

# Electrooptic Light Modulators

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**Abstract**—The field of electrooptic light modulation by means of the Pockels and Kerr effects in crystals is summarized with particular attention to communications applications using the optical maser. All available data on electrooptic materials are tabulated, and design considerations and operating principles for various modulator configurations are outlined.

## I. INTRODUCTION

APPLICATIONS of the optical maser often require a means for modulating the amplitude, phase, frequency, or direction of a light beam at high speed. Mechanical shutters and moving mirrors have too much inertia to permit modulation at the required frequencies, which range from megahertz to gigahertz. Hence, it is necessary to rely upon optical interactions with electrical, magnetic, and acoustic fields at the modulating frequency via the nonlinearities of matter. Some of these interactions are intrinsically lossy at the optical frequency: e.g., free carrier absorption, and Franz-Keldysh effect (band edge shift by an electric field); others are intrinsically reactive (or parametric in the electrical engi-

neering sense): e.g., magnetooptic Faraday effect, acoustooptic effect, and electrooptic Kerr and Pockels effects. This paper is concerned only with reactive electrooptic effects in solids; that is, the change in refractive index produced by an applied electric field.

Before the turn of the century Kerr observed a quadratic electrooptic effect in liquids such as carbon disulfide, and Röntgen and Kundt observed a linear effect in quartz. Pockels examined the linear effect in crystals of quartz, tourmaline, potassium chlorate, and Rochelle salt. He demonstrated the existence of a *direct* effect (independent of piezoelectrically induced strain) and characterized the linear electrooptic effect in crystals of various point symmetry using either the applied electric field or dielectric polarization as bases [1].

In 1944 Zwicker and Scherrer reported the dc electrooptic properties of  $\text{KH}_2\text{PO}_4$  and  $\text{KD}_2\text{PO}_4$  and related these properties to the ferroelectric behavior of these crystals. They observed that the electrooptic coefficient, based on electric fields, was proportional to the dielectric constant, exhibiting a Curie-Weiss behavior as a function of temperature. The electrooptic coefficient based on dielectric polarization is the same temperature-independent constant for both crystals [2], [3]. In 1949 Billings-

Manuscript received June 30, 1966.

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and later Carpenter, built and studied the properties of high-speed (about 1 MHz) light shutters using  $\text{KH}_2\text{PO}_4$  and  $\text{NH}_4\text{H}_2\text{PO}_4$  for use in recording sound on film and other engineering applications [4], [5]. In 1961, Holsinger, von Foerster, and Clark reported on a microwave liquid Kerr cell for use in studying high-speed photomixing [6]; and Froome and Bradsell described a microwave modulator employing the Pockels effect in  $\text{NH}_4\text{H}_2\text{PO}_4$  for use in a distance measuring device [7].

Since the advent of the optical maser with its potential application to communication and switching, the electrooptic properties of a number of different materials have been studied. These measurements are summarized below, and the general properties of the materials commented on briefly. Several new modulator configurations have been proposed recently and the principles and characteristics of their operation are outlined in a later section, along with some general design considerations. Before getting into the details of modulator materials and designs, however, a description of the electrooptic effect and its application to various types of optical modulation is given.

## II. ELECTROOPTIC BEHAVIOR OF CRYSTALS<sup>1</sup>

It is convenient to consider the change in  $1/n^2$  with application of a field, where  $n$  is the refractive index, rather than a change in  $n$  directly. The quantity  $1/n^2$  can be written

$$\frac{1}{n^2} = \frac{1}{n_0^2} + rE + RE^2 + \dots, \quad (1)$$

where  $r$  and  $R$  are the linear and quadratic electrooptic coefficients, respectively. The coefficients in (1) are those for a direct (primary) effect which is independent of crystal strain. In addition, if the crystal develops macroscopic strain under the influence of the field, there will be a change in index through the elasto-optic effect. All solids exhibit an elasto-optic effect and all solids are strained by an electric field, either through the converse piezoelectric effect (strain =  $dE$ ) or through electrostriction (strain =  $\gamma E^2$ ). The resultant secondary effect can be shown to depend on crystal symmetry in the same way as the direct effect. It is not, however, necessary that the direct and secondary effects have the same algebraic sign: the overall electrooptic effect in a crystal strained by the field can be larger or smaller than the direct effect alone [9]. If the driving fields are at a frequency corresponding to an acoustic resonance of the material, the secondary effect may be as large as, or larger than, the direct one because of large strain amplitudes. At sufficiently high frequencies the material cannot strain macroscopically and only the direct effect is important.

If the material has a center of symmetry, reversing the sense of the applied field  $E$  does not change the physical situation and, in particular,  $1/n^2$  will be independent of

the sign of  $E$ . Terms of odd power in  $E$  in (1) will change sign, however, so the coefficients of these terms must vanish in centrosymmetric materials. Only noncentrosymmetric (piezoelectric) crystals can produce a linear effect. There is, of course, no restriction on the terms of even powers of  $E$ .

In order to carry the discussion further, it must be recognized that the index of refraction of a crystal depends on optical polarization relative to crystal axes, that the electric field is a vector quantity, and that the  $r$  and  $R$  coefficients must reflect the crystal symmetry. The optical properties of a crystal are frequently described in terms of the *index ellipsoid* (or *indicatrix*). The equation of this surface is

$$\frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} = 1, \quad (2)$$

where the coordinates  $x_i$  are parallel to the axes of the ellipsoid and  $n_i$  are the principal refractive indices. The properties of the indicatrix can be seen from a simple example. If a wavefront has its normal in the  $x_3$  direction, then we consider the ellipse formed by the indicatrix and the  $x_3=0$  plane. The wave has components polarized along  $x_1$  and  $x_2$  and indices given by the semi-axes of the ellipse ( $n_1$  and  $n_2$ ). In a more general case, the wave normal direction can be chosen arbitrarily and the two indices obtained as the semi-axes of the elliptical section perpendicular to the arbitrary direction.

If an electric field is applied to a crystal, the general equation of the indicatrix can be written as

$$\sum_{i,j,k,l} \left( \frac{1}{n_{ij}^2} + z_{ijk}E_k + R_{ijkl}E_kE_l \right) x_i x_j = 1 \quad (3)$$

where the indices run from 1 to 3. The  $z_{ijk}$  and  $R_{ijkl}$  are linear and quadratic electrooptic tensor components, respectively. The indices  $i, j$  can be interchanged, as can  $k$  and  $l$ , so the usual contraction can be made:  $r_{mk} \leftrightarrow z_{(ij)k}$  and  $R_{mn} \leftrightarrow R_{(ij)(kl)}$ , where  $m$  and  $n$  run from 1 to 6 and  $m$  is related to  $(ij)$  and  $n$  to  $(kl)$  as follows:  $1 \leftrightarrow 11$ ,  $2 \leftrightarrow 22$ ,  $3 \leftrightarrow 33$ ,  $4 \leftrightarrow 23$ ,  $5 \leftrightarrow 13$ ,  $6 \leftrightarrow 12$ . The linear electrooptic matrix for a specific crystal class has the same form as the inverse of the piezoelectric coefficient matrix, but no factors of 2 appear in the electrooptic case [8], [10].

The entire formalism outlined above could have been written using dielectric polarization rather than electric field as a basis. In fact, such a description would be more appropriate since polarization is a property of the physical medium in which the effect occurs. In the case of the linear effect, however, the electric field dependence (i.e.,  $r$  as defined above) is usually given, since it is most nearly the measured quantity, and this practice is followed here. In the quadratic case there is not as much precedent in the literature and, instead of terms such as  $R_{mn}E_kE_l$  in (3), the polarization terms  $g_{mn}P_kP_l$  are used. Since  $P_k = \epsilon_0(\epsilon_{ki} - 1)E_i$ , where  $\epsilon_{ki}$  is the permittivity, the descriptions can be interchanged. In the situations considered here only diagonal elements,  $\epsilon_{ii} \equiv \epsilon_i$ , are required. For

<sup>1</sup> A clear, concise description of the properties of crystals alluded to here is given in [8].



simplicity, we denote RF and optical dielectric constants by  $\epsilon$  and  $n^2$ , respectively.

It may be useful to consider an example of the use of the indicatrix in describing the electrooptic effect. In a crystal in which only the linear effect is appreciable, if a wave normal along  $x_3$  is chosen and the applied field is along  $x_1$ , then the equation for the  $x_3=0$  section of the indicatrix is

$$\left(\frac{1}{n_1^2} + r_{11}E_1\right)x_1^2 + \left(\frac{1}{n_2^2} + r_{21}E_1\right)x_2^2 + 2r_{61}E_1x_1x_2 = 1. \quad (4)$$

Depending on symmetry,  $n_1$  and  $n_2$  may be equal and one or more  $r_{mi}$  may be equal or may vanish. If the term in  $r_{61}$  is disregarded for the moment, it is seen that the effect of  $r_{11}E_1$  is to change the index of refraction for a wave polarized along  $x_1$ , so that the new index  $(n_1 + \Delta n_1)$  is given by

$$\frac{1}{(n_1 + \Delta n_1)^2} = \left(\frac{1}{n_1^2} + r_{11}E_1\right).$$

Now,  $\Delta n_1$  is a small quantity compared to  $n_1$ , so to good accuracy we have

$$\Delta n_1 = -\frac{n_1^3 r_{11} E_1}{2}.$$

Similarly, for the wave polarized along  $x_2$ ,

$$\Delta n_2 = -\frac{n_2^3 r_{21} E_1}{2}.$$

The  $x_3$ -directed wave at frequency  $\omega$  polarized along  $x_2$  can be described by

$$A_2 \exp i\left(\omega t - \frac{2\pi n_2 x_3}{\lambda_0}\right),$$

where  $\lambda_0$  is the free space wavelength. An  $x_1$  polarized wave can be described similarly. Clearly the phase of the wave depends upon the value of  $n_2$ . After traversing a length  $x_3=L$ , the change in phase due to the electrooptic effect is

$$-\frac{2\pi L}{\lambda_0} [n_2 - (n_2 + \Delta n_2)] = -\frac{\pi n_2^3 r_{21} E_1 L}{\lambda_0} \equiv \eta. \quad (5)$$

If  $E_1$  varies sinusoidally with time, then the phase delay of the wave varies sinusoidally with peak value  $\eta$ , the modulation index. In this sense, the electrooptic effect leads most naturally to phase modulation.

In order to obtain amplitude modulation it is necessary to consider interference of phase modulated components. For example, in the same crystal, if the incident beam is plane polarized at  $45^\circ$  to  $x_1$  and  $x_2$  so that  $A_1=A_2=A/\sqrt{2}$ , the emergent beams are, respectively,

$$\frac{A}{\sqrt{2}} \exp i\left(\omega t - \frac{2\pi n_1 L}{\lambda_0}\right)$$

and

$$\frac{A}{\sqrt{2}} \exp i\left(\omega t - \frac{2\pi n_2 L}{\lambda_0}\right).$$

Since free space is isotropic we can choose any pair of orthogonal polarizations to describe the resultant combination. In particular, components parallel and normal to the incident polarization have amplitudes

$$A \cos \frac{\pi L}{\lambda_0} (n_1 - n_2 + \Delta n_1 - \Delta n_2) = A \cos(\Gamma/2) \quad (6)$$

and

$$A \sin \frac{\pi L}{\lambda_0} (n_1 - n_2 + \Delta n_1 - \Delta n_2) = A \sin(\Gamma/2)$$

where  $\Gamma$  is the retardation.

If  $\pi L(n_1 - n_2)/\lambda_0$  is an even multiple of  $\pi/2$ , the parallel amplitude is zero except for the part contributed by the electrooptic effect. Its value is

$$\pm \cos \left[ \frac{\pi L}{2\lambda_0} (n_2^3 r_{21} - n_1^3 r_{11}) E_1 \right] \\ \approx 1 - \frac{1}{2} \left[ \frac{\pi L}{2\lambda_0} (n_2^3 r_{21} - n_1^3 r_{11}) E_1 \right]^2,$$

where the approximation is for small values of the argument. The modulation contains only even powers of  $E$  and is relatively small. If  $\pi L(n_1 - n_2)/\lambda_0$  is an odd multiple of  $\pi/2$ , the roles of the polarizations are interchanged and the above is true for the perpendicular component. If  $\pi L(n_1 - n_2)/\lambda_0$  is an odd multiple of  $\pi/4$ , the amplitude of either parallel or perpendicular polarization is

$$\pm \frac{1}{\sqrt{2}} \left( 1 \pm \sin \frac{\pi L}{2\lambda_0} (n_2^3 r_{21} - n_1^3 r_{11}) E_1 \right) \\ \approx \pm \frac{1}{\sqrt{2}} \left( 1 \pm \frac{\pi L}{2\lambda_0} (n_2^3 r_{21} - n_1^3 r_{11}) E_1 \right)$$

and the amplitude modulation is approximately linear in  $E_1$  and larger than in the previous case. The condition that  $\pi L(n_1 - n_2)/\lambda_0$  be an odd multiple of  $\pi/4$  is sometimes referred to as *optical bias*. A fixed external compensator with axes of birefringence along  $x_1$  and  $x_2$  can be used to obtain this quarter wave bias if  $n_1=n_2$ . If  $n_1 \neq n_2$ , the temperature dependence of birefringence in the crystal itself allows one to meet the condition, but at the same time it can impose stringent requirements on temperature control of the crystal in order to keep the optical bias in the proper range. Alternatively, the temperature may be fixed and a variable external compensator employed.

Referring back to (4), the third pertinent coefficient for  $x_3$  directed waves with  $E_1$  applied is a skew coefficient  $r_{61}$ . One effect of this coefficient is to rotate the axes of the elliptical cross section by an angle  $\alpha$ , where

$$\tan 2\alpha = \frac{2r_{61}E_1}{\frac{1}{n_1^2} - \frac{1}{n_2^2} + (r_{11} - r_{21})E_1} \quad (7)$$



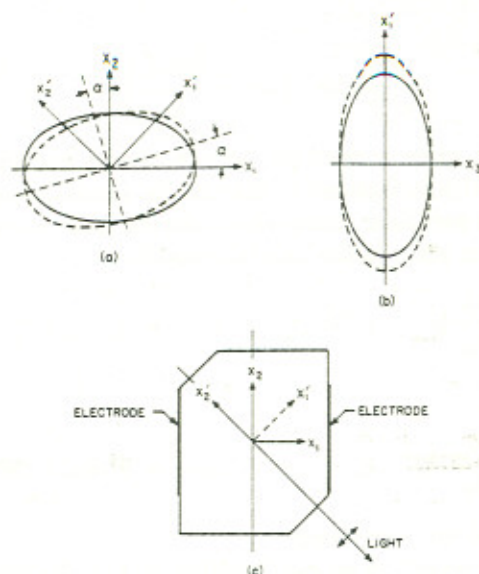


Fig. 1. (a)  $x_3=0$  cross section of the indicatrix with  $x_1$  directed field (dashed) and no field (solid). The effects of  $r_{11}E_1$  and  $r_{21}E_1$  have been omitted. The change in  $1/x_1'^2$ , where  $x_1'$  is the radius vector, is a maximum when  $x_1'$  is at  $45^\circ$  to  $x_1$ . The change in  $x_1'$  (and hence in index of refraction) is a maximum at angles near  $45^\circ$  unless the natural birefringence is very large as in the sketch. (b)  $x_3=0$  cross section of the indicatrix with  $x_1$  directed field (dashed) and no field (solid). The change in  $x_1'$  axis is due to  $r_{61}E_1$ . The effect of  $r_{21}E_1$  on the  $x_2$ -axis has been neglected. (c) Crystal cut for measurement or use of  $r_{61}$  coefficient. Propagation direction and polarization of the light are indicated.

If the natural birefringence ( $n_1 - n_2$ ) is appreciable, this angle is very small. The lengths of the axes (and hence the indices) are changed by an amount of second order in  $r_{61}E_1$  that is usually negligible. However, the radius vector of the ellipse at  $45^\circ$  to  $x_1$  and  $x_2$  is changed linearly in  $E_1$  by an amount  $n^2 r_{61} E_1 / 2$ , where  $n'$  is an effective index intermediate between the principal indices. The situation is indicated in Fig. 1(a). Since this radius is not an axis of the elliptical section normal to  $x_3$ , it does not correspond to the polarization of a principal wave propagating along  $x_3$ . The first-order effect does occur for a wave propagating in some other direction for which the radius vector at  $45^\circ$  to  $x_1$  and  $x_2$  is a principal axis. For example, if the wave normal is at  $45^\circ$  to  $-x_1$  and  $x_2$  [along  $x_2'$  in Fig. 1(a)], the perpendicular section is

$$\left\{ \frac{1}{2} \left( \frac{1}{n_1^2} + \frac{1}{n_2^2} \right) + r_{61}E_1 + \frac{(r_{11} + r_{21})}{2} E_1 \right\} x_1'^2 + \left\{ \frac{1}{n_3^2} + r_{31}E_1 \right\} x_3^2 + \sqrt{2} r_{31}E_1 x_1' x_3 + \sqrt{2} r_{41}E_1 x_1' x_3 = 1 \quad (8)$$

where  $x_1'$  is at  $45^\circ$  to  $x_1$  and  $x_2$ . The axes of this ellipse are determined in large part by the birefringence of the crystal. The effect of  $r_{41}$  and  $r_{31}$  is a small rotation of axes, as in (7). The alteration of the  $x_2'=0$  section described in (8) is indicated in Fig. 1(b). A crystal cut which allows observation of the linear change  $r_{61}E_1$  is shown in Fig. 1(c). From (8) we see that  $r_{11}$  and  $r_{21}$  also cause first-order effects. If we had chosen the  $x_2'$  polarization of the  $x_1'$

directed wave the signs of  $r_{11}$  and  $r_{21}$  terms would remain unchanged, but the  $r_{61}$  term would be reversed. Thus, for one case the effects of the coefficients add and in the other they subtract.

The fact that specific elements of the electrooptic coefficient matrix (including skew components) can be used in producing phase modulation has been shown above, and the fact that the interference of two such waves produces amplitude modulation has also been indicated. In doing this, the restrictions imposed on the matrix elements by symmetry have not been used. At this point, one effect of crystal symmetry will be mentioned specifically. In crystals with a threefold axis it is possible to rotate a birefringent section of constant retardation by rotation of the applied field, which in turn allows construction of single sideband modulators and frequency shifters [11]. If a wave normal is directed along  $x_3$ , in this case a threefold axis, then the perpendicular section is circular in the absence of an applied field; i.e.,  $n_1 = n_2$ . Moreover, symmetry requires that

$$\begin{aligned} r_{12} &= r_{61} = -r_{22} \\ r_{21} &= r_{62} = -r_{11}. \end{aligned} \quad (9)$$

If fields  $E_1$  and  $E_2$  are applied, the equation of the  $x_3=0$  section is

$$\begin{aligned} \left[ \frac{1}{n_1^2} + (r_{11}E_1 - r_{22}E_2) \right] x_1^2 &+ \left[ \frac{1}{n_1^2} + (r_{22}E_2 - r_{11}E_1) \right] x_2^2 \\ &+ 2[-r_{22}E_1 - r_{11}E_2] x_1 x_2 = 1. \end{aligned} \quad (10)$$

If we choose new axes  $x_1', x_2'$  along the axes of the ellipse in the  $x_3=0$  plane, (10) can be written

$$\begin{aligned} \left[ \frac{1}{n_1'^2} + (r_{11}'^2 + r_{22}'^2)^{1/2} E \right] x_1'^2 &+ \left[ \frac{1}{n_1'^2} - (r_{11}'^2 + r_{22}'^2)^{1/2} E \right] x_2'^2 = 1, \end{aligned} \quad (11)$$

where  $E$  is the applied field with components  $E_1 = E \cos \Phi$ ,  $E_2 = E \sin \Phi$ . As shown in [11] the primed axes are rotated relative to the crystal axes through an angle

$$\theta = -\frac{1}{2} \left[ \Phi + \arcsin \frac{r_{22}}{\sqrt{r_{11}^2 + r_{22}^2}} \right]. \quad (12)$$

From (11) we note that a field of fixed magnitude causes a specific amount of birefringence (and hence a fixed magnitude of retardation  $\Gamma$ ) in the  $x_3=0$  plane, regardless of field orientation in this plane. From (12) we see that the axes of the birefringence rotate through an angle  $\theta = -\frac{1}{2}\Phi$  when the field rotates through an angle  $\Phi$ .

The effect of a rotating birefringent plate on an incident circularly polarized wave is merely summarized here in order to indicate how single sideband modulation can be effected [12]. The emergent wave has a component in the



TABLE I  
KDP-ADP TYPE: POINT GROUP ( $\bar{4}2m$ ) ABOVE  $T_c$

	$T_c$	$r_{32}$	$r_{41}$	$n_2$	$n_1$	$\epsilon_2$	$\epsilon_1$	$\tan \delta_2$	$\tan \delta_1$
KH <sub>2</sub> PO <sub>4</sub> (KDP)	123 [2]	(T) -10.5 [5] (S) 9.7 [26]	+8.6 [5]	1.47 [27]	1.51 [27]	(T) 21 [28] (S) 21 [29]	42 [28] 44 [29]	(T) see [76], [32] (S) $7.5 \times 10^{-2}$ [29]	$4.5 \times 10^{-2}$ [29]
KD <sub>2</sub> PO <sub>4</sub> (DKDP)	222 [16]	(T) 26.4 [16]	8.8 [24]	1.47 [27a]	1.51 [27a]	(T) 50 [16] (S) 48 [14]	58 [14]	(T) see [33] (S) $1.0 \times 10^{-1}$ [14]	$2.5 \times 10^{-2}$ [14]
KH <sub>2</sub> AsO <sub>4</sub> (KDA)	97 [2]	(T) 10.9 [24]	12.5 [24]	1.52 [24]	1.57 [24]	(T) 21 [28] (S) 19 [14]	54 [28] 53 [14]	(S) $8.0 \times 10^{-2}$ [14]	$7.5 \times 10^{-2}$ [14]
RbH <sub>2</sub> AsO <sub>4</sub> (RDA)	110 [2]	(T) 13.0 [24]		1.52 [24]	1.56 [24]	(T) 27 [31] (S) 24 [31]	41 [31] 39 [31]	(T) see [31] (S) $5 \times 10^{-2}$ [31]	$3 \times 10^{-2}$ [31]
NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub> (ADP)	148* [2]	(T) -8.5 [5] (S) 5.5 [5]	+24.5 [24]	1.48 [27]	1.53 [27]	(T) 15 [28] (S) 14 [14]	56 [28] 58 [14]	(T) see [76] (S) $6.0 \times 10^{-2}$ [14]	$7.0 \times 10^{-2}$ [14]

\* Antiferroelectric transition temperature;  $T_c$  in °K;  $r_{mi}$  in  $10^{-12}$ m/V. (T) = constant stress, (S) = constant strain; refractive index at  $0.546 \mu$ ;  $\tan \delta(S)$  at  $\sim 10^{10}$  c/s

original sense of circular polarization of amplitude  $\cos \Gamma/2$  and phase independent of  $\theta$ . In addition, there is a component of opposite sense whose amplitude is  $\sin \Gamma/2$  and whose phase is proportional to  $2\theta$  (or  $-\Phi$ ). Thus, if the field rotates at a rate  $\omega_m$ , the phase of the wave with altered sense of circular polarization varies as  $-\omega_m t$  and the instantaneous frequency of this wave is changed by  $\omega_m$ . The direction of change depends on the relative direction of field rotation and incident circular polarization. The amplitude of the frequency shifted component is constant in time.

### III. MATERIALS

The electrooptic materials are grouped according to their general crystallographic and physical properties as follows: 1) KDP, ADP, and their isomorphs, 2) ABO<sub>3</sub> crystals similar to perovskites, 3) AB-type semiconductors with cubic or hexagonal ZnS structure, and 4) various miscellaneous crystals. The tabulations of electrooptic coefficients may give two or more conflicting values for the same crystal. Oftentimes, poor materials are the cause. The reader should consult the original works to decide which result is more reliable.

#### KDP-ADP Type

Potassium dihydrogen phosphate (KDP) and ammonium dihydrogen phosphate (ADP) are the most widely known electrooptic crystals. Their general properties are reviewed elsewhere [2], [3]. They are grown at room temperature from a water solution and are free of the strains often found in crystals grown at high temperature. Excellent crystals as large as 5 cm in any dimension can be obtained commercially at nominal cost. Although the crystals are water soluble and fragile, they can be handled, cut, and polished without difficulty. The resistivity of these crystals is typically  $10^{10}$  ohm-cm [13].

Both KDP and ADP belong to the piezoelectric point group  $\bar{4}2m$  at room temperature where they are normally used. Below the Curie temperature  $T_c$ , KDP type crystals become ferroelectric and, below the transition temperature, ADP type crystals become antiferroelectric. No electrooptic measurements have been made below  $T_c$  because of the experimental complexity involved.

The atoms K, H, P in KH<sub>2</sub>PO<sub>4</sub> can be replaced by some of the atoms from corresponding columns in the periodic

table without changing the crystal structure. A dramatic change in dielectric properties occurs when H is replaced by deuterium. For partially deuterated KDP, KD<sub>2-x</sub>H<sub>2x-1</sub>PO<sub>4</sub>, the Curie temperature is given [14] approximately by

$$T_c \approx (123 + 106x)^\circ\text{K}. \quad (13)$$

The KDP-ADP isomorphs for which electrooptic coefficients have been measured are listed in Table I along with pertinent electrical and optical properties. Additional data will often be found in the references given. Measurements at constant stress are noted by (T) and those at constant strain (high frequency) by (S). The only nonvanishing  $r_{mi}$  coefficients are  $r_{41} = r_{32}$  and  $r_{63}$ . At  $0.63 \mu$ , optical loss [15] in KDP is  $\frac{1}{2}$  dB/m, which is about as good as that found in the best fused quartz. The refractive indices and ultraviolet absorption, which are associated with electronic transitions in the oxygen ions, are about the same for all isomorphs. The crystals are transparent for wavelengths as short as  $0.2 \mu$  [16]–[18]. The infrared absorption is the result of hydrogen vibrations, the frequencies of which are approximately inversely proportional to the square root of the proton mass. Thus, the low-frequency absorption edge for the deuterated salt occurs at roughly  $\sqrt{2}$  times the wavelength for undeuterated salts: KDP,  $1.55 \mu$  [16]; ADP,  $1.4 \mu$  [19]; DKDP,  $2.15 \mu$  [19].

The quantity  $r_{63}/(\epsilon_3 - 1)$  is roughly the same for all isomorphs and, despite the rapid increase in  $\epsilon_3$  near  $T_c$ , is independent of temperature [2], [3]. It is possible to obtain larger  $r_{63}$  and, hence, lower modulating voltage by operating near the Curie temperature or by choosing an isomorph with  $T_c$  closer to room temperature so as to increase  $\epsilon_3$ . However, the loss tangent also increases and in such a way as to make this expedient unattractive in some applications [14], [20]. The electrooptic coefficient  $r_{63}$  is practically independent of wavelength in the transparent region for KDP and ADP [5], [21], [22].

In the absence of an applied electric field, KDP-type crystals are uniaxial: light polarized parallel to or normal to the  $z$ -axis travels as a principal wave with refractive index  $n_3$  or  $n_1$ , respectively. When a field  $E_3$  is applied along the  $x_3$ -axis, the principal axes become  $x_3$  and  $x_1'$  and  $x_2'$ , at  $45^\circ$  to the  $x_1$  and  $x_2$  axes. The refractive index for  $x_3$ -polarization remains  $n_3$  while,

$$n_{1'} \approx n_1 - \frac{1}{2} n_1^3 r_{63} E_3, \quad n_{2'} \approx n_1 + \frac{1}{2} n_1^3 r_{63} E_3.$$



Light polarized along  $x_1'$  or  $x_2'$  traveling through a crystal of length  $L$  experiences a phase modulation with index

$$\eta = \pi n_1^3 r_{63} E_3 L / \lambda. \quad (14)$$

Light traveling along  $x_3$  and initially polarized along  $x_1$  or  $x_2$  experiences a phase retardation

$$\Gamma = 2\eta. \quad (15)$$

The voltage  $E_3 L$  required to produce a retardation of  $\pi$  radians is called the *half-wave voltage*

$$V_{1/2} = \lambda / 2n_1^3 r_{63}. \quad (16)$$

For a wide area light shutter [4] or amplitude modulation both applied field and light path are along  $x_3$ . Because of natural birefringence in directions off the  $x_3$ -axis, the angular aperture is severely restricted for thick samples. Methods for increasing the aperture are described by Billings [4]. Natural birefringence is not normally a problem with a well-collimated optical maser beam. Phase or amplitude modulation with field normal to the optical path may be accomplished with electric field along  $x_3$ , optical polarization along  $x_1'$ , and optical path along  $x_2'$ .

Small strains in the crystal can partially destroy the relative phase relationships required to produce amplitude modulation [119]. Normally, KDP-type crystals as grown are quite strain-free. However, despite the relatively low loss tangent, the crystal is heated throughout its volume by the modulating field but cooled only on its surface. The resultant thermal gradient produces strains that are sufficiently great when the power dissipated in the crystal is greater than a watt, independent of crystal dimensions, to make amplitude modulation ineffective [23].

A field applied along  $x_1$  rotates the indicatrix through a small angle about  $x_1$ . The semi-axis along  $x_1$  remains unchanged and the other axes experience changes of order  $(r_{41}E_1)^2$ . The situation is similar to that discussed in Section II, where the effect of the skew coefficient  $r_{61}$  was mentioned. To obtain first-order changes in refractive index [5], [24], light should be polarized in the  $x_2x_3$  plane along  $x_2''$  or  $x_3''$ , at  $45^\circ$  to  $x_2$  and  $x_3$ , and propagated in the  $x_3''$  or  $x_2''$  direction, respectively. The  $x_2''=0$  section of the indicatrix is

$$\frac{x_1^2}{n_1^2} + \left[ \frac{1}{2} \left( \frac{1}{n_1^2} + \frac{1}{n_3^2} \right) + r_{41}E_1 \right] x_3''^2 = 1$$

and the modulation index for  $x_3''$  polarization

$$\eta = 2\pi\sqrt{2} \left( \frac{1}{n_1^2} + \frac{1}{n_3^2} \right)^{-3/2} r_{41}E_1L/\lambda \\ \approx \pi n_1^3 r_{41}E_1L/\lambda. \quad (17)$$

Since  $r_{41}$  at constant stress is large in ADP, it has been suggested that a modulator with  $E$  along  $x_1$  might be advantageous [10]. However, inasmuch as  $r_{41}$  at constant strain is not known, it is not clear that this configuration will be useful at high frequency. For intensity modulation using this configuration, there is the added complication that the ordinary and extraordinary ray paths are not

parallel. A two crystal method for overcoming this difficulty is described by Ley [25], [30].

### Perovskite Family

The large group of crystals with structure resembling that of the mineral perovskite,  $\text{CaTiO}_3$ , form the perovskite family [34]. Of particular interest are the oxides  $\text{A}^{2+}\text{B}^{4+}\text{O}_3$  and  $\text{A}^{1+}\text{B}^{5+}\text{O}_3$ , which often exhibit ferroelectric behavior. Their properties are discussed in detail elsewhere [2], [3]. In general, they are insoluble in water and are more rugged and have larger refractive index and dielectric constant than KDP. As a rule, the oxides are transparent between 0.4 and  $6\mu$  [35]–[37]. The infrared absorption is caused largely by vibrations of the  $\text{BO}_6$  octahedra and the ultraviolet absorption by electronic transitions in the oxygen ions.

Perovskites may exist in several forms, with different point symmetries, that are derived from the ideal cubic perovskite structure by continuous lattice distortions. The cubic form, which is often the high temperature phase, belongs to the nonpiezoelectric, nonferroelectric point group  $m\bar{3}m$ . In the ferroelectric phase, the crystals of interest here are tetragonal  $4mm$ , with the  $c$ -axis along one of the original cube edges, or rhombohedral  $3m$ , with the  $c$ -axis along one of the cube body diagonals. Both phases are piezoelectric. The cubic (paraelectric) and ferroelectric phases of various perovskites are discussed separately below.

**Cubic:**  $\text{BaTiO}_3$ ,  $\text{SrTiO}_3$ ,  $\text{KTaO}_3$ ,  $\text{K}(\text{Ta}, \text{Nb})\text{O}_3$ : Since the cubic phase is centrosymmetric the change in refractive index is a quadratic function of applied field or dielectric polarization. It is convenient to use the polarization  $P$  as a basis because the corresponding electrooptic coefficients  $g_{mn}$  are then insensitive to temperature and optical wavelength far from the band edges [35]. As discussed in Section II,

$$\Delta \left( \frac{1}{n_m^2} \right) = \sum g_{mn} P_j P_k \quad (18)$$

where  $m, n$  run from 1 to 6 and  $j, k$  from 1 to 3. For  $m\bar{3}m$  the only nonvanishing components are  $g_{11}=g_{22}=g_{33}$ ,  $g_{12}=g_{13}=g_{23}=g_{32}=g_{31}=g_{21}$ , and  $g_{44}=g_{55}=g_{66}$ . To obtain a linear effect, which is both larger in magnitude and more suitable for most applications, it is customary to induce a large dc bias polarization  $P_{dc}$  along with the much smaller RF modulation polarization  $(\epsilon-1)\epsilon_0 E_i$ . In effect,  $P_{dc}$  a vector quantity removes the center of symmetry. If  $P_{dc}$  is along a cube diagonal the symmetry is lowered to  $3m$ ; if  $P_{dc}$  is along a cube edge the symmetry becomes  $4mm$ .

If  $P_{dc}$  has only an  $x_3$ -component,

$$\Delta(1/n_1^2) = \Delta(1/n_2^2) = g_{12}P_{dc}(P_{dc} + 2\epsilon\epsilon_0 E_3) \\ \Delta(1/n_3^2) = g_{11}P_{dc}(P_{dc} + 2\epsilon\epsilon_0 E_3) \\ \Delta(1/n_4^2) = g_{44}P_{dc}\epsilon\epsilon_0 E_2, \quad \Delta(1/n_5^2) = g_{44}P_{dc}\epsilon\epsilon_0 E_1 \\ \Delta(1/n_6^2) = 0. \quad (19)$$

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