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Technical Report 165

LARGE-APERTURE OPTICAL MODULATOR MATERIALS

LEAD LANTHANUM ZIRCONATE TITANATE CERAMIC AND LITHIUM NIOBATE CRYSTAL SHOW PROMISE AS MODULATOR MATERIALS FOR OPTICAL TRANSMITTERS WITH UP TO 6-INCH APERTURES

RP Bocker, GM Meana, MA Monahan, GC Mooradian, WE Richards, and HF Taylor

11 October 1977

Final Report
Covering the period October 1976-October 1977

Approved for public release; distribution is unlimited

NAVAL OCEAN SYSTEMS CENTER
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Released by
WE Richards, Head
Communications Research and
Technology Division

Under authority of
RO Eastman, Head
Communications Systems
and Technology
Department

METRIC EQUIVALENTS

1 inch = 25.4 mm
1 degree (angle) = 0.175 rad
1 oersted = 79.6 A/m

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Six categories of active optical materials were found to qualify as potential large-aperture optical modulator material candidates. Two of these, the electro-optical linear Pockels lithium niobate crystals and the ferroelectric ceramic lead lanthanum zirconate titanate wafers showed real promise. Both of these satisfy the requirements of field of view, optical quality, frequency response, and economic availability, and both performed above expectations when tested in an actual optical communications test link. Interdigital lithium niobate electrodes buried on both large optical surfaces of the crystal may further reduce half-wave voltage requirements as well as arcing problems encountered in past experiments. The structural integrity of the ceramic wafer could be increased

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by developing a bonded version. Optical modulators of increased are structure of smaller elements.

OBJECTIVE

Identify, classify, test, and evaluate various optically active materials which have the potential of being used for large-aperture, wide acceptance angle, high-quality optical modulators in optical communication systems.

RESULTS

Six categories of active optical materials were identified and classified. Selected for test and evaluation from materials in these categories were four active materials that seemed likely to be able to satisfy the large-aperture optical modulator requirements. These four material candidates are lithium niobate and potassium dideuterium phosphate (electro-optical linear Pockels crystals), nitrobenzene (an electro-optical quadratic Kerr liquid), and lead lanthanum zirconate titanate (a ferroelectric ceramic). Of these four material candidates, only the lithium niobate crystal and the ceramic showed real promise.

Lithium niobate crystals and single-element ceramic wafers presently can be fabricated with clear apertures of 2 and 4 inches, respectively. For larger area modulators, a mosaic structure of modulator elements would have to be considered for both materials. Both the lithium niobate crystals and ceramic wafers satisfy the requirements of field of view, optical quality, frequency response, and economic availability. Both materials performed above expectations when tested in an actual optical communications test link.

Although potassium dideuterium phosphate can be grown in single-crystal form to diameters of 12 inches, it is highly sensitive to the angle of arrival of the incoming light beam. This problem can be eliminated by using two properly oriented crystals in series. Its only other drawback is its cost, which for a given aperture size is presently five times greater than that of the ceramic or lithium niobate units, in quantities of one.

Neither nitrobenzene nor any of the other Kerr liquids was tested. These materials are extremely toxic, and our laboratory facilities are inadequate to handle them. However, a feasibility study was performed concerning the concept of an interdigital Kerr cell modulator. It appears that the concept would work, but at present lithium niobate and the ceramic show much greater promise.

RECOMMENDATIONS

1. Place emphasis on the use of lead lanthanum zirconate titanate ceramic and lithium niobate crystal as materials for future optical modulator applications in which a large aperture is required.

2. Consider potassium dideuterium phosphate further only if its cost can be brought in line with the cost of these two materials.

3. For future work which could improve the performance of lithium niobate crystal, consider buried-channel interdigital electrodes on both large optical surfaces of the crystal to further reduce both the half-wave voltage requirements and the arcing problems encountered in some of the past experiments.

4. Consider bonded versions of lead lanthanum zirconate titanate, which would provide a very desirable increase in its structural integrity.

5. In future work with optical modulators of larger area, address the problems associated with fabricating a mosaic structure from smaller, individual modulator elements.

CONTENTS

INTRODUCTION

The intermediate objectives of the Large-Aperture Optical Modulator Program were to identify, classify, and evaluate various active optical materials for their potential use in a large-aperture (typically having a 6-inch diameter), wide acceptance angle (approximately ±20 degrees), high-quality optical modulator with turn-on and turnoff times of 10–1000 μs. The final objective of the program was to fabricate a large-aperture optical modulator using the active optical material evaluated as most promising in the earlier stages of the program and to perform in-house tests at the Naval Ocean System Center (NOSC) to demonstrate feasibility.

Two immediate naval optical communication systems applications require such a modulator device: those employing coherent laser illumination and those employing large incoherent light sources. Typical off-the-shelf electromechanical modulators have response times in the millisecond range and are limited to 2-inch apertures. Therefore, in order to achieve the modulator requirements specified above, active optical materials (electro-optical, magneto-optical, acousto-optical, etc) employing solid-state technology were considered as potential candidates for study.

PRELIMINARY ASSESSMENT

During the early stages of the program a comprehensive investigation was performed to identify and classify optical materials which might show promise in fulfilling the desired requirements. Six categories of active optical materials were found that qualify as potential large-aperture optical modulator candidates:

Magneto-optical
Electro-optical
Ferroelectric
Semiconductor
Acousto-optical
Miscellaneous

MAGNETO-OPTICAL MATERIALS

Magneto-optical materials are those whose optical transmission characteristics can be altered by the application of an external magnetic field. Six magneto-optical effects are described to various degrees in the literature:

Faraday effect
Cotton-Mouton effect
Magneto-optic Kerr effect
Majorana effect
Voigt effect
Zeeman effect

Of these, only the first has been given considerable emphasis as a feasible means of physically realizing a magneto-optical modulator, and this is therefore the only magneto-optical effect of any potential importance to us in the large-aperture optical modulator program.

The Faraday effect concerns the rotation of the plane of polarization produced when plane-polarized light is passed through an optical medium in the presence of an external magnetic field applied in the direction of the light. For a given substance, the rotation is proportional to the path length of the light in the medium and to the magnetic field strength. The constant of proportionality is known as the Verdet constant. Figure 1 depicts the geometry of a typical magneto-optical modulator employing the Faraday effect. The modulator consists of two linear polarizers whose preferred transmission axes are orthogonal (crossed), a solid-state optical material surrounded by an electrical coil, and a set of driver electronics connected to the electrical coil. The transmission of the modulator device is given by the expression

$$T = \sin^2(\Theta_F), \tag{1}$$

where the angle Θ_F represents the amount of rotation of the plane of polarization. This rotation angle

$$\Theta_F = VBL. \tag{2}$$

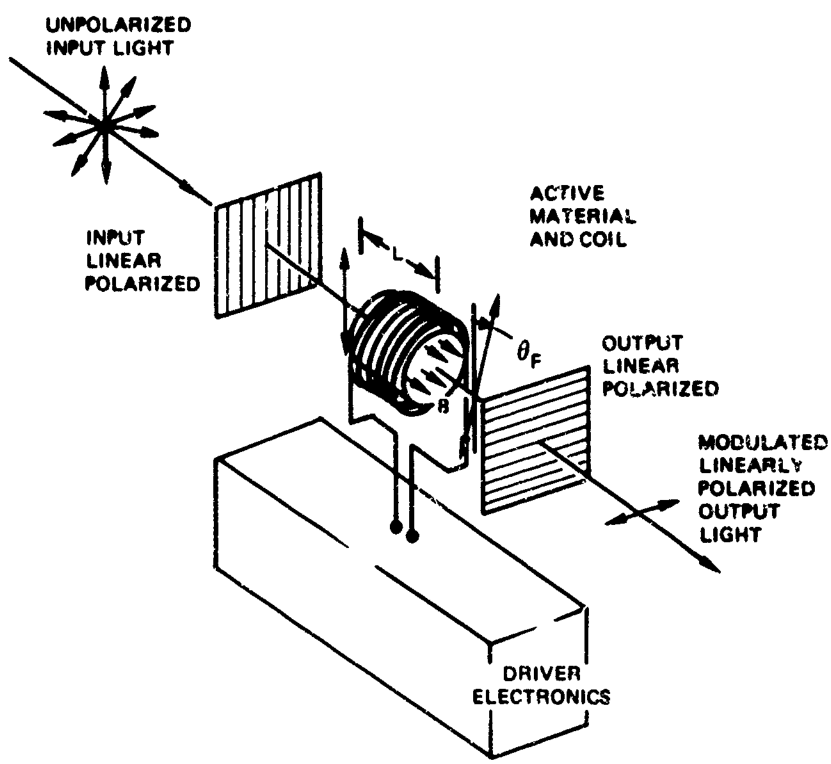

Figure 1 Magneto-optical modulator employing the Faraday effect.

where B is the field strength of the externally applied magnetic field, L is the length of the optical medium, and V is the Verdet constant. The most widely used material in these types of modulators is lead glass, which has a Verdet constant of 1.77 degrees per kiloersted-centimeter for a wavelength of 0.633 μm. The magnetic field strength, B, is a function of the electrical current within the coil surrounding the optical material and the physical geometry of the coil. The coil current is supplied by the driver electronics.

To date, magneto-optical modulators employing the Faraday rotation effect operate only in a pulsed mode. These modulators have been and are currently undergoing development for laser fusion experiments in which apertures as large as 12 inches are required. Their principal advantage, from the standpoint of the program requirements, is that large-aperture devices may be easily realized since the optical medium is typically glass. In addition, several industrial companies have developed large pulsed electromagnets (coils) as well as the driver electronics required to power them. These systems may be purchased for about $30k each for a several-inch aperture device. However, the principal disadvantage is that these modulators presently only work in a pulsed mode, with 10000 joules of energy per pulse commonly required to rotate the plane of polarization through an angle of 90 degrees. To realize a magneto-optical modulator with a 6-inch or larger aperture for use in an analog mode would require further extensive development by these industrial companies.

In summary, magneto-optical modulators may be realized with large apertures, but they presently operate in a pulsed mode, are expensive, and require highly sophisticated driver electronics. Nevertheless, if a large platform could be utilized for the driver electronics in an application calling for a pulsed mode of operation, then magneto-optical materials would have to be ranked very high as a large-aperture modulator candidate.

ELECTRO-OPTICAL MATERIALS

Electro-optical materials are those whose optical transmission characteristics can be altered by the application of an external electric field. The interaction of the electric field and the optical medium takes place on an atomic level. Over 60 percent of the work reported in the literature on optical modulators deals with this category alone. There are three electro-optical effects of prime importance in modulator work: the Kerr effect, the Pockels effect, and the Stark effect. Only the first two, however, have been studied to any great depth for modulator applications.

POCKELS EFFECT

The Pockels effect is the alteration of the refractive properties of a piezoelectric crystal caused by the application of a strong external electric field. The effect is linearly related to the electric field strength.

Depicted in figures 2 and 3 are the two most common geometries employed for electro-optical modulators employing the Pockels effect. Figure 2 represents the geometry employed for the longitudinal Pockels effect, whereas figure 3 depicts that used for the transverse effect. For both cases, the modulator geometry consists of two linear polarizers whose preferred transmission axes are crossed, an electro-optical crystalline material which has polished optical surfaces and is sandwiched between parallel conductive plates, and a set of

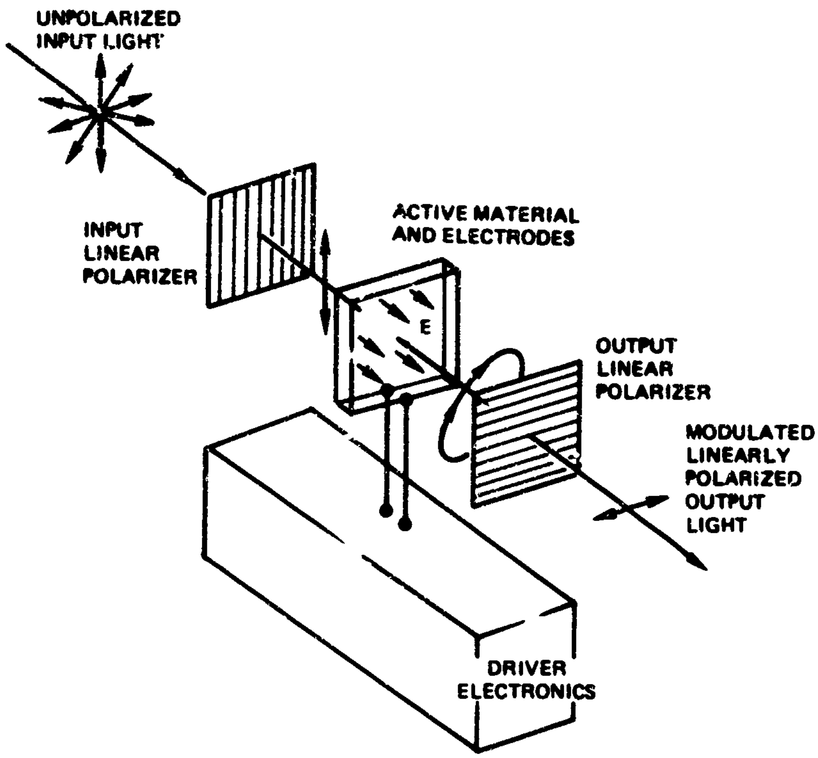

Figure 2. Electro-optical modulator employing the longitudinal Pockels effect.

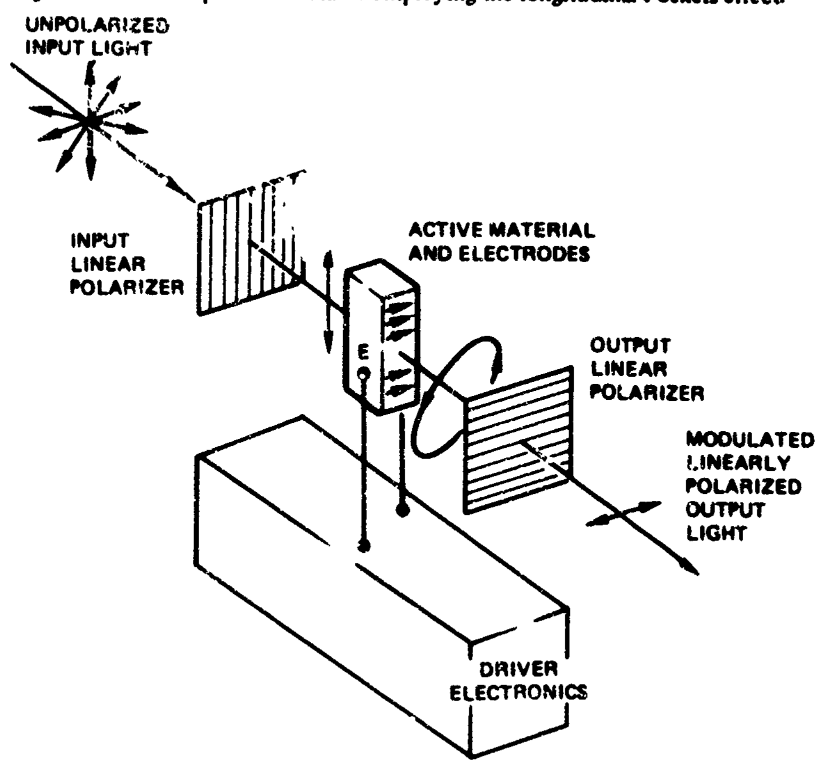

Figure 3. Electro-optical modulator employing the transverse Pockels effect.

driver electronics. Ideally these types of optical modulators behave electrically as a parallel-plate capacitor. By applying an electrical potential difference across the parallel plates, it is possible to change the birefringent properties of the electro-optical crystal. When used in combination with the crossed polarizer pair, the optical transmission of the device for the case of normal incidence is given by (1) except that the angle of rotation here is given by the expression

$$\Theta_P = \pi V/2V_{1/2} \tag{3}$$

where V represents the applied potential difference and $V_{1/2}$ the half-wave voltage. The half-wave voltage represents the potential difference required to introduce a half-wave retardation between the two normal modes of polarization of the electro-optical crystal. This half-wave voltage is a function of the modulator geometry, the wavelength of light used, the indices of refraction of the electro-optical crystal, and the electro-optical coefficients of the crystal.

There are a number of electro-optical crystals which exhibit either the longitudinal or the transverse Pockels effect or both. However, there are only a select few which are of any real importance to us in the large-aperture optical modulator program. One is potassium dideuterium phosphate (KD_2PO_4), a longitudinal Pockels effect crystal commonly referred to as KDDP or KD*P. This crystalline material has a low half-wave voltage and can be grown with very large aperture sizes ($\sim$12 inches) from a heavy-water solution. A transverse Pockels effect crystal of extreme popularity is lithium niobate ($LiNbO_3$). This crystal is relatively inexpensive. It has a low half-wave voltage, a high index of refraction, excellent physical properties for grinding and polishing, and can be fabricated with apertures of 1 inch for optical-grade material and 2 inches for acoustical-grade material.

In addition to the traditional parallel-plate electrode geometries of figures 2 and 3, a new geometry for realizing a large aperture optical modulator has been proposed and tested successfully by NOSC scientists.* This new geometry is depicted in figure 4 for a transverse Pockels effect crystal. (The geometry would have to be slightly modified for use with a longitudinal Pockels effect crystal.) The basic configuration shown in figure 4 consists of an electro-optical crystal having a set of interdigital electrodes fabricated on either one or both optical surfaces of the crystal and a set of driver electronics. Application of a potential difference across the terminals of the modulator sets up a spatially periodic electric field distribution within the crystal, which in turn gives rise to a spatially periodic variation in its optical indices of refraction. The result is that we have a means for realizing a phase diffraction grating whose diffractive properties can be altered by the application of an external electric field. The diffraction grating modulator has the property that the input beam of light is split into a zeroth order (the order of interest) and a number of higher-order diffracted beams. By changing the magnitude of the applied voltage it is possible to change the distribution of light energy appearing in the various orders. The result of interest is that the zeroth diffraction order can be modulated in time. This effect can be enhanced through the use of input and output polarizers.

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*Patent disclosure Large Apeture Phased Element Modulator/Antenna, by WE Richards and HF Taylor; Navy Case 61352

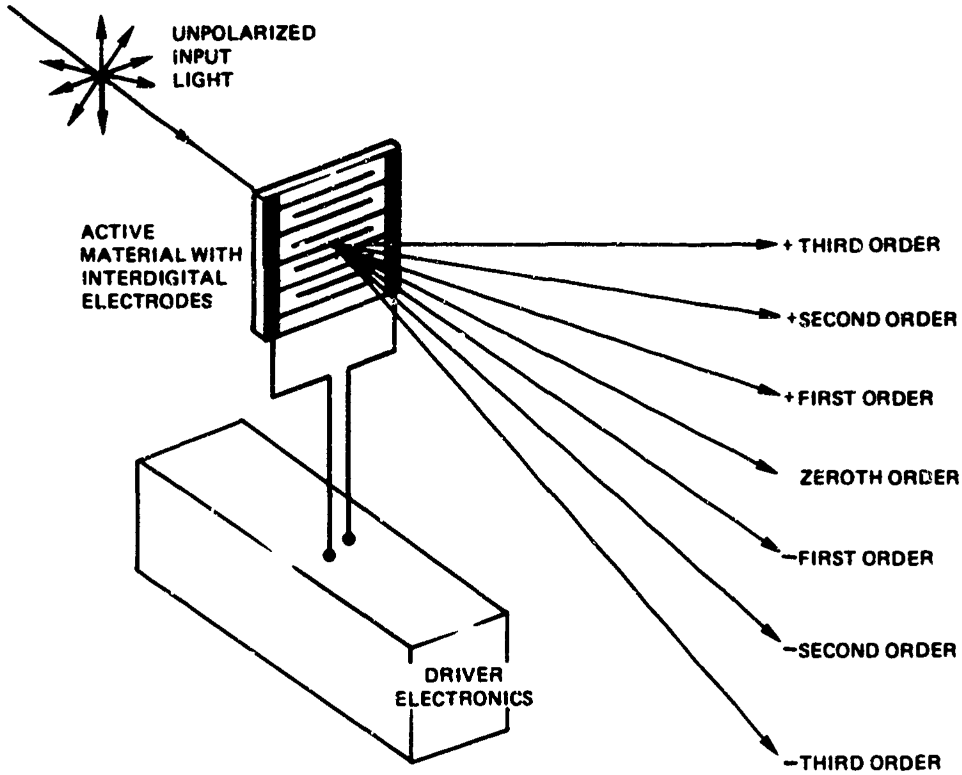

Figure 4. Electro-optical modulator employing the transverse Pockels effect with interdigital electrodes.

KERR EFFECT

The Kerr effect is the occurrence of induced birefringence in a transparent isotropic medium when it is placed in an external electric field. The medium behaves like a uniaxial crystal with its optic axis lying along the direction of the applied electric field. The modulation effect is related to the square of the electric field strength.

The geometry used for the conventional Kerr type modulators is basically the same as that depicted in figure 3 for the transverse Pockels effect modulator employing parallel-plate electrodes. The Kerr effect modulator differs primarily in that an enclosed hollow transparent cell containing a Kerr electro-optic liquid replaces the Pockels-effect crystal. The largest Kerr cells to date have a clear aperture of about 1 inch and require on the order of 60 kilovolts to generate a half-wave retardation. Several liquids can be used in these cells, but the most popular is nitrobenzene ($C_6H_5NO_2$), which has a Kerr constant of 4.4 x 10^{10} cm/volt^2.

Kerr-effect modulators have excellent field-of-view properties and optical bulk and surface qualities. To be useful in the large-aperture optical modulator program, however, a modified geometry would have to be employed that would allow for larger apertures. The concept of using an interdigital electrode approach appears attractive, but the concept is untested. With an interdigital electrode geometry it would be possible, at least in principle, to make the modulator aperture as large as desired, since the electro-optical medium is a liquid.

In summary, the use of electro-optical materials for a large-aperture optical modulator appears quite attractive. Particular emphasis was placed on the evaluation of lithium niobate, potassium dideuterium phosphate, and several Kerr liquids.

FERROELECTRIC MATERIALS

At present, PLZT ceramic is the one particular ferroelectric material which is receiving considerable attention as an optical shutter material. PLZT, the abbreviation for lead lanthanum zirconate titanate, is a clear ferroelectric ceramic which was initially developed at Sandia Laboratories. This material has undergone extensive development for applications in which a high-speed electro-optic shutter is required, such as for flashblindness protective goggles, stereoscopic (three-dimensional) TV display shutters, and medium-aperture photographic shutters. The geometry of present devices is similar to that of the interdigital electrode approach of figure 4 except that it also requires a pair of polarizers. PLZT has the advantage that it is a polycrystalline ceramic which can be made with apertures easily up to 4 inches by using present day hot-pressing techniques. Its half-wave voltage is on the order of several hundred volts, it has excellent response times, and it can be made inexpensively. As with the electro-optical materials of interest, PLZT was tested and evaluated in this study as a large-aperture optical modulator material.

SEMICONDUCTOR MATERIALS

Semiconductor materials have been demonstrated in the laboratory as optical modulators for the past 20 years. An extensive reference search indicates that almost all work on optical modulation has been in the infrared spectrum, with such materials as GaAs and Ge. Furthermore, previous work involved modulation at the source, consequently dealt with only small-size entrance apertures. Our NOSC program is concerned with large-aperture modulation, with particular emphasis near the peak of the visible spectrum (ie, 0.5 μm). At this time, a semiconductor modulator suitable for this application is unavailable for laboratory evaluation.

Limited information has been found concerning a visible optical filter which can be fabricated from ternary (GaN, GaP, and $In_{1-X}Al_XP$) compounds. Such a device would operate by the same physical mechanism as used by the long-wavelength semiconductor modulators: the Franz-Keldysch effect. In this effect, modulating electric field is applied across the ternary alloy semiconductor crystal, resulting in enhanced absorption of visible photons at the band edge. The electric field decreases the semiconductor bandgap energy to the same value as an incident photon's energy. This effect is reversible, hence the effective absorption coefficient follows the modulation voltage. The compound could be vapor deposited on a sapphire substrate with transparent electrodes and the resultant low-voltage (10–100 volts) modulator module could be configured to cover large apertures. Development of such a device is clearly outside the scope of this program's time and funding constraints, but it should be considered in future NOSC work in this area.

ACOUSTO-OPTIC MATERIALS

An acoustic wave in a transparent medium sets up a periodic modulation of its refractive index, which can be used to deflect or modulate a light beam. Of the many categories of acousto-optic devices which can be defined, only those which can be used as analog optical modulators will be addressed by this report. In particular, the three acousto-optic diffraction (phase) grating devices we will discuss will utilize the Bragg, Raman-Nath, and the surface-acoustic-wave (SAW) effects.

A high-frequency acoustic wave with wavelength much smaller than the optical beam width sets up a phase grating which diffracts light that passes through the material. The form of the diffraction depends on the interaction length. If the width of the acoustic wave is moderately narrow, as in figure 5, the interaction length is moderately short and the light is diffracted into many orders (Raman-Nath regime). Moving away from this interaction length toward one extreme, where the width of the acoustic wave in the interaction length is very wide (Bragg condition), the light will be diffracted with high efficiency into a single order, as shown in figure 6. At the other extreme, diffraction by a surface acoustic wave (SAW) can conceivably be employed to modulate a light beam by an acoustic wave in the interaction length that is very narrow. The principles of this method are similiar to those for the bulk acoustic wave effects except that the wave itself, and hence the interaction, is confined to a thin surface region of the medium. In this case, illustrated in figure 7, it is convenient to consider a given diffracted order to be the net result of two separate interactions. The first interaction involves diffraction by a thin internal periodic strain structure induced by the surface wave and similiar to the bulk waves described above, whereas the second interaction is with the surface corrugation itself. It should be noted that the internal contribution to a diffracted order can add destructively to the surface contribution. Depending upon the acoustic medium and the incident polarization, this destructive interference can even result in total elimination of the diffracted beam.

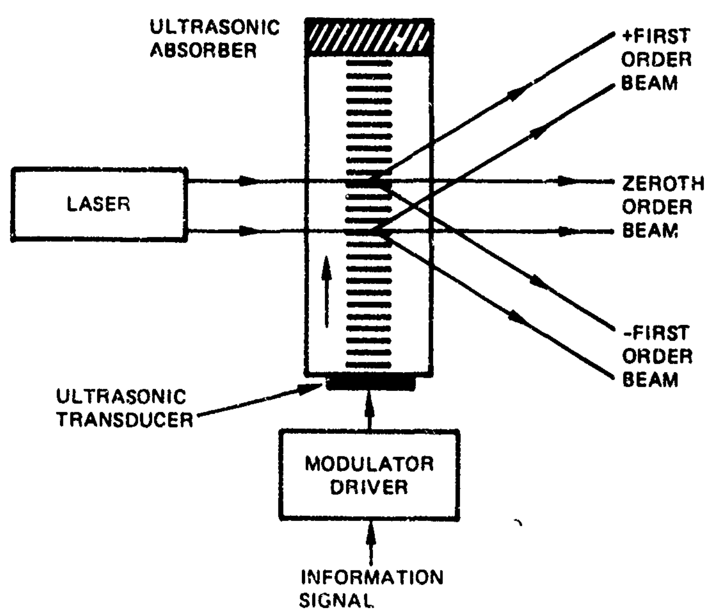

Figure 5. Raman-Nath acousto-optic modulator.

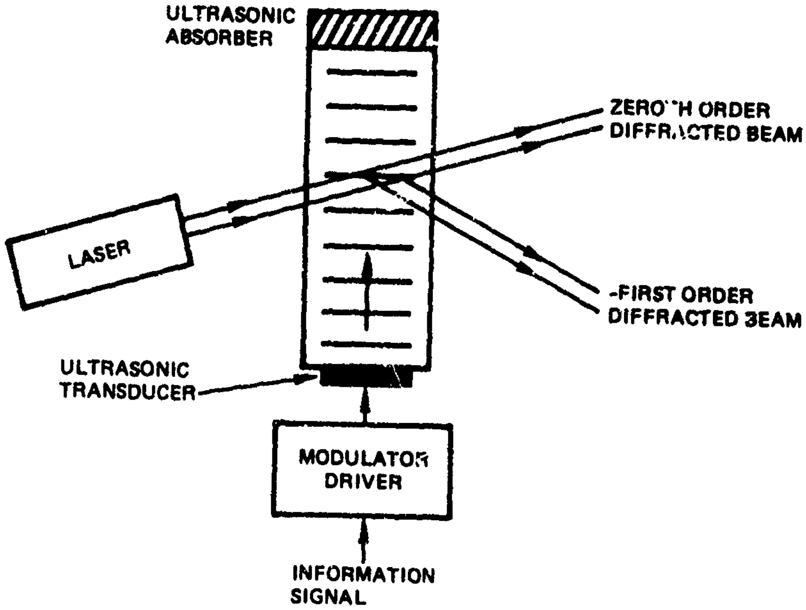

Figure 6. Bragg angle (Θ) acousto-optic modulator.

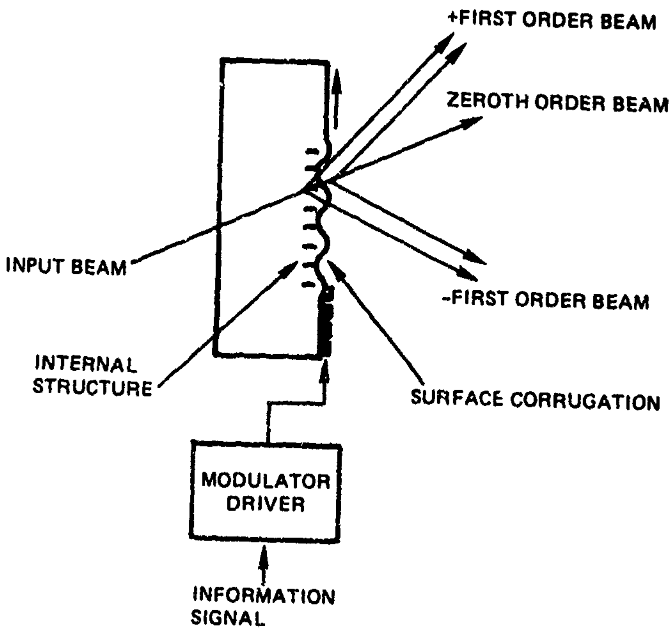

Figure 7. Simplified model of surface-acoustic-wave modulator with two-step interaction.

There are several key parameters for the required modulator which need addressing. In particular, we must consider the required aperture size (∿6 inches), modulation bandwidth (1–100 kHz), field of view (±20 degrees), and depth of modulation (20–50%). The bandwidth of a typical acousto-optic device used as a modulator is dictated by the transit time of an acoustic wave across the useful aperture of the device. Considering that the velocity of both bulk and surface waves in typical materials is on the order of 10^5 cm/sec, a 6-inch aperture device would support a modulation bandwidth of over 30 kHz, easily sufficient for our requirements. On the other hand, the field-of-view and depth-of-modulation specifications for the two devices are in opposition to one another. The field of view varies from fractions of degrees in a Bragg device to tens of degrees in a surface-wave device. This, taken alone, points to a SAW device as the optimum choice. However, the depth of modulation achievable decreases from 100 percent down to a few percent as one again goes from the Bragg device to the SAW device. Thus if a SAW device were to be considered further, additional study would need to be done to determine the optimum conditions for maximum depth of modulation.

In addition to the low depth of modulation achievable with a SAW device, there are other fundamental problems which must be addressed. First of all, it is important that the acoustic attenuation of the ultrasonic beam be low enough to be uniform across the useful aperture of the device. This requirement can apparently be nearly met with a SAW device, but for a bulk device and an attenuation rate on the order of 2 db/cm, the acoustic amplitude is reduced by over 99 percent in 6 inches.

Probably the biggest obstacle in achieving a large aperture in an acousto-optic device is its power limitation. In a 6-inch device, over 20 watts of input power at 20 MHz would be required even to partially overcome the attenuation losses. This power level would probably destroy the transducer or crack the substrate material. While the power requirements for a SAW device would seem to be considerably lower, the impedance associated with the large launching electrodes required will again require high power. It is not clear at this point whether this will result in serious problems and whether a matrix of smaller electrode structures might be the approach to take.

With the possible exception of a carefully designed launching electrode structure on a large-aperture SAW device, it is apparent that a large-aperture (6 inch) acousto-optic device is not practical. There remains, then, one other approach to achieve an effective large aperture: to arrange an array of smaller modulators and operate them in parallel. The mechanics and electrical balancing of such an arrangement have not, to our knowledge, been addressed. In light of the overall prioritization of modulator candidates for this project, an acousto-optic array device was not further considered due to limitations on manpower and funding constraints.

MISCELLANEOUS MATERIALS

There are a number of materials whose optical transmission characteristics could be altered by some external mechanism but which do not fit into the first five categories. A few examples are photochromic, photodichroic, liquid crystalline, and bleachable dye materials. Most of these materials have been utilized in application areas other than those requiring a temporal optical modulator. On the basis of information gathered from the literature and contacts with industry, these materials could conceivably qualify as large-aperture optical modulators, but only after undergoing a substantial R&D effort to overcome certain present deficiencies relative to our required needs. With the existing resource constraints on manpower and material funds in the large-aperture optical modulator program, we will therefore have to limit ourselves to only those materials which have already had a substantial industrial R&D history in the optical modulator area.

The next phase of the program was concerned with an in-house test and evaluation of those economically available active optical materials identified in the assessment phase of the program that showed the highest potential as large-aperture optical modulators. We have identified the following four material candidates in particular as showing a high potential and which are economically available for in-house test and evaluation, at least in a 2-inch diameter clear aperture format:

1. The large-area longitudinal Pockels effect potassium dideuterium phosphate crystal (KD_2PO_4), which is grown by Interactive Radiation, Northvale, New Jersey, for use as a shutter in the laser fusion program at the Lawrence Livermore Laboratory.

2. The transverse Pockels effect lithium niobate crystal ($LiNbO_3$), grown by Union Carbide Crystal in San Diego, California, for use in acoustic-surface-wave devices and laser Q-switches.

3. The ferroelectric, lead lanthanum zirconate titanate (PLZT), a clear ceramic initially developed at Sandia Laboratories in Albuquerque, New Mexico. This material is presently undergoing advanced development at Honeywell, Minneapolis, Minnesota, to be used as a large-aperture shutter in nuclear flashblindness prevention goggles.

4. The Kerr-effect liquid, nitrobenzene ($C_6H_5NO_2$), used by Kappa Scientific in Santa Barbara, California, in the fabrication of high speed laser modulators and photographic shutters.

Our goal was to test and evaluate each of these materials in a 2-inch aperture modulator geometry in order to single out the particular material which would best satisfy our present large-aperture optical modulator requirements. The remainder of this report concerns a more detailed description of each of these materials and their merits as we presently see them.

POCKELS EFFECT CRYSTALS

In most crystals, the interaction of electromagnetic radiation (light) with the crystalline material is a highly involved and complicated process. Fortunately, the theoretical models describing this interaction are well at hand and give tremendous insight into how the crystal should be cut, polished, and oriented with respect to the direction of the applied electric field to take full advantage of the electro-optic Pockels effect. In addition, these models indicate the preferred directions of light propagation within the crystal and the preferred polarization states. For the purpose of this study, a classical electromagnetic approach to the problem is quite acceptable.

Basic electromagnetic theory holds that the stored electric field energy density, W_e, associated with an electromagnetic wave in a material in the absence of any applied electric field is given by the simple equation

$$W_e = (1/8\pi)\, \bar{E} \cdot \bar{D}, \tag{4}$$

where $\bar{E}$ and $\bar{D}$ are the electric field and electric displacement vectors, respectively, associated with the electromagnetic disturbance. The cgs system of units is employed. The electric field vector, $\bar{E}$, and the displacement vector, $\bar{D}$, are related through the macroscopic polarization vector, $\bar{P}$, by the equation

$$\bar{D} = \bar{E} + 4\pi\bar{P}. \tag{5}$$

The basic distinguishing optical feature of the crystalline state is the fact that crystals are generally electrically anisotropic. This means that the polarization, $\bar{P}$, produced in the crystal by the electric field vector, $\bar{E}$, is not just a simple scalar constant times the electric field, but varies in a manner that depends on the direction of the electric field in relation to the crystal lattice. Thus the actual dependence of $\bar{P}$ on $\bar{E}$ is expressible as a tensor relation in the form

$$\bar{P} = \bar{\bar{\chi}}\,\bar{E}, \tag{6}$$

where $\bar{\bar{\chi}}$ is the susceptibility tensor:

$$\bar{\bar{\chi}} = \begin{bmatrix} \chi_{11} & \chi_{12} & \chi_{13} \\ \chi_{21} & \chi_{22} & \chi_{23} \\ \chi_{31} & \chi_{32} & \chi_{33} \end{bmatrix} . \tag{7}$$

There exists a set of coordinate axes, called the principal axes, such that the susceptibility tensor assumes the diagonal form

$$\bar{\bar{\chi}} = \begin{bmatrix} \chi_{11} & 0 & 0 \\ 0 & \chi_{22} & 0 \\ 0 & 0 & \chi_{33} \end{bmatrix} . \tag{8}$$

The three χ's in (8) are known as the principal susceptibilities. In the principal axes frame we thus find from Equations (5), (6), and (8) that the components of $\bar{E}$ and $\bar{D}$ are related through the equations

$$\begin{aligned} D_x &= n_1^2\,E_x \\ D_y &= n_2^2\,E_y, \\ D_z &= n_3^2\,E_z \end{aligned} \tag{9}$$

where the n's are the principal indices of refraction and are given by the equations

$$\begin{aligned} n_1^2 &= 1 + 4\pi\chi_{11} \\ n_2^2 &= 1 + 4\pi\chi_{22}. \\ n_3^2 &= 1 + 4\pi\chi_{33} \end{aligned} \tag{10}$$

With (9), the equation for the electric field energy density stored can be rewritten in the form

$$8\pi W_e = D_x^2/n_1^2 + D_y^2/n_2^2 + D_z^2/n_3^2. \tag{11}$$

Equation (11) tells us that the constant energy (W_e) surfaces in (D_x,D_y,D_z) space are ellipsoids. For convenience let's write x,y,z in place of $D_x/(8\pi W_e)^{1/2}$, $D_y/(8\pi W_e)^{1/2}$, $D_z/(8\pi W_e)^{1/2}$ and consider these as Cartesian coordinates in space. Then (11) reduces to

$$x^2/n_1^2 + y^2/n_2^2 + z^2/n_3^2 = 1. \tag{12}$$

This equation is commonly referred to as the index ellipsoid equation, the optical indicatrix equation, or the reciprocal ellipsoid equation. The properties of the index ellipsoid described by (12) can be seen from a simple example. If an electromagnetic plane wave propagating through the crystal has its normal lying along the z-direction, then we consider the ellipse formed by the index ellipsoid and the z = 0 plane. The directions of the major and minor axes of this ellipse are those of the two allowed polarization eigenstates; for this case the x- and y- directions specify the allowed polarizations. The refractive indices associated with these polarization eigenstates are given by the length of the semiaxes of the ellipse, for this case n_1 and n_2. In a more general case, the wave normal direction can be chosen arbitrarily and the two indices can be obtained as the semiaxes of the elliptical section perpendicular to the arbitrary direction.

For the case of materials in the presence of an externally applied electric field, such as electro-optical crystals exhibiting the Pockels effect, the indices of refraction appearing in the index ellipsoid equation change in magnitude with the application of the external electric field. In addition, certain types of electro-optical crystals have the property that the index ellipsoid actually changes orientation as a result of the applied electric field. For these types of crystals the principal axes associated with the crystal will change direction with the application of the external field. In order to handle these additional effects, a more generalized index ellipsoid equation must be used. It has been shown that if the bound outer electrons in the crystalline material, which are primarily responsible for the resulting macroscopic polarization, $\bar{P}$, are treated as aharmonic oscillators (ie. nonlinear restoring forces), then the resulting index ellipsoid equation of interest takes on the form

$$(1/n_1^2 + a_{11})x^2 + (1/n_2^2 + a_{22})y^2 + (1/n_3^2 + a_{33})z^2 + 2\,a_{23}\,yz + 2\,a_{31}\,zx + 2\,a_{12}\,xy = 1. \tag{13}$$

In general, however, x, y, and z no longer correspond to the principal directions. The coefficients a_{ij} appearing in (11) are related to the Cartesian components of the externally applied electric field, $\bar{E}$, by the matrix equation

$$\begin{bmatrix} a_{11} \\ a_{22} \\ a_{33} \\ a_{23} \\ a_{31} \\ a_{12} \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}. \tag{14}$$

The 3 x 6 matrix of coefficients r_{ij} is commonly known as the electro-optic tensor. All electro-optic Pockels crystals have such a tensor uniquely associated with them. The form, but not the magnitude, of the tensor coefficients r_{ij} can be derived from group symmetry considerations, which dictate the particular 18 r_{ij} coefficients which are zero and the relationships that exist between the remaining coefficients. The indices of refraction appearing in (13) represent the principal indices of refraction of the crystal in the absence of an applied electric field. We see from (14) that when the applied electric field is zero, the coefficients a_{ij} are also zero, implying that the index ellipsoid equation in (13) degenerates to the specialized version represented by (12). Therefore, using (13) and (14) with a knowledge of the values of the nonzero Pockels coefficients allows us to adequately describe the interaction of light with an electro-optic crystal exhibiting the Pockels effect.

POTASSIUM DIDEUTERIUM PHOSPHATE

Potassium dideuterium phosphate (KD_2PO_4) belongs to the tetragonal $\bar{4}2m$ (D_{2d}) class of crystals and exhibits the Pockels electro-optic effect. The electro-optic tensor describing the potassium dideuterium phosphate crystal is of the form

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{63} \end{bmatrix},$$

where the nonzero coefficients have the values

$$r_{41} = 8.8 \times 10^{-12} \text{ m/V}$$

$$r_{63} = 26.4 \times 10^{-12} \text{ m/V}$$

for 0.546 μm light. In addition, the indices of refraction for this same wavelength are given by

$$n_1 = n_o = 1.508$$

$$n_2 = n_o = 1.508.$$

$$n_3 = n_e = 1.468$$

It is noted that the KD_2PO_4 crystal is a negative uniaxial crystal whose optic axis lies along the z-direction. For a uniaxial crystal, the quantities n_o and n_e are referred to as the ordinary and extraordinary indices of refraction, respectively. Because the electro-optic coefficient r_{63} is roughly three times larger in value than the r_{41} coefficient for KD_2PO_4, it is natural to look for the geometrical conditions for which the high value of the r_{63} coefficient is taken full advantage of. Without going into further detail here, it can be shown from (13) and (14) and the electro-optic tensor information for KD_2PO_4 that the optimum geometry for using a KD_2PO_4 crystal in a large-aperature modulator format is what is commonly known as the longitudinal mode of operation, as depicted in figure 8. In this figure is shown a z-cut KD_2PO_4 crystal with an electric field applied along the z-direction (optic axis). Wave propagation is normally also along the z-direction. In addition, the modulator geometry requires the use of two linear polarizers whose preferred transmission axes are at +45° and -45°, respectively, to the x-axis of the crystal. The

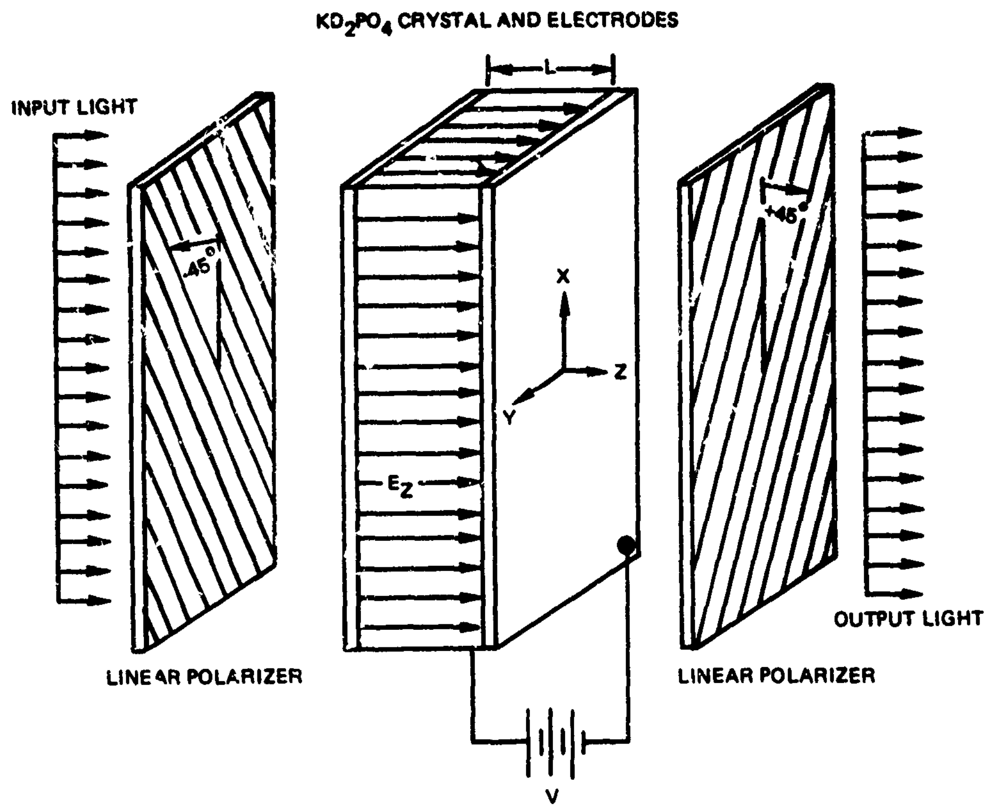

Figure 8. Modulator geometry for the KD_2PO_4 crystal.

electric field within the crystal results from the application of a potential difference across two transparent conducting electrodes on the large optically polished crystal surfaces which are perpendicular to the z-axis. The optical transmission of the modulator as a function of applied voltage for normal incidence is given by the equation

$$T = \sin^2(\pi V/2V_{1/2}), \qquad (15)$$

where V is the applied voltage, equal to $E_z \cdot L$. The quantity $V_{1/2}$ is the half-wave voltage and is given by the relationship

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

For a wavelength λ equal to 0.546 μm we find that the half-wave voltage is equal to 3015 volts.

The potassium dideuterium phosphate crystal modulator has most of the desirable features we are looking for in a large-aperture modulator. First, these crystals can be grown to diameters up to 12 inches. Second, their frequency response is certainly adequate for the immediate applications at hand. And third, their optical quality is more than acceptable. However, there are two matters of concern. First, these particular crystals are significantly more expensive than the other three modulator materials under consideration. Second, we have reservations about the useful acceptance angle of these devices. This point deserves further discussion. Depicted in figure 9 is a KD_2PO_4 modulator that is illuminated by a plane wave whose direction of propagation within the material makes an angle ϕ with respect to the optic axis of the crystal. (Note: this is not the most general case, but corresponds only to those angles measured in the y-z or z-x planes.) If we use the index ellipsoid equations as we did before for the case of normal incidence, we find that the transmission of the modulator as a function of ϕ is now given by the equation

$$T(\phi) = \sin^2 \left[\frac{\pi V}{2V_{1/2}(\phi)} + \alpha(\phi)\right] , \tag{17}$$

where

$$V_{1/2}(\phi) = V_{1/2} \cdot \left[(2\cos\phi)/(1 + \cos^2\phi)\right] \tag{18}$$

and

$$\alpha(\phi) = \pi(L/\lambda)(n_o/2)(n_o^2/n_e^2-1)(\sin^2\phi/\cos\phi). \tag{19}$$

Shown in figure 10 is a plot of the half-wave voltage, $V_{1/2}(\phi)$, (see (18)), as a function of ϕ, for 0.546 μm light. We see from this figure that $V_{1/2}(\phi)$ is essentially constant over the interval ($-20° \leq \phi \leq +20°$). For the field of views of interest, this curve implies that we can essentially neglect the effect of the angle ϕ on $V_{1/2}(\phi)$. However, the phase angle $\alpha(\phi)$ greatly changes, as depicted in figure 11. This is particularly disconcerting, since in general we will not have a priori knowledge concerning the angle of arrival of an incoming plane wave for the applications of interest: hence $\alpha(\phi)$ is also unknown. Without knowing this information it is impossible to electronically bias the crystal to some predetermined voltage in order to compensate for this phase term. If it is not dealt with, this phase term could potentially present problems in terms of signal degradation, because $\alpha(\phi)$ essentially shifts the position of the $\sin^2$ response curve relative to the ideal operating voltage range which is defined for $\alpha(\phi) = 0$. Hence in general we would not necessarily be working in the linear region of the $\sin^2$ curve. The potential for degrading effects thus exists.

There is, however, one way around this potential difficulty: to use two potassium dideuterium phosphate crystals in series. By rotating one crystal 90 degrees about the z-axis relative to the other we can minimize the effects of $\alpha(\phi)$. It is noted that $\alpha(\phi)$ arises solely from the natural birefringence of the crystal and is independent of the applied voltage. The use of a second rotated crystal thus compensates for the phase term $\alpha(\phi)$ introduced by the first crystal. For the two crystals in series, we find that the expressions for the transmission $T(\phi)$ and the half-wave voltage $V_{1/2}(\phi)$ for the combination are identical to the expressions for the single crystal device given by (17) and (18), respectively. For the combination, however, the quantity V in (17) is now given by the relationship

$$V = V_1 + V_2. \tag{20}$$

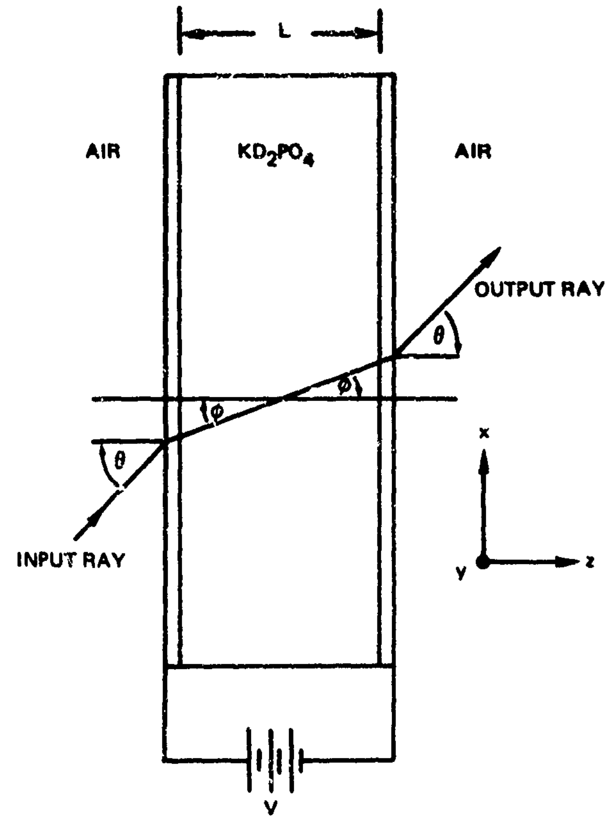

Figure 9. Geometry depicting nonnormal incidence.

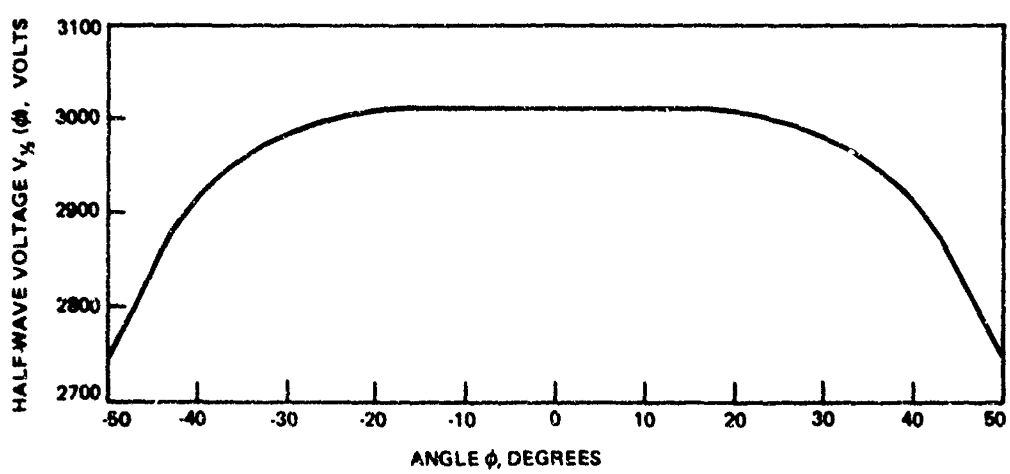

Figure 10. Plot of half-wave voltage $V_{½}(\phi)$ versus ϕ for KD_2PO_4 for a wavelength of 0.546 μm.

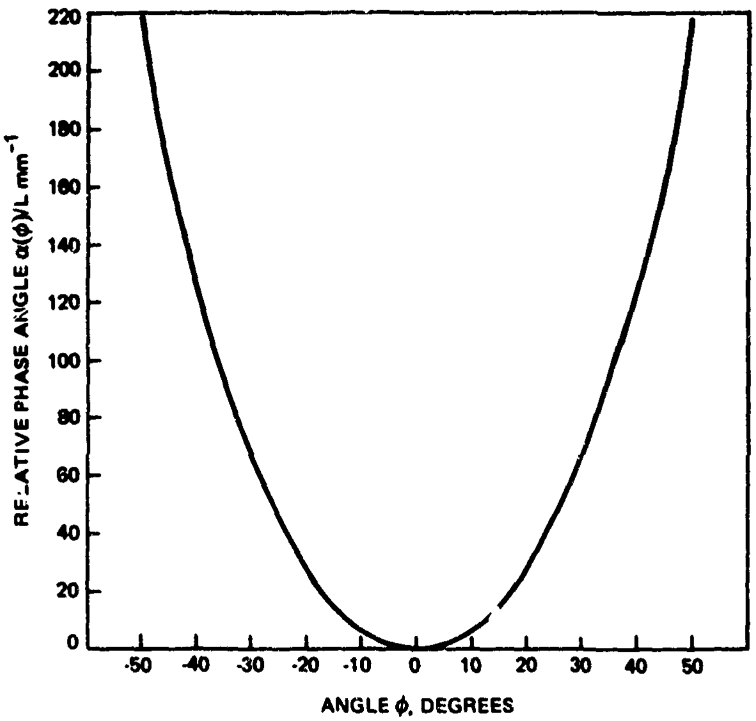

Figure 11. Plot of the relative phase angle $\alpha(\phi)$ for KD_2PO_4, for a wavelength of 0.546 μm.

The quantities V_1 and V_2 represent the applied voltages on crystals 1 and 2, respectively. The phase term $\alpha(\phi)$ for the two crystals in series is given by the relationship

$$\alpha(\phi) = \pi(L_1 - L_2)(n_o/2\lambda)(n_o^2/n_e^2 - 1)(\sin^2\phi/\cos\phi), \quad (21)$$

where L_1 and L_2 represent the thicknesses of crystals 1 and 2, respectively. We see that if L_1 equals L_2, the phase term $\alpha(\phi)$ is identically equal to zero for all values of ϕ.

In order to obtain hands-on experience with a potassium dideuterium phosphate crystal modulator, we had one designed and fabricated by Interactive Radiation for $3760. As previously indicated, Interactive Radiation is heavily involved in contract work with Lawrence Livermore Laboratory to fabricate large-aperture KD_2PO_4 Pockels shutters (∿12 inches) for high energy laser systems associated with the ongoing laser fusion experiments. It was decided that since KD_2PO_4 crystals are hydroscopic and cost approximately $200 per cubic centimeter for the raw crystals alone, it would be better to have Interactive Radiation, with their expertise, fabricate the entire modulator device as opposed to our starting anew with the raw crystals and building the device ourselves. The specifications pertinent to this modulator are as follows:

Modulator material:	KD_2PO_4 crystal (50 x 50 x 10 mm)
Transparent electrodes:	Platinum (0.1 μm thick)
Windows:	Schott glass with AR coatings
Transmission range:	0.35 to 1.25 μm
Percent transmission:	60% at 0.63 μm

Half-wave voltage:	3500V at 0.63 μm
Maximum safe voltage:	7000V
Capacitance:	180 pF
Frequency response:	30 kHz
Turn-on/turn-off ratio:	150:1 at 0.63 μm
Single-pass wavefront distortion:	$\lambda/4$ or better at 0.63 μm

Figure 12 is a photograph of the final modulator device delivered to NOSC.

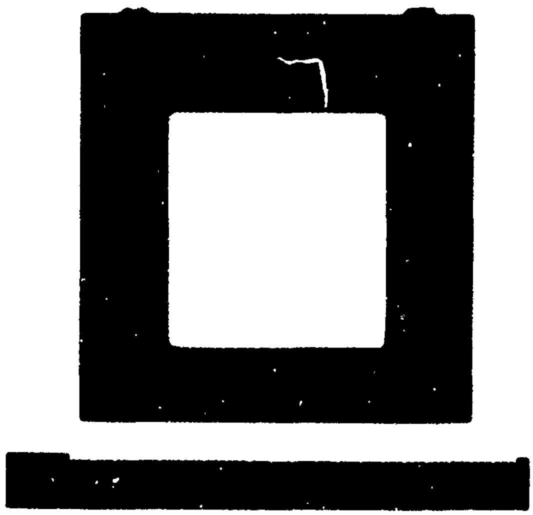

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Figure 12. 50 X 50 mm clear aperture KD_2PO_4 crystal modulator.

This modulator was tested and evaluated both in the laboratory and in the field. As the theory predicted, experimental measurements verified that the phase term $\alpha(\phi)$ does indeed manifest itself in the transmission characteristics of the device. In terms of optical communications we found that for this modulator the angle of arrival of a light beam greatly affected the depth of modulation c a carrier wave impressed on that light beam. This effect gave rise to a limited field of view, ie, there were directions for which the depth of modulation of the impressed signal was large (clear audible communication was possible) and other directions for which the depth of modulation was near zero (no communication at all). Thus the phase angle $\alpha(\phi)$ affected only the depth of modulation of the carrier.

LITHIUM NIOBATE

The Pockels electro-optic crystal lithium niobate ($LiNbO_3$) belongs to the trigonal 3M (C_{3v}) class of crystals. The electro-optic tensor describing this crystal is of the form

$$\begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix}$$

where the nonzero Pockels coefficients have the values

$$r_{13} = 9.6 \times 10^{-12}\ \text{m/V}$$

$$r_{22} = 6.6 \times 10^{-12}\ \text{m/V}$$

$$r_{33} = 31.0 \times 10^{-12}\ \text{m/V}$$

$$r_{42} = 32.0 \times 10^{-12}\ \text{m/V}$$

for 0.633 μm light In addition, the indices of refraction for this wavelength are given by

$$n_1 = n_o = 2.291$$

$$n_2 = n_o = 2.291$$

$$n_3 = n_e = 2.200 \quad .$$

Like potassium dideuterium phosphate, lithium niobate is also a negative uniaxial crystal whose optic axis lies along the z-direction.

By going back to the index ellipsoid equation and using the electro-optic tenser information for $LiNbO_3$, we find that the optimum geometry for using $LiNbO_3$ as an optical modulator is the transverse mode of operation. This corresponds to the case in which the applied electric field is approximately at right angles to the direction of light propagation. To keep voltage levels down, an interdigital electrode configuration, as shown in figure 13, is preferred over the parallel-plate electrode geometry normally used. In this figure is depicted a y-cut $LiNbO_3$ crystal with interdigital electrodes lying perpendicular to the z-axis (optic axis) of the crystal. Wave propagation would normally be along the y-direction.

When this geometry is used in the conventional Pockels mode, two linear polarizers are required, as shown in figure 13, with the transmission axes of the two polarizers at +45 and -45 degrees to the x-axis of the crystal. The electric field generated within the crystal for the purpose of optical modulation is established by applying a potential difference across adjacent electrode fingers in the interdigital array. When operated in this mode we find that the optical transmission of the combined polarizer pair and crystal array for the case of normal incidence is given by

$$T = \sin^2(\pi V/2V_{1/2} + \alpha), \tag{22}$$

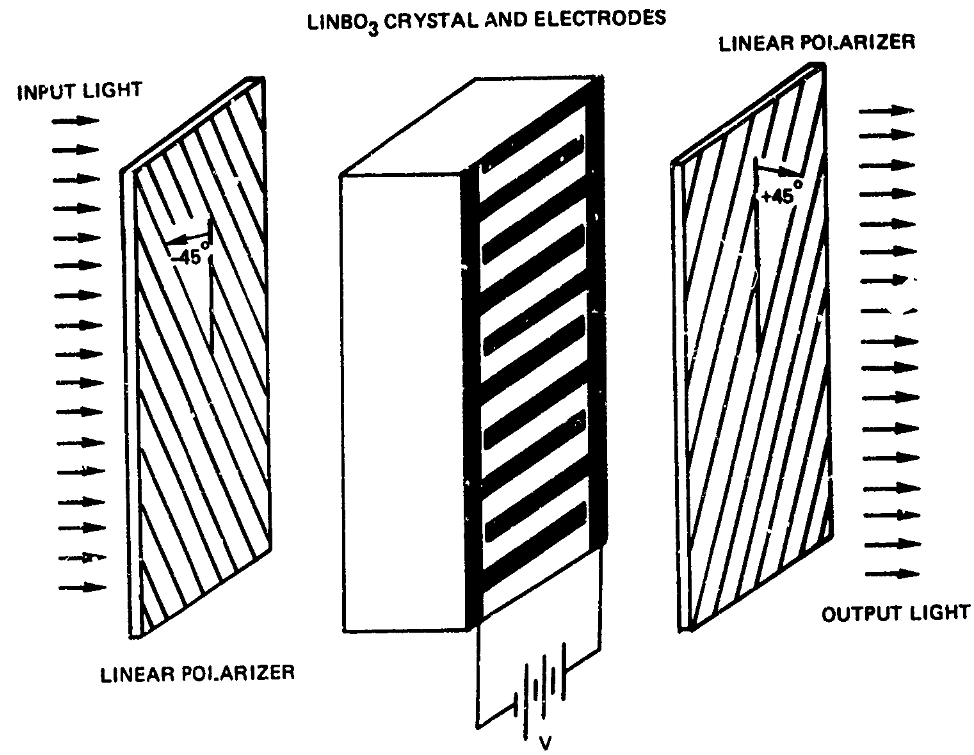

Figure 13. Modulator geometry for the $LiNbO_3$ crystal in Pockels mode.

where, as before, V is the applied voltage, $V_{1/2}$ the half-wave voltage required to fully turn the modulator on, and α the phase term resulting from the natural birefringence of the crystal. The half-wave voltage of lithium niobate when used in the conventional Pockels mode is given by the expression

$$V_{1/2} = \lambda(d/L)/(n_e^3 r_{33} - n_o^3 r_{13}), \tag{23}$$

and the phase angle α is given by the expression

$$\alpha = \pi(L/\lambda)(n_e - n_o), \tag{24}$$

where λ corresponds to the wavelength of light, d the center-to-center spacing between adjacent interdigital electrode fingers, and L the effective crystal thickness in the y-direction. We note that for this geometry the effective thickness L is not the actual crystal thickness, but only represents that distance over which the electric field penetration is appreciable. For 0.633 μm light we find from (23) that the half-wave voltage for a single-pass transmission is equal to 2950 volts when d is equal to L.

Like potassium dideuterium phosphate, lithium niobate, at least from a theoretical point of view, may not provide a useful acceptance angle when used in the conventional Pockels mode. Going back to the index ellipsoid equations and considering the case of nonnormal incidence in the y-z plane, we find that the transmission of the lithium niobate modulator as a function of the angle ϕ is given by (17), where now

$$V_{1/2}(\phi) = \lambda(d/L)\cos\phi/[(n_e^3 r_{33} - n_o^3 r_{13}) + n_e^3(r_{13} - r_{33})\sin^2\phi] \tag{25}$$

and

$$\alpha(\phi) = \frac{\pi\left(\frac{L}{\lambda}\right)\left[(n_e - n_o) - \left(\frac{n_e}{2}\right)\left(\frac{n_e^2}{n_o^2} - 1\right)\sin^2\phi\right]}{\cos\phi} . \tag{26}$$

Plots of the quantities $V_{1/2}(\phi)$ and $\alpha(\phi)/L$ as a function of ϕ are shown in figures 14 and 15, respectively. From these figures we see that the dependence of $V_{1/2}(\phi)$ on ϕ is insignificant over the range of values ($-10° \leqslant \phi \leqslant +10°$). However, the phase angle $\alpha(\phi)$ greatly changes with ϕ, as was the case with potassium dideuterium phosphate. Hence, the previous discussion of the potential effects of $\alpha(\phi)$ on signal distortion for KD_2PO_4 also pertains to $LiNbO_3$. An analysis was performed for $LiNbO_3$ similar to that performed for KD_2PO_4, to determine whether the phase term $\alpha(\phi)$ could be compensated for by using a second $LiNbO_3$ crystal of predetermined thickness and orientation, but we have not found a satisfactory technique to compensate for this phase term as we did for the KD_2PO_4 crystal. However, since $LiNbO_3$ is used in a transverse mode with interdigital electrodes, there is a second technique of operation that can be used for modulating an incoming light beam. The geometry depicting this mode of operation, which we refer to as the tunable diffraction grating mode, is shown in figure 16. An output polarizer (analyzer) is not required for this mode, and the input polarizer's transmission axis is parallel to the optic axis of the lithium niobate crystal. In this mode, the energy distribution in the far-field pattern (Fraunhofer region) of the crystal modulator, for the case of normal incidence, is predicted by the equation

$$I(r,s) = I_o\left[\frac{\sin^2(\pi cr)}{(\pi cr)^2}\right]\left[\frac{\sin^2(N\pi r)}{N^2\sin^2(\pi r)}\right]\left[\frac{\cos^2(\pi r + \pi s/2)}{\cos^2(\pi r)}\right] , \tag{27}$$

where

$$r = d\theta/\lambda \tag{28}$$

$$s = V/V_{1/2} \tag{29}$$

$$c = \epsilon/d \tag{30}$$

$$V_{1/2} = \lambda(d/L)/2n_e^3 r_{33} \tag{31}$$

and

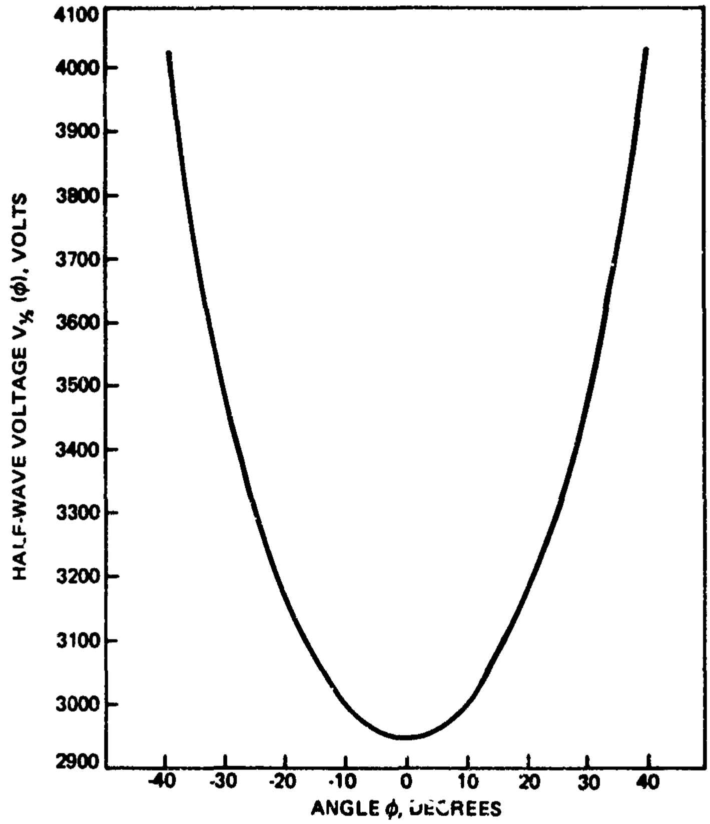

Figure 14. Plot of half-wave voltage $V_{1/2}(\phi)$ versus ϕ for $LiNbO_3$, for a wavelength of 0.633 μm.

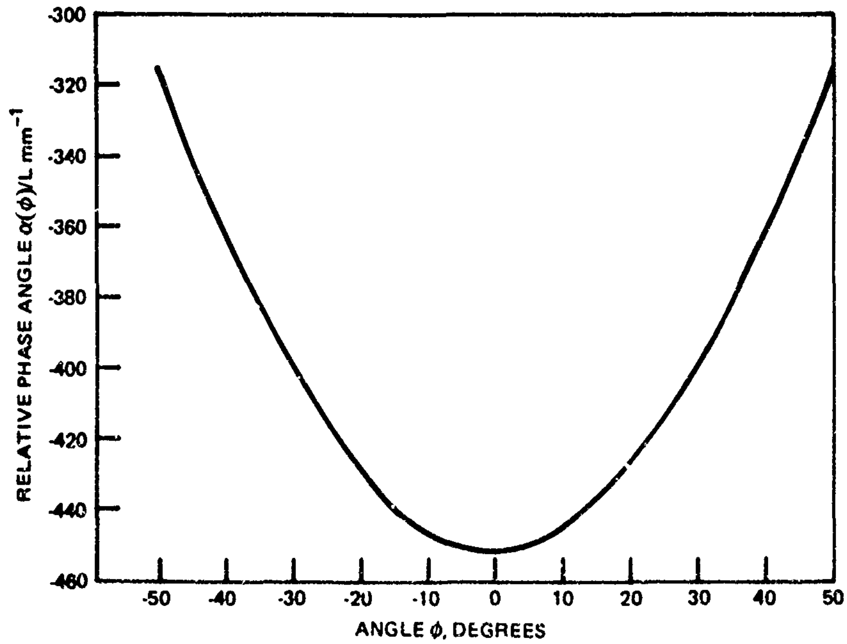

Figure 15. Plot of relative phase angle $\alpha(\phi)/L$ versus ϕ for $LiNbO_3$, for a wavelength of 0.633 μm.

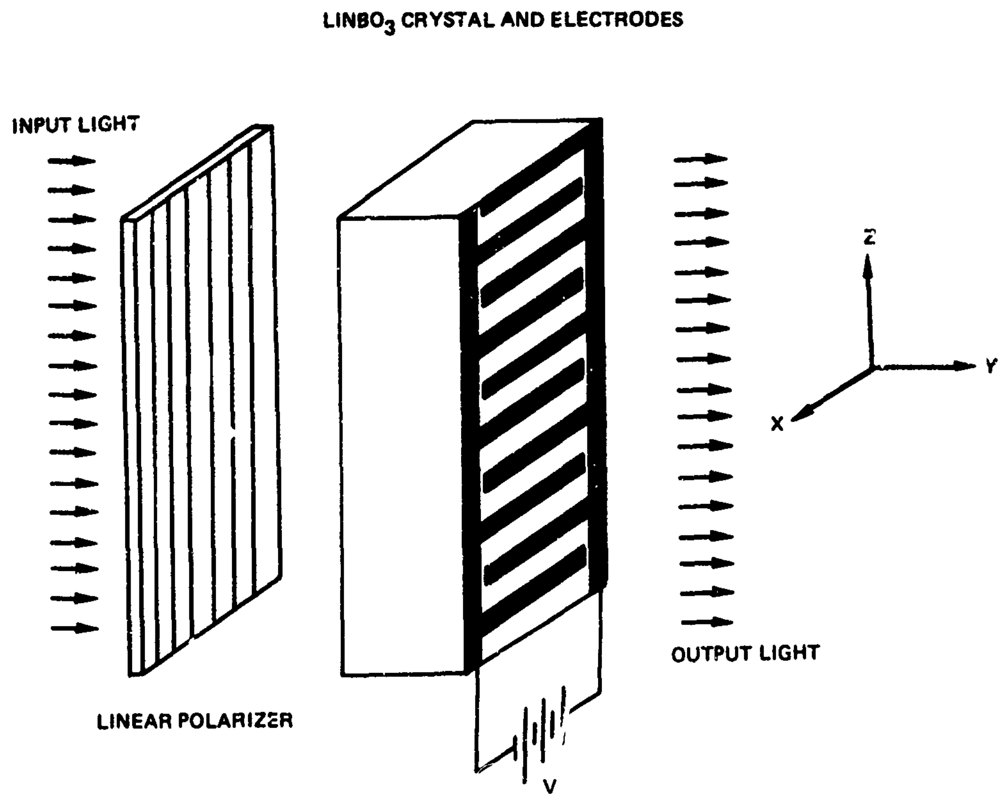

Figure 16. Tunable diffraction grating modulator geometry fo: the $LiNbO_3$ crystal.

I_o = light intensity for r and s equal to zero

ϵ = slit width

d = center-to-center spacing between electrodes

N = number of slits in the array

$V_{1/2}$ = half-wave voltage

L = effective crystal thickness

λ = wavelength of light

θ = half-angle measured from y-axis in the y-z plane

Shown in figure 17 is a series of plots depicting how the far-field pattern changes as a function of applied voltage. The order of interest is the zeroth order, and from (27) the light intensity associated with this order is determined by setting θ equal to zero. Thus we find that the transmission of the modulator for the zeroth order is given by the relationship

$$T = \cos^2 (\pi V/2V_{1/2}). \qquad (32)$$

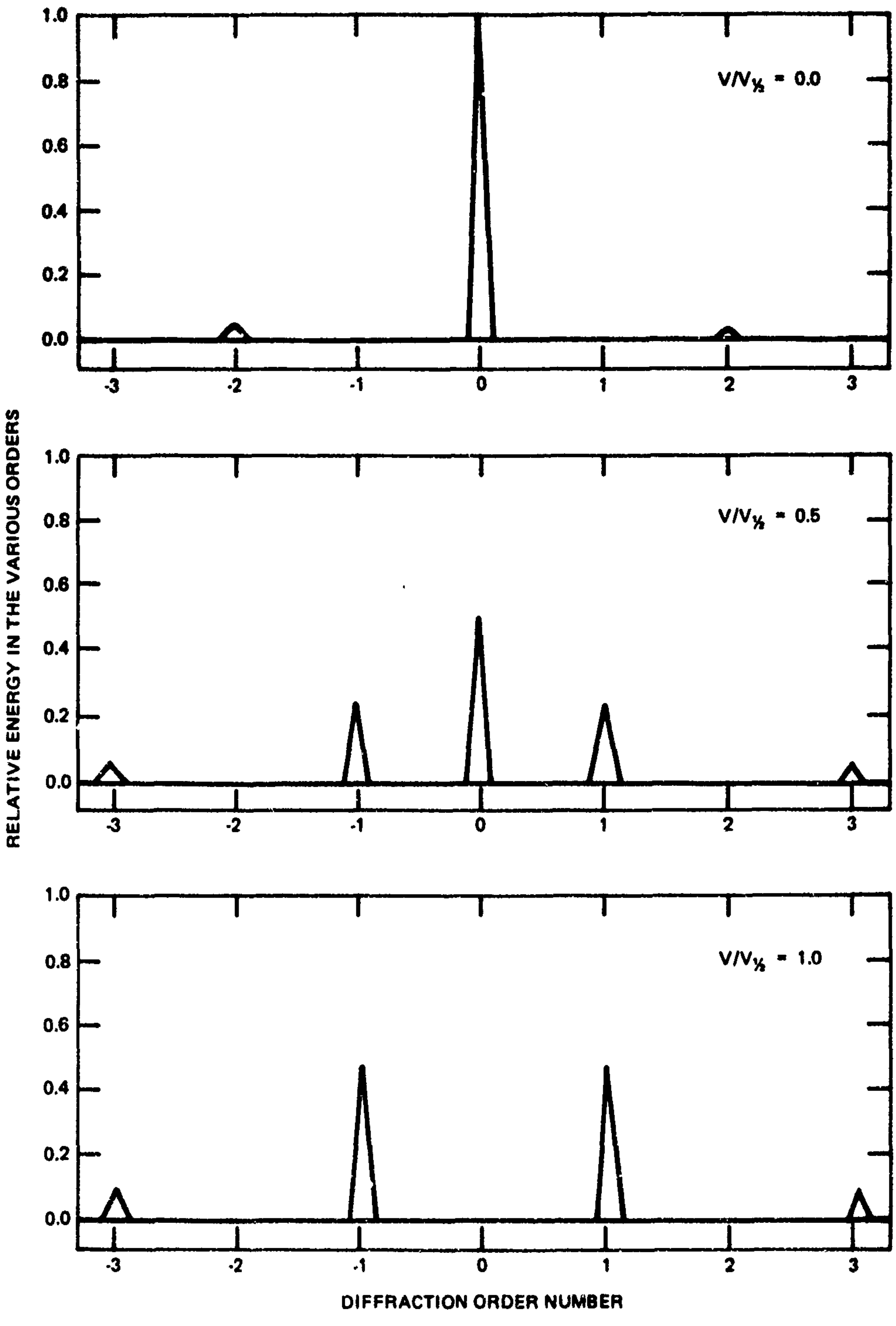

Figure 17. Effect of the applied voltage on the far-field energy distribution of the various diffraction orders.

We see that by changing the applied voltage, V, it is possible to change the amount of energy in the order of interest. For this mode of operation the total energy in all the diffraction orders combined is constant regardless of the applied voltage, for a constant light input. The effect of the applied voltage is merely to redistribute this energy within the various orders. One advantage of the diffraction grating mode of operation is that the required half-wave voltage as defined by (31) is lower than given by (23) for the conventional Pockels mode. In fact for d equal to L we find that for 0.633 μm light, $V_{1/2}$ is equal to 950 volts for the diffraction grating mode as opposed to 2950 volts for the conventional Pockels mode.

The concept of using an interdigital electrode modulator with a lithium niobate crystal was tested experimentally both in the laboratory and in an optical communications test link. Shown in figure 18 is a photograph of a modulator of this type that was designed, fabricated, and assembled in house. The modulator was made from a lithium niobate crystal of acoustic grade quality purchased from Union Carbide Crystal Company of San Diego, California, for $250. The clear aperture of the crystal is 45 X 55 mm. A set of aluminum interdigital electrodes (0.2 μm thick) was fabricated on one of the optical surfaces of the crystal and then given a protective overcoat of 0.4 μm of silicon dioxide. Each interdigital electrode finger in the array is 100 μm wide, and the center-to-center spacing between adjacent electrodes is 1 mm. As previously mentioned, the optic axis (C or z-axis) of the crystal lies in the plane of the electrode array orthogonal to the interdigital electrode fingers.

The results of tests performed to date using this modulator in the conventional Pockels mode depicted in figure 13 have been unsatisfactory, principally because in the experiments we have been unable to reach the half-wave voltage required to turn the modulator device fully on. At about 1500 volts, electrical arcing between adjacent electrodes

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Figure 18. 45 X 55 mm clear aperture $LiNbO_3$ crystal modulator with interdigital electrodes.

begins to take place. It has been hypothesized that the present vacuum deposition technique used for overcoating the crystal with silicon dioxide is unacceptable. The problem possibly is due to incomplete overcoating of the aluminum electrodes, particularly on the electrode facets which are perpendicular to the crystal surface on which they are fabricated. If this is the case, one would expect to see arcing as one approached the dielectric breakdown voltage of air. It has been suggested that this problem could be eliminated by burying the electrodes within the crystal surface (say 100 angstroms deep) before overcoating with the silicon dioxide, a technique that is yet to be tested.

The results of tests performed using the lithium niobate modulator in the diffraction grating mode depicted in figure 16 have been highly satisfactory. As indicated before, the half-wave voltage for this mode is approximately one-third the half-wave voltage for the conventional Pockels mode of operation. For the diffraction grating mode we were able to operate the crystal modulator below 1000 volts; thus arcing was not a problem. Figure 19 shows the transmission characteristics of the lithium niobate modulator associated with the zeroth diffraction order as a function of the applied dc voltage. We note that this curve follows closely the cosine-squared curve predicted by (32) for a half-wave voltage of approximately 900 volts. When the lithium niobate modulator used in the diffraction grating mode was tested in an optical communications test link, we found that it performed above expectations. Voice quality was excellent over fields of view up to ±35 degrees and over ranges up to 1 mile.

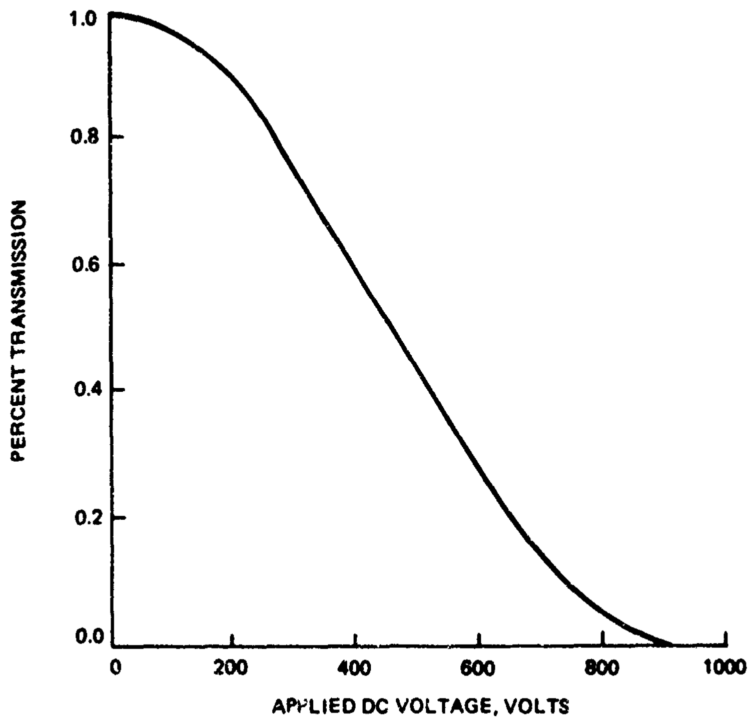

Figure 19. Transmission characteristics of $LiNbO_3$ in the diffraction grating mode for the zeroth order as a function of applied dc voltage.

KERR EFFECT LIQUIDS

The quadratic electro-optic Kerr effect, like the linear electro-optic Pockels effect, is fairly well understood from a theoretical point of view. Like the Pockels crystals, Kerr materials can also be described in terms of an index ellipsoid equation, provided the Kerr tensor coefficients associated with the liquid of interest are known. Our investigation of Kerr liquids as a potential large-aperture optical modulator, however, was strictly limited to determining whether the concept of a large-aperture Kerr cell was feasible. Therefore, a theoretical treatment of the interaction of light with a Kerr liquid subjected to a strong external electric field will not be presented.

There are a number of electro-optical liquids which could be potentially used in a Kerr cell geometry. The primary requirement is that the molecules making up the liquid have an associated permanent electric dipole moment which can interact with an externally applied electric field. The application of the field has the tendency to align molecules in the liquid in a preferred direction, making the liquid optically anisotropic at the macroscopic level. Removal of the field allows the molecules to reorient to a random distribution, making the liquid optically isotropic. Turn-on and turn-off times in the subnanosecond range are not uncommon.

Nitrobenzene ($C_6H_5NO_2$) is one of the Kerr liquids that is commonly used due to its large Kerr coefficient. An important advantage of using an electro-optic liquid is that, in principle, a single modulator device could be made with a clear aperture as large as desired, whereas solid-state material is size-limited. However, the Kerr cell modulators fabricated to date employ a transverse parallel-plate electrode geometry, as depicted in figure 3. Thus for a transverse mode of operation, the required half-wave voltage increases with the parallel-plate spacing. The largest fabricated modulators using nitrobenzene have typically clear apertures on the order of 1 inch square and require on the order of 60 kilovolts for operation of a cell with a 1-inch optical path length. A way to counteract the high voltage requirement while maintaining a large clear aperture has been proposed and briefly investigated by NOSC scientists. The concept consists of a Kerr cell modulator employing interdigital electrodes, an approach which is analogous to that used for the lithium niobate crystal modulator. Based on information gathered, it was our opinion that although this was a high-risk approach, such a modulator could have a dramatic impact on the large-aperture modulator problem if it were successful. The concept of an interdigital electrode Kerr liquid modulator appears to be untested, as judged from publications in the field. A principal disadvantage of this approach is that nitrobenzene, like many of the other organic liquids with high Kerr coefficients, is an extremely toxic liquid for which special handling procedures must be used. Unfortunately we were not in a position to handle these chemicals safely within the present facilities set up for our large-aperture optical modulator program. The high risk factor and the toxicity of these materials were the primary reasons our efforts were concentrated on the other modulator material candidates. However, we did assess this approach to determine whether future work would be warranted.

Preliminary calculations were performed for an interdigital electrode array embedded in a Kerr liquid medium. The interdigital electrode array geometry considered was that used for the lithium niobate crystal modulator. As before, the electrode fingers are 100 μm wide with a 1-mm center-to-center spacing. The active area of the electrode array is 33 X 55 mm.

Listed in table 1 is pertinent information regarding a variety of the electro-optical Kerr liquids considered. We see from this table that even for nitrobenzene, the most widely used Kerr liquid, a half-wave voltage of approximately 22 kilovolts would be required for this geometry. In contrast, the lithium niobate crystal has a half-wave voltage near 900 volts for the same geometry. Based on the results of this preliminary investigation, it was recommended that no further effort along these lines be pursued as part of the large-aperture optical modulator program for the duration of this fiscal year (1978).

TABLE 1. ELECTRO-OPTICAL KERR LIQUID CHARACTERISTICS.

	B	K	$V_{1/2}$	c	C
Nitrobenzene	4.4	34.82	21.6	0.206	374.0
Nitrotoluene	2.0	27.40	32.1	0.161	294.0
Acetone	0.16	20.00	114.0	0.118	214.0
Carbon disulfide	0.035	2.64	243.0	0.016	28.4
Distilled water	0.040	80.37	227.0	0.476	864.0

B = Kerr constant $(m/V^2) \times 10^{-12}$

K = Relative dielectric constant

$V_{1/2}$ = Half-wave voltage (kilovolts)

c = Capacitance per unit area $(\mu F/m^2)$

C = Total capacitance (pF)

FERROELECTRIC CERAMIC PLZT

Lead Lanthanum Zirconate Titanate (PLZT) is a clear ferroelectric ceramic whose optical transmission properties can be altered by the application of an external electric field. During the last few years a considerable amount of experimental work has been performed at the Sandia Laboratories as well as other laboratories to ascertain the basic properties of this material. At the present, no unified theory equivalent to the index ellipsoid approach used to describe the electro-optic Pockels and Kerr effects has yet emerged to explain PLZT behavior.

A particular area of main concern at various laboratories has dealt with changing the optical transmission characteristics of the PLZT ceramic by the application of an external electric field. A variety of techniques have been explored. The most common one in use today entails fabricating a set of interdigital electrodes on the two large surfaces of a thin PLZT ceramic wafer and operating the material in a transverse mode. This approach is analogous to that adopted at NOSC for the electrical excitation of lithium niobate crystals. PLZT is being used in a transverse mode of operation in several application areas. For the most part, however, these applications require that the ceramic be used only in an on/off optical shutter mode of operation. For example, PLZT is currently being developed as a lens element for nuclear flashblindness prevention goggles, as a lens element for glasses used for stereoscopic TV viewing, and as a lens element in welders' helmets. Very little work, if any, has been done in evaluating these ceramic materials for their analog modulation capabilities, particularly for a large-area ceramic wafer.

To investigate the use of PLZT as a large-aperture optical modulator, both 2- and 4-inch diameter PLZT ceramic wafers were obtained. These materials consist of 65% lead zirconate and 35% lead titanate, with approximately 9 atomic percent of the lead replaced with lanthanum. This particular composition exhibits a large transverse quadratic effect (similar to the Kerr effect in liquids) with minor hysteresis effects. The most important property of interest to us is the change in transmission of the ceramic with applied voltage. The curve in figure 20 represents the transmission response of a 2-inch diameter PLZT wafer having a thickness of about one-third millimeter, for two-way transmission using 0.633 μm light, as a function of applied dc voltage. A combination of gold and chrome interdigital electrodes 1 micron thick located on both surfaces of the ceramic wafer was used for electrically exciting the ceramic. The center-to-center spacing between electrodes is about 1.25 mm. The 2-inch diameter PLZT wafer with electrodes was provided to us by Honeywell Corporation of Minneapolis, Minnesota (see figure 21). For the two-way transmission experiment a single polarizer was used that served both as an input polarizer and an output analyzer. The transmission axis of the polarizer was oriented 45 degrees from the interdigital electrode fingers on the PLZT wafer. As seen from the experimental data in figure 20, the transmission response of the ceramic is fairly flat from zero to about 400 volts. Above this level the transmission falls off rapidly to a minimum at about 600 volts, and it then begins to increase with a further increase in voltage. The associated depth of modulation, defined by the equation

$$DM = \frac{(T_{max} - T_{min})}{(T_{max} + T_{min})} , \quad (33)$$

was measured at better than 90 percent, based on these data. T_{max} and T_{min} represent the maximum and minimum values of the transmission of the ceramic, from figure 20. An important observation and very positive result is that this transmission curve was relatively insensitive to angles of incidence up to ±20 degrees. The curve in figure 20 would thus indicate that biasing the PLZT wafer to 500 volts dc and then swinging the voltage plus and minus 100 volts about the bias may be a very desirable way to modulate the PLZT. In order to test this theory, a special-purpose electronic driver was designed and built in house, by NOSC. This driver has the capability of electrically biasing the ceramic anywhere from 175 to 600 volts dc and swinging this bias up to ±300 volts for frequencies in the kilohertz range. The schematic diagram, figure 22, shows the electronic driver circuitry; figure 23 shows the electronic driver biasing circuitry; and figure 24 is a photograph of the finished driver. This same driver can be used to drive the lithium niobate and potassium dideuterium phosphate crystal modulators as well. However, because of the differences in capacitance from from one modulator to the next, the excursion in ac voltage swing as a function of driver frequency will be different for each type of modulator. Using this electronic driver and the 2-inch PLZT modulator, we have been able to demonstrate successful optical communications in the laboratory, using 0.633 μm light. The carrier frequency was varied from 14 to 24 kilohertz, and the resultant voice quality was excellent.

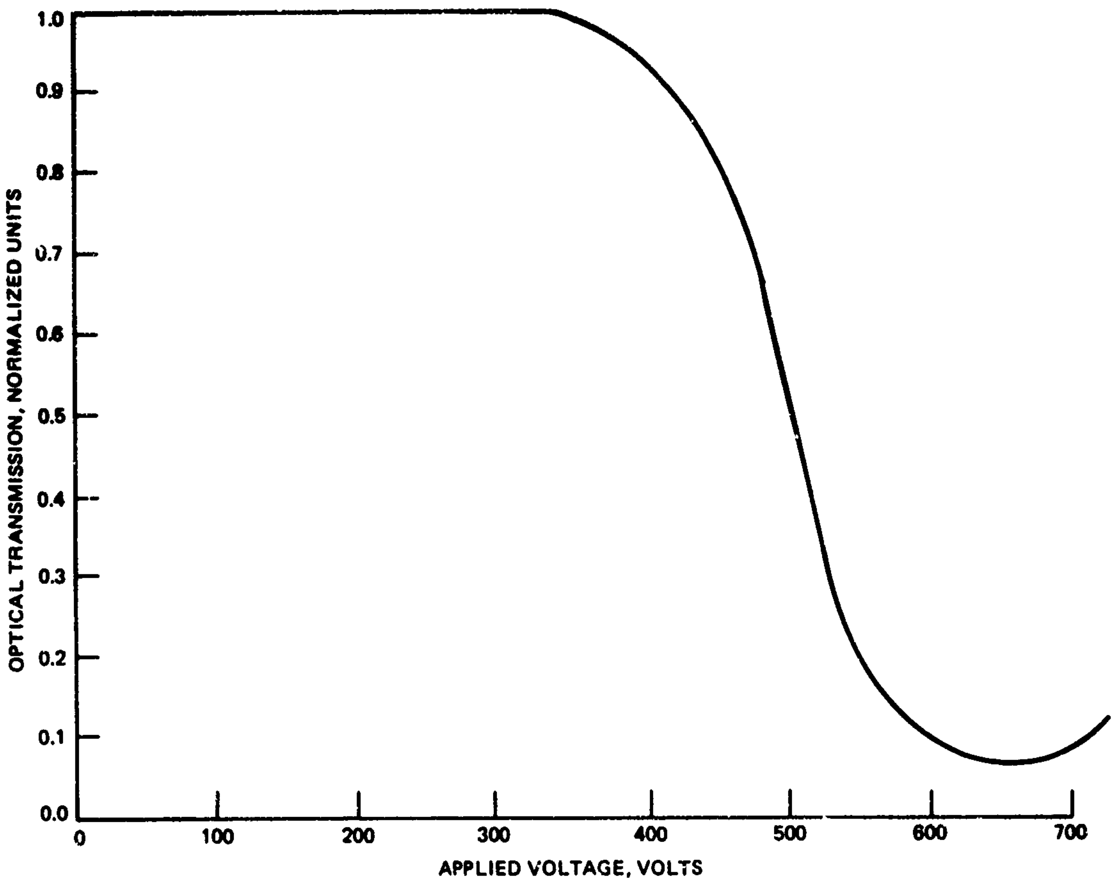

Figure 20. Transmission characteristics of PLZT as a function of applied voltage.

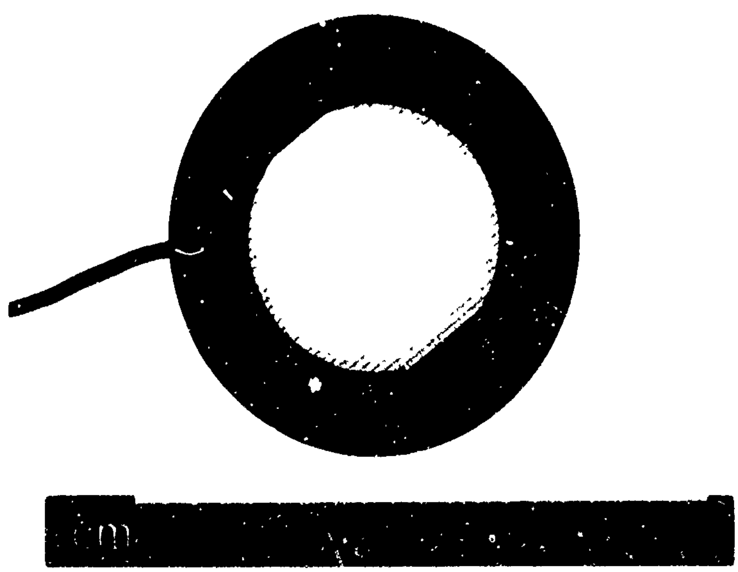

Figure 21. 50-mm diameter clear aperture PLZT ceramic modulator with interdigital electrodes.

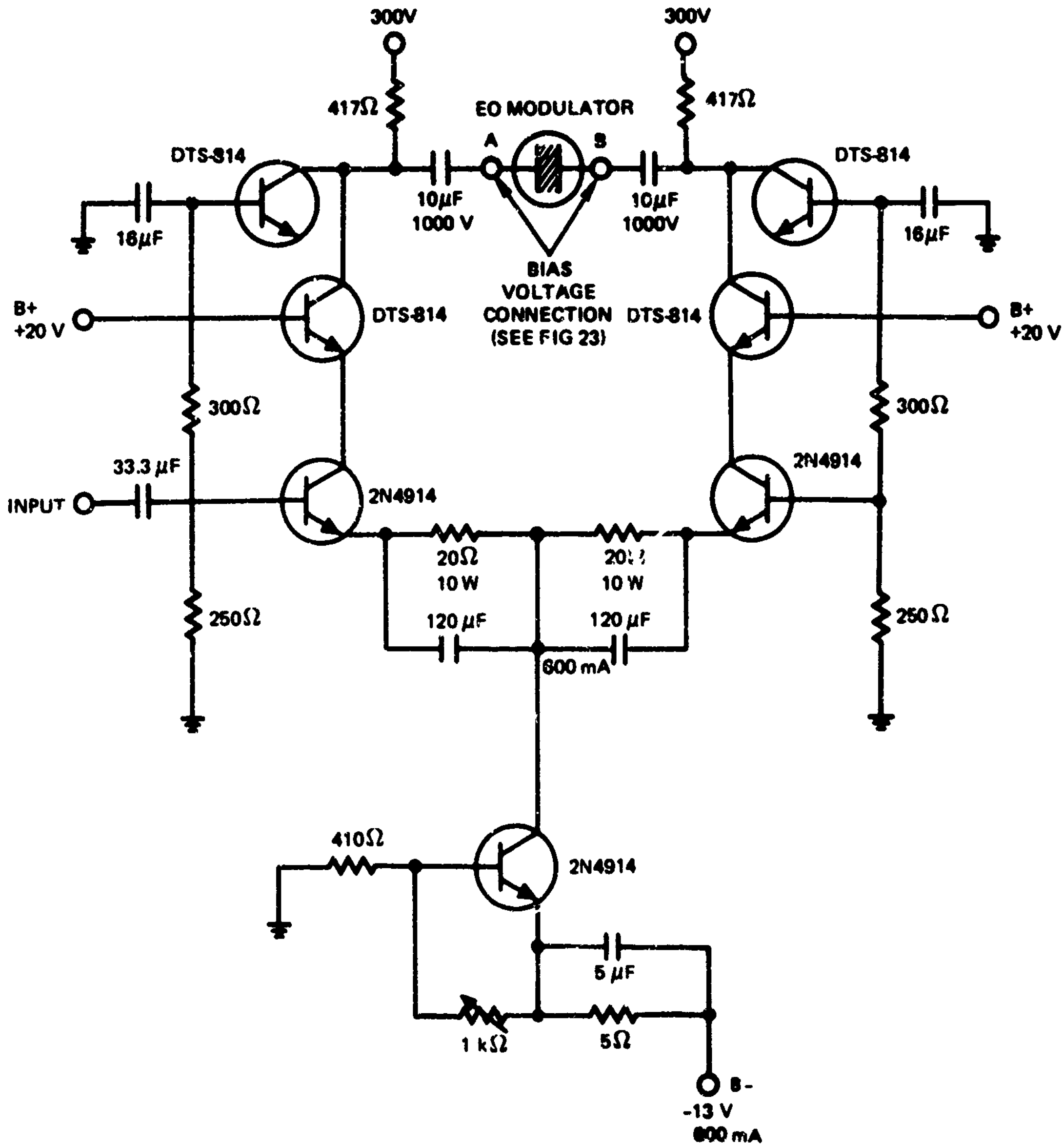

Figure 22. Electronic driver modulator circuitry.

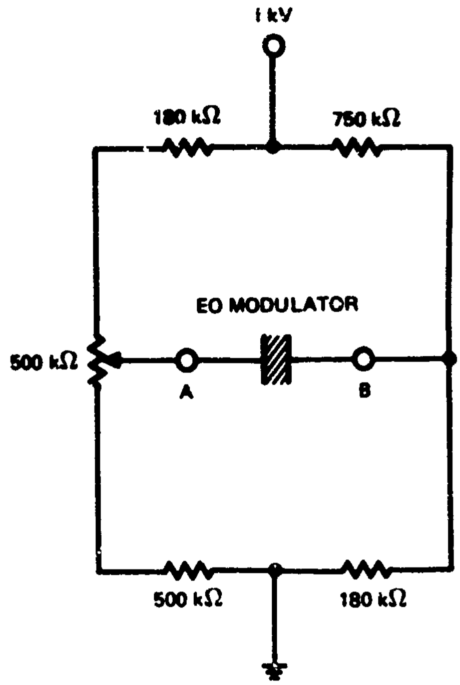

Figure 23. Electronic driver biasing circuitry.

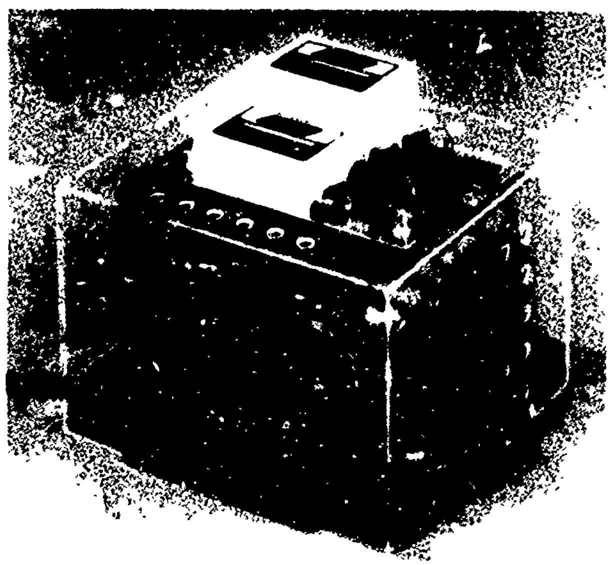

Figure 24. Electronic driver.

After completing tests on the 2-inch diameter PLZT ceramic wafer, we laboratory-tested a 4-inch diameter PLZT wafer with interdigital electrodes that was obtained from the Ceramics Center at Sandia Laboratories in Albuquerque, New Mexico, on a 6-month loan agreement. The electrode structure on the 4-inch version was identical to that on the 2-inch ceramic in terms of composition and center-to-center spacing between adjacent electrode fingers. Figure 25 is a photograph of the 4-inch diameter PLZT modulator mounted in a special-purpose holder that was designed and fabricated at NOSC. The electronic driver used for the 2-inch PLZT wafer was the same as that used to drive the larger version. For the tests with the 4-inch PLZT modulator, the carrier frequency was varied from 5 to 10 kilohertz. Figure 26 shows how the carrier frequency amplitude level varies as a function of the applied dc bias voltage, with the ac swing voltage as the parameter for a 5 kilohertz carrier signal. These curves show that the carrier frequency amplitude levels out at between 500 and 600 volts, indicating that a bias voltage in this range appears to be optimum for the ceramic under test. We also note that the amplitude level can be increased by increasing the ac voltage swing. Plus and minus 150 volts was the limit to which we could push the present driver with the 4-inch diameter modulator.

There are two final points regarding the PLZT ceramic as a modulator material. First, the largest PLZT wafers Honeywell has fabricated to date (using hot pressing techniques) are 4 inches in diameter. To fabricate a larger area device would require going to a mosaic type of structure. Second, the ceramic wafers tested in house at NOSC are unbonded. Bonding is a technique used by Honeywell for sandwiching a PLZT ceramic wafer with electrodes between two optical-quality glass plates, to provide structural integrity. Honeywell Corporation will be going into production later this year in fabricating 4-inch diameter bonded PLZT ceramic shutters for the Air Force Nuclear Flashblindness Prevention Goggle Program. On a production basis, these shutters will cost in the neighborhood of $600 per unit.

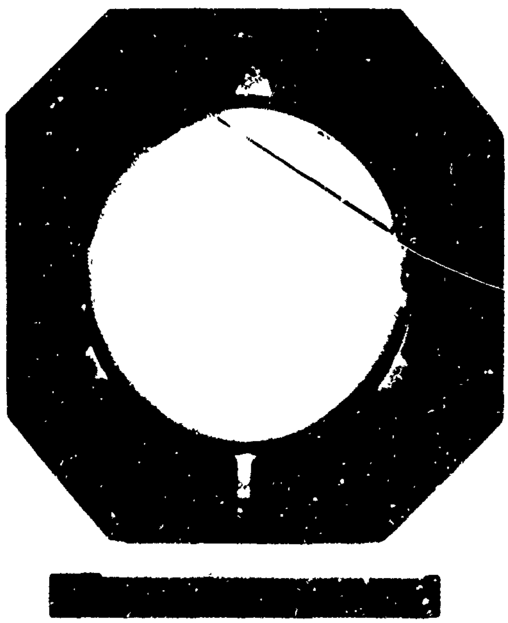

Figure 25. 100-mm diameter clear aperture PLZT ceramic modulator with interdigital electrodes obtained from Sandia Laboratories in Albuquerque, New Mexico.

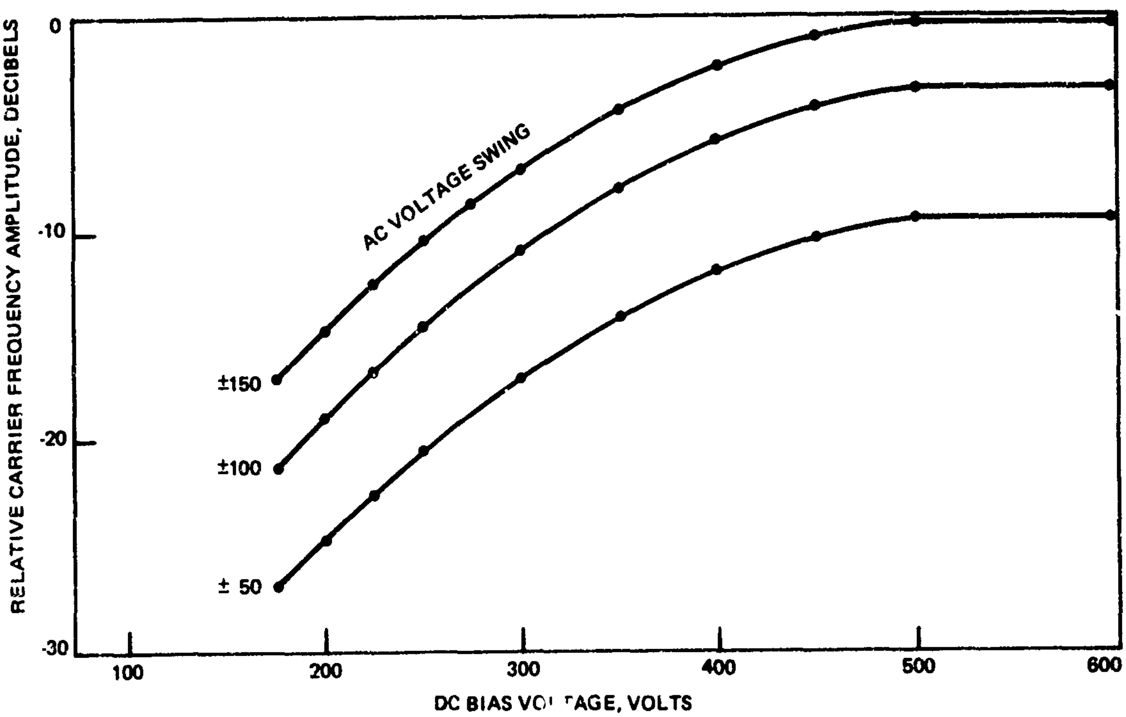

Figure 26. Relative carrier frequency amplitude level versus dc bias voltage for 5 kilohertz carrier frequency (Parameter: ac voltage swing).

Our general consensus now is that the PLZT ceramic would serve as an excellent large-aperture optical modulator for the various optical channels of concern. Definitely, it has the various properties sought in a large aperture modulator: large aperture (up to a 4-inch diameter for a single device), large field of view (±20 degrees), insensitivity to the angle of arrival of the incoming wavefront, able to be fabricated with excellent optical quality, operable at audio frequencies, and able to be fabricated at reasonable cost, on a production basis.

CONCLUSIONS

Six categories of active optical materials were identified and classified. Selected test and evaluation from materials in these categories were four active materials that seemed likely to be able to satisfy the large-aperture optical modulator requirements. These four material candidates are lithium niobate and potassium dideuterium phosphate (electro-optical linear Pockels crystals), nitrobenzene (an electro-optical quadratic Kerr liquid), and lead lanthanum zirconate titanate (a ferroelectric ceramic). Of these four material candidates, only the lithium niobate crystal and the ceramic showed real promise.

Lithium niobate crystals and single-element ceramic wafers presently can be fabricated with clear apertures of 2 and 4 inches, respectively. For larger area modulators, a mosaic structure of modulator elements would have to be considered for both materials. Both the lithium niobate crystals and ceramic wafers satisfy the requirements of field of view, optical quality, frequency response, and economic availability. Both materials performed above expectations when tested in an actual optical communications test link.

Although potassium dideuterium phosphate can be grown in single-crystal form to diameters of 12 inches, it is highly sensitive to the angle of arrival of the incoming light beam. This problem can be eliminated by using two properly oriented crystals in series. Its only other drawback is its cost, which for a given aperture size is presently five times greater than that of the ceramic or lithium niobate units, in quantities of one.

Neither nitrobenzene nor any of the other Kerr liquids was tested. These materials are extremely toxic, and our laboratory facilities are inadequate to handle them. However, a feasibility study was performed concerning the concept of an interdigital Kerr cell modulator. It appears that the concept would work, but at present lithium niobate and the ceramic show much greater promise.

RECOMMENDATIONS

1. Place emphasis on the use of lead lanthanum zirconate titanate ceramic and lithium niobate crystal as materials for future optical modulator applications in which a large aperture is required.

2. Consider potassium dideuterium phosphate further only if its cost can be brought in line with the cost of these two materials.

3. For future work which could improve the performance of lithium niobate crystal, consider buried channel interdigital electrodes on both large optical surfaces of the crystal to further reduce both the half-wave voltage requirements and the arcing problems encountered in some of the past experiments.

4. Consider bonded versions of lead lanthanum zirconate titanate, which would provide a very desirable increase in its structural integrity.

5. In future work with optical modulators of larger area, address the problems associated with fabricating a mosaic stucture from smaller, individual modulator elements.

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