ELECTRO-OPTIC AND MAGNETO-OPTIC MODULATORS

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ABSTRACT

This report describes research in the use of gallium arsenide (GaAs), gallium phosphide (GaP), and potassium tantalate niobate (KTN) crystal materials for electro-optic light modulators. Gallium arsenide, which has the potential to modulate at wave lengths as great as 16 microns, was found the most useful for laser modulation. Yttrium iron garnet (YIG) is also examined for use as a wideband magneto-optic modulator. A wideband YIG modulator has recently been developed which represents a great improvement over other magneto-optic modulators.

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INTRODUCTION

It is now possible in principle to make optical communication systems of extremely large capacity. There are four key elements in such systems: the source, the modulator, the transmission medium, and the detector, all of which must be wideband and relatively efficient. For high-capacity communication, the weakest elements at present are the modulator and transmission medium.

The number of methods for modulating light with a bandwidth of several hundred MHz or greater is very limited and each method has its own particular difficulties. Electro-optic modulators using, for example, potassium dihydrogen phosphate (KDP) require excessively large modulating power per percent bandwidth. Also, the material itself is difficult to prepare to optical tolerances and is not very stable after it is prepared. Potassium tantalate niobate (KTN), with its quadratic electro-optic effect, is much more efficient, but the growth of crystals of sufficient optical quality and size proved to be a formidable problem. Also, its temperature sensitivity is such that in most applications, the temperature must be controlled to within about $0.01°C$. Other electro-optic materials, such as gallium arsenide (GaAs), gallium phosphide (GaP) (Fe-doped), and lithium niobate, look more promising.

Semiconductor p-n junction modulators have recently shown encouraging possibilities, and are capable of high speeds (Reference 1). Their principal disadvantage is that they require highly critical focusing of the light incident edgewise on the junction. This focusing must be of the order of a few microns. The reproducibility of junctions having the desired properties is also a difficult problem.

A few years ago, GaAs showed little potential as an electro-optic modulator because the low resistivity of available crystals prevented application of the large electric fields required for an acceptable percent modulation. However, further research resulted in the development of GaAs crystals with very high resistivity, on the order of 1 megohm-cm.

A cubic electro-optic crystal, such as GaAs, is optically isotropic in the absence of an electrical field. The application of an electric field along certain crystal directions causes

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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.

The objective of the program described here was to develop a laser modulator capable of producing 40 percent depth of modulation for an applied voltage of 400 volts rms over a bandwidth from dc to 6 MHz. The program was a parallel effort on GaAs and GaP electro-optic crystals. In addition, some work was done to grow KTN crystals, but the results as yet are inconclusive.

The theory of the linear electro-optic effect in crystals such as Zincblende (ZnS), GaAs and GaP is described by Sterzer, Blattner, and Miniter (Reference 2). The theory of the quadratic electro-optic effect in perovskite crystals such as KTN is described by Geusic et al. (References 3 and 4). The GaAs crystals were grown by the horizontal Bridgeman technique (Reference 5). The GaP crystals were grown both by the Czochralski technique from gallium in a phosphorous atmosphere (Reference 6) and by the vapor deposition technique (Reference 7) using gallium chloride and phosphine (PH_3) in a hydrogen carrier gas. The KTN crystal was grown by the Czochralski technique in a platinum boat from potassium carbonate, tantalum pentoxide, and niobium pentoxide (Reference 3).

GaAs ELECTRO-OPTIC MODULATOR

The best modulator crystal produced under this program was a GaAs crystal incorporated into the modulator shown in Figures 1 and 2, which operated in the wave length range from 0.9 to 3.0 microns. The modulator achieved a depth of modulation over 50 percent for an rms modulation signal of 400 volts, from dc to over 20 MHz.
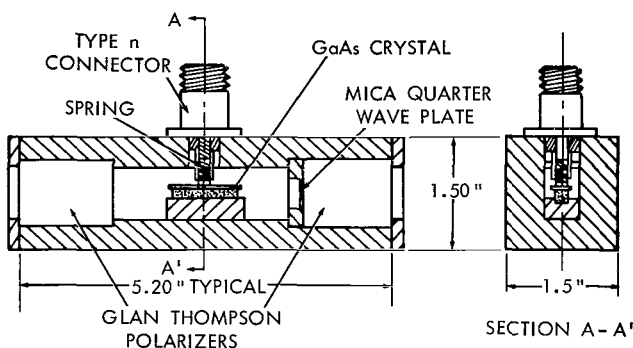

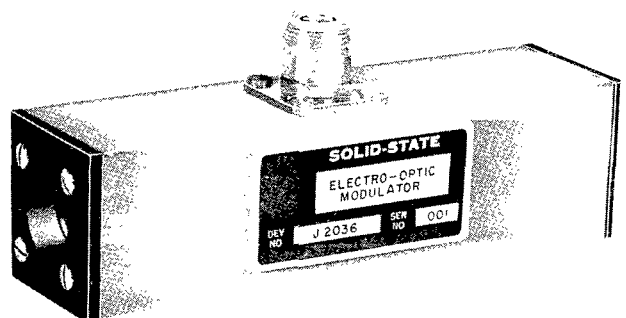Figure 1—Gallium arsenide electro-optic modulator cross section.

Figure 2—Gallium arsenide electro-optic modulator.

Crystal Growth And Properties

Crystals for the GaAs modulator are boat-grown in a horizontal Bridgeman furnace from gallium and arsenic. They are doped with iron during the growth to raise their resistivity above 10^6 ohm-cm for the entire length of the ingot. The crystals are hard, non-hygroscopic, and possess a relatively high thermal conductivity. They are strain-free as grown, and easily cut and polished flat to 1/10 wavelength of, say, the yellow line of sodium without introducing appreciable strain. The extinction ratio of crystals 1 cm thick between crossed polarizers is greater than 100 to 1 after all cutting and polishing operations, and they can be handled 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.

The crystals are opaque in the visible spectrum, but are transparent in the infrared between 0.9 and 16 microns. The optical quality is comparable to that of good optical glass. Physical constants for the GaAs crystal are given in Table 1.

Table 1

Physical Constants of GaAs Crystal.

Crystal type	Valence
Crystal structure	Cubic
Index of refraction	3.5 (at $\lambda = 1\mu$) 3.30 (at $\lambda = 4\mu - 16\mu$)
Dielectric constant	11-12
Loss tangent less than	0.0005
Electro-optic coefficient	10^{-10} cm/volt at $\lambda = 1\mu$
Retardation voltage, $V_{\lambda/2}$, (kv)	13.3 width/length at $\lambda = 1\mu$
Spectral range of transparency	$1-16\,\mu$
Angular field of view	18 degrees

Drive Voltage Requirements

The basic question concerning an electro-optic modulator is the voltage required to produce a given change in transmittance. For amplitude modulation, the transmission is given by

$$I = I_0 \sin^2\left(\frac{\pi}{2} \cdot \frac{V \sin \omega t}{V_{\lambda/2}} + \frac{\pi}{4}\right) ,$$

where $V_{\lambda/2}$ is the half-wave retardation voltage which produces a 180 degree phase difference between the emerging optical components.

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To achieve an acceptably linear transfer function, the electro-optic modulator must be biased either electrically or optically (Reference 8). The latter is easier and can be accomplished by placing a quarter-wave plate, properly oriented to obtain circularly polarized light between the polarizer and the crystal. With a $\lambda/4$ plate, we attain not only the greatest sensitivity but also the greatest linearity.

The percent modulation is given by

$$m = \frac{\Delta I}{\frac{I_0}{2}} \cdot 100 = \frac{I - \frac{I_0}{2}}{\frac{I_0}{2}} \cdot 100 = \left[\sin\left(\frac{\pi V \sin \omega t}{V_{\lambda/2}}\right)\right] \cdot 100 ,$$

$$= \left[\sin \frac{\pi V_m}{V_{\lambda/2}}\right] \cdot 100 .$$

The electric field E is perpendicular to the (1,1,1) plane, and the peak-to-peak drive voltage needed to achieve 100 percent modulation is

$$V_{\lambda/2} = \frac{1}{\sqrt{3}} \cdot \frac{\lambda \cdot t}{r_{41} \, n^3 \, \ell} ,$$

where

I_0 = intensity of laser source (W),

ω = frequency of modulating signal (Hz),

V = peak amplitude of modulating voltage (v),

V_m = peak modulating voltage (v),

$V_{\lambda/2}$ = half-wave retardation voltage (v),

λ = wave length of incident laser light (cm),

t = crystal thickness in direction of applied electric field (cm),

ℓ = crystal length in direction of incident laser light beam (cm),

n = index of refraction at wave length λ,

r_{41} = electro-optic coefficient at wave length λ (cm/v),

Modulator Construction And Performance

Figure 1 shows a complete modulator consisting of a GaAs crystal and a mica quarter-wave plate placed between two calcite Glan Thompson polarizers. The GaAs crystal is mounted on the end of a 50-ohm coaxial line and presents a 3-picofarad capacitive load to the line. The openings in the mount for passage of the laser beam are cut-off waveguides at the modulation frequencies to prevent radiation of the modulating signal. The angular aperture is limited by the size of the Glan Thomsom polarizers, which have a 1-cm aperture. The performance of the modulator with a 1.2-micron quarter-wave plate is illustrated in Figure 3, which shows the change in transmission produced by a 600-volt peak signal. The wavelength response of the modulator can be shaped by using different wave plates (Reference 8). Figure 4 shows the change in transmission produced by a 600-volt signal when different wave plates are used.
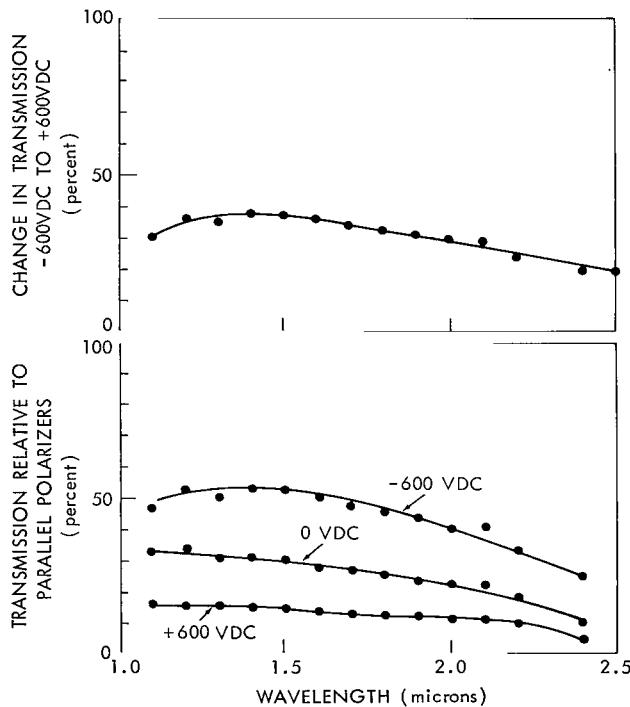

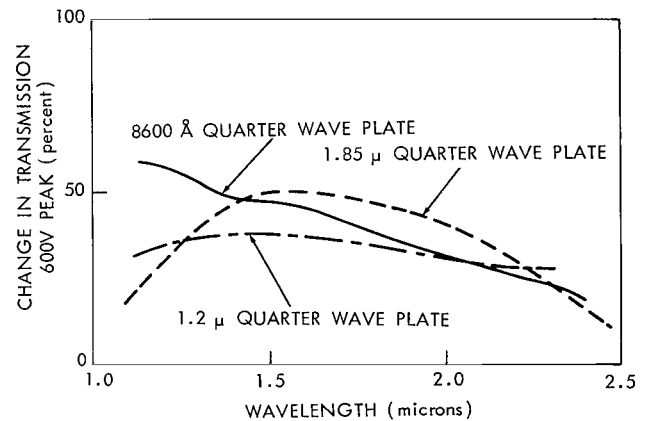Figure 3—Gallium arsenide electro-optic modulator performance with 1.2 microns

Figure 4—Gallium arsenide electro-optic modulator performance with different quarter-wave plates.

Figure 5 shows the electro-optic coefficient, r_{41}, as a function of wave length. This is relatively constant, indicating that the operating wavelength can be increased at the expense of a proportionate increase in the operating voltage.
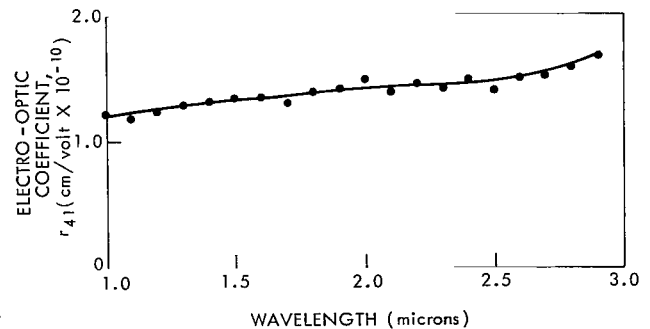
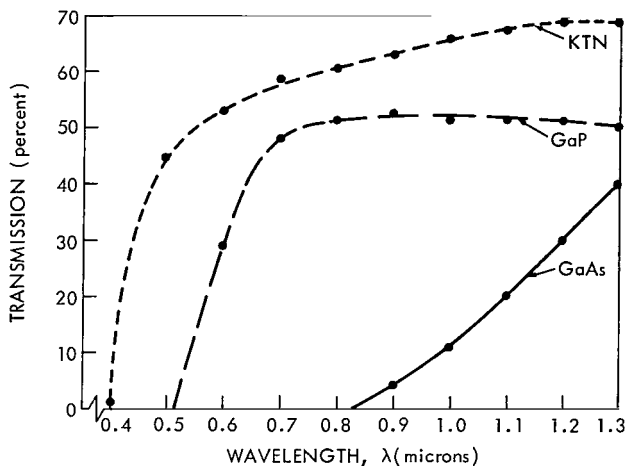Figure 5—Electro-optic coefficient, r_{41}, versus wavelength.

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Figure 6—Transmittance of GaAs, GaP, and KTN
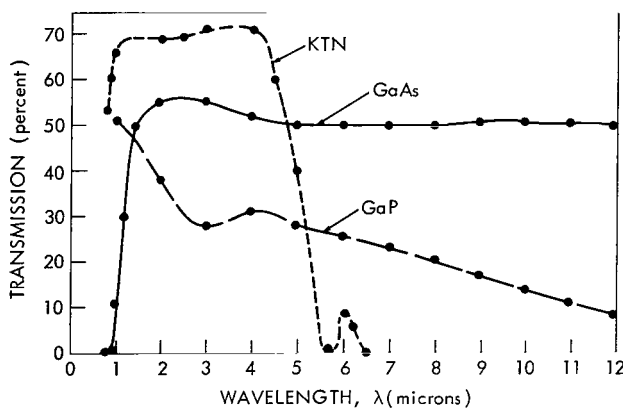(for wavelengths of 0.4 to 1.3 microns).

Figure 7—Transmittance of GaAs, GaP, and KTN (for
wavelengths of 1 to 12 microns).

The upper limit of three microns in the operating wavelength is caused by absorption in the calcite Glan Thompson polarizers. The GaAs crystal is transparent out to 16 microns, as shown in Figures 6 and 7, and could be used for modulation at these longer wavelengths provided suitable polarizers and quarter-wave plates could be obtained. In this graph the transmission loss in the spectral band from 1.4 to 16 microns is negligibly low, practically all the attenuation being due to reflection at the ends of the crystal. Therefore, with anti-reflection coatings on its ends, the transmission of the crystal can be increased by approximately 48 percent.

The frequency response was tested at 1.15 microns using a fast detector (a 7102 photo tube or the collector-base junction of a high-frequency germanium transistor, i.e., 2N1195 as photo diode) and a gas laser at 1.15 microns as source. 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 occured at 700 KHz. At this resonance, the modulation effect is greatly increased over the nonresonant effect. One hundred percent modulation was observed for 5 volts of drive signal at this frequency.

Figure 8 shows the arrangement of an electro-optic TV communications system with baseband modulation employing a GaAs electro-optic crystal (3mm X 3mm X 17mm) which modulated the intensity of a laser beam at 1.15 microns.

The video signal was simply amplified and applied directly across the crystal. As a fast detector, the collector-base junction of a high-frequency germanium transistor (2N1195) was used. The detected signal was amplified up by a wideband amplifier (Keithley Instrument, model 104).

The operation of this system was successfully demonstrated. With baseband modulation, the resultant TV picture is subject to "herringbone" interference due to piezoelectric resonances. With FM-subcarrier modulation methods, no such interference appears. Through the use of FM, the modulation spectrum can be shifted away from the piezoelectric resonance range, thus avoiding signal distortion.
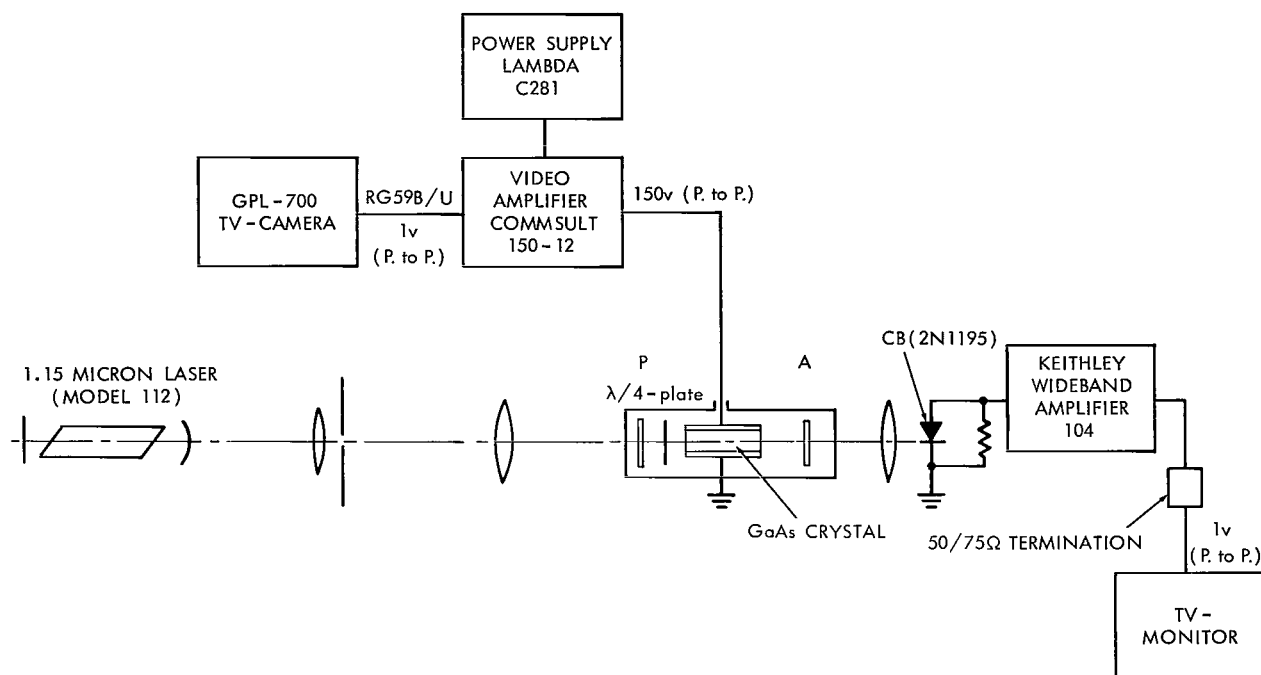
Figure 8—Arrangement of an electro-optic TV-communications system at 1.15 microns.

Labels in figure:
POWER SUPPLY LAMBDA C281
GPL-700 TV-CAMERA
RG59B/U 1v (P. to P.)
VIDEO AMPLIFIER COMMSULT 150-12
150v (P. to P.)
1.15 MICRON LASER (MODEL 112)
P
λ/4-plate
A
GaAs CRYSTAL
CB(2N1195)
KEITHLEY WIDEBAND AMPLIFIER 104
50/75Ω TERMINATION
1v (P. to P.)
TV-MONITOR

GaP ELECTRO-OPTIC MODULATOR

The transmission range of GaP is shown in Figures 6 and 7. The short-wavelength cutoff occurs at 6000 Å, making it potentially useful for modulating visible lasers, such as the helium-neon laser at 6328Å. The GaP crystals grown were of good optical quality and took a good optical polish, but their resistivity was too low for modulation purposes. Several attempts were made to compensate the crystals by diffusion of copper, a technique which produces high resistivity gallium arsenide (Reference 5), but no crystals were obtained which could withstand more than 30 volts before drawing excessive current.

Recently, RCA was successful in growing iron-doped GaP which shows promise as modulator material in the visible region from 5200Å into the infrared region up to 16 microns. The intrinsic band gap absorption edge occurs at 5200Å.

KTN ELECTRO-OPTIC MODULATOR

Geusic (Reference 9) has shown that KTN crystals provide high percent modulation with exceptionally low drive voltage. He measured half-wave retardation voltages as low as 15.3 volts in KTN crystals, operated with a dc bias of about 300 volts. The drive voltage required for KTN is more than two orders of magnitude lower than that of any of the linear transverse crystals.

One problem, due to the dielectric constant being three orders of magnitude higher than that of the linear transverse crystal, is that the capacitive load presented by KTN is rather large

(1000 pF). Hence, although the drive voltage requirement is small, the drive current requirement is large. In other words, the problem of designing a wideband, high-voltage amplifier has been traded for the problem of designing a wideband, high-current amplifier. A second problem is that the operating temperature of KTN must be controlled to within 0.2°C, necessitating automatic temperature control. A third problem is that KTN is an ionic crystal. To achieve high percent modulation, it is necessary to apply a dc bias across the crystal. The dc field forces the ions to drift toward the electrodes, causing the crystal to become polarized. Under normal operating conditions, polarization can occur within one-half hour, preventing the crystal from functioning properly until it is depolarized. A fourth problem is that the crystals are extremely difficult to grow. Crystals grown to date are very small and not entirely cubic. Physical constants for the KTN crystal are given in Table 2.

Table 2

Physical Constants of a KTN Crystal.

Crystal type	Ionic
Crystal structure	Cubic
Index of refraction	2.29
Dielectric constant	10,000
Loss tangent	0.004
Modulation	Quadratic, transverse
Electro-optic coefficient	$(g_{11} - g_{12}) = 0.17\,m^4/°C$
Half-wave voltage	–
Transparency range	$0.5 - 6.9\mu$
Largest available length	0.3 cm
Environmental considerations	Controlled temperature $20° \pm 0.2°C$

A crystal of KTN was grown, cut, and polished. The transmission of KTN extends throughout the visible and near-infrared spectrum, as shown in Figures 6 and 7. The Curie point of the crystal was slightly above room temperature and, consequently, it had to be heated slightly to operate in the paraelectric phase. The crystal showed a good deal of strain, but a sizeable electro-optic effect could be observed visually when 300 volts were applied, the magnitude of the effect depending on how close the crystal temperature was to the Curie point. Although the crystal was transparent, it scattered a laser beam so badly that no attempt was made to incorporate it into a modulator. In addition, the crystal exhibited many piezoelectric resonances, which would cause severe distortion in a baseband modulation system.

Although KTN shows great promise, there are formidable research problems to be overcome before this type of crystal can be used in practical systems.

CONCLUDING REMARKS

Of the three materials investigated, GaAs is the most useful for laser modulation because of the advanced state of GaAs crystal technology. It has the potential to modulate at wave lengths as great as 16 microns and should be the first choice for long-wavelength applications. KTN and GaP require more development to produce crystals with the excellent optical properties of existing GaAs.

HIGH SPEED MAGNETO-OPTIC MODULATOR

Until recently, the most efficient magnetic-optic modulator used Faraday rotation in $CrBr_3$ (Reference 10), a material studied extensively by Dillon. However, this modulator required operation at 4.2°K or lower to obtain a good rotation figure of merit, which can be defined as the rotation in degrees per db of insertion loss. The best figure of merit in $CrBr_3$ of 30 was obtained at 1.5°K at a wavelength of 0.5 micron.

At the Bell Telephone Laboratories, Inc., much higher rotation figures of merit have been recently observed at room temperature in yttrium iron garnet (YIG). Pure YIG is almost completely transparent in the infrared.

A wideband YIG modulator has been developed by Dr. R. C. LeCraw in BTL* which has shown an order of magnitude improvement in several important respects over other magneto-optic modulators.

The most important improvements are: λ = 1.52 microns a bandwidth of 200 MHz, an insertion loss of 0.5 db, and a modulation power of only 86 mw for a modulation index of 40 percent. Also, the low voltage required (about 3v) is ideally suited for transistors. In addition to its efficiency and suitability for transistors, the modulator can be operated at room temperature with no oven or temperature controls required beyond normal ambient limits. It would be desirable if these modulator characteristics were also available in the visible spectrum, which is easier to work with. However, the usefulness and importance of the infrared is steadily increasing in commercial and military applications. Because of the very low drive voltage requirement, Mr. William A. Scanga of the AAI Corporation suggested investigating YIG with various doping materials as modulator material at 10.6 microns.

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*Talk given at Intermag Conference, Stuttgart, Germany, April 1966.

REFERENCES

1. Nelson, D. F., and Reinhart, F. K., "Light Modulation by the Electro-Optic Effect in Reverse-Biased GaP P-N Junctions," *Appl. Phys. Letters* 5:148-150, 1964.

2. Sterzer, F., Blattner, D. T., and Miniter, S. F., "Cuprous Chloride Light Modulators," *J. Opt. Soc. Am.* 54:62-68, 1964 .

3. Geusic, J. E., Kurtz, S. K., Van Uitert, L. G., and Wemple, S. H., "Electro-Optic Properties of Some ABO_3 Perovskites in the Paraelectric Phase," *Appl. Phys. Letters* 4:141-143, 1964.

4. Chen, F. S., Geusic, J. E., Kurtz, S. K., Skinner, J. G., and Wemple, S. H., "Light Modulation and Beam Deflection with Potassium Tantalate-Niobate Crystals," *J. Appl. Phys.* 37:388-398, 1966.

5. Blanc, J., Bube, R. H., and MacDonald, H. E., "Properties of High-Resistivity Gallium Arsenide Compensated with Diffused Copper," *J. Appl. Phys.* 32:1666-1679, 1961.

6. Frosch, C. J., and Derick, L., "The Preparation and Floating Zone Processing of Gallium Phosphide," *J. Electochem. Soc.* 108:251-257, 1961.

7. Amick, J. A., "The Growth of Single-Crystal Gallium Arsenide Layers on Germanium and Metallic Substrates," *RCA Review* 24:555, 1963.

8. Hirschmann, E., "Electro-Optic Light Modulators," NASA Technical Note D-3678, December 1966.

9. Chen, F. S., Geusic, J. E., Kurtz, S. K., Skinner, J. G., and Wemple, S. H., "The Use of Perovskite Paraelectric in Beam Deflectors and Light Modulators," *Proc. IEEE* 52:1258-1259, 1964.

10. Hanlon, J. T., and Dillon, J. F., Jr., "Microwave Modulation of Light in Ferromagnetic Resonance," *J. Appl. Phys.* 36:1269-1270, 1965.

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