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# MODULATION OF INFRA-RED LASER BEAM USING GALLIUM ARSENIDE CRYSTAL.

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## ABSTRACT

Recent developments in laser technology have aroused interest in problems of modulation of optical beams of light. The high coherency of modulated laser beams makes them technically applicable in a variety of ways. These include the device of Avionic Head Up display (HUD) to provide pilots with essential flight information, cutting of metals, welding in medicine and in several others ways. This work aims at investigating modulation characteristics of infra-red laser beam ($\lambda = 3.39 \times 10^{-6}$m) using Gallium Arsenide (GaAs) crystal as the modulator and liguid Helium-Neon (He-Ne) as the active medium. The investigation includes (a) determination of the half-wave voltage for the modulation, (b) determination of the frequency characteristics for estimating the frequency range for piezo-electric effect and (c) determination of amplitude characteristics for various applied currents to the active medium. It was observed that the crystal behaved like a piezo-electric crystal at the frequency range of about 450 to 1000 KHz. The half-wave voltage of the crystal was about 2200 volts. The amplitude of the output signal increased with increase in the current applied to the active medium. A close correlation was found between theory and experimental results.

## THEORY

The two main methods of modulation of laser beams are internal and external modulations Kathis, (1969); Kheludev, (1969). The choice of modulation depends on the objectives of the research, the specific type of laser beam and the speed of modulation. Our laser beam for this work was the infrared radiation ($\lambda = 3.39 \times 10^{-6}$ m). Two types of electrooptic effect can be distinguished – linear, common in solid bodies, particularly in crystals having no centre of symmetry and quadratic, common in liquid media and in crystals having centre of symmetry, Kravsov, (1970). Research work has been intensified on modulation based on linear electrooptic effect more than on other effects. It is possible to obtain a frequency of modulation as high as $10^9$ to $10^{10}$ Hz with visible and infrared radiation, Mustel et al, (1970). Kharikov et al, (1965) established the various advantages of using cubic crystals for modulation as against using other types of crystals, the ease of handling being a major advantage, Koblova et al, (1969).

Gallium Arsenide crystal (which was used as a modulator for this work) has the following properties:

(i) It has linear electrooptic effect.

(ii) It is optically isotropic and belongs to the cubic system of crystals and less complicated to handle than the optically anisotropic (uniaxial or biaxial) group of crystals.

(iii) In GaAs crystal it is possible, by a very careful orientation of the crystal, to obtain only one polarised light beam whereas in most other crystals, neither of the two polarised beams of light that normally emerge from a crystal can be easily and perfectly suppressed.

The equation of the optical indicatrix in a Cartesian coordinate system with the axes XYZ along the principle directions is given by

$$a_{10}X^2 + a_{20}Y^2 + a_{30}Z^2 = 1$$

where

$$a_{10} = 1/n_x^2; \quad a_{20} = 1/n_y^2; \quad a_{30} = 1/n_z^2 \qquad (1)$$

n is the refractive index of the crystal in the given direction.

On applying an electrical field the optical indicatrix changes direction and is deformed. The equation of the optical indicatrix in the old coordinate system XYZ now takes the form :

$$a_1X^2 + a_2Y^2 + a_3Z^2 + 2a_4YZ + 2a_5ZX + 2a_6XY = 1 \qquad (2)$$

In case of linear electrooptic effect we have

$$a_k - a_{k0} = \sum_{i=1}^{3} r_{ik} E_i \quad (i = 1, 2, 3) \qquad (3)$$

where $a_i$ = polarisation constant, Mustel et al, (1970).

In practical form, equation (2) can be written as

$$a(X')^2 + b(Y')^2 + c(Z')^2 = 1 \qquad (4)$$

where $a = 1/n_x^2$ $b = 1/n_y^2$ $c = 1/n_z^2$

And Z , Y , Z are the new directions of the principal axes Kheludev, (1969)

Solving the cubic equation

$$\begin{vmatrix} a_1 - \lambda & a_6 & a_5 \\ a_6 & a_2 - \lambda & a_4 \\ a_5 & a_4 & a_3 - \lambda \end{vmatrix} = 0 \qquad (5)$$

the roots of the equation, $\lambda_i$, can be found from the values of a, b, and c. The directions of the principal axes can then be found for every value of $\lambda_i$ (i = 1, 2, 3) from the following system of equations.

$$\begin{aligned}(a_1-\lambda_i)X + a_6 Y + a_5 Z &= 0\\ a_6 X + (a_2-\lambda_i) Y + a_4 Z &= 0\\ a_5 X + a_4 Y + (a_3-\lambda_i) Z &= 0\end{aligned} \qquad (6)$$

from where the ratio X:Y:Z can be estimated.

The directions of the principal axes can be found from the equation

$$\begin{aligned}\cos\phi_1 &= (X/Z)/\sqrt{1+(X/Z)^2+(Y/Z)^2}\\ \cos\phi_2 &= (Y/Z)/\sqrt{1+(X/Z)^2+(Y/Z)^2}\\ \cos\phi_3 &= 1\sqrt{1+(X/Z)^2+(Y/Z)^2}\end{aligned} \qquad (7)$$

For GaAs crystal, only a few components of the tensor $r_{ki}$ in equation (3) are not zero, namely

$$r_{41} = r_{52} = r_{63} = r$$

Besides, in the presence of an applied electric field, $a_{10} = a_{20} = a_{30} = a_o$. Then, equation (2) for optical indicatrix for GaAs crystal now takes the form.

$$a_o(X^2 + Y^2 + Z^2) + 2r\,(E_z YZ + E_y XZ + E_z XY) = 1 \qquad (8)$$

The characteristic equation (5) then takes the form

$$\begin{vmatrix} a_0-\lambda & rE_z & rE_y \\ rE_z & a_0-\lambda & rE_x \\ rE_y & rE_x & a_0-\lambda \end{vmatrix} = 0 \qquad (9)$$

Various orientations of the crystal were tried for optimum results and the orientation illustrated in fig. I. was found best for an effective modulation. The axes XYZ correspond with the crystal axes [100],[010], and [001]. The electric field vector E lies on the plane [001] and is perpendicular to the plane [110]. The light vector $\varepsilon$ lies along the axis [001]. The directional propagation vector of light K and the other two vectors E and $\varepsilon$ are all orthogonal to one another. From the above we have.

$$E_z = 0;\ E_x = E_y = E/\sqrt{2} \qquad (10)$$

As a result of equation (10), the solution to equation (9) gives

$$\lambda_1 = a_o;\ \lambda_2 = a_o - rE;\ \lambda_3 = a_o + rE \qquad (11)$$

From where

$$n_{x'} = 1/\sqrt{\lambda_1} = 1/\sqrt{a_0} = n_0$$

$$n_{y'} = 1/\sqrt{\lambda_2} = n_0/\sqrt{1 - rn_0^{\,2}E} \cong n_0(1 + \tfrac{1}{2}n_0^{\,2}rE) = n_0 + \tfrac{1}{2}rn_0^{\,3}E \quad (12)$$

$$n_{z'} = 1/\sqrt{\lambda_3} \cong n_0 - \tfrac{1}{2}rn_0^{\,3}E$$

Also from equation (6) and (10) we have

$$X/Z = rE_y/(a_o - \lambda),\ Y/Z = -rE_x/(a_o - \lambda) \quad (13)$$

From equations (7), (10) and (13) we can calculate the directions of the principal axes and obtain the result below:

For OZ' ($\lambda = a_o + rE$)

$$\cos\phi_1 = \cos\phi_2 = 1/2\ ;\ \cos\phi_3 = 1/\sqrt{2}$$

For OY' ($\lambda = a_o - rE$)

$$\cos\phi_1 = \cos\phi_2 = -\tfrac{1}{2}\ ;\ \cos\phi_3 = \tfrac{1}{2}$$

For OX' ($\lambda = a_o$)

$$\cos\phi_1 = \cos\phi_2 = 1/\sqrt{2}\ ;\ \cos\phi_3 = 0 \quad (14$$

Linear polarisation of the beam takes place along the OZ axis, and passing through the crystal splits into two equal amplitude components. The phase velocities of the signal components are $V_{Y'}$ and $V_{z'}$ respectively and the phase difference $\theta$ is given by

$$\theta = (2\pi/\lambda)(n_{Y'} - n_{z'})L$$

Where $\lambda$ = wavelength in vacuum,

L = length of the path of the signal through the crystal.

From equations (12) and (14) we have

$$\theta = (2\pi/\lambda)(r\, n_o^{\,3}\, UL/d) \quad (15)$$

where U = Ed = the constant voltage applied to the crystal.

The intensity of the signal at the exit from the crystal, $I_p$, is given by

$$I_p = I_o \cos^2(\theta/2) \quad (16)$$

where $I_o$ is the intensity of the input signal. The vertical component of the output signal $1_v$ is given by

$$I_v = I_o \sin^2(\theta/2) \quad (17)$$

The voltage corresponding to a phase difference $\theta = \pi$ is called the half-wave voltage. It is equal to the voltage for the minimum intensity of the signal, and is given by:

$$U_{\lambda\,2} = (\lambda D)/(2n_o^{\,3}rL) \quad (18)$$

The values of $n_o$ and r for GaAs crystal (at $\lambda = 3.39\times 10^{6}$m) are given by Voronkova et. al., (1965) and Mustel et al (1970) as

$n_o$ = 3.1 to 3.3, and

r = (1.2 to 1. 6) $10^{10}$ cm/V

Substituting the mean values as $n_o$ = 3.2 and r = $1.4\times 10^{10}$cm/V into equation (18) we have

$$U_{\lambda/2} = 3.7 \times 10^4 \text{ (d/L) volts.} \qquad (19)$$

## EXPERIMENTAL WORK

The infrared laser generator was constructed in such a way that only one polarisation of the generated beam circulated inside the resonator, the so called P- polarisation (as opposed to the orthogonal S- polarisation). This was achieved by making the incident angle of the laser beam (as well as the exit angle of the beam) on the crystal equal to Brewster's angle, so that $\tan i_B = n$ where $i_B$ = Brewster's angle and n = refractive index (≅ 3.2).
Fig. 2 shows the schematic diagram of the crystal arrangement. The cut off angle of the crystal $i_{coff} = i_B = \arctan n = \arctan 3.2 \cong 72.5^\circ$.

The wavelength of the infrared laser beam was $3.39 \times 10^{-6}$ m

**The objectives of this work were:**

(a) To determine the half wave voltage, $U_{\lambda/2}$, of the electrooptic modulator

(b) To determine the frequency characteristics so as to estimate the frequency range for piezo electric effect.

(c) To determine the amplitude **characteristics** for different applied currents to the active medium.

External modulation is frequently used for the first two investigations above while internal modulation gives best results for the last investigation. Fig. 3 shows the block diagram for internal modulation of the laser beam while fig. 4 shows the external amplitude modulation of the beam. Fig. 5 shows the principal electrical scheme for the electrooptic modulator.

Equipment set up was as in fig. 4 for the determination of the half-wave voltage of the electrooptic modulator. Fig. 6 shows a graph of relative intensity of signal passing through the modulator (3) and the polariser (9) against the controlling voltage V on the modulator (see fig. 4). The voltage corresponding to the minimum relative intensity, $I_r$, from the graph is equivalent to $U_{\lambda/2}$ and this is about 2200 V from the graph shown in fig. 6.

Using equation (19) with d/L = 0.058 we have $U_{\lambda/2}$ = 2150, showing a close correlation between theory and experiment.

Investigation of frequency characteristics of the modulator was carried out in the same way as above. In this case, a controlling sinusoidal voltage of 200V and a constant effective amplitude were applied with a constant voltage of 1000V on the crystal (see fig. 5). The oscillograph in fig.4 was used for studying the relationship between relative intensity, $I_r$, and frequency, f of modulation. The result is shown in fig. 7. Piezo-electric effect was observed at a frequency range of about 450 to 1000KHz. This effect was more pronounced between 650 and 800KHz

Fig. 3 illustrates internal modulation of laser beam for studying amplitude characteristics. This was achieved by measuring the amplitude of the output signals on the screen of the oscillograph in fig. 3. For the different applied currents, $I_{app}$ = 8, 10, and 13mA, Dalenkov et al, (1971). Maximum amplitude was achieved for the maximum applied current and vice versa, fig.8.

Standard deviation $S_{1out}$ was computed from the equation.

$$S_{1out} = \sqrt{n(n-1)\sum_{i=1}^{3}(I_{out} - \mathbf{I}_{out})^2} \qquad (20)$$

where $I_{out}$ = mean value of output signal and n = number of readings.

The confidence interval $\Delta \mathbf{I}_{out}$ was computed with the formula

$$\Delta \mathbf{I}_{out} = \alpha\sqrt{(S_{Iout})^2 + \sigma^2} \qquad (21)$$

where $\sigma = \delta^2/3$ = dispersion error of the instrument

$\delta$ = minimum width of the squares on the screen of the oscillograph = 1mm

$\alpha$ = proportionality constant depending upon the properties of the equipment. It is equal to 4.4 for this equipment. For example, if $\mathbf{I}_{out}$ = 73.3mm and $S_{i\,out}$ = 0.3333 then

$$\Delta\mathbf{I}_{out} = 2.9\text{mm and } \mathbf{I}_{out} = 76.3 \pm 2.9\text{mm}.$$

The percentage relative error therefore is equal to (2.9/ 73.3)x100 = 3.96%

## RESULTS AND DISCUSSION

The following results were obtained from this work:

(a) The half-wave voltage, $U_{\lambda/2}$, that is, the voltage that gives the minimum signal intensity for GaAs crystal was established as 2200V. The theoretical value was 2150V. The correlation between theory and practical investigation was quite satisfactory.

(b) The frequency range for piezo- electric effect in GaAs crystal was found to be between 450 and 1000KHz . This effect was particularly strong within the frequency range of 650 to 800KHz (fig.8). In recent times, piezo-electric properties of crystals have acquired considerable industrial significance, Asokhia (1994)

(c) The results of the investigation have given a clue to the optimum working conditions for internal electrooptic modulation of infrared laser beam using GaAs crystal as the modulator and He-Ne gas as the active medium. In particular, it was established that increase in the applied current to the active medium increases the amplitude of the signal generated (fig.8)

## CONCLUSION

As a result of this work, the half-wave voltage, that is the minimum optimum voltage for the modulation of infra-red laser beam with GaAs crystal, using liquified He-Ne gas as the active medium was established. The frequency range for pieze-electric effect for this crystal was also established. The behaviour of the crystal under the application of various ranges of electric current was successfully investigated. It is hoped that industrialists would make the best use of these results. It is recommended that the scope of the modulation of laser beams be expanded to include the use of other types of crystals and active media for their modulation.

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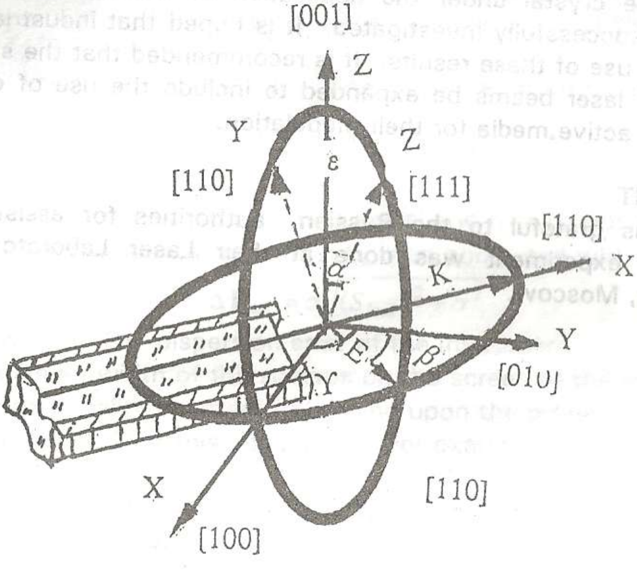

Fig. 1 Orientation vector **K**, **E**, ε, the principal axes X, Y, Z, and the new axes X', Y', Z', as a result of applied electric field to crystal.

**E** = Electric field intensity vector

**K** = Directional propagation vector of light

ε = Light vector, $\alpha = 45^0$, $\beta = 45^0$, $Y = 135^0$

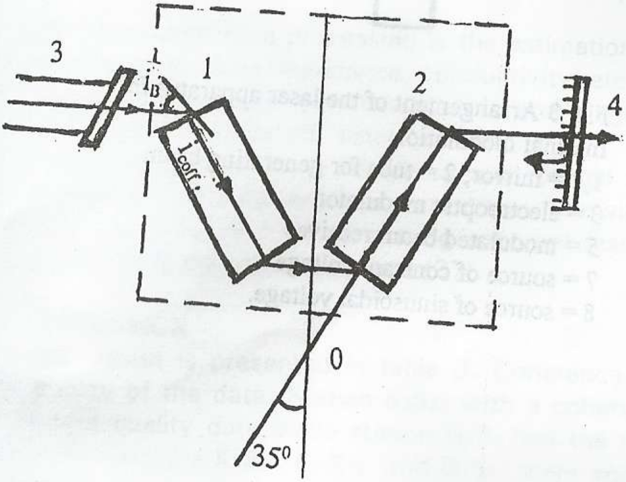

Fig. 2 Arrangement of the crystal in the modulator
1 = tube for generating beam
2,3 = electrooptic crystal; 4 = mirror
$\phi$ = Brewster's angle; $\alpha = 35^0$

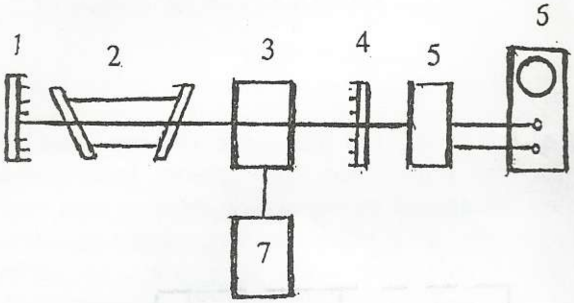

Fig. 3 Arrangement of the laser apparatus for internal modulation
1,4 = mirror; 2 = tube for generating beam
3 = electrooptic modulator
5 = modulated beam receiver
7 = source of constant voltage
8 = source of sinusoidal voltage.

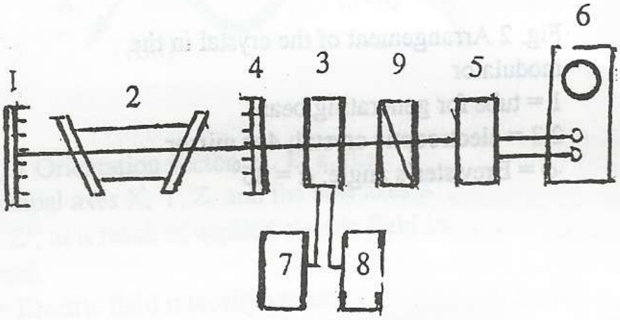

Fig. 4 Arrangement of laser apparatus for external amplitude modulation
1 to 8 as in fig. 3.

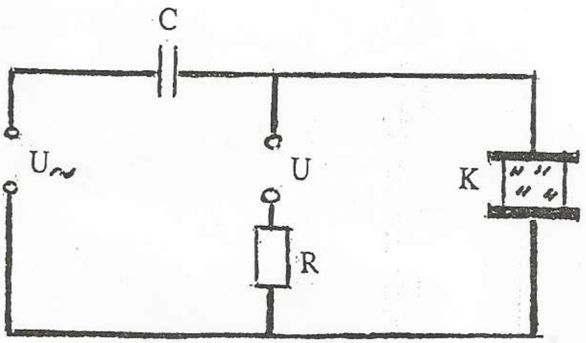

Fig. 5 Electrical diagram for modulator
U = Sinusoidal voltage
$U_{\sim}$ = Constant voltage
R = Resistance = 1MΩ
C = Capacitance = 1500 pF

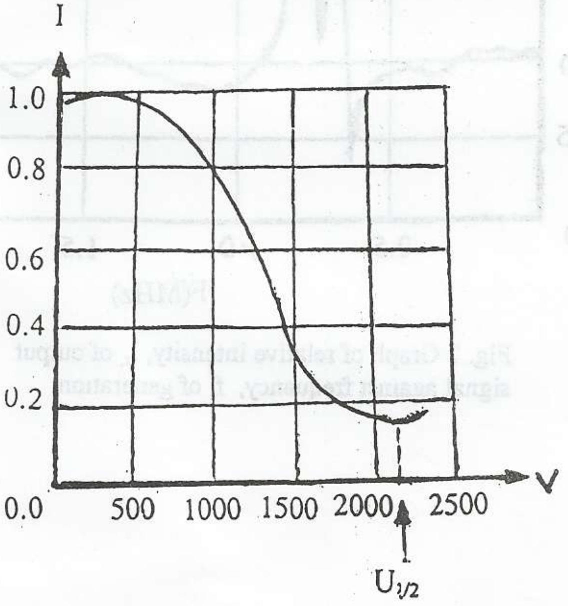

Fig. 6, Graph of relative intensity, $I_r$, of signal passing through the modulator against applied voltage V
$U_{\lambda/2}$ = half wave voltage
$I_r$ = relative intensity of output signal

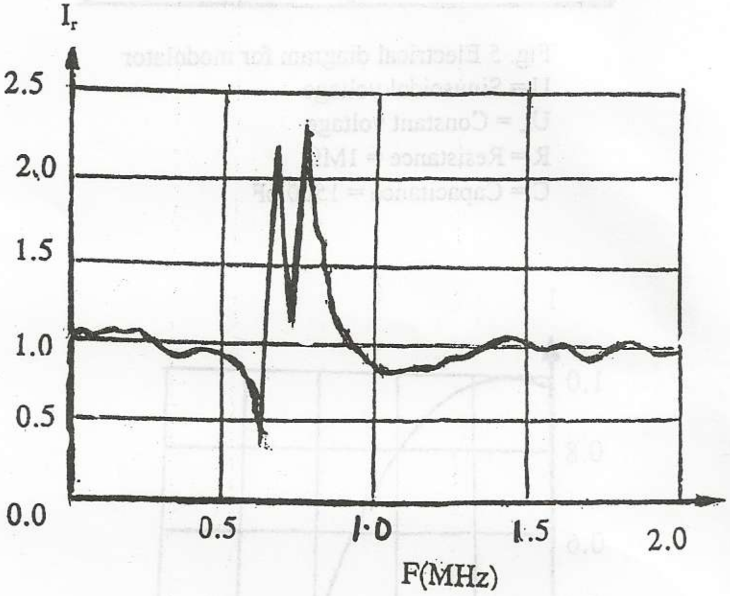

Fig. 7 Graph of relative intensity, $I_r$, of output signal against frequency, f, of generation

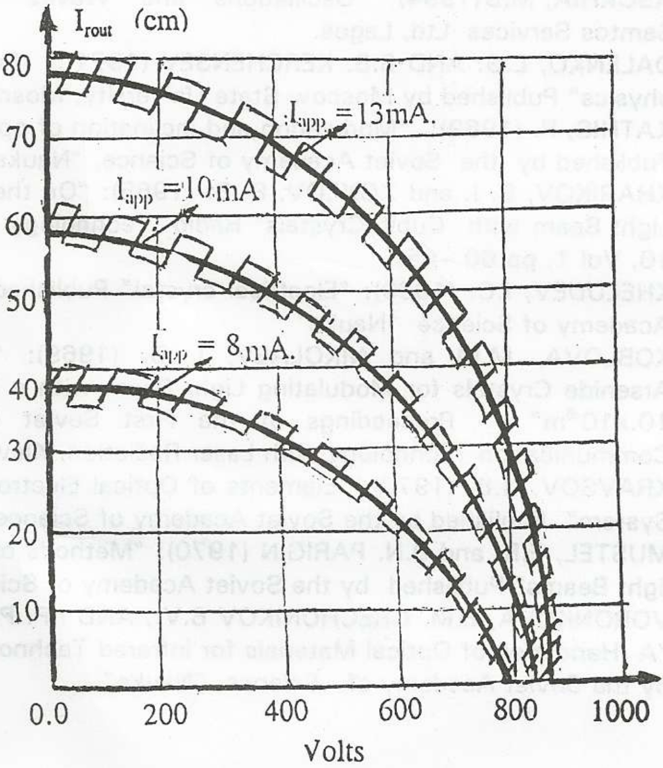

Fig. 8. Graph of amplitude characteristics for various applied currents to the active medium.
$I_{app}$ = applied current to active medium (mA)
$I_r$ = relative intensity of signal.

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