NASA TECHNICAL NOTE

NASA TN D-4049

NASA TN D-4049

DEVELOPMENT OF A 10.6-MICRON LASER MODULATOR

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1967

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ABSTRACT

Previous investigations of several materials showed that gallium arsenide is the most suitable electro-optic crystal material for infrared modulation between 0.9 and 16 microns.

The advent of the CO_2-laser has generated the need for a 10.6-micron gallium arsenide modulator. A 10.6-micron laser modulator has been constructed which gives 61 percent 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 gallium arsenide throughout the range.

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INTRODUCTION

The advent of the CO_2 laser has generated the need for a 10.6-micron infrared modulator. From several investigated materials (References 1, 2, and 3), gallium arsenide appears as the most suitable material for infrared modulation. Practical electro-optic modulators for the infrared region 0.9 to 16 microns have been constructed using large single crystals of high-resistivity gallium arsenide. These modulators operate from dc to several hundred megahertz and have been used to transmit television signals on infrared beams. The electro-optic coefficient of GaAs has been measured over the wavelength 0.9 to 16 microns at frequencies from dc to 1.7 gigahertz. The existence of an electro-optic effect at gigahertz frequencies, together with the low value of loss tangent measured here, suggests that gigahertz-bandwidth microwave modulation could be achieved with GaAs.

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 percent was required for an applied voltage of 1000 volts RMS over a bandwidth from dc to over 10 MHz. A modulator (Reference 3) similar to this was developed for the wavelength range 0.9 to 3.0 microns. The extension of the operating wavelength to 10.6 microns required the development of polarizers and wave plates for this wavelength.

ELECTRO-OPTIC MODULATION

The electro-optic effect is an electric-field-induced change in the optical indices of refraction of a crystal. A cubic electro-optical crystal such as gallium arsenide 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.

A review of the theory for cubic crystals such as gallium arsenide is given by Namba (Reference 4) and by Sterzer, Blattner, and Miniter (Reference 5).

The following physical properties of an electro-optic crystal are important for modulators such as those of Figure 1.

1. The index of refraction n, which determines the speed of light in the crystal and the reflection loss at its surfaces.
2. The relative dielectric constant ϵ, which determines the capacitance of the crystal and the speed of propagation of electric fields in the crystal.
3. The electro-optic coefficient r_{41}, which relates the induced birefringence Δn to the applied electric field E (References 4, 5, and 6). For the modulators of Figure 1(a) and 1(c),

$$\Delta n = n^3 r_{41} E . \tag{1}$$

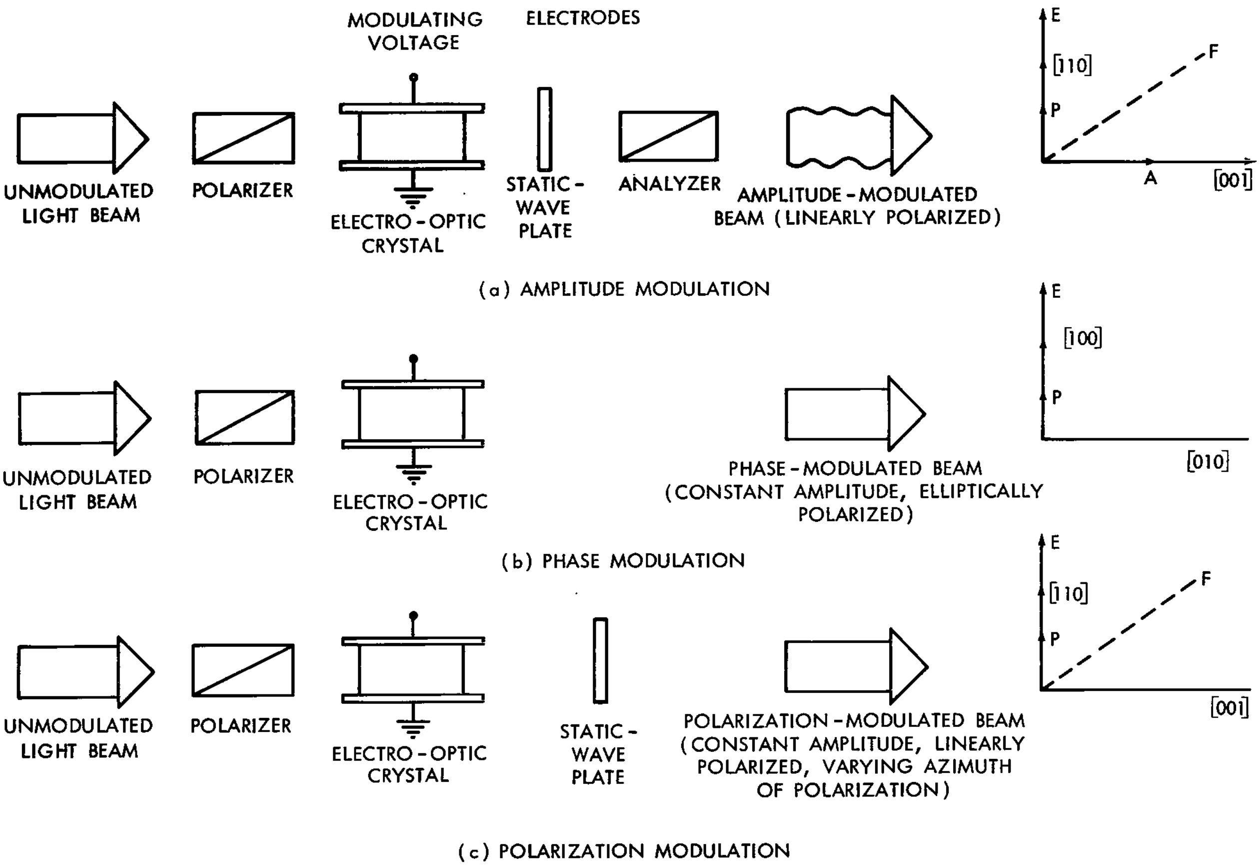

Figure 1—Three optical systems for electrically modulating a light beam using an electro-optic crystal.

For the modulator of Figure 1(b),

$$\Delta n = \frac{1}{2} n^3 r_{41} E. \quad (2)$$

4. The optical absorption coefficient k, which determines the optical loss in the crystal.
5. The dielectric loss tangent, tan δ, which determines the electrical loss in the crystal.
6. The crystal strain, which must be low to allow a cooperative electro-optic effect in adjacent areas of the crystal.
7. The "hardness", which determines the resistance of the crystals to straining during cutting and polishing.
8. The solubility, which determines the ability to withstand moist ambient conditions.
9. The thermal conductivity, which determines the deleterious birefringence due to thermal gradients in a crystal heated by electrical or optical absorption.

CRYSTAL GROWTH AND PROPERTIES

Growth

The crystals are boat-grown in a horizontal Bridgeman furnace from element 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. The crystals are hard and nonhygroscopic, and possess a relatively high thermal conductivity. They are virtually strain-free as grown, and 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; additional strain is not introduced by normal handling. Since the crystals are insoluble in water and dissociate at 800°C, no special precautions are necessary with regard to ambient temperature and humidity.

Optical Properties

The crystals are opaque in the visible region, but are transparent in the infrared between 0.9 and 16 microns. 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 that 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 2. The smallest absorption coefficient that 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 percent. This low transmittance is due to the high index of refraction of GaAs, shown in Figure 3. The external transmittance T is given in terms of the refractive index n by the expression

$$T = \frac{2n}{n^2 + 1} . \tag{3}$$

The transmittance at 10.6 microns was increased to 90 percent by antireflecting coating the modulator crystal with zinc sulfide. The effect of the coating on the modulator transmittance is shown in Figure 4.

Electrical Properties

The dielectric constant and loss tangent were measured at microwave frequencies of 2.5, 5.6, and 10 gigahertz. No change in either the dielectric constant or loss tangent was observed

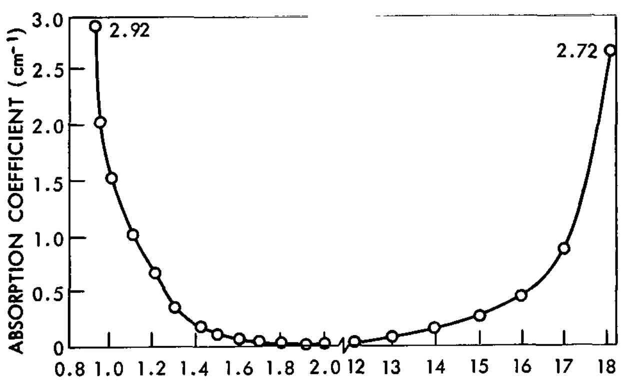

Figure 2—Absorption coefficient of gallium arsenide as a function of wavelength.

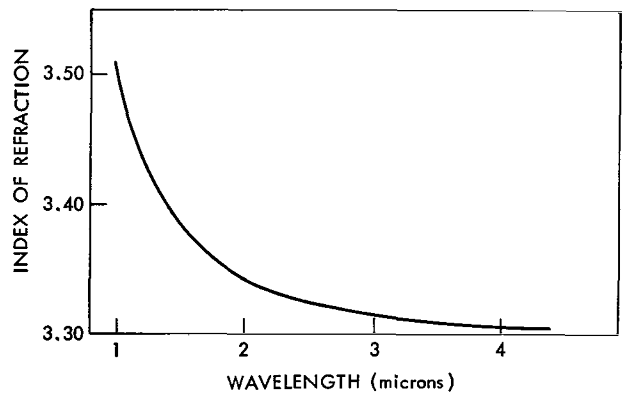

Figure 3—Index of refraction of gallium arsenide as a function of wavelength.

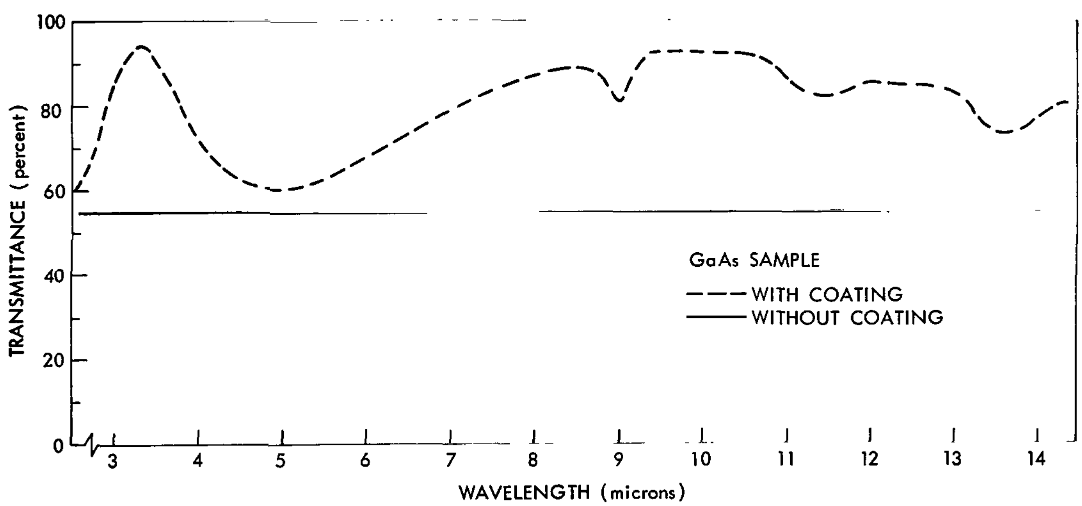

Figure 4—Effect of anti-reflection coating on the modulator transmittance of a gallium-arsenide crystal.

over this frequency range. The relative dielectric constant was 11.0 and the loss tangent was 0.001. This value of loss tangent gives a microwave resistivity in agreement with the observed dc resistivity of the crystals.

Electro-optic Coefficient

The unclamped electro-optic coefficient r_{41} of GaAs was measured in the wavelength range 0.9 to 2.5 microns by placing the crystal between parallel polarizers and measuring the decrease in transmittance when a dc voltage was applied to the crystal. In this case, the transmittance is given by

$$T = T_0 \cos^2\phi , \tag{4}$$

where

$$\phi = \frac{2\pi\ell}{\lambda} n^3 r_{41} \left(\frac{V}{t}\right) \tag{5}$$

is the retardation of the GaAs crystal with voltage V applied. In these equations,

T = transmittance with voltage V applied
T_0 = transmittance when $V = 0$
n = index of refraction at wavelength λ
t = crystal thickness in the direction of the electric field
ℓ = crystal length in the direction of the light beam.

In addition, a microwave measurement of r_{41} was made at 2.36 microns on a GaAs crystal in a re-entrant cavity resonant at 1.7 GHz. The crystal was placed between crossed polarizers and the microwave signal was amplitude-modulated at 1000 Hz. With this arrangement, the modulated infrared beam leaving the cavity contained a 1000-Hz signal component, which was detected with a slow but sensitive PbS infrared detector. The value of r_{41} obtained by this method was 0.94×10^{-10} cm/v, in good agreement with the low-frequency results.

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 degrees to the plane of passage of the polarizers. The phase retardation produced by the CdS wave plate was $(5/4)\lambda$ at 9.0 microns, $(7/4)\lambda$ at 7.1 microns, $(9/4)\lambda$ at 5.6 microns, and so on toward shorter wavelengths. At these wavelengths the transmittance of the configuration is given by

$$T = T_0 \cos^2\left[\frac{\phi}{2} + (4M - 1)\frac{\pi}{4}\right] \qquad M = 0, 1, 2, 3, \cdots$$

$$T = \frac{T_0}{2}\left\{1 + \cos\left[\phi + (4M - 1)\frac{\pi}{2}\right]\right\}$$

$$T = \frac{T_0}{2}\{1 + \sin\phi\}, \qquad (6)$$

where $\phi = 2\pi\ell/\lambda\, n^3 r_{41}\, (V/t)$ 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

$$r_{41} = \frac{\lambda t}{2\pi n^3 V\ell} \sin^{-1}\left[\frac{T - \frac{T_0}{2}}{\frac{T_0}{2}}\right]. \qquad (7)$$

The values of r_{41} obtained by this method are shown in Figure 5.

The measurements of r_{41} versus wavelength shown in Figure 5 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 resonance of the crystal, which occurred at the harmonics of 700 kHz. At a resonance, the modulation increased by a factor of about 10^3 over the nonresonant 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. The magnitude of the electro-optic effect above the resonance is the same as the value below the resonance, i.e., the clamped and unclamped electro-optic coefficients are the same.

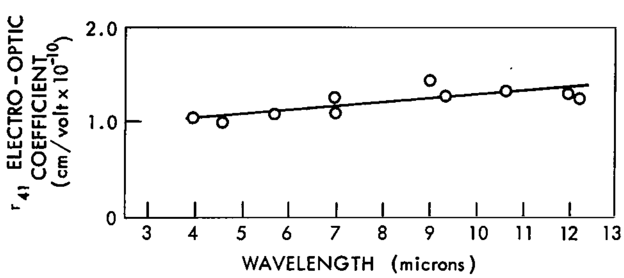

Figure 5—Electro-optic coefficient of gallium arsenide as a function of wavelength.

DESIGN EQUATIONS AND MODULATORS PERFORMANCE

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

Design Equations

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

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

$$T = T_0 \sin^2\left(\frac{\phi}{2} + \frac{\psi}{2}\right), \qquad (8)$$

where ϕ is the retardation due to the electro-optic crystal and ψ is the static retardation of the wave plate. The factor T_0 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 $\psi = \pi/2$. This can be seen by taking the derivative of T with respect to V in Equation 8 and then finding the maximum value of this derivative as a function of ψ. This maximum occurs for $\phi + \psi = \pi/2$. For ϕ small compared to ψ, as it must be to avoid distortion in the modulation, this reduces to $\psi = \pi/2$. 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 $\psi = \pi/2$, Equation 8 becomes

$$\frac{T - \frac{T_0}{2}}{\frac{T_0}{2}} = \sin\phi \, . \qquad (9)$$

The left side of Equation 9 is the modulation index m of the amplitude-modulated beam. In terms of the crystal parameters and the voltage,

$$m = \sin \frac{2\pi n^3 r_{41} \ell}{\lambda t} V \, . \qquad (10)$$

Equation 10 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/t. The final point to be made is that the relatively low value of r_{41} for GaAs is compensated for by its large index of refraction which enters cubed in Equation 10.

Modulator Construction and Performance

A modulator designed for operation in the range 2 to 12 microns is shown in Figure 6. The GaAs crystal is 3 × 3 mm in cross-section and 6.7 cm long and 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 modulator shown in Figure 6 consists of a gallium-arsenide crystal and a wave plate placed between two polarizers. The wave plate 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.

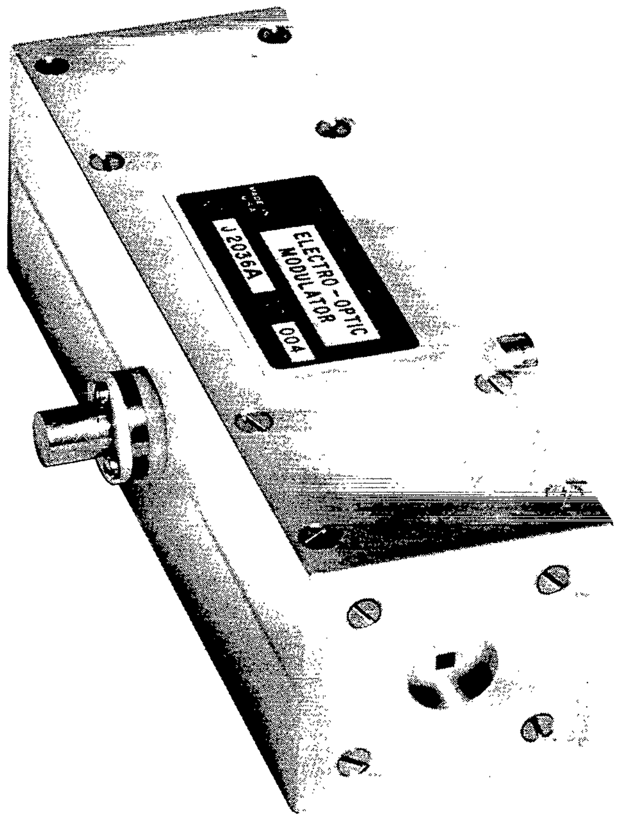

Figure 6—Gallium arsenide electro-optic modulator.

Each polarizer consists of two plates of high-resistivity germanium set at Brewster's angle. Two plates are sufficient to polarize over 99 percent of the incident radiation, because of the high index of refraction of germanium ($n = 4$). The plates are arranged so that there is no deflection of the laser beam upon passage through the polarizers.

This modulator has been used to amplitude modulate the output of a 10-watt CO_2 gas laser operating continuously at 10.6 microns. The modulator was tested at 10.6 microns with 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 percent. 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 indicate that the modulator has a range of operation extending from 2μ to 12μ. The lower and upper limits to the operating wavelength of this modulator are set by absorption in the germanium polarizers and GaAs, CdS respectively. The performance of the modulator is illustrated in Figure 7, which shows the depth of modulation for peak applied signal of 600 volts.

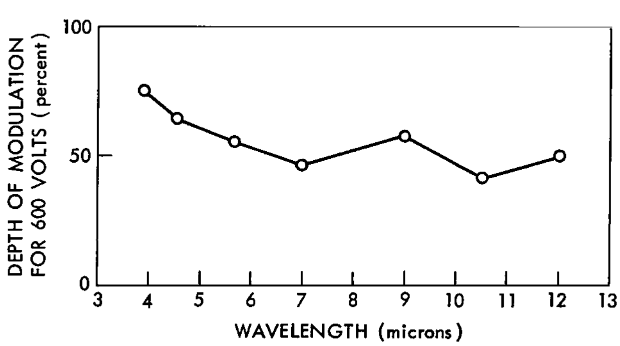

Figure 7—Depth of modulation versus wavelength.

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.

CONCLUSION

A 10.6-micron GaAs modulator has been constructed which gives 61-percent 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.

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841-11-78-01-51

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