideally only one value of refractive index in the direction of light propagation through the optic axis. This is demonstrated when a collimated, randomly-polarized beam of light is applied to the crystal, parallel to its optic *(Z)* axis. The emerging beam will be in its original polarization form. The only noticeable effect in a perfect crystal is beam attenuation resulting from absorption and reflection losses.

Figure 3A shows a block of suitable uniaxial crystal

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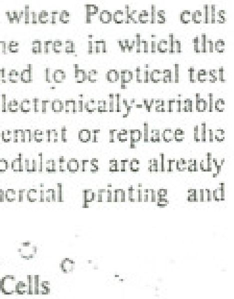

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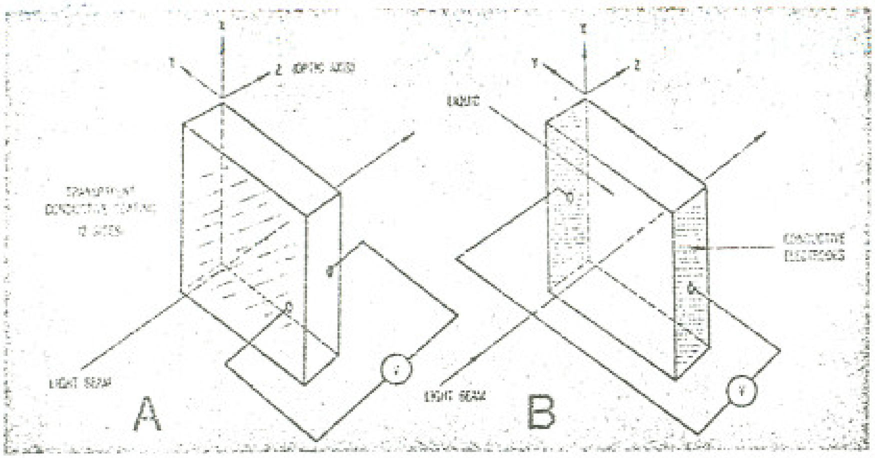

Figure 1—*Electric fields are applied longitudinal to the light beam for Pockels effect modulators (A) and transversely for Kerr effect devices (B).*

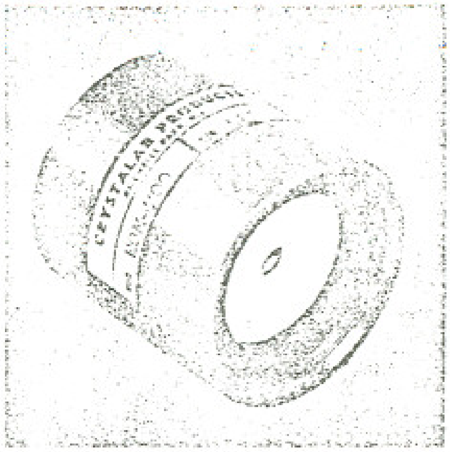

Figure 2—*An example of a longitudinal electro-optic light modulator is the Crystalab Products model EOM-700.*

material and the orientation of the index ellipsoid relative to the crystallographic axis. The index ellipsoid is an ellipse of revolution about the optic *(Z)* axis. As indicated in Figure 3B, the index ellipsoid projects as a circle on a plane perpendicular to the optic axis. The projection of a circle indicates that the crystal is not birefringent in the direction of the optic axis. This is the ideal case. In reality, the crystals available are slightly birefringent, thus, two concentric circles might be projected. However, the amount of birefringence without an external electric field is small enough to be insignificant in all but the most specialized applications.

When an electric field is applied parallel to the crystal optic axis as shown in Figure 4, the shape but not the orientation of the index ellipsoid is changed. As the shape of the ellipsoid changes, so does its projection. From a circle at no voltage, the projection becomes an ellipse with axes *X'* and *Y'* making a 45-degree angle with the *X* and *Y* crystallographic axes. The length of the ellipse axes in the *X'* and *Y'* direction are proportional to the reciprocals of the indices of refraction in these two directions. The crystal now appears to be biaxially birefringent in the direction of the optical axis.

Light rays propagated through the optic axis, polarized in the direction of the induced axes, will have velocities that are a function of the electric field modified refractive indices. This relationship can be shown by propagating a beam of linearly-polarized light through the crystal. The direction of polarization can be parallel to either the *X* or *Y* axes. The output beam is then resolvable into the two orthogonal components in the *X'* and *Y'* directions indicated in Figure 4.

At zero voltage, the two orthogonal components are equal and define the radius of the circle projected from the index ellipsoid. As the voltage is increased, the circle elongates in a direction parallel to one of the induced axes. The degree of ellipticity is indicative of the phase change between the *O* and *E* waves and, as a general rule, orthogonal components undergoing a relative phase shift generate elliptically-polarized waves. Over-all phase shift between the orthogonal components corresponding to the *O* and *E* waves is the retardation introduced. In the longitudinal mode, retardation $\delta$ is defined as

$$\delta = \frac{\eta_o^3 \; r_{63} \; \nu_Z}{\lambda} \qquad (1)$$

where $\delta$ = number of wavelengths retarded, $\eta_o$ = ordinary index of refraction of crystal, $r_{63}$ = electro-optic constant in microns/volt x $10^{-6}$, $\nu_Z$ = longitudinally-applied voltage in volts, and $\lambda$ = wavelength of light used in microns.

For a given wavelength of light, retardation is independent of crystal dimensions and is directly proportional to the voltage applied across the crystal optic axis. It is important to note from equation (1) that different wavelengths of light will require specific voltages to obtain a given retardation.

Two particular values of phase shift are of interest, these are the 1/4- and 1/2-wave retardations. At the 1/4-wave point—which corresponds to a 45-degree rotation of the polarization plane—and with linearly polarized light being applied as before, the output beam from the crystal is circularly polarized. At the 1/2-wave point, the output beam is linearly polarized and the plane of polarization has been rotated 90 degrees.

## Crystals

A number of crystal materials available for use as longitudinal modulators are listed in Table 1. The half-wave retardation voltages—which can be used as a figure of merit—are for a d-c applied voltage and an electrode structure that produces a uniform electric field over the area of the crystal through which light is passing.

Of the materials shown, the most readily available in high optical quality are ADP (ammonium dihydrogen phosphate), KDP (potassium dihydrogen phosphate) and KD*P (potassium dideuterium phosphate). In addition to being quite costly and limited in supply, the remaining crystals do not offer significant performance advantages for most applications. For this reason, almost all Pockels cells at present use one of the three preferred materials.

The choice of ADP, KDP, or KD*P is usually made on

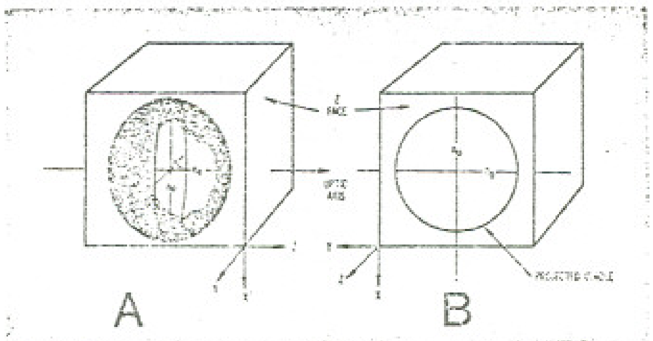

Figure 3—*Orientation of the index ellipsoid relative to the crystallographic axis (A) and its projection on a plane perpendicular to the optic axis (B).*

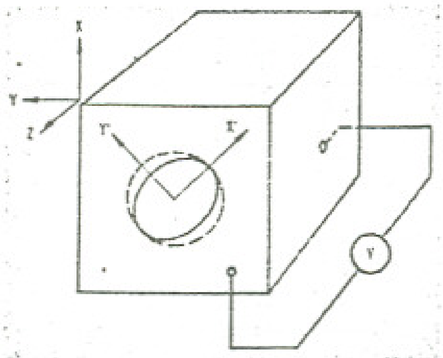

Figure 4–*Change in shape induced in X and Y axes of index ellipsoid when an electric field is applied parallel to the crystal optic axes.*

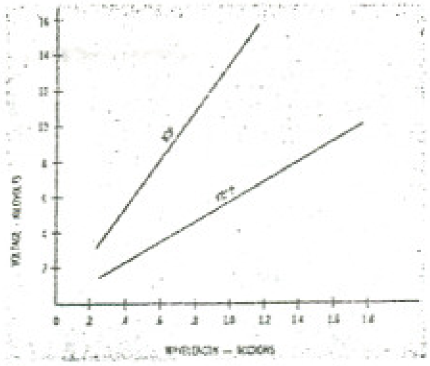

Figure 5–*Voltage required to produce one-half wave retardation as a function of wavelengths, in KDP and KD*P.*

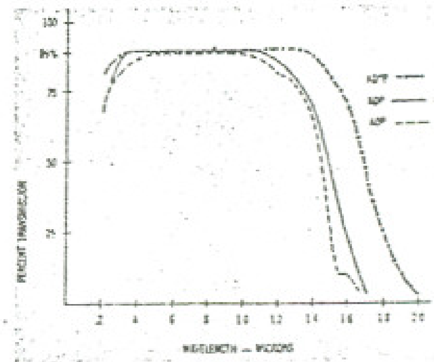

Figure 6–*Spectral response of electro-optic crystals shows KD*P has the advantage of being useable at wavelengths approaching two microns.*

the basis of application. ADP, once the most popular material, has been largely replaced by KDP which has a lower half-wave voltage. One disadvantage of ADP is that it has a higher piezoelectric constant than does KDP. The value is high enough in ADP to generate ringing oscillations in the transmitted light beam when the crystal is excited by a pulse of voltage. This effect is not evident in the same modulator structures when KDP or KD*P is used.

If the lowest possible range of operating voltages is necessary, KD*P must be specified. The reduction in voltage requirements for a given retardation is more than 50 percent as compared to KDP. The theoretical variation (equation 1) of 1/2-wave voltage as a function of wavelength for KDP and KD*P are shown in Figure 5. KD*P has the added advantage of being useable at wavelengths approaching 2 microns as shown in the spectral response curves of Figure 6. The midrange transmission loss of about 10% to 12% is due to reflection (4% per surface) and absorption losses ($\approx$3% for thicknesses between .25 and 1.0 inch).

## Electrode Structures

Electrodes used for applying voltage to the crystal faces are either metal or metal oxides, bonded or evaporated onto the crystals. Metallic electrodes are fabricated from soft metals–such as aluminum, copper, and indium. To protect the assembly, optical windows of glass or quartz are then laminated over the electrodes, thus sealing the aperture area from moisture damage.

The most efficient electrode, in terms of uniformity of electric field, is obtained when a conductive metal oxide coating–such as SnO, CdO, or InO–is deposited directly onto the crystal faces. This intimate contact at the conductor-crystal interface maximizes the electro-optic effect at low drive frequencies because the electric field is not insulated from the crystal by bonding agents or minute air gaps.

Deposited electrodes are most useful where d-c electrical response and uniform retardation over a large clear aperture are required. However, there are some limitations. For example, the thickness of the conductive layers affects two parameters of modulator performance. . . .transmission and frequency response. In general, highest transmission is obtained with thin conductive layers and lower electrode resistance–corresponding to higher frequency response–occurs with thick layers. Therefore, a tradeoff must be made between light transmission and modulation frequency.

In practice, a film thickness giving a resistance of 500 to 1000 ohms/square is most useful. In this resistance range, maximum transmission is approximately 75 percent for a complete modulator with two windows. The maximum frequency at which such a device can be modulated is about 20 kilohertz. Above this frequency, heating effects in the conductive layers could damage the crystal.

Performance of electrodes deposited onto the crystal might be closely approached by use of electrodes which are

TABLE 1

Characteristics of Longitudinal Modulator Crystals

| Material | Electro-Optic Constant, $r_{63}$ $\mu$/V x $10^{-6}$ | Typical 1/2 wave voltage at 5461A, kv | $\eta_0$, approx |
|---|---|---|---|
| ADP (ammonium dihydrogen phosphate) | 8.5 | 9.2 | 1.526 |
| KDP (potassium dihydrogen phosphate) | 10.5 | 7.5 | 1.51 |
| KD*P (potassium dideuterium phosphate) | 26.4 | 2.9-3-4* | 1.52 |
| KDA (potassium dihydrogen arsenate) | 10.9 | 6.4 | 1.57 |
| RDP (rubidium dihydrogen phosphate) | 11.0 | 7.3 | — |
| ADA (ammonium dihydrogen arsenate) | 5.5 | 13 | 1.58 |

*Voltage depends on deuterium content. 99% $D_2$ corresponds to 2.9 kv.

deposited on the protective windows. Although the conductive materials are identical in both cases, the windows--with their conductive side facing the crystal--are usually bonded to the crystal with an index-matching cement. The presence of the cement reduces the effect of the electric field by from two to five percent. This attenuation results from the insulating effect of the cement which causes a voltage division, thereby reducing the amount of voltage across the crystal. The insulating effect is partially capacitive, thus it influences the modulator frequency response. Units with a 200 kilohertz upper limit are possible with low-resistance (10- to 25-ohm) electrodes. However, the cement layers make these modulators unsuitable for use with d-c voltages and frequencies lower than 10 to 20 hertz. When a d-c or an unsymmetrical a-c voltage (of any frequency) is applied, the cement layers can undergo electrolysis, causing separation of the optical elements. Despite these limitations, modulators utilizing window electrodes are usually the least expensive and are recommended for general low-power light modulation applications.

Modulators with a conductive film electrode of either type cannot be used in high-power, pulse applications such as laser Q-switching. The films absorb a considerable percentage of the total optical energy and will actually burn off. In addition, the relatively high film resistance limits the pulse response to rise times greater than 10 microseconds.

High optical power (up to 350 megawatts/cm$^2$) and sub-nanosecond response are attainable through the use of relatively thick metal ring electrodes. This configuration gives a large clear aperture, typically 0.375 to 0.75 inch in diameter. The electrodes are bonded to the crystal surfaces and are held in place by compression or a bead of cement. Because there is no dielectric between crystal and metal, the frequency response of these units extends from d-c to better than 500 megahertz. However, high-frequency, continuous-wave operation might once again be limited by electrical heating of the electrodes and the difficulty in generating the necessary voltage at frequencies above 10 megahertz.

The main drawback of ring electrodes is their geometry which gives rise to a non-uniform electric field across the clear aperture. The field strength in the aperture varies from a maximum around the inner edge of the rings to a minimum at the geometric center. Fringing necessitates operation at voltages about 10 to 15 percent higher than if the field were uniformly applied. Partial compensation is ained by making the crystal length roughly 30 percent greater than the clear aperture diameter.

Another type of deposited electrode that permits operation at d-c and at frequencies up to 2 megahertz consists of gold grids or concentric rings deposited onto the crystals. These designs reduce the fringing effect, lowering the voltage requirements. However, the presence of the opaque conductive lines forming the electrodes reduces light transmission to about 65 percent, maximum.

## Applications

Generation of resolvable polarization planes is the property of crystal modulators that permits control of light intensity. This control is exercised with polarization devices such as Glan-Thompson, Nicol, or Wollaston prisms, or the various types of polarizing films. These elements serve to define particular polarization directions for the light entering and leaving the modulator.

Figure 7 indicates the simplest setup for producing an intensity-modulated light beam. In this arrangement, col-

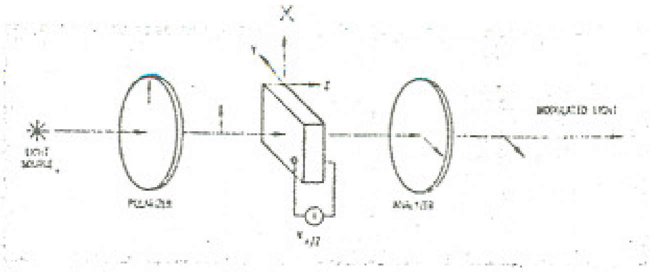


Figure 7–*Simple setup for intensity modulating a light beam using an electro-optic modulator between crossed polarizers.*

limated light–typically from a gas laser–impinges on the input polarizer which produces linearly-polarized light. The input polarizer is oriented so that its direction of polarization is parallel to either the *X*- or *Y*- axis of the crystal. . . .in the instance indicated in Figure 7, the *X* axis. The output polarizer (analyzer) is positioned to have its polarization direction at 90 degrees to the input–that is, the *Y* axis. This orientation of elements produces a transmission minimum when there is no voltage applied to the crystal.

The absolute value of the transmission minimum is dependent upon several factors, namely:

- Uniformity of the applied electric field;
- Light leakage caused by slight birefringence that might exist in a crystal even though no voltage is applied.
- Quality of the polarizer and analyzer and the accuracy of their orientation; and
- Divergence angle of the incident beam.

When the voltage across the crystal is increased, the light transmitted will also increase until a maximum transmission is reached. The applied voltage at maximum transmission is defined as the half-wave retardation voltage $\nu_{\lambda/2}$. At this level of voltage, the orthogonal components of the beam have undergone a relative phase shift of 180° in passing through the crystal while the plane of polarization has been rotated 90°. The new direction of the beam coincides with the orientation of the analyzer, permitting maximum light transmission. Thus, applying a polarized beam with varying ellipticity to a linear polarizer produces linearly-polarized light of varying intensity. The ratio of maximum-to-minimum output intensity is the contrast, or extinction ratio.

Applied voltage and intensity of the transmitted beam are related by

$$I_{out} = I_{in} \sin^2\left(\frac{\pi \eta_0^3 \, r_{63} \, \nu_z}{\lambda}\right) = I_{in} \sin^2 (\pi \delta) \qquad (2)$$

where $I_{out}$ and $I_{in}$ are the output and input beam intensities, respectively.

It appears that while retardation is a linear function of voltage, intensity has a sine squared relation to that voltage. This can be ascertained graphically from Figure 8 which shows the symmetry of response about the zero voltage axis. The curve applies for the array of elements shown in Figure 7. The values plotted are normalized with respect to the $\nu_{\lambda/2}$ value, from an expression for relative transmission:

$$T = \sin^2\left(\frac{\pi \nu_z}{2 \nu_{\lambda/2}}\right) \qquad (3)$$

where *T* is the relative transmission.

If the situation requires that maximum transmission occur at zero rather than full voltage, the position of either polarizer or analyzer is changed to produce a parallel

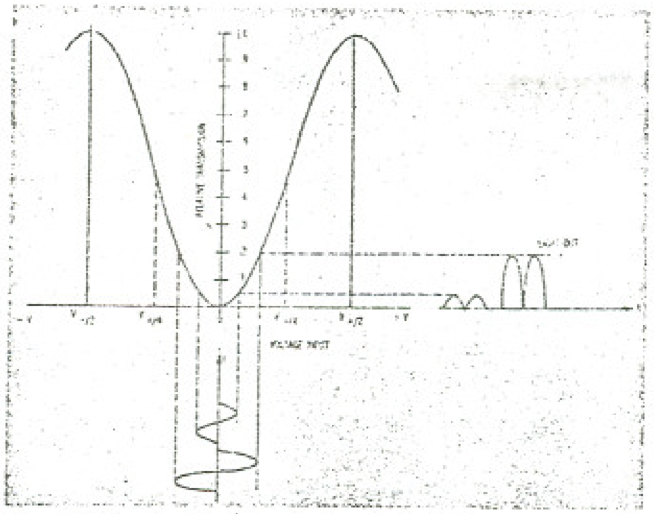

Figure 8—*Transfer function of a longitudinal electro-optic modulator and crossed polarizers shows symmetry of response about the zero voltage axis.*

polarizer condition. The output beam of the crystal then, in changing from zero polarization at zero voltage to 90° polarization at $\nu\lambda/2$, will generate the minimum transmission at $\nu\lambda/2$. For this configuration, intensity has a cosine squared relation to voltage.

As a result of the sine-squared or cosine-squared relation of transmission to voltage, and the zero-voltage, zero-transmission operating point, a sinusoidal modulation voltage will generate a light output having only even harmonics of the input voltage modulation frequency. The second harmonic predominates and is the lowest frequency that may be filtered out after the light is detected. This characteristic limits the use of the configuration in Figure 7 to cases where modulation frequency doubling is necessary or where the pockels cell performs as an optical shutter or chopper.

Linear modulation of the light output can be obtained by operating the combination shown in Figure 7 with a d-c voltage that biases the optical transmission to the 50 percent point (1/4-wave voltage). Operation at this point may also be obtained by introducing a 1/4-wave retardation at the input to the crystal. The effect of biased operation on the output waveform is shown in Figure 9. The optical component most commonly used as a 1/4-wave retarder is a disk of mica, cleaved to produce the desired retardation at a given wavelength. When transmission is biased to the 50-percent level and an a-c signal voltage applied, the modulated light output will contain the fundamental a-c frequency and its odd harmonics if operation is limited to the more linear regions of the transfer curve. At modulation levels approaching 75 percent where transmission varies between 12.5 to 87.5 percent, the third harmonic is approximately 3 percent of the fundamental amplitude. The other harmonics are negligible.

Operation with an optical or electrical bias can be used to advantage to generate large-amplitude light pulses which must reproduce the electrical signal linearly. These pulses may be obtained by adjusting the bias to the 12.5-percent transmission level. By driving the cell with a voltage pulse of proper polarity and an amplitude corresponding to 85-percent transmission, the full 75-percent linear modulation range can be utilized. In some applications the static light output at 12.5-percent transmission cannot be tolerated. If photographic film is the detecting medium, it might be necessary to interpose a mechanical shutter between the film and cell-polarizer combination. Should a photomultiplier or similar detecting device be used, the detector output can be capacitor coupled to block the d-c voltage generated by light passed at the bias level. Only the output pulse will be passed.

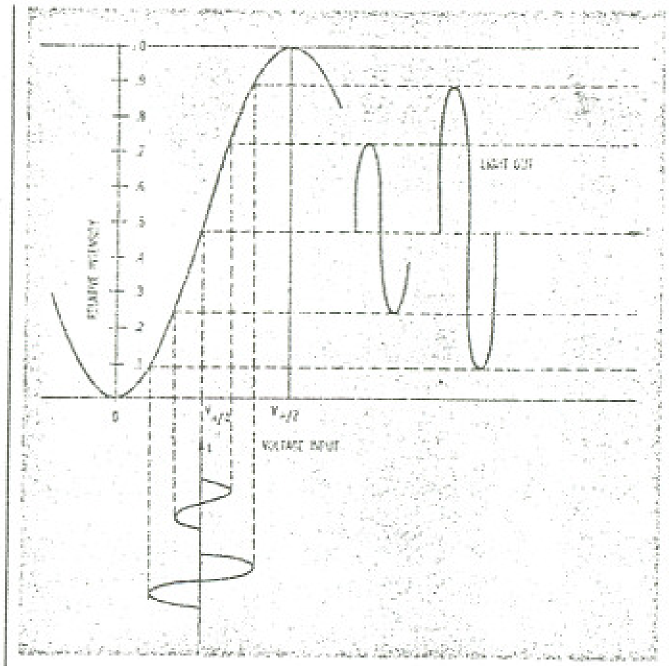



Figure 9—*Transfer function of longitudinal electro-optic modulator and crossed polarizers shows effect of one-fourth wave retardation on the output waveform.*

For optimum performance in most applications, the radiation propagating through the electro-optical modulator should pass parallel to the crystal optic axis. This means that the electro-optical modulator has to be well aligned in the optical path and implies that the beam must have no angular divergence. Beams with a finite divergence will not be uniformly retarded, resulting in light leakage and subsequent decrease in contrast ratio. Degradation is the result of a slight birefringence of the crystal which has the greatest effect on off-axis rays. In practice, with a thin crystal, a contrast ratio of 100:1 can be obtained with a beam divergence of 2 degrees. As crystal thickness increases, the acceptable beam divergence angle decreases. The variation of $\Theta$, the angular aperture for 100:1 contrast ratio follows the approximate relation

$$\Theta = k\sqrt{\lambda/t}$$

where $\lambda$ = wavelength in microns, $t$ = crystal thickness in inches, and $K$ = a constant determined by the material and its quality—typically between 0.75 and 1.0 (KDP $\approx$ 0.85). Generally, contrast ratios of between 1000:1 and 200:1 are attainable with monochromatic, low-divergence laser radiation.

Giant pulses of optical radiation can be generated by Q-switching an optically-pumped laser with a longitudinal modulator. The technique involves controlling the laser beam polarization direction within the optical cavity. This action prevents premature emission and allows energy to be stored in the laser material through population inversion of the metastable states. When the inversion is maximized, the electro-optical modulator is de-energized and the available stored energy is discharged in a single, high-power pulse. Typically, the pulse has a duration of between 5 and 50 nanoseconds and peak power densities of 100 to more than 500 megawatts/cm$^2$.

A typical arrangement of components is shown in

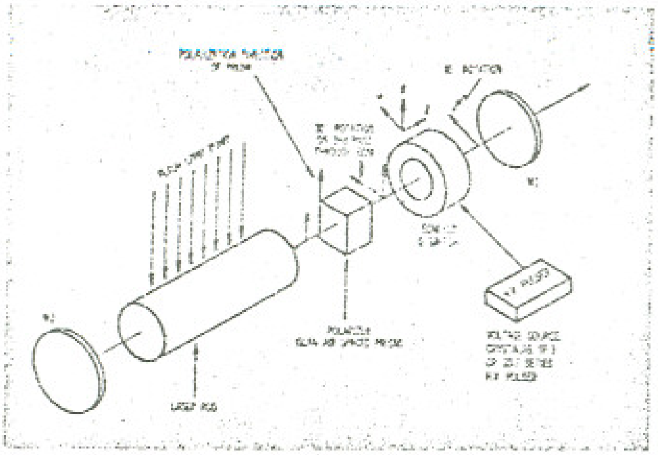

Figure 10–*Orientation of elements for Q-switching a laser using a Crystalab Products' model EOM-512 electro-optic modulator.*

Figure 10. The inclusion of a polarizer is not essential if the laser rod output is strongly polarized, its presence however improves system performance by raising the threshold for spontaneous emission.

To establish the proper conditions for Q-switching, the light modulator crystal must be aligned so that either the $X$ or $Y$ crystallographic axis is parallel to the polarization rection of the laser. Furthermore, the optic axis must be parallel to the laser beam direction to within thirty arc-minutes or less. The polarizer must also be accurately oriented with its polarization axis parallel to that of the laser. With the components shown in Figure 11, the sequence of operation is as follows:

(1) A voltage equal to $\nu\lambda/4$ at the laser wavelength is applied to the electro-optical modulator. At this value of voltage, the polarizing effect of the modulator reduces the cavity Q to a minimum (high-loss state).

(2) The flashlamp pump source is fired and some of the pump energy is stored in the laser material.

(3) As the laser begins to emit spontaneously, the linearly polarized radiation passes through the electro-optical modulator and becomes circularly polarized. After being reflected at mirror $M$ (Figure 11), the radiation again passes through the electro-optical modulator and undergoes another $\lambda/4$ retardation, becoming linearly polarized but at 90° to its original direction. This radiation is absorbed or deflected out of the laser cavity by the polarizer, preventing optical feedback in the cavity and subsequent laser emission while the electro-optical modulator is in the activated state.

(4) After a period of time, determined by the laser material, the voltage applied to the electro-optical modulator is switched to zero permitting the modulator to pass the beam without introducing any retardation. Oscillations within the cavity build up and after a short, nanosecond delay, a high-power pulse is emitted through $M$ (Figure 10).

## In Conclusion

The applications given in this article form the basis for a wide variety of modulator uses. These and many more sophisticated applications are detailed in the extensive bibliography following. This Listing is by no means complete, and does not include the titles of government funded projects involving electro-optical modulations. It is expected that the number of reports and publications will increase rapidly as designers find new uses for Pockels cell light modulators.

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