RICE UNIVERSITY

INVESTIGATION OF GaAs MODULATORS AT 10.6 AND 337 MICRONS

by

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ABSTRACT

INVESTIGATION OF GaAs MODULATORS AT 10.6 AND 337 MICRONS

PAUL JOEL EPTON

An attempt was made to electrooptically modulate the 10.6 μm light from a CO₂ laser. The modulator was a 130 μm thick epitaxial layer of GaAs grown on a degenerately doped GaAs substrate. The modulator was situated in a microwave cavity and DC biased into Limited Space-Charge Accumulation (LSA) mode oscillation. The electric field for the electrooptic effect was provided by the DC bias pulse and the microwave oscillation. Bias pulse heating of the GaAs substantially changed its infrared transmission and prevented observation of any electrooptic modulation that occurred.

A study was also carried out of wide bandwidth amplitude modulation of the 337 μm light from an HCN laser. The modulator was a 100 μm thick epitaxial layer of GaAs grown on an insulating GaAs substrate. The doping density of the epilayer was \( N_D = 4.61 \times 10^{14} \) cm\(^{-3}\) and \( N_A = 2.45 \times 10^{14} \) cm\(^{-3}\). The modulator was immersed in liquid helium, freezing out the free carriers on the donor impurities. Pulsed microwave radiation was used to impact ionize the impurities for modulation, and the transmission of the GaAs
increased as the neutral donors were ionized. A peak in the modulation index of 29% was obtained at 200 mW of absorbed microwave power for the GaAs situated in a terminated waveguide. A 10% modulation index with better coupling of the 337 μm light and poorer microwave coupling was obtained for a microwave cavity configuration. From a measurement limited by the detector bandwidth, the modulator risetime was found to be less than 150 ns.
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I. INTRODUCTION

1. Background

The far-infrared and submillimeter region of the spectrum has undergone considerable development in recent years. The high power available from the CO$_2$ laser at 10.6 $\mu$m has focused particular interest on research at this wavelength [1]. With the development of optically pumped molecular waveguide lasers and the improvement of available detectors, activity at the longer submillimeter wavelengths has also begun to increase [2]. Throughout this spectral region, there is still room for development of high-speed modulators. Communications systems, study of transients in thermonuclear plasmas [3], and investigation of detector response time are but a few of the situations where fast risetime, wide bandwidth modulators would find application.

At 10.6 $\mu$m, the electrooptic effect has been used extensively [4]. Several workers have reported systems based on passive GaAs devices and have achieved modulation at frequencies up to 10 GHz [5]. To obtain such high frequencies, the system requires application of microwave fields which have been modulated with the information to be transmitted. Another approach is to use active devices,
where the microwave field is generated within the modulator and the information can be impressed on the DC bias voltage. Gunn effect devices have been used up to 4 GHz by letting domains intercept the light [6].

In the submillimeter region, the simplest modulator is the mechanical chopper, which is restricted to square wave or rectangular pulses and low modulation rates. Stark modulation can be used with waveguide laser sources for combined frequency and amplitude modulation. The modulation characteristics, however, are specific to the individual laser transition [7]. Free carrier absorption in cooled, impact ionized Ge has been reported over most of the submillimeter region. The observed bandwidth is 100 MHz, and the modulation depth is about 50% at a wavelength of 337 μm [8].

2. Present Work

The work presented here deals with two modulators, one for use at 10.6 μm and the other for the region 100-350 μm. The former is an active GaAs device operating in the Limited Space-Charge Accumulation (LSA) mode. Since the LSA mode is a bulk effect, less stringent requirements exist on light focusing than apply to Gunn effect devices,
and higher electric fields for the electrooptic interaction may be used. In addition, the LSA device can sustain a higher duty cycle. The second device is a microwave biased GaAs impact ionization modulator. A distinctive feature of this device is that ionization increases the submillimeter transmission, in contrast to the Ge absorption modulator.

Chapter II treats the LSA device. A simple analysis of the LSA mode of oscillation is presented. This is followed by a discussion of the electrooptic effect. Finally, the experimental results for modulation at 10.6 μm are presented.

Chapter III describes the electrical behavior predicted for microwave biased GaAs cooled to 4.2°K. The important optical processes at 337 μm, the experimental wavelength, are also calculated. Experimental results for two different modulator configurations are presented next. The results of two diagnostic experiments, performed to help further the understanding of the impact ionization modulator, conclude the chapter.

Chapter IV includes a summary of the results obtained and some considerations for possible extensions and improvements of the devices studied.
II. GaAs ELECTROOPTIC MODULATOR AT 10.6 μm

1. Introduction

The feasibility of an infrared modulator for 10.6 μm radiation was investigated. The device utilized the linear electrooptic (Pockels) effect in GaAs. The required electric fields were supplied by an active layer of GaAs undergoing Limited Space-Charge Accumulation (LSA) mode microwave oscillation.

GaAs is a direct gap semiconductor with an energy gap $E_g = 1.43$ eV located at the center of the Brillouin zone (Figure 1) [9]. In addition to the central conduction valley, there are satellite valleys in the six $\langle 100 \rangle$ directions located an additional energy $\Delta E = 0.38$ eV above the central valley [10]. For low applied electric fields, almost all of the electrons are in the central valley, but at a threshold field around 3.2 kV/cm, the carriers begin to transfer to the satellite valleys. The carrier effective mass is substantially higher and the scattering time somewhat shorter in the satellite valleys, leading to a lower mobility for these "warm" carriers [11]. The drop in average mobility as more and more of the carriers change valley is large enough that GaAs displays a negative
Figure II-1. GaAs Band Structure
differential conductivity (n.d.c.) around the threshold field and a decreased positive conductivity above it.

GaAs DC biased into the n.d.c. region is electrically unstable. The steady state toward which the system evolves is characterized by a small high-field region, or domain, which travels across the sample and a large region where the electric field is below threshold \[11\]. The current oscillates with a period equal to the saturated domain transit time in the Gunn mode. The domain can be suppressed by a rapid reduction of the electric field below threshold before the buildup has time to occur \[12\]. The field is then essentially uniform across the sample and the bulk n.d.c. can be directly utilized. This is the LSA mode.

The actual oscillation frequency is now circuit dependent and can be approximated with the aid of a model by Camp, shown in Figure 2 \[13\]. When the instantaneous device voltage \(V(t)\) is below the threshold value \(V_T\), the device is modeled as a resistance \(R_o\). The other elements are the load resistance \(R_L\), the device and package capacitance \(C\), and the circuit inductance \(L\). The device voltage at the start of an rf cycle is \(V_A = (\frac{I_v}{I_p})V_T\) and increases asymptotically toward the applied bias \(V_B\) as the voltage
(b) \( V(t) < V_T \)

\[
V(t) = V_A + V_B (1 - e^{-(R_0/L)t})
\]

(c) \( V(t) > V_T \)

Figure II-2. Camp's LSA Oscillator Model [13]
across $L$ relaxes toward zero. The expression for the voltage as a function of time is given as

$$V(t) = V_A + (V_B - V_A)(1 - e^{-(R_o/L)t}) \quad V(t) < V_T \quad (1)$$

The time spent below threshold can be found by setting $V(t)$ equal to $V_T$, giving

$$t_b = -\frac{L}{R_o} \ln [1 - (V_T - V_A)/(V_B - V_A)]$$

$$\approx \frac{L}{R_o}(V_T - V_A)/(V_B - V_A) \quad (2)$$

At threshold, the device switches to the low differential mobility state and is approximated as a current source with the valley current $I_V$. The voltage expression is now

$$V(t) = V_B e^{-t/2R_LC} [(V_T - V_B) \cos \Omega t + (V_T QL/2R_o) \sin \Omega t] \quad V(t) > V_T \quad (3)$$

where $\Omega = \sqrt{(1/LC - (1/2R_LC)^2)}$

For large $V_B$, the cosine term dominates and the device stays above threshold for almost a full cycle if the loading is light. The time spent above threshold in this limit is

$$t_a = 2\pi \sqrt{LC} \quad (4)$$

The total period for one oscillation is

$$t = t_a + t_b = 1/f = (L/R_o)(V_T - V_A)/(V_B - V_A) + 2\pi \sqrt{LC} \quad (5)$$

In the limit of large bias voltage, the circuit approaches as asymptotic frequency

$$f_A = 1/2\pi \sqrt{LC} \quad (6)$$
independent of the GaAs I-V characteristic. The optimum operating frequency is about half the asymptotic value.

2. The Linear Electrooptic Effect and Electrooptic Modulation

The relation between the polarization and the electric field in a crystal is in general nonlinear. For small deviations from linearity, the polarization can be expressed as a power series in the electric field,

$$P = \xi_0 [\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} \cdot \mathbf{E} \mathbf{E} + \chi^{(3)} \cdot \mathbf{E} \mathbf{E} \mathbf{E} + \cdots]$$

where the $\chi^{(i)}$ are the tensor susceptibilities. If the electric field consists of a DC field $\mathbf{E}^{(0)}$ and an optical field $\mathbf{E}^{(\omega)}$, then the linear electrooptic effect arises from the polarization term

$$P^{(\omega)} = \xi_0 \chi^{(2)} \cdot \mathbf{E}^{(0)} \mathbf{E}^{(\omega)}$$

$\chi^{(2)}$ also leads to a static nonlinearity in the polarization and to second harmonic generation.

By symmetry arguments, $\chi^{(2)}$, actually a third order tensor, can be shown to be nonzero only if the crystal lattice lacks inversion symmetry. For GaAs, with 43m tetrahedral symmetry, this is the case. In addition, for this particular lattice the $\chi^{(2)}$ tensor can be simplified considerably by choosing the reference axes along the $(100)$ directions. In discussing the electrooptic effect,
it is more convenient to replace the polarization with the index of refraction and the susceptibility by the electro-optic coefficient. For $\vec{E}(\omega)$ in the (001) direction and incident light $\vec{E}(\omega)=\vec{E}_{\parallel}(\omega)+\vec{E}_{\perp}(\omega)$ propagating in the (110) direction (Figure 3), there are two indices of refraction (14)

$$n_{\parallel}=n_{o}$$
$$n_{\perp}=n_{o}+n_{o}^{3}r_{41}E^{(s)}/2$$

where $n_{o}$ = index of refraction in the absence of external fields

$r_{41}$ = electrooptic coefficient

The different indices of refraction cause a phase difference between $\vec{E}_{\parallel}(\omega)$ and $\vec{E}_{\perp}(\omega)$,

$$\Gamma=(\pi/\lambda)ln_{o}^{3}r_{41}V/d$$

where $\lambda$ = vacuum wavelength

$l$ = sample length

$V$ = applied voltage

$d$ = sample thickness

The phase difference can be utilized to obtain amplitude modulated polarized light. The electrooptic material is placed between crossed polarizers with their easy axes oriented $\pm 45^\circ$ from the direction of $\vec{E}(\omega)$. The percent modulation using ideal polarizers is given by [15]

$$(\text{percent modulation})/100=2J_{1}(\pi V/V_{m})$$
Figure II-3. Crystal Orientation for Electrooptic Modulation
where \( J_1 \) = Bessel function of the first kind

\[ V = \text{applied voltage} \]

\[ V_p = \text{voltage to obtain } 180^\circ \text{ phase shift} \]

By inverting (10) with \( \Gamma = \pi, \lambda = 10.6 \, \mu m, d = 130 \, \mu m, \xi = 30 \, \text{mils}, \]
and \( n_o \Gamma_{41} = 5.9 \times 10^{-9} \, \text{V/cm} \) [16], \( V_p = 3.1 \times 10^4 \, \text{V} \). For applied peak voltages of 550 V, the theoretically predicted modulation is 5.5%, corresponding to an effective rotation of just over 3.2°. The detector signal-to-noise was well below 5.5%. The polarizers, however, were not ideal and in fact could resolve only a 2.7° rotation. Thus the predicted electrooptic modulation was just above the system detection limit. Attempts to increase the modulation index by applying higher voltages were unsuccessful due to electrical breakdown of the LSA diodes. Increasing the interaction length by making longer diodes was also unsuccessful since the increased capacitance modified the resonant circuit and led to a loss of space charge control.

3. LSA Diode Material and Microwave Cavity Details

The LSA devices used were fabricated from a wafer of epitaxial (100) GaAs. The active layer was doped at \( 7 \times 10^{15} \) carriers per cm\(^3\), near the upper limit for LSA oscillation in the 130 \( \mu \)m active layer [17]. The sub-
strate was degenerately doped. Typical dimensions were 30 mils long by 20 mils wide, giving a resistance of $R_0 = 3\Omega$. Two edges were cleaved along (110) crystal planes, while the other two edges were wire-sawed along (\bar{1}10) planes (Figure 3). (See appendix 1 for details of device fabrication.)

The devices were situated in a coaxial cavity (Figure 4). The active layer capacitance was about .3 pfd, and the cavity inductance was about 1.7 nh, giving a calculated asymptotic frequency of 7 GHz. The oscillation threshold was about 25 V, and typical bias levels ranged up to 280 VDC, giving a 550 V peak during each oscillation cycle. The bias pulse length ranged from .2 \mu s to 4 \mu s with a risetime for the oscillation of less than .05 \mu s. Typical duty cycles were less than .1%.

4. Experimental Configuration

The experimental configuration used to observe the modulation is shown in Figure 5. The radiation source was a Sylvania model 941 3 watt CO$_2$ laser. The required optical polarization was obtained with a grid polarizer (P1) having its easy axis oriented 45° from the vertical. (See appendix 2 for details of the polarizer.) The microwave
Figure XI-4. LSA Oscillator Cavity
Figure II-5. Experimental Configuration for GaAs Electrooptic Modulator
cavity which contained the LSA diode included two small (.125") holes through which the 10.6 μm light passed. A second grid polarizer (P2), with its easy axis oriented perpendicular to the first one, was used as an analyzer. The signal was then detected by a cooled Ge:Cu photoconductive detector. (See appendix 3 for details of the detector.)

The polarized light was focused onto one of the cleaved faces of the device with a 1\frac{1}{2}" focal length Ge lens (L1). The spot size was measured as approximately 100 μm, and the cavity was adjusted to center the spot on the diode. After passing through the diode, the modulated light exited the cavity and was recollimated by a 2\frac{1}{2}" focal length Ge lens (L2).

5. Observations

Modulation of 10.6 μm radiation was observed, but with substantially different temporal behavior than that of the LSA pulse. In addition, the modulation was independent of polarization. For a 1 μs LSA pulse, the modulation had a 2 μs risetime and a duration of 3-4 μs. The decay was in two stages, with time constants of 10-40 μs and .2-1 ms, respectively. The modulation was primarily an absorption
of 25-65% of the light, but in some instances a 50-100% increase in the light level was observed. The magnitude and sign of the signal were altered by moving the device about within the optical beam as well as by changing the bias pulse amplitude, and some modulation was present even for bias below the LSA threshold.

The observed characteristic is believed to result from thermal effects. The bias pulse can be modeled as delivering a thermal impulse to the GaAs active layer. The temperature rises rapidly to a value determined by the impulse energy and the heat capacity of the active layer. It then decays as the thermal energy flows into the substrate and then across a thermal contact resistance into the mounting post for the device. For a 150 V bias pulse, the initial temperature rise is calculated to be about 65°C. Based on Bravman's model for thermal effects in active GaAs devices [18], various parts of the thermal circuit contribute time constants ranging from microseconds to milliseconds. In particular, a calculated time constant of about 700 μs is associated with a 130 μm thick active layer.

The time constants observed clearly support the suggestion of thermal effects being dominant. An attempt
was made to simply heat the device and record its transmission as a function of temperature. While there was some evidence for temperature-dependent effects, difficulties in maintaining alignment during the thermal cycling precluded definitive results.
III. GaAs IMPACT IONIZATION MODULATOR AT 337 μm

1. Introduction

The feasibility of a far-infrared modulator for 337 μm radiation was studied. High purity n-GaAs cooled to 4.2°K shows a large increase in resistance as the average free carrier energy decreases and the majority of the electrons freeze out on impurity sites. By applying sufficiently large electric fields, the electrons can be impact ionized back to the conduction band. Modulation of 337 μm light can occur because of the difference in optical absorption of the neutralized donor impurities and of the free carriers. The electric fields to initiate impact ionization can be supplied by pulsed microwave radiation.

The modulator was a piece of high purity epitaxial n-GaAs grown on an insulating substrate (Figure 1). (The material was obtained from Cayuga, a Narda subsidiary.) The epilayer was 100 μm thick with donor and acceptor concentrations of $N_D=4.61 \times 10^{14} \text{ cm}^{-3}$ and $N_A=2.45 \times 10^{14} \text{ cm}^{-3}$, respectively. The DC mobility was estimated to be $4 \times 10^4 \text{ cm}^2/\text{V-sec}$ at 4.2°K, the free carrier concentration was estimated to be $7 \times 10^9 \text{ cm}^{-3}$ [19], and the recombination time was believed to be approximately 5 ns [20].
Figure III-1. GaAs Impact Ionization Modulator Chip
2. Impact Ionization in GaAs

Impact ionization of donor impurities in cooled GaAs has been observed by several workers at fields in the range 5-25 V/cm [21,22]. Koenig, et.al. [23] have done an extensive theoretical and experimental study of this effect in Ge. Their results are based on rather general grounds, and Oliver [22] has explained non-ohmic behavior in GaAs similarly. For electric fields somewhat below the avalanche breakdown field, the thermally generated free carriers heat up and their recombination time increases. This leads to an increase in the carrier concentration. At a threshold field of about 6.6 V/cm for the GaAs samples used in the present work, impact ionization causes a rapid increase in carrier concentration of several orders of magnitude.

The usual means of initiating and studying the ionization process is to apply voltage pulses to the sample and observe the resultant current or Hall voltage. To facilitate working with short pulses, the mechanism used in this experiment was the application of 9.9 GHz X-band microwave pulses. Since the microwave oscillation period is shorter than the DC recombination time by over an order of magnitude, the carrier heating that leads to the initial conductivity increase should not appear. More signifi-
cantly, the oscillating electric field will cause the carriers to oscillate with a calculated amplitude comparable to the impurity spacing. The probability of interacting with a neutral impurity with sufficient strength to cause impact ionization becomes much smaller, and thus the increase in free carrier concentration with electric field will be much less dramatic than in the DC case.

3. Optical Interactions in GaAs

The interaction of high purity n-GaAs with submillimeter radiation has been used previously to make fast, sensitive detectors for the 100-350 μm region (Figure 2) [20,24,25]. These devices are operated at liquid helium temperatures. Light is absorbed when photons ionize the electrons frozen out on donor sites. The donor sites can be treated as modified hydrogen atoms, where the usual hydrogen energy levels given by

$$E_n = -\frac{\hbar^2}{8}\frac{m}{\epsilon_n^2} n^2$$  \hspace{1cm} (1)

must be corrected for the effective mass and dielectric constant of GaAs. The resultant energy difference between the ground and first excited states is $E_2 - E_1 = 4.34$ meV, corresponding to a photon of $\lambda = 282$ μm. This bound state excitation has been found to dominate the submillimeter
Figure III-2. GaAs Donor Energy Levels and Photoconductive Response
absorption spectrum for low excitation levels. The observed photoconductive response results from the subsequent thermal ionization of the excited electrons into the conduction band [26,27].

Lax [28] treats the photoabsorption cross section for bound impurity states. He finds that integrating over all frequencies gives a cross section that is independent to first order of the detailed lineshape:

$$\sigma_{ba} = \frac{\varepsilon_r^2 (E_e / E)^2 (2\pi \hbar e^2/m^* c)^2}{f_{ba}} = 1.09 \times 10^{-16} \varepsilon_r^2 (m/m^*) f_{ba} \text{ (cm}^2\text{-eV)}$$

(2)

where $E_e / E = \text{ratio of local field to average radiation field}$

$a \approx 1$ for large orbits

$f_{ba} = \text{oscillator strength for transitions from state } a \text{ to state } b$

The oscillator strength is calculated from the theory for the hydrogen atom. The value for the transition between the ground and first excited state ($1s$-$2p$) is $f_{21} = 0.416$, independent of bulk parameters such as $m^*$ and $\varepsilon_r$. Thus the value for the hydrogen atom can be directly used in calculations for GaAs. Using reported photoconductivity spectra to obtain a lineshape [19], the 337 $\mu$m differential cross section is calculated to be $\sigma(337) = 4 \times 10^{-13}$ $\text{cm}^2$. An alternative calculation may be performed by using the observed
photoconductive responsivity of the modulator material [21]. A lower bound of \( \sigma(337) = 1.5 \times 10^{-13} \text{ cm}^2 \) is obtained from the measured change in resistance for a given light flux. Since the transmission increase reported below requires \( \sigma(337) \geq 2.3 \times 10^{-13} \text{ cm}^2 \), the correct value is probably closer to the theoretical calculation.

The second relevant optical interaction is free carrier absorption by the thermally generated or impact ionized electrons. The free carrier absorption coefficient is given as [29]

\[
\alpha = N \nu \mu/[ \varepsilon_r \varepsilon_\circ c (1 + \nu^2 \tau^2)]
\] (3)

where \( N \) = carrier concentration
\( \mu \) = DC mobility
\( \varepsilon_r \) = relative dielectric constant
\( \tau \) = mobility scattering time

For 337 \( \mu \text{m} \) radiation and \( \mu = 4 \times 10^4 \text{ cm}^2/\text{V-sec} \), \( m^* = 0.0665 m_0 \) [30],

\[
\omega \tau = \omega \mu m^*/e
\]

\[
= 8.46
\] (4)

so a short wavelength limiting form can be used. Dividing through by \( N \) gives the short wavelength absorption cross section

\[
\sigma = \lambda^2 e^3 / 4\pi^2 \varepsilon_\circ m^* c^3 \mu \varepsilon_r^\lambda
\] (5)
Using values for the parameters appropriate to GaAs, this expression yields a cross section of $\sigma(337)=9.9 \times 10^{-15} \text{ cm}^2$. Bean and Perkowitz [31] present measurements of free carrier absorption in GaAs from which a value of $\sigma(337)=8.8 \times 10^{-15} \text{ cm}^2$ can be inferred for the present sample at 4.2°K. These results are an order of magnitude less than the neutral donor cross section, indicating that as electrons are excited from the bound donor states into the conduction band, the transmission of 337 μm light should increase.

The room temperature submillimeter photoabsorption can be explained by free carrier interactions without reference to ionized donor absorption. Thus the impact ionized donors at 4.2°K will not contribute to the submillimeter absorption. The plasma frequency is given by [29]

$$\omega_p=\left(\frac{Ne^2}{m*\varepsilon_0\varepsilon_\infty}\right)^{1/2}$$

and is calculated to lie in the range 32-102 GHz for carrier concentrations in the range $10^9 - 10^{14} \text{ cm}^{-3}$ possible with the sample. This is well below the optical frequency, so plasma effects are also insignificant.

4. Experimental Configuration

The experimental configuration used to study the
modulator characteristics is shown in Figure 3. The microwave bias was supplied by a klystron followed by a TWT amplifier. The klystron was modulated by a fast risetime pulse generator. The microwave power incident on the GaAs was controlled by a precision attenuator, and both the incident and reflected power were measured. The modulator could be matched to the microwave source by adjusting the slide screw tuner (SST) until there was no reflected microwave signal. The device was mounted on a quarter-wave-length polyethylene support at the end of a shorted waveguide to maximize the electric field available for impact ionization (Figure 4a). The waveguide and modulator were at the bottom of a liquid helium dewar.

An HCN gas discharge laser with about 10 mW of output power at 337 μm was used as the submillimeter source. The laser beam was focused into a ½ in. dia. stainless steel light pipe and through an optical switch that directed the light either to a calibrated thermopile or to the waveguide. The light was coupled into the waveguide via a 1/8 in. dia. hole in a mitered corner at the top of the dewar. The bottom end of the waveguide had another 1/8 in. dia. hole through which the modulated light passed to a detector. The detector was also made of GaAs and was
Figure III-3. Experimental Configuration for GaAs Impact Ionization Modulator
Figure III-4. Details of Modulator and Detector Assemblies
used in the DC biased photoconductive mode. The submillimeter coupling hole was made long enough to prevent leakage of the evanescent X-band wave used as the modulating signal.

The submillimeter beam could not be directly focused either into the waveguide or onto the modulator with the above configuration. This led to a relatively low submillimeter power reaching the detector. A second configuration, shown in Figure 4b, had better submillimeter coupling. The modulator was placed in a microwave cavity which was coupled to the waveguide by an adjustable probe. Consequently, the submillimeter radiation could be directed to the modulator through a light pipe separated from the waveguide. The light pipe terminated in a combined metal and dielectric cone that concentrated the light directly onto the modulator. (See appendix 4 for details of the cone system.) The bottom of the cavity had a \( \frac{1}{4} \) in. dia. hole through which the light passed to reach the detector. The hole was again made long enough to keep the X-band radiation from reaching the detector.

5. Modulator Characteristics--Terminated Waveguide

The modulator has been characterized in terms of
absorbed microwave power and pulse width. In the terminated waveguide configuration, the SST was used to match the modulator to the microwave source at low power. At a threshold of 12 mW, part of the microwave power began to be reflected, indicating the onset of impact ionization. The SST was readjusted to regain the match condition. The GaAs conductivity appeared to change smoothly with increasing microwave power, and the SST had to be reset for each data point. Figure 5 is a photograph of the submillimeter detector response for a 64 μs microwave modulating pulse synchronized with a mechanical chopper which was located between the laser and the modulator. The increased transmission can be clearly seen as the small pulse at the center of the "on" portion of the chopped light. The modulation index peaked at 29% for 200 mW of microwave power and then decreased as the microwave power continued to increase (Figure 6). Duty cycle did not effect the index, so the observed results do not arise from microwave heating of the GaAs.

6. Modulator Characteristics—Microwave Cavity

The modulation data described above was for a signal-to-noise ratio of about 15 at the peak signal. By
Figure III-5. Detector Response to Combined Chopped and Impact Ionization Modulated 337 μm Light
vertical scale: 200 mV/div
horizontal scale: 200 μs/div
Figure III-6.  Modulation Index vs. Absorbed Microwave Power for Terminated Waveguide (64 μs pulse width, 2.7 MHz repetition rate, 2.5 mW of 337 μm light)
using the cavity configuration, a higher S/N was possible at the expense of poorer microwave coupling and lower peak modulation index. The cavity was resonant below the impact ionization threshold at about 9.3 GHz with a 7 MHz bandwidth for a Q of greater than 1300. Above threshold, the system absorbed substantial microwave power over a several hundred megahertz range centered around 9.8 GHz. The center of the resonance depended in part on the position of the coupling probe. Experimentally, the cavity could be tuned to match the source for only certain values of the microwave power and frequency. Consequently, the cavity was tuned below threshold, the klystron was set to an operating frequency in the breakdown region, and no further attempt was made to adjust the probe. Figure 7 shows the modulation index as a function of absorbed microwave power for a 1 µs pulse width.

With the higher S/N available in the cavity configuration, structure could be observed superimposed on the submillimeter modulation pulse (Figure 8). This structure was dependent on the incident microwave power level and the level of incident submillimeter radiation and could be correlated with structure in the reflected microwave power. Just above the breakdown threshold, it took several micro-
Figure III-7. Modulation Index vs. Absorbed Microwave Power for Microwave Cavity (1 μs pulse width, 1 kHz repetition rate, 1 mW of 337 μm light)
Figure III-8. Modulation Waveform for Various Absorbed Microwave Powers a) 12 mW, b) 15 mW, c) 31 mW, d) 58 mW, e) 101 mW, f) 162 mW (23 μs pulse width, 3.2 KHz repetition rate, 1 mW of 337 μm light)
seconds for impact ionization and modulation to begin. As the bias power was increased, the structure underwent a series of changes during part or all of the microwave pulse. Of particular note were the 10-15 μs period pulse-to-pulse coherent oscillations observable at certain points. Similar oscillations have been observed on DC avalanched samples of GaAs, and the period corresponds to the carrier transit time for electric fields of about 2.5 V/cm. While this value is comparable to that required for impact ionization, no explanation has been advanced for the appearance and disappearance of these oscillations.

Risetime measurements yielded a detector limited value of 150 ns. The microwave biasing system had an observed risetime of less than 70 ns. The DC biased GaAs detector had a resistance of about 3 MΩ. With a 3 MΩ load resistor (the optimum responsivity load), the risetime of the detection system was approximately 1 ms. Reduction of the load resistor improved the risetime until the bias potentiometer became the limiting resistor. Capacitively shunting the potentiometer and reducing the load resistor to 100 Ω (Figure 9) lowered the risetime to 150 ns. Further reduction of the load decreased the responsivity so far that signal-to-noise problems prevented further obser-
Figure III-9. Detector Bias Circuit
vations. The ultimate risetime of the modulation itself
could not be determined.

7. Thermal Experiment

To relate the modulation index to the free carrier
concentration in the GaAs, a thermal experiment was per-
formed. The modulator was replaced by a piece of the same
material with electrical contacts applied. This piece and
the detector were then mounted at opposite ends of a 1/8
in. dia. hole in an assembly at the bottom of the liquid
helium dewar (Figure 10). The hole was smaller than the
upper piece of GaAs, so all of the light reaching the de-
tector had to pass through this transmission sample. A
resistance heater warmed the upper piece by thermal con-
duction through the copper block while the detector
remained below the liquid helium level and was not heated.

Stillman, et al. [19] have shown that for tempera-
tures below about 10°K, the free carrier concentration
depends exponentially on temperature and is directly
related to the uncompensated donor density for densities
below about 4x10^{14} cm^{-3}. Furthermore, the mobility is
approximately linear with temperature and can be reliably
estimated from the density of ionized impurities, which
Figure III-10. Details of Thermal Experiment Assembly
is twice the compensated donor density [19]. For changes in resistance less than a few orders of magnitude, therefore, the resistance is a good measure of the carrier concentration relative to the 4.2°K value. In addition, the absolute concentration can be estimated from the doping density. Care must be taken that the material is well shielded from stray light or the measured resistance will not be the thermal equilibrium value and incorrect numbers for transmission vs. carrier concentration will result.

The laser beam was mechanically chopped at several hundred hertz. Figure 11 shows the transmission change relative to the 4.2°K value. Removing the transmission sample to obtain a reference value for absolute transmission calculations disturbed the optical system too much to permit accurate results. The general form of an initial increase in transmission followed by a decrease was similar to the modulation index behavior. An interaction between the decreasing number of neutral donors and a thermal broadening of the absorption peak may account for the drop and subsequent rise of the transmission, but verification would have required a detailed theoretical and experimental study of line broadening in GaAs. The transmission was nevertheless a very sensitive function of sample resist-
Figure III-11. Change in Transmission vs. Relative Free Carrier Concentration
ance, or equivalently carrier concentration. As Crowley has shown for a DC biased detector, the sample resistance is quite dependent on configuration, probably through the variation in thermal background radiation, as well as on temperature and submillimeter intensity [21]. Since the modulator configurations were different from the transmission test, the thermal background and the unbiased carrier concentrations were probably also different. The results for the various microwave biased modulation systems could thus not be compared unambiguously with the thermal results. The bias power was limited by the available TWT amplifier, so the modulation data could not be extended to determine if the transmission began to increase again or continued to decrease below the unmodulated value. The carrier concentration for complete thermal ionization of the impurities was several orders of magnitude higher, so it is clear that in either case the microwave impact ionization must have excited only a small fraction of the frozen out donors.

8. Microwave Impedance Measurements

Microwave impedance measurements were carried out to determine the carrier concentration as a function of the
microwave power and to relate this back to the modulation index and the thermally determined transmission vs. carrier concentration. The terminated waveguide was used, with the microwave bias supplied through a microwave bridge circuit (Figure 12). Impedance, propagation constant, and complex dielectric constant can be determined from the measured return loss and phase shift. Since the waveguide was only partially filled, the propagation constant and complex dielectric constant were no longer simply related [32]. Even a simple model for the partially filled waveguide was inappropriate because end effects were important and the microwave fields were not pure TE$_{01}$ for the short sample being studied. While the data (Figure 13) were clear enough, the theory was too complex to permit its evaluation.
Figure III-12. Experimental Configuration for Microwave Impedance Measurements
Figure III-13. Phase Shift and Return Loss vs. Incident Microwave Power
Electrooptic modulation was not observed at 10.6 μm. The predicted modulation was only slightly above the detection system resolution limit, and there was a substantially stronger thermal effect. Several modifications would improve the potential for applying the LSA oscillator to electrooptic modulation. First and foremost, the LSA cavity must be redesigned. With an appropriate cavity, both higher bias voltages and longer devices should be possible. This would permit realization of a greater modulation index, ideally as high as 100%. A second important change involves the thermal contact between the active layer and the heat sink. While heating should not interfere to first order with the electrooptic effect, the requirements of heat dissipation restrict the pulse width and duty cycle of the device. A minor modification would be the use of polarizers with less insertion loss and a higher extinction coefficient so that the modulation index could be more accurately measured. Finally, with a sufficiently fast infrared detector such as an MIM diode [33], the microwave frequency interaction rather than just the modulation envelope could be observed.
The cooled, impact ionized GaAs used at 337 \( \mu \text{m} \) did demonstrate modulation in the form of an increased transmission. The maximum observed modulation index was 29\%. Thermal data indicate that improved focusing of the submillimeter beam and increased microwave power could lead to an index of 100\%, while duty cycle studies indicated that the modulation itself was not thermal. A thicker epilayer would absorb all of the incident light, allowing transmission only when biased above breakdown and the generation of submillimeter pulses. The risetime was measured as less than 150 ns, limited by the submillimeter detection circuit. The modulator response time should be 5 ns, limited by the free carrier recombination time in GaAs \([20]\). The same recombination time defines the response time of the GaAs detector. This detection limit could be realized by using a cryogenic amplifier \([34]\) or by employing a microwave biased detection system \([25]\). Other possible detectors include MOM tunnel diodes \([35]\) and Schottky barrier diodes \([31]\). These faster detectors should allow utilization of the full modulation bandwidth.

One advantage of microwave biasing the modulator is that it allows the relatively high GaAs resistance to be transformed down to a low microwave impedance, substan-
tially reducing the RC time constant encountered in the usual DC biased breakdown system. In addition, the power dissipated in the GaAs is typically 200 mW, an order of magnitude less than that dissipated in the Ge impact ionization modulator [8], where modulation depends on greatly increasing the free carrier concentration. This results in a reduced heat load on the cryogenic system employed and would have important applications in any practical system.
V. APPENDICES

1. LSA Device Fabrication

The LSA devices were prepared from a 1 cm square wafer of GaAs. It proved possible to obtain good oscillators with chips sawed on all four sides, but the surface scattering of 10.6 \( \mu \)m light rendered these devices useless for electrooptic modulation. According to Runyan [37], III-V semiconductors tend to cleave most readily along the (110) planes needed for this experiment, and this behavior was in fact observed. The first cleaving technique tried was to wire-saw a long strip of the desired width and then fracture it by lightly tapping on a razor blade. This technique tended to provide damaged ends, so another approach was used. Black wax was melted on a flexible piece of PC board and the strip of GaAs was placed on the wax. As the wax cooled, the GaAs was bonded to the board. Working under a microscope, a diamond scribe was used to lightly scratch the surface of the GaAs. The PC board was then gently flexed, and the GaAs cleaved at the scratches. Misaligned scratches often gave cleaves containing several steps but all in (110) planes. The minimum length possible was about 20 mils. The black wax was then melted again and
the chips were removed for ultrasonic cleaning in a succession of solvents: xylene, TCE, acetone, and finally methanol. The cleaned chips were indium-soldered to brass mounting posts. The posts, with a small piece of indium and a small amount of flux on top, were heated on a hot plate under a microscope. When the solder began to flow, a GaAs chip was centered on the post with its active layer up, and the post was removed from the hot plate to air cool.

Typical oscillator dimensions were 30 mils long by 20 mils wide. Chips longer than 50 mils rarely oscillated, though not all of the shorter chips worked. The maximum DC bias level that could be attained before breakdown was 450 V, but more typical peaks were in the 250-300 V range.

2. Wire Grid Polarizers

Wire grid polarizers were fabricated to properly polarize the 10.6 μm light and to detect the change in polarization after the light passed through the GaAs modulator. Light polarized parallel to the wires causes a current to flow and the polarizer to behave like a metal mirror. Current cannot flow perpendicular to the wires, so light polarized in this direction is transmitted.
Diffraction effects are negligible for a wire spacing of $d<\lambda/4$. Wires cannot actually be mounted with the spacing required for 10.6 $\mu$m light, but metal can be vacuum deposited on a transparent substrate and etched away. An alternative technique is to develop a physical relief pattern in some transparent material and then deposit metal on only the peaks of the pattern.

The polarizers were fabricated on 2 in. dia. polished Si substrates. The wafers were cleaned in TCE, acetone, and isopropanol, in succession. The grating was defined by exposing a 1.2 $\mu$m thick layer of Shipley AZ1350 photoresist with interference fringes from an argon ion laser operating at 4880 Å. The laser beam was split and the two beams were spatially filtered, collimated, and directed onto the photoresist with a half-angle of 7°, giving a 2 $\mu$m fringe spacing (Figure 1). The wafers were pre-exposed for 2 sec under a mercury vapor discharge, then exposed for 4 minutes with a power density of several milliwatts per cm$^2$. The photoresist was developed for 45 sec and baked for 15 minutes at 125°C to harden it. Since the photoresist develops approximately linearly with exposure, a physical relief pattern resulted. The initial technique involved vacuum depositing an Al film directly
Figure V-1. Experimental Configuration for Photoresist Grating Exposure
on the Si and developing the photoresist with the intent of etching away lines of Al. This proved unsuccessful because the Al surface was too rough to get good gratings. Subsequent attempts used photoresist on the Si. After the resist was baked, the wafer was placed in a vacuum system for Al evaporation. By orienting the wafer 15° from the evaporation direction, Al was deposited on only the peaks of the photoresist pattern.

The polarizers were of variable quality. Due to inhomogeneities in either the photoresist of the laser system, the results were not uniform across each wafer. The most successful polarizers had an easy axis transmission of .39 and a hard axis transmission of .0014, for an extinction coefficient of 280. The loss for the easy axis can be explained largely by the high dielectric reflection from the Si substrate.

3. Ge:Cu Detector Fabrication

A copper-doped germanium (Ge:Cu) detector was fabricated for detection of the 10.6 μm light. The starting material was a block of 10 Ω-cm n-type Ge. A slice was wire-sawed from the block, polished with 1.0 μm grit, ultrasonically cleaned in acetone, and etched for 10 sec
in CP4 at 0°C (5 parts HNO₃, 3 parts HF, 3 parts acetic acid, and 10 drops Br per 50 ml of solution). Copper metal was then vacuum deposited on both sides of the slice.

The sample was placed in a diffusion furnace and held at 750°C in a reducing atmosphere (flowing gas, .75-2 cfh of N₂ and .25-1 cfh of H₂). The diffusion continued for 22 hours, then the furnace was turned off and purged with N₂ gas before the Ge:Cu was removed and air quenched. The final impurity concentration was determined to be 1.2x10⁻¹⁶ cm⁻³ from the measured resistivity of .366 Ω-cm.

The doped slice was polished with 1700 mesh on one side and 1.0 µm grit on the other. 200 mil long samples with widths between 50 and 200 mils were wire-sawed from the polished slice, and one sample of each size was etched for about 10 sec in CP4. The samples were 20 mils thick. The element ultimately used was the 200 mil square etched chip. It was indium-soldered between two parallel copper strips spaced 125 mils apart. The room temperature resistance of the detector was 8-9 Ω.

At 4.2 K, the detector resistance was nonlinear with current and was on the order of .5 MΩ for the bias currents used. Electrical breakdown occurred at a bias current of
about 130 μA. The responsivity was approximately 200 V/W with a 500 Hz bandwidth for a 1 MΩ load. With a 470 Ω load, the detector bandwidth surpassed 1 MHz with a responsivity of about 1 V/W.

4. Cone Condenser System

A cone condenser was used as an alternative to a lens for focusing the light from the ¼ in. dia. light pipe onto the .38 cm wide modulator. The parameters describing a cone condenser are its input and output apertures and its length or cone angle. The focusing properties of a cone can be determined by ray tracing and define the minimum length required to have no light reflected back to the input [38]. The usual cone is made of metal, but a dielectric cone utilizing total internal reflection can also be constructed.

In the present system, these two approaches were combined such that the cone was essentially metal with a polyethylene insert that terminated in a rod which further guided the light down to the modulator. The metal and polyethylene cones had half-angles of approximately 2° and output apertures of .1 in. The rod portion of the polyethylene was .350 in. long. The metal cone was constructed
by rolling a thin metal foil to the required dimensions. The polyethylene was turned to size on a lathe.

The combined condenser resulted in an output spot with a diameter of less than .1 in. About 18% of the light incident on the light pipe was transmitted. By comparison, the light pipe alone transmitted about 43% of the light but with much less light directed onto the modulator.
VI. REFERENCES


