MICROWAVE MODULATION OF THE ELECTRO-OPTIC EFFECT IN KH_2PO_4

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KH_2PO_4 (KDP) is a colorless transparent crystal that belongs to the tetragonal group $\bar{4}2m$ (V_d), which lacks a center of inversion, and exhibits a linear electro-optic effect. It undergoes a ferroelectric phase transition at 120°K.[1] According to a model of KDP and isomorphous compounds, the dielectric polarization depends upon the motion of the protons in a double minimum potential.[1,2] These protonic motions can alter the symmetry and magnitude of the electronic polarizability and, hence, the optical properties of the crystal.

In the paraelectric phase, KDP is optically uniaxial with the optic axis along the tetragonal Z axis. Light propagating along Z travels with the same velocity irrespective of the plane of polarization. The application of an electric field E along Z reduces the crystal symmetry to orthorhombic and the optical symmetry to biaxial.[3] Hence, the index of refraction for light propagating along Z is different for light polarized in the two principal planes. After passing through a length L, the phase retardation Γ between the principal waves is

$$\Gamma = \pi EL/V_0, \qquad (1)$$

where V_0 is the (zero-strain) value of EL for half-wave retardation.

Measurements of the dielectric constant at a frequency of 25 kMc/sec (at 25°C) agree with the low-frequency dielectric constant of a clamped crystal.[1,4] Since the electro-optic effect is proportional to the polarization,[1] one would not expect any appreciable reduction in V_0 below 25 kMc/sec.[5] Previous measurements have shown V_0 to be frequency independent to 500 Mc/sec.[6] We have observed the electro-optic effect in KDP at room temperature and 9.25 kMc/sec and find V_0 to be of the same order as the low-frequency value.

The apparatus [Fig. 1(a)] consists of a 25-watt zirconium concentrated arc lamp with a Corning 7-69 infrared filter peaked at 8000 A, a Glan-Thompson polarizer and crossed analyzer, an RCA 7102 (S-1) photomultiplier, and a pulsed X-band magnetron which feeds a cylindrical cavity containing the KDP rod. The cavity is filled with polystyrene and the dimensions are

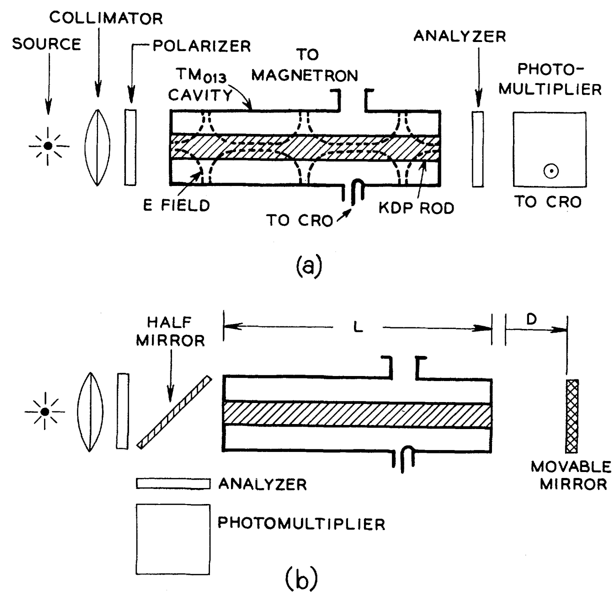

FIG. 1. (a) Transmission apparatus. (b) Reflection apparatus.

adjusted so that the microwave phase velocity approximates the light velocity when the cavity is excited in the "TM_{013}-like" mode. If the cavity standing wave is decomposed into a forward and a backward travelling wave, it can be shown that, to good approximation, the backward wave produces no net retardation when the velocities are matched, while the forward wave provides a constant E at a given point in the light wave train as it passes through the crystal.[7] The light velocity in the crystal is $c/1.47$; the microwave velocity at 9.25 kMc/sec is $c/1.38$.

With the polarizer and analyzer crossed, pulses from the photomultiplier are observed coincident with the microwave pulses (3 μsec at 60 pulses/sec). In order to obtain direct evidence of microwave modulation, a movable mirror and half mirror are placed as shown in Fig. 1(b). When the transit time for light leaving the end of the crystal, reflecting from the movable mirror, and re-entering the crystal is equal to an odd multiple of the microwave half-period, light pulses are observed in the photomultiplier. When the mirror is moved a distance D equal to one-quarter the free-space microwave wavelength, no pulses are observed

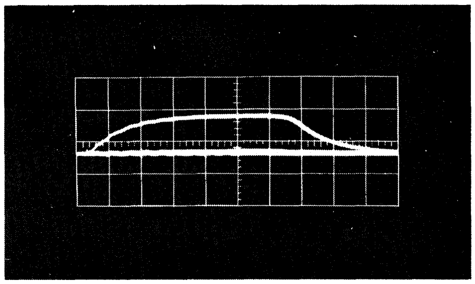

FIG. 2. Photomultiplier response with mirror set for maximum signal (top). With mirror displaced $\lambda/4$, the response is nearly coincident with that obtained by covering the source (bottom). ($\frac{1}{2}$ μsec/div. Circuit time constant ~ $\frac{1}{2}$ μsec.)

(Fig. 2). In the first case, the retardation is doubled, while in the latter the net retardation is zero.

The time-average relative intensity for modulated light with crossed polarizers, $\rho_\perp$, and with parallel polarizers, $\rho_\parallel$, is[8]

$$\rho_\perp = \tfrac{1}{2}[1 - J_0(\Gamma_p)], \quad \rho_\parallel = \tfrac{1}{2}[1 + J_0(\Gamma_p)], \tag{2}$$

where J_0 is the zero-order Bessel function and Γ_p is the peak retardation. With a peak power P of 760 watts absorbed in the cavity, $\rho_\perp = \rho_\parallel$ (Fig. 3) and $\Gamma_p = 2.40$.

The peak field intensity in the forward wave E may be estimated by assuming a uniform longitudinal E across the rod with sinusoidal variation along the rod and assuming all the power P to be dissipated in the rod. Then

$$E \sim (QP/\omega\epsilon\epsilon_0 v)^{1/2} \sim 70 \text{ volts/mm}, \tag{3}$$

in which ϵ and Q are the dielectric constant and dielectric Q for the rod at angular frequency ω

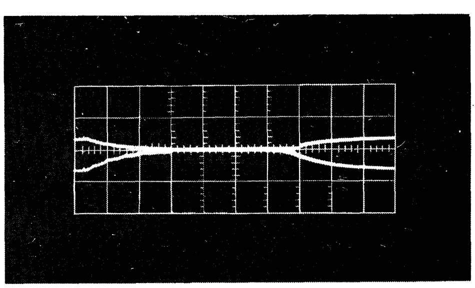

FIG. 3. Photomultiplier response with parallel polarizers (upper) and with crossed polarizers (lower) for $\rho_\perp = \rho_\parallel$.

and v is the rod volume ($L = 35.5$ mm, diameter 4 mm). In the absence of 9-kMc/sec data, we have used the 25-kMc/sec values[4] $\epsilon \sim 20$, $Q \sim 30$. For $\Gamma_p = 2.40$,

$$V_0 = \pi E 2L/\Gamma_p \sim 7 \text{ kv}. \tag{4}$$

This estimate may be compared with the low-frequency clamped value of 11 kv obtained by extrapolating measurements of W. L. Bond to 8000 A.

KDP is transparent between 4000 A and 13 000 A. Since V_0 decreases with decreasing wavelength,[6] the effect may be enhanced by operating at shorter wavelengths. Further enhancement, with increased loss, may be obtained by increasing L and by operating nearer to the Curie temperature, either by reducing the temperature, or by choosing an isomorphous compound with a higher Curie temperature.[2]

The tunnelling frequency[2] for protons in the double minimum potential occurs at ~200 cm^{-1} (6000 kMc/sec). Therefore, it may be possible to extend the modulating frequency to much higher frequencies than the 9.25 kMc/sec used here.

It may also be possible to construct a broad-band low-power microwave light modulator, using more sophisticated structures or other materials, for use in a practical optical communication system.[9] The bandwidth for the present structure is limited by the cavity Q: $\Delta f \sim f/150 \sim 60$ Mc/sec. In a pure travelling wave structure, a limitation would be the band over which the microwave and light velocities can be matched.

A microwave light modulator might also be used as an instrument for studying short relaxation times and other effects in optically pumped systems or for refined measurements of the velocity of light.

It is a pleasure to acknowledge instructive discussions with R. Kompfner, A. G. Fox, E. H. Turner, and R. F. Trambarulo, and the assistance of F. A. Dunn.

[1] W. Känzig, in Solid State Physics, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1957), Vol. 4.

[2] R. Blinc, J. Phys. Chem. Solids 13, 204 (1960).

[3] B. H. Billings, J. Opt. Soc. Am. 39, 797 (1949).

[4] W. A. Yager, quoted in Piezoelectric Crystals and Their Application to Ultrasonics, edited by W. P. Mason (D. Van Nostrand and Company, New York, 1950), p. 258.

[5]N. Bloembergen, P. S. Pershan, and L. R. Wilcox, Phys. Rev. 120, 2014 (1960).

[6]R. O'B. Carpenter, J. Opt. Soc. Am. 40, 225 (1950).

[7]The use of a travelling wave structure has been suggested by N. Bloembergen [talk, NEREM, Boston, No. 1960] and the possibility of using the standing wave structure by R. Kompfner.

[8]Clark, Holshouser, and von Foerster, Technical Note 1-2, Engineering Experimental Station, University of Illinois, 1957 (unpublished).

[9]E. H. Turner attempted to observe microwave light modulation (1952) using $NH_4H_2PO_4$ (ADP) in a rectangular TE_{101} cavity but was unsuccessful because of the short length of ADP permitted by the structure. Bloembergen, Pershan, and Wilcox[5] have suggested, independently, the use of dihydrogen phosphates for microwave modulation of light.

EVIDENCE FOR FOCUSING COLLISIONS IN IRRADIATED PLATINUM

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Focusing collisions along close-packed directions in face-centered cubic metals were first predicted by Silsbee.[1] A more elaborate theory has recently been developed by Leibfried and co-workers,[2] for the case of ⟨110⟩ focusing.

Gibson, Goland, Milgram, and Vineyard[3] found evidence for this process by means of machine calculations on a dynamical model. They showed, moreover, that focusing also occurs along ⟨100⟩ and ⟨111⟩ directions; this was attributed to the influence of the neighboring rows.

Direct experimental evidence is practically limited to the sputtering experiments of Thompson.[4] He found that preferential ejection of atoms occurs along ⟨110⟩, ⟨100⟩, and ⟨111⟩ directions. The focusing effect along the non-close-packed rows was explained using an optical analogy.[5]

The rapid decrease in internal friction on irradiation has been attributed to the preferential formation of defects at dislocations as a consequence of focusing collisions.[6]

In this note we wish to present some rather direct evidence of a completely different type, which was obtained during the electron optical examination of irradiated platinum foils.

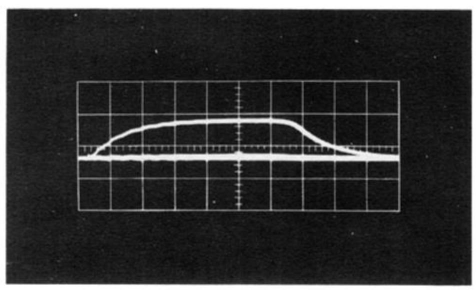
The specimens consisted of about 0.1-micron thick beaten foil, annealed for one hour at 800°C in order to eliminate part of the dislocations and to obtain a reasonable grain size. The anneal also resulted in the formation of annealing twins, generally limited by coherent twin boundaries.

Such specimens were mounted in contact with uranium foils and irradiated at reactor temperature (≈80°C) in the BR-1 reactor over periods of $\frac{1}{2}$, 2, and 5 hours. The number of fission fragments that penetrated into the platinum foil under these circumstances were, respectively, 2.5×10^9, 1×10^{10}, and 2.5×10^{10} cm^{-2}. After the irradiation the specimens were examined with the Philips electron microscope operated at 100 kv. Figure 1 shows the increasing concentration of black dots with increasing dose. Such "measles" have been observed previously in other irradiated materials.[7-9]

By pulse annealing it was verified that the "measles" disappear at about 400-500°C in accord with the annealing peak found by Piercy[10] and attributed by him to the motion of vacancies. From this evidence and from the approximate proportionality of their concentration with dose, it is reasonable to accept that the black dots correspond to defect clusters. The most significant feature of this investigation is, however, that measles appear preferentially along coherent twin boundaries as shown in Fig. 2; and much less pronounced along ordinary boundaries. This fact can, of course, not be attributed to preferential impinging of fission fragments along the coherent twin interface.

It is therefore difficult to avoid the conclusion that momentum transfer has taken place resulting in the preferential creation of defects along the twin boundary. Since coherent twin boundaries do not act as sources or sinks for point defects, as shown by Barnes,[7] the defects would not easily disappear there as would be the case if they were formed at ordinary boundaries.

The preferential formation of defects at coherent twin boundaries can easily be understood on the basis of the theory of focusing collisions. Suppose that momentum transfer occurs along a ⟨110⟩ direction, as would be the case in the Silsbee type of focusing. The ⟨110⟩ direction



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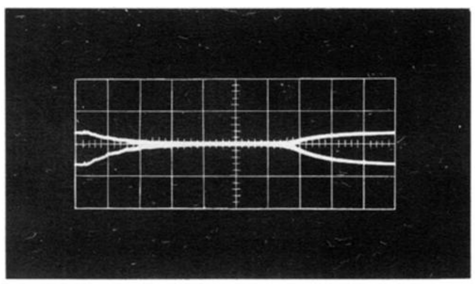

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