3 DEVELOPMENT OF A 10.6-MICRON LASER MODULATOR 4

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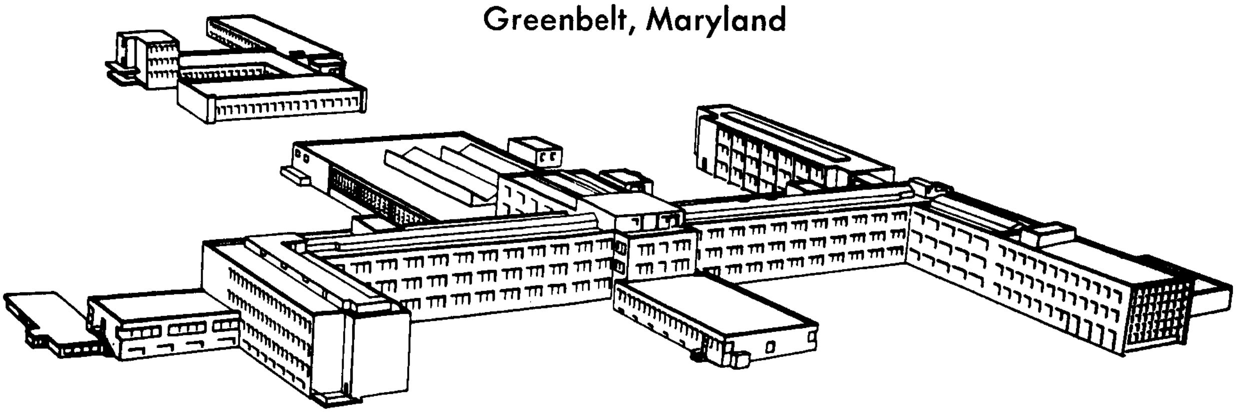

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DEVELOPMENT OF
A 10.6-MICRON LASER MODULATOR

I. Objectives

The objective of this program was to develop a Gallium Arsenide electro-optic modulator capable of modulating the output from a 10.6 micron laser. A depth of modulation greater than 35% was required for an applied voltage of 1000 volts rms over a bandwidth from dc to over 10 MHz. A modulator similar to this was developed for the wavelength range 0.9 to 3.0 microns under Contract NAS 5-9620. The extension of the operating wavelength to 10.6 microns required the development of polarizers and waveplates for this wavelength.

II. Electro-Optic Modulation

The electro-optic effect is an electric field induced change in the optical indices of refraction of a crystal. There is no satisfactory microscopic theory which predicts the magnitude of the effect from the crystal properties, although Heilmeier(1) has presented a theory for the molecular crystal Hexamethylenetetramine giving good agreement with the observed value. There is, however, a complete phenomenological theory(2) so that once the electro-optic coefficients of a material are measured, the effect of an electric field in the crystal on the transmittance of a light beam through the crystal can be predicted for any orientation of the crystal axes with respect to both the electric field and the light beam. A review of the theory for cubic crystals such as Gallium Arsenide is given by Namba(3) and by Sterzer et al(4).

A cubic electro-optic crystal like GaAs is optically isotropic in the absence of an electric field. The application of an electric field along certain crystal directions causes the crystal to become birefringent by an amount proportional to the electric field. The crystal is therefore an optical wave plate with a voltage controlled retardation and can be used in various optical systems to electrically modulate the intensity, phase, or polarization of a light beam. Three such configurations are shown in Figure 1.

III. Crystal Growth and Properties

A. Growth

The crystals are boat grown in a horizontal Bridgeman furnace from elemental Gallium and Arsenic. They are doped with Iron during growth to raise their resistivity above 10^6 ohm cm over the entire length of the ingot. A typical ingot and a modulator crystal cut from the ingot are shown in Figure 2. The ingot is 1 1/2 cm in diameter and 8 cm long. It has been seeded to make most of its length useful for modulator crystals. The crystals are hard, non-hygroscopic, and possess a relatively high thermal conductivity. They are virtually strain free as grown and are easily cut and polished flat to 1/10 wavelength of visible light without introducing appreciable strain. The extinction ratio of 1 cm thick crystals between crossed polarizers is greater than 100 to 1 after all cutting and polishing operations and they can be handled rather carelessly without introducing additional strain. Since the crystals are insoluble in water and dissociate at 800°C, no special precautions are necessary with regard to ambient temperature and humidity.

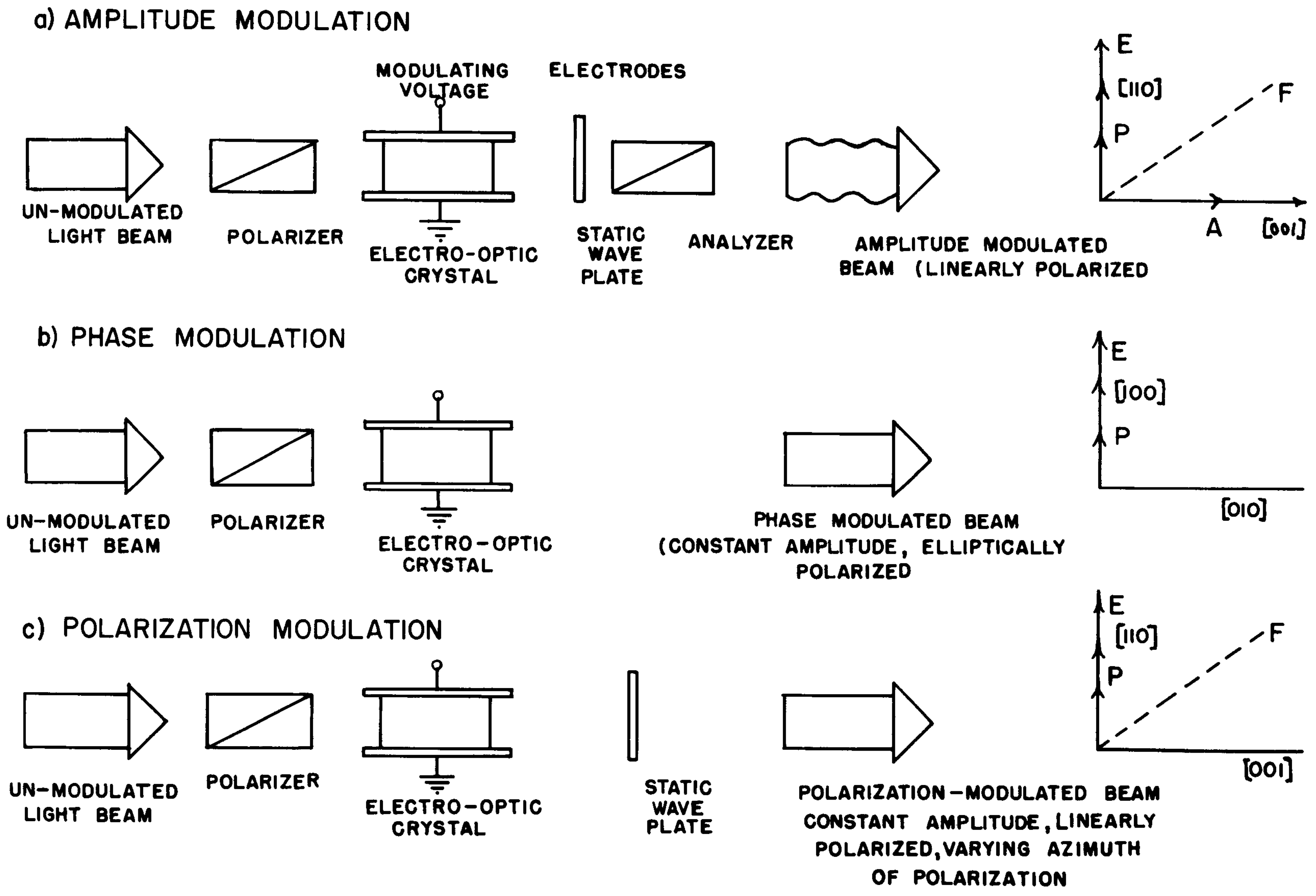

Fig. 1 — Three optical systems for electrically modulating a light beam using an electro-optic crystal.

Fig. 2 — A gallium-arsenide ingot and a modulator crystal cut from the ingot.

B. Optical Properties

The crystals are opaque in the visible, but are transparent in the infrared between 0.9 and 16 microns. The excellent optical quality of the crystals in the infrared is illustrated in Figure 3 which is a photograph of a Gallium Arsenide crystal on a metal scale. The photograph was taken with the aid of an infrared image converter sensitive to wavelengths near 1 micron. The optical quality is comparable to that of good optical glass.

The optical absorption coefficient k was determined by measuring the transmittance of a crystal which was polished on four faces to provide two unequal path lengths through the crystal. This permits correction for the reflection losses which are equal for the two directions. The absorption coefficient determined in this manner is shown as a function of wavelength in Figure 4. The smallest absorption coefficient which could be measured on the spectrometers used was 0.01 cm^{-1}.

At those wavelengths where negligible absorption exists, reflection losses limit the external transmittance of a plane-parallel plate of GaAs to 55%. This low transmittance is due to the high index of refraction of GaAs, shown in Figure 5. The external transmittance T is given in terms of the refractive index N by the expression

$$T = \frac{2N}{N^2 + 1} \qquad (1)$$

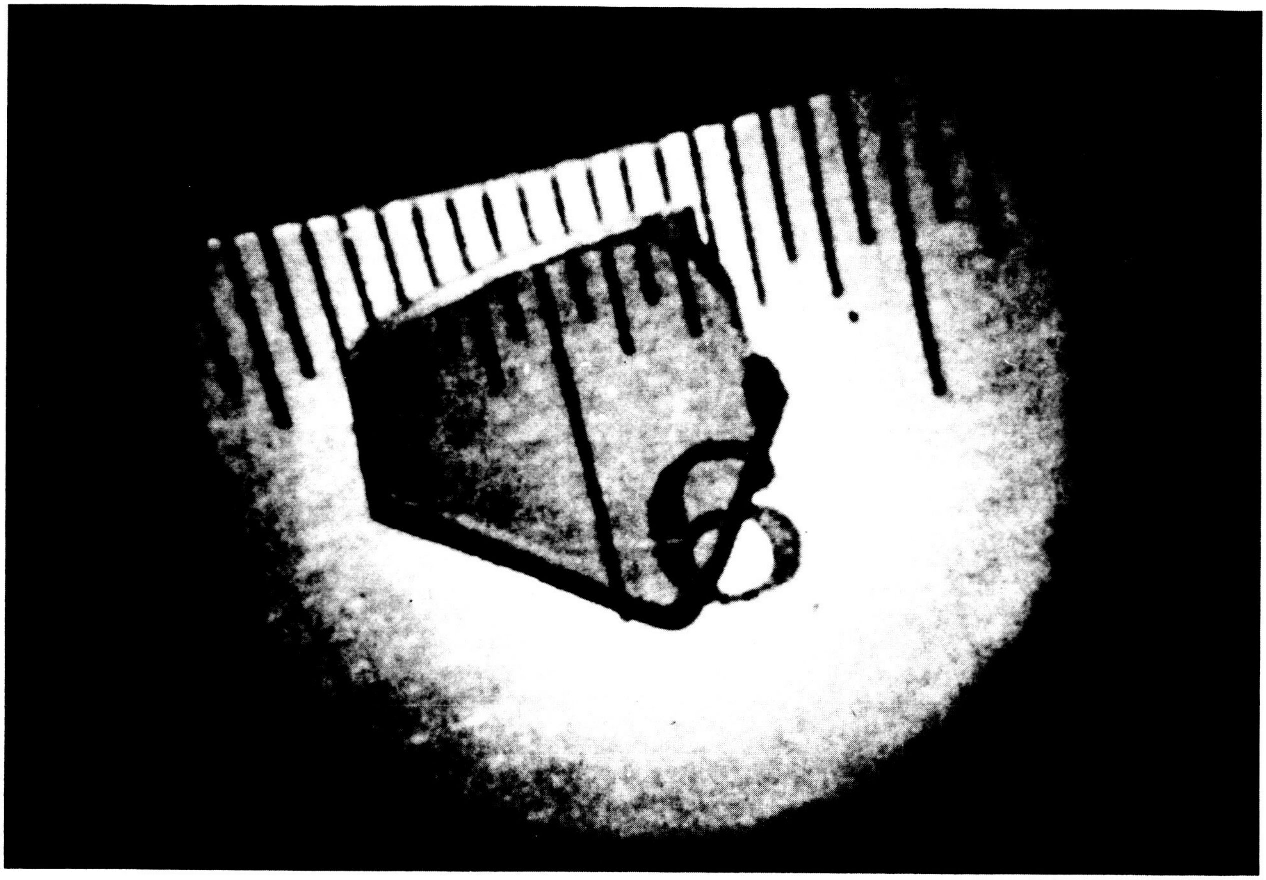

Fig. 3 — Infrared photograph of a gallium-arsenide crystal resting on a metal scale.

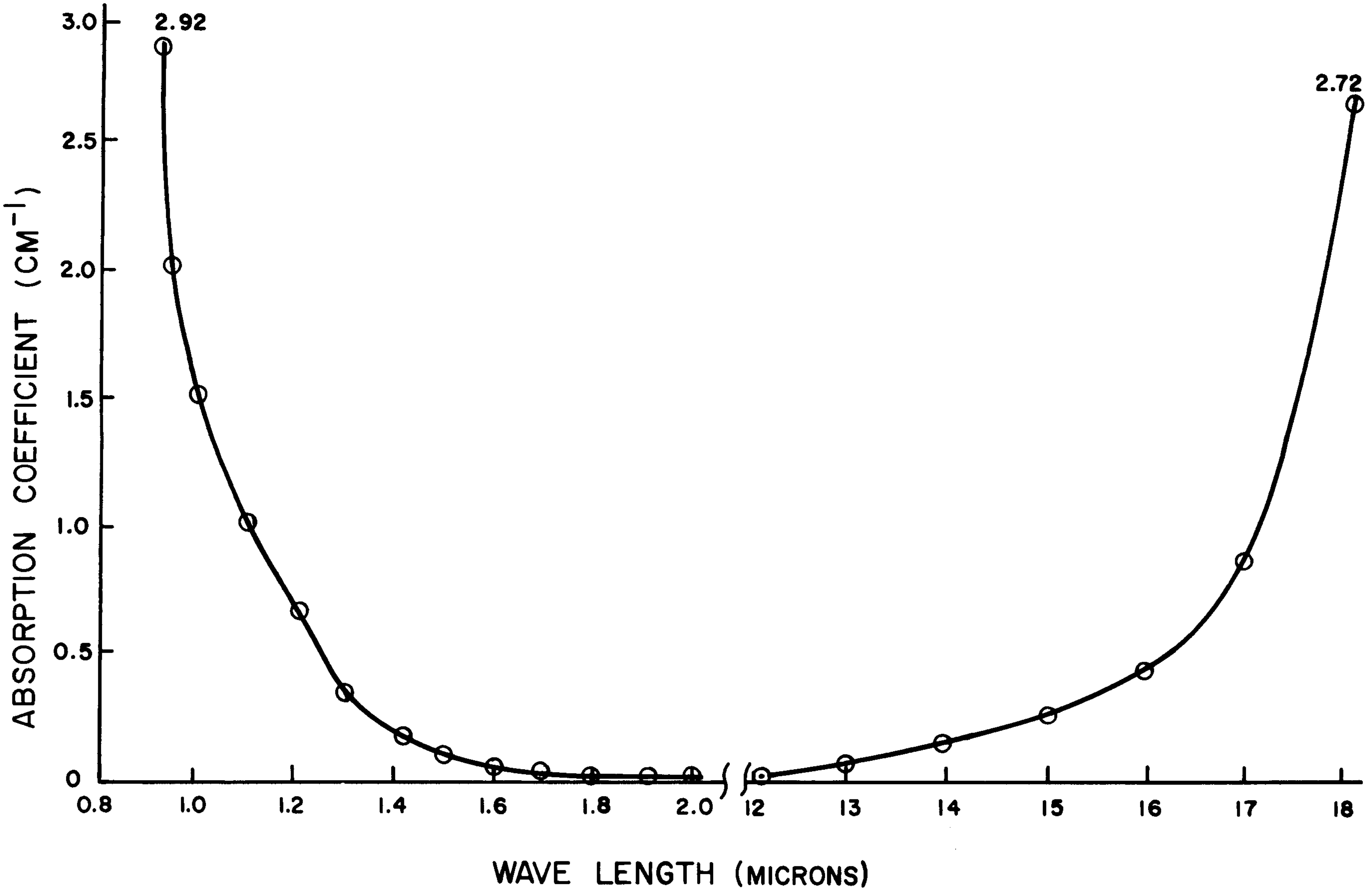

Fig. 4 — Absorption coefficient of gallium arsenide as a function of wavelength.

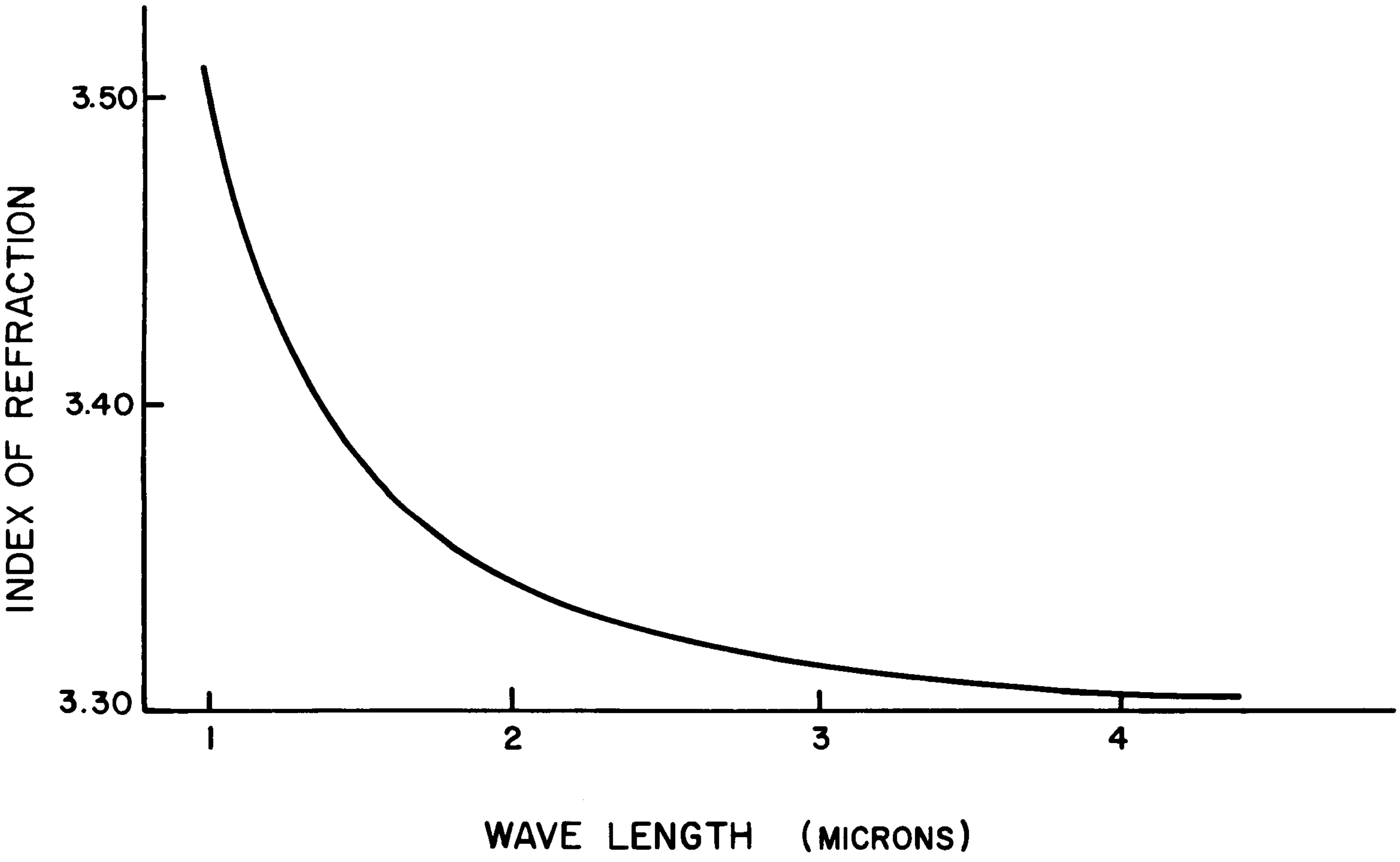

Fig. 5 — Index of refraction of gallium arsenide as a function of wavelength.

The transmittance at 10.6 microns was increased to 90% by anti-reflection coating the modulator crystal with Zinc Sulfide. The effect of the coating on the modulator transmittance is shown in Figure 6.

C. Electro-optic Coefficient

The electro-optic coefficient of GaAs was measured in the wavelength range 2.5 to 12 microns by the following method. The Gallium Arsenide crystal was placed between parallel polarizers and a thick wave plate of Cadmium Sulfide was also placed between the parallel polarizers and oriented with its fast axis at 45° to the plane of passage of the polarizers. The phase retardation produced by the CdS wave plate was $\frac{5}{4}$ wavelength at 9.0 microns, $\frac{7}{4}\lambda$ at 7.1 microns, $\frac{9}{4}\lambda$ at 5.6 microns, and so on toward shorter wavelengths. At these wavelengths, the transmittance of the configuration is given by

$$T = To \cos^2 \left[\frac{\phi}{2} + (2M + 1)\frac{\pi}{4}\right] \quad (M = 1,2,3,4,\ldots)$$

$$= \frac{1}{2} To \left\{1 + \cos\left[\phi + (2M + 1)\frac{\pi}{2}\right]\right\}$$

$$= \frac{1}{2} To \quad (1 + \sin\phi)$$

where $\phi = \frac{2\pi\ell}{\lambda} N^3 r_{41} \frac{V}{d}$ is the retardation produced by the Gallium Arsenide crystal. These equations can be solved for r_{41} in terms of the observed change in transmittance.

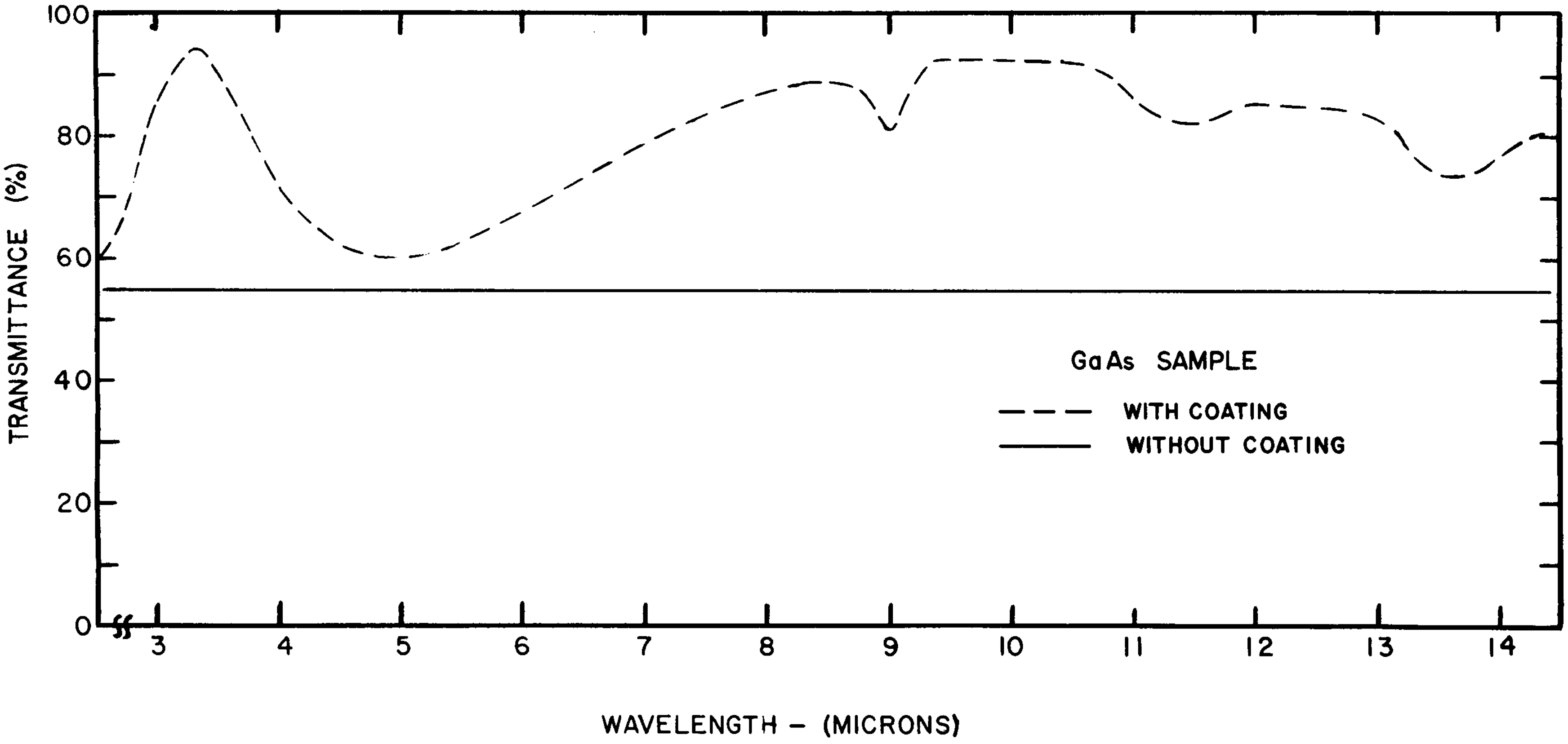

Fig. 6 — Effect of anti-reflection coating on the modulator transmittance of a gallium-arsenide crystal.

$$r_{41} = \frac{\lambda d}{2\pi N^3 \ell V} \sin^{-1}\left[\frac{T - \frac{To}{2}}{\frac{To}{2}}\right] \qquad (2)$$

The values of r_{41} obtained by this method are shown in Figure 6.

The measurements of r_{41} versus wavelength shown in Figure 7 were made with dc voltages applied to the crystal. The dependence of r_{41} on the frequency of the modulating electric field was determined at the fixed infrared wavelength of 1 micron using the configuration shown in Figure 1(a). The modulating frequency was varied from dc to 20 MHz and the modulation was detected with a 7102 photomultiplier terminated with a 50 ohm resistor. The observed modulation was constant over this frequency range except near the piezoelectric resonances of the crystal, which occurred at 700 KHz. At a resonance, the modulation increased by a factor of about 10^3 over the non-resonant effect. This provides a means for obtaining single frequency on-off modulation of a CO_2 laser with an applied voltage of only about 10 volts.

IV. Design Equations and Modulator Performance

In this section the design equations for electro-optic amplitude modulators are presented and the performance data of the 10.6 micron modulator are given.

A. Design Equations

The basic question concerning an electro-optic modulator is what voltage is required to produce a given change in transmittance.

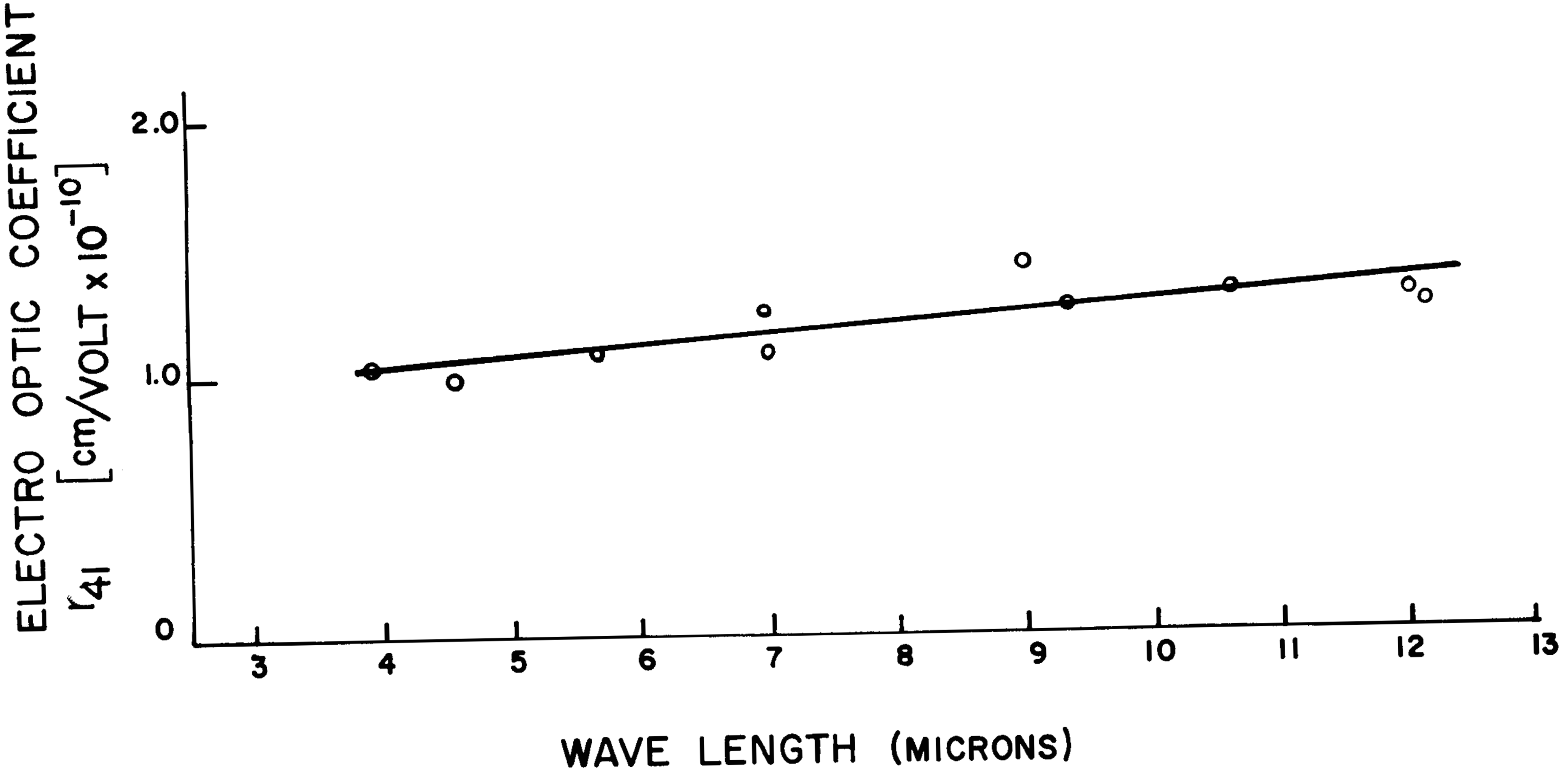

Fig. 7 — Electro-optic coefficient of gallium arsenide as a function of wavelength.

For the configuration shown in Figure 1(a), the transmittance is given by

$$T = T_o \sin^2\left[\frac{\phi}{2} + \frac{\psi}{2}\right] \tag{3}$$

where $\phi = \frac{2\pi}{\lambda} N^3 r_{41} \frac{V\ell}{d}$ is the retardation due to the electro-optic crystal and ψ is the static retardation of the wave plate. The factor To includes the effects of any reflection and absorption losses in the crystal, polarizers, and wave plate. The greatest change in T for small values of V occurs when $\psi = \frac{\pi}{2}$. This can be seen by taking the derivation of T with respect to V in equation 3 and then finding the maximum value of this derivative as a function of ψ . This maximum occurs for $\phi + \psi = \frac{\pi}{2}$. For ϕ small compared to ψ , as it must be to avoid distortion in the modulation, this reduces to $\psi = \frac{\pi}{2}$. This value of ψ gives not only the greatest sensitivity, but also the greatest linearity since it is an inflection point on the T versus ϕ curve. With $\psi = \frac{\pi}{2}$, equation(3) becomes

$$\frac{T - \frac{T_o}{2}}{\frac{T_o}{2}} = \sin\phi \tag{4}$$

The left side of equation (4) is the modulation index (5) m of the amplitude modulated beam. In terms of the crystal parameters and the voltage,

$$m = \sin \frac{2\pi N^3 r_{41} \ell}{\lambda d} V \qquad (5)$$

Equation (5) shows that the depth of modulation decreases as the wavelength increases. It also shows that the decrease may be offset by using a crystal with a larger length-to-width ratio ℓ/d. The final point to be made is that the relatively low value of r_{41} of GaAs is compensated for by its large index of refraction which enters cubed in equation (5).

A. Modulator Construction and Performance

The modulator is shown in Figure 8. The GaAs crystal, 3mm x 3mm in cross section and 6.7 cm long, is held between spring loaded parallel plate electrodes. The electrodes are insulated from the aluminum body of the modulator and their position allows the modulator to be connected directly between the plate terminals of two push-pull output tubes of a driving amplifier. The total capacitance of the modulator including the crystal is 14 picofarads.

The wave plate, shown next to the modulator body in Figure 8, is a single crystal of Cadmium Sulfide whose thickness is such as to provide a phase retardation of five quarter-wavelengths at 10.6 microns.

Each polarizer consists of two plates of high resistivity Germanium set at Brewster's angle. Two plates are sufficient to polarize over 99% of the incident radiation because of the high index of refraction of Germanium (N = 4). The plates are arranged so that there

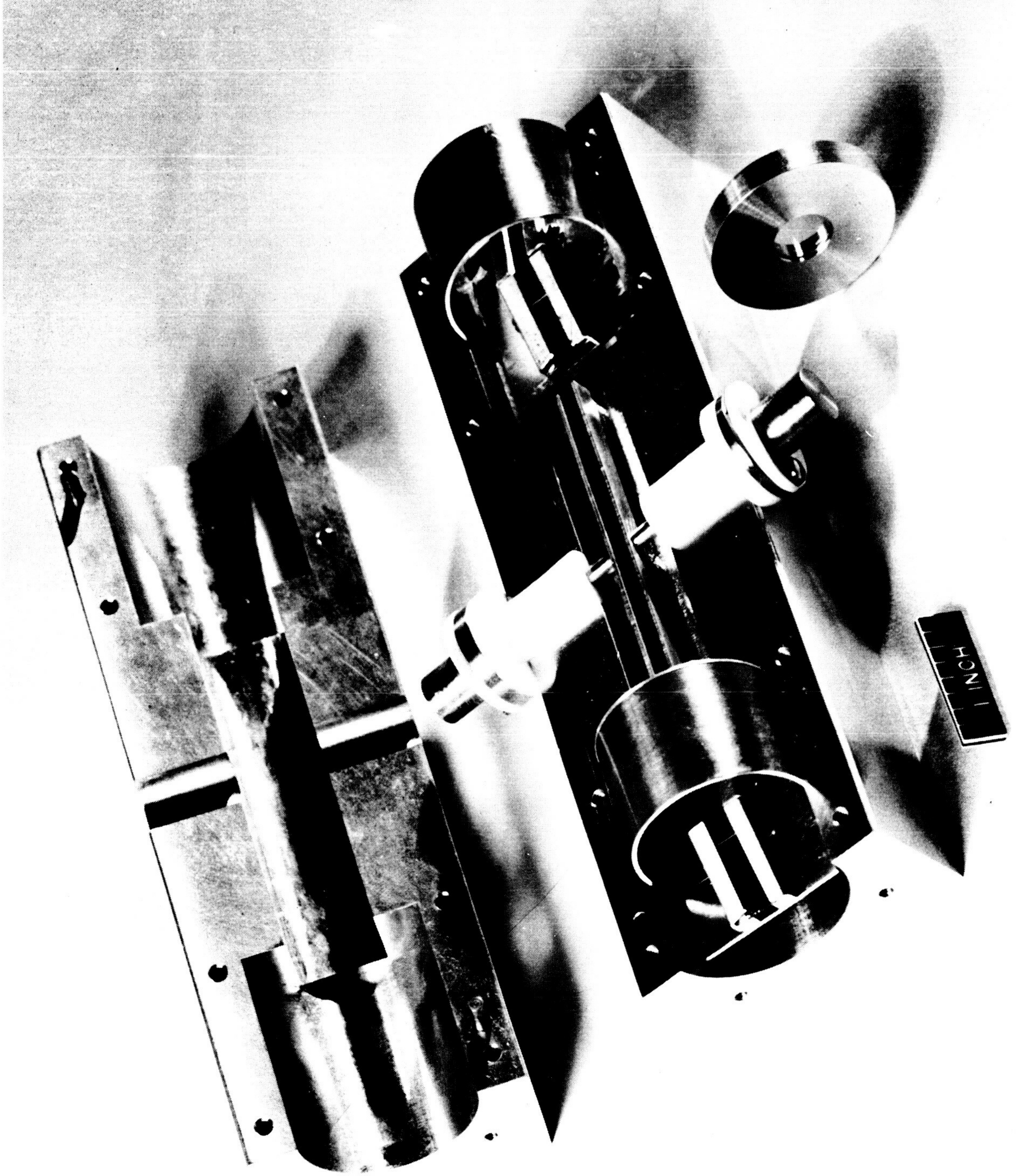

Fig. 8 — RCA J-2036A solid-state electro-optic modulator.

is no deflection of the laser beam upon passage through the polarizers.

The modulator was tested at 10.6 microns with a CO_2 laser and a Mercury doped Germanium detector. The measured depth of modulation was linear with applied voltage up to 1000 volts peak, at which level the depth of modulation was 61%. This is considerably better performance than required by the specifications.

The modulator was also tested with a spectrometer at those wavelengths where the wave plate gave an odd multiple of a quarter wave retardation. These results, shown in Figure 9, indicate that the modulator has a range of operation extending from 2μ (absorption in the Germanium polarizers) to 12μ (absorption in the GaAs and CdS).

The frequency response was tested at 1 micron using a 7102 phototube terminated in a 50 ohm load as the fast detector, and a Xenon lamp as the source. For this test the Germanium polarizers were replaced with Calcite Glan-Thompson polarizers. The observed modulation was constant as a function of frequency from dc to over 20 MHz, except near the piezoelectric resonances in the crystal, the strongest of which occurred at 700 KHz. At this resonance, the photoelastic effect adds to the modulation via the piezoelectric response of the crystal. The net modulation effect is greatly increased (about 1000 times) over the non-resonant effect. 100% modulation was observed for 1 volt of drive signal at this single frequency.

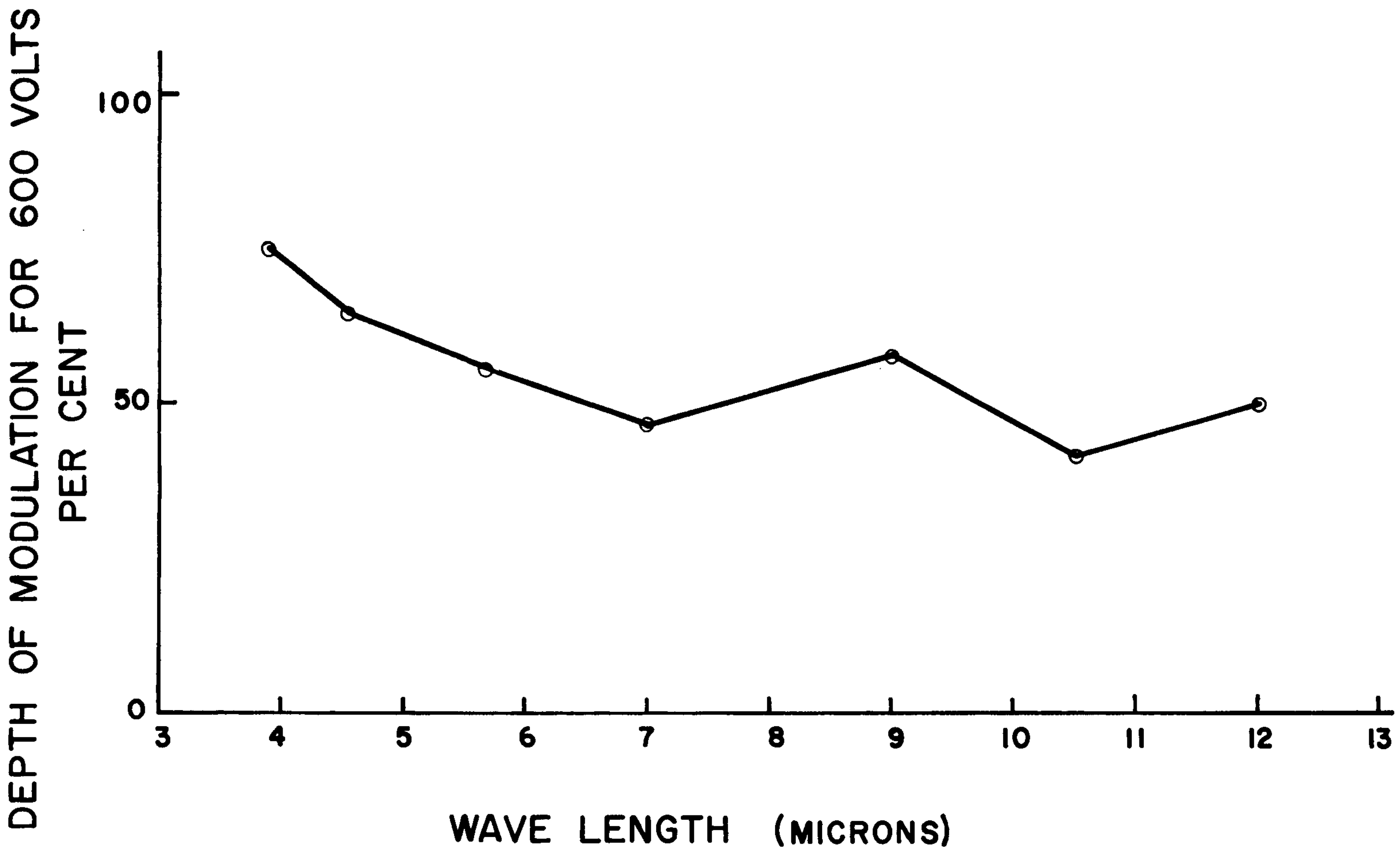

Fig. 9 — RCA J-2036A solid-state electro-optic modulator. Depth of modulation vs wavelength.

V. Conclusions

A 10.6 micron GaAs modulator has been constructed which gives 61% depth of modulation for 1000 volts peak modulating signal over a bandwidth from dc to over 20 MHz. Efficient and compact quarter wave plate and polarizers were developed for use at this wavelength. The modulator can be used at wavelengths from 2 to 12 microns and was used to measure the electro-optic coefficient of GaAs throughout the range.

Footnotes

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3. S. Namba, "Electro-Optical Effect of Zincblende," Journal of the Optical Society of America, Vol. 51, No. 1, p. 76, January 1961.

4. F. Sterzer, D. Blattner, S. Miniter, "Cuprous Chloride Light Modulators," Journal of the Optical Society of America, Vol. 34, No. 1, p. 62, January 1964.

5. F. Terman, "Electronic and Radio Engineering," p. 523, McGraw-Hill Book Co., Inc., New York, 1955.