Detectors for 10.6 micron TEA CO<sub>2</sub> laser radiation

by

John W. T. Malcolm

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Department of Engineering Physics, McMaster University, Hamilton, Ontario

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#### Abstract

In this report various means of infra-red laser radiation detection were investigated. For the measurement of the energy of pulses of 10.6 µm laser radiation for energies up to 15-20 joules and also for energies up to 200 joules, two pyroelectric detector designs were researched. These two detector designs acted as monitors, using 10% of the beam for detection and allowing 90% to be used for other purposes. Responsivities of as much as 120 mV/J for the 15-20 joule detector and 16.7 mV/J for the 200 joule detector were obtained.

Also three types of photon drag materials, used for pulse shape analysis and power detection were investigated. InAs and Te were compared to Ge for a possible faster and more sensitive alternative. Also a means of impedance matching and amplifying the output of these rather low sensitivity detectors using a magnetic current probe was analyzed.

Finally an inexpensive and easily constructed container and mount for the 15-20 joules pyroelectric detector was designed along with an attachment to the Lumonics series 100 TEA lasers for ease of alignment with the beam.

#### PART A

#### Pyroelectric Detectors

In view of the high energy and high peak powers now available from TEA CO<sub>2</sub> lasers there is a need for an energy detector which can withstand the energy and power and at the same time be sufficiently sensitive at room temperature. Also a reasonably fast response is desired to allow a fast laser pulsing rate. In particular 15 J and 50 MW peak power from the Lumonics TEA 103 laser and 200 J and 1 GW peak power from the Lumonics 600 series laser are approximately the maximum pulses that must be detected.

Such devices as totally absorbing thermopiles have a low surface damage threshold and also a very slow response hindering the pulse repetition frequency.

Pyroelectric detectors offer a much increased response time but also suffer surface damage. They can also depole due to overheating. To overcome these two problems a pyroelectric detector design was proposed which employed a nickel surface on a lead zirconate-titanate pyroelectric plate about .020" thick. 10.6 µm radiation incident on the optically finished flat nickel surface at 45° would be 90% reflected and 10% absorbed. The heat obtained by the 10% absorption would then be detected by the sensing element. The high Curie temperature of lead zirconate-titanate (Clevite PZT-5A) combined with a 90% reduction in the heat conversion by the nickel reflector would keep the element from overheating and causing surface damage or depolarization.

#### Theory

The mechanical construction of the proposed detector is shown in figure 1. Two sizes of these elements were designed, one 2-1/2" in diameter to handle a 15 J, 50 MW, 2 sq. in. crossection beam, the other 5 in. in diameter, to handle a 200 J, 1GW, 9 sq. in. beam. The ceramic is bonded to the aluminum heat sink with a conducting epoxy. The heat sink conducts heat away from the pyroelectric element between pulses thus keeping the average temperature quite low and increasing the response time of the detector. Leads are attached to the nickel front surface and to the heat sink.

Assuming that the heat is conducted from the nickel to the ceramic very quickly compared to the ceramic's thermal time constant and that the radiation pulse is quite short compared to the thermal time constant, the average temperature of the ceramic when irradiated by a short pulse and one face kept at zero temperature by the heat sink can be described by

$$\overline{\theta} = \frac{\int_{C_{T}}^{T} F(t) dt}{C_{T}} e^{-\frac{t}{\tau}}$$
(1)

where  $\overline{\theta}$  is the average temperature of the ceramic,

 $\tau$  is the thermal time constant,

$$C_{m} = pSl$$

where  $\rho$  is the density of the ceramic

S is the specific heat of the ceramic

l is the thickness of the ceramic and F(t) is the power density of the incident pulse. Now the electrical equivalent circuit for the pyroelectric device is given below (fig. 2).



Figure 2. Equivalent circuit of pyroelectric device

For the pyroelectric element  $R' \gtrsim 10^{13} \Omega$  (ie  $R' >> R_e$ ). Therefore the differential equation describing this circuit is

$$IR_e + \frac{\int Idt}{C_e} = V_s.$$

Now a change in temperature in a pyroelectric material produces a change in its polarization and thus a charge buildup on its surfaces.

Therefore

$$dQ_s = A\lambda d\overline{\theta}$$

where  $\lambda$  is the pyroelectric coefficient,

A is the area of the element

and Q is the charge.

Therefore

$$dV_{s} = \frac{dQ_{s}}{C_{e}}$$
$$V_{s} = \frac{A\lambda\overline{\theta}}{C_{o}}.$$

Therefore

$$IR_{e} + \frac{\int Idt}{C_{e}} = \frac{A\lambda\overline{\theta}}{C_{e}} .$$

Differentiating

$$R_{e} \frac{dI}{dt} + \frac{I}{C_{e}} = \frac{A\lambda}{C_{e}} \frac{d\overline{\theta}}{dt} .$$

Since I =  $\frac{V_o}{R_e}$ 

$$\frac{\mathrm{d}\mathbf{V}_{o}}{\mathrm{d}t} + \frac{\mathbf{V}_{o}}{\mathrm{R}_{e}\mathrm{C}_{e}} = \frac{\mathrm{A}\lambda}{\mathrm{C}_{e}} \frac{\mathrm{d}\overline{\theta}}{\mathrm{d}t} \ .$$

From eqn. (1)

$$C_{e} \frac{dV_{o}}{dt} + \frac{V_{o}}{R_{e}} = A\lambda \frac{d}{dt} \left( \frac{O}{C_{T}} - \frac{t}{\tau} \right)$$
$$= \frac{A}{C_{T}} F(t) e^{-\frac{t}{\tau}} - \frac{A\lambda}{C_{T}\tau} \int_{0}^{t} F(t) dt e^{-\frac{t}{\tau}}.$$

Solving this equation for t > duration of pulse (ie F(t) = 0)

$$V_{oc} = Be^{-\frac{C}{R_eC_e}}$$

$$\mathbf{V}_{op} = \mathbf{D}\mathbf{e}^{-\frac{t}{R_eC_e}} \int_{0}^{t} \mathbf{e}^{-\frac{t}{R_eC_e}} \mathbf{e}^{-\frac{t}{\tau}} \mathbf{F}(t) dt.$$

Assuming  $R_e C_e$ ,  $\tau >>$  duration of pulse

$$V_{op} \stackrel{\sim}{\sim} D e^{-\frac{t}{\tau}} \int_{0}^{t} F(t) dt.$$

Therefore

$$D = \frac{-A\lambda}{C_{T}\tau} \left(\frac{1}{-\frac{C_{e}}{\tau} + \frac{1}{R_{e}}}\right)$$
$$= \frac{\lambda}{\rho S \varepsilon} \frac{1}{1 - \frac{\tau}{R_{e}C_{e}}}$$

where  $\varepsilon$  is the permittivity of the ceramic.

Therefore

$$V_{o} = B e^{-\frac{\tau}{R_{e}C_{e}}} + \frac{\lambda}{\rho S \varepsilon} \frac{1}{1 - \frac{\tau}{R_{e}C_{e}}} \int_{0}^{t} F(t) dt e^{-\frac{\tau}{\tau}}.$$
 (2)

Now  $V_0(0) = 0$ .

Therefore

$$C_{e} \left(\frac{dV_{o}}{d\epsilon}\right)_{t=0} = \frac{A\lambda}{C_{T}} (F(t)e^{-\frac{t}{\tau}})_{t=0}$$

$$C_{e} \left(\frac{dV_{o}}{dt}\right)_{t=0} = \frac{\lambda}{\rho S \epsilon} F(o) . \qquad (3)$$

But from eqn. (2)

$$\frac{dv_{o}}{dt} = -\frac{B}{R_{e}C_{e}} e^{-\frac{t}{R_{e}C_{e}}} + \frac{dB}{dt} e^{-\frac{t}{R_{e}C_{e}}}$$

$$+ \frac{\lambda}{\rho S \varepsilon} \frac{1}{1 - \frac{\tau}{R_{e}C_{e}}} F(t) e^{-\frac{t}{\tau}} + \frac{\lambda}{\rho S \varepsilon} \frac{1}{1 - \frac{\tau}{R_{e}C_{e}}} (-\frac{1}{\tau}) \int_{0}^{t} F(t) dt e^{-\frac{t}{\tau}}$$

Since B can be a function of t at t = 0 therefore

$$\begin{pmatrix} \frac{dV_{o}}{dt} \end{pmatrix}_{t=0} = - \frac{B(o)}{R_{e}C_{e}} + \left(\frac{dB}{dt}\right)_{t=0} + \frac{\lambda}{\rho S \varepsilon} \frac{1}{1 - \frac{\tau}{R_{e}S_{e}}} F(o) .$$

From equ. (3), therefore

$$-\frac{B(o)}{R_e C_e} + \left(\frac{dB}{dt}\right)_{t=0} = \frac{\lambda}{\rho S \varepsilon} F(o) \left(1 - \frac{1}{1 - \frac{\tau}{R_e C_e}}\right).$$

A solution is

$$B = -\frac{\frac{\tau}{R_e C_e}}{1 - \frac{\tau}{R_e C_e}} \int_0^t F(t) dt.$$

Therefore

$$\mathbf{V}_{o} = \frac{\lambda}{\rho S \varepsilon} \left( \frac{e^{-\frac{t}{\tau}} - \frac{\tau}{R_{e}C_{e}} e^{-\frac{t}{R_{e}C_{e}}}}{1 - \frac{\tau}{R_{e}C_{e}}} \right) \int_{O}^{t} \mathbf{F}(t) dt$$

This is the result given by Lachambre [1].

For the case of short duration pulses it can be seen that the maximum voltage is directly related to the input energy.

$$V_{o \max} = \frac{\lambda}{\rho S \varepsilon} \int_{0}^{t} F(t) dt.$$

For the material to be used, Clevite ceramic PZT-5A,

$$\lambda = .02 \times 10^{-6} \text{ coul/cm}^2 \circ \text{C. at } 30 \circ \text{C.}$$

$$\rho = 7.7 \text{ g/cm}^3$$

$$\epsilon = 1700 \epsilon_0$$

$$S = .420 \text{ joules/g} \circ \text{C}$$

Therefore for the 2-1/2" diameter detector the sensitivity should be .0668 V/J, taking into account the 90% attenuation and for the 5" diameter detector .0167 V/J.

In practice the rise time of the signal is considerably longer due to the thermal time constant of the absorbing coating, nickel and conductive epoxy. The radiation is quickly absorbed in this coating and then slowly diffuses toward the pyroelectric element. As stated by Cooper [2] complete heat transfer in the time required will occur when  $M_{coating} << (\rho SKT_{rise})^{1/2}$ where K is the thermal diffusivity of the ceramic,  $T_{rise}$  is the risetime resolution required, and  $M_{coating}$  is the thermal mass of the absorbing coating. Now

$$\tau = R_{T}C_{T}$$
$$= \left(\frac{\pounds}{2K}\right) \left(\rho S \pounds\right)$$

Therefore  $\tau = .225$  sec for a .020" thick plate of PZT-5A.

The theoretical electrical time constant for the 2-1/2" diameter ceramic is .185 sec. and for the 5" diameter ceramic is .740 sec.

#### Experimental

The original design for both sizes of detectors called for a lead zirconate-titanate, .025" thick disc to be bonded with electrically conducting epoxy to a 1/2" thick aluminum heat sink. The ceramic was to be poled along the thickness beforehand. The front surface of the ceramic was to be ground and lapped parallel to the back surface to within 15' of arc to ensure constant response over the whole surface. The epoxied side of the aluminum was to be machined flat to ensure a flat reflecting surface so that the reflected beam would not break up. The open face of the ceramic was then to be coated with nickel or nichrome to a surface polish of 5 waves in the visible and of sufficient thickness to be less than 50  $\Omega$  between edges.

The fabricated detectors received were not completely satisfactory. The nickel surface was found to absorb about 90%

of the 10.6 µm. radiation and reflect about 10%, although the reflected light did not break up. This suggested that the surface polish was to specifications. The surface also had a very dull appearance, not a metallic lustre as would be expected. Also, pin-pricks of white light on the surface as the radiation hit, indicated that the surface was gradually deteriorating from pulse to pulse. The poor quality of the surface was probably due to oxidation upon cooling after the evaporation process. Finally when the coating was removed from one of the large diameter elements, 6 or 7 radial cracks were observed. These could have been due to overstressing as the epoxy cured. The cracks did not appear to affect the performance from point to point across the surface.

In an attempt to improve the quality of the coating a small diameter detector was taken to the optical laboratory at the National Research Council. The existing surface was lapped off and the ceramic was then polished to as fine a finish as possible. A thin coating (about 500 Å) of nickel was then evaporated on the surface at approximately room temperature. This surface was then tested. This time approximately 90% of the 10.6  $\mu$ m. radiation was reflected at 45° angle of incidence. It was noticed however that pin-pricks of white light were present when the radiation hit the surface, suggesting that surface damage was occurring. The coating was observed under the microscope and is shown in figure 3. The defects in this surface

were the defects of the ceramic substrate, the ceramic being obviously quite porous and not taking a good polish.

The next step taken was to try to build up a sufficiently thick nickel surface so that it could be polished independent of the ceramic. Since only about a 2  $\mu$ m film could be obtained with evaporated coatings, electroplating was tried as an alternative, also at NRC. With this procedure 50 to 100  $\mu$ m. could theoretically be deposited. First a film of copper of resistance across the diameter of less than 50  $\Omega$  was evaporated onto a polished ceramic to provide an electrode for the electroplating process. However the etching process, necessary prior to the electroplating, resulted in the copper film flaking away from the ceramic.

A material with reportedly improved adherence to the hard ceramic, chrome, was then tried. An evaporated chrome film amount 1  $\mu$ m thick survived the etching process but only about 1 to 2  $\mu$ m of nickel could be built up before peeling of the chrome-nickel combination was observed. Electroplating was then attempted with a sputtered chrome surface, also done at NRC, but to no greater success. The ceramic was too hard for any reasonably thick surface to adhere to it.

A different approach to the problem was then attempted. This was to bond a thin strip of nickel to the front surface with an electrically and thermally conducting epoxy and then polish this to an optical finish. The nickel strip was about

99% pure and .002" thick. Two different types of epoxy were tested, one highly thermally conducting but electrically nonconducting and electrically conducting with unknown thermal properties. An electrically non-conducting epoxy would give the advantage of being homogeneous and thus easier to spread thinly and evenly. Conductive epoxies are usually made conductive by the addition of fine silver particles. In each case the fine nickel strip was rolled onto the lapped ceramic surface, on which a dilute epoxy layer had been applied to obtain as flat a surface as possible. After being tested for sensitivity this surface was then sent to the optical laboratory at NRC to be polished to an optical finish.

In observing the effects of electrically non-conducting epoxy on the output of the detector the theoretical basis for the observations should be dealt with for comparison.

The equivalent circuit for such a setup is as follows, with the element being equivalent to a 2-dielectric capacitor.



C is the capacitance of the epoxy layer. The differential equation for this circuit is

$$IR_{e} + \frac{\int Idt}{C_{e}} + \frac{\int Idt}{C} = \frac{A\lambda\overline{\theta}}{C_{e}}.$$

Differentiating,

$$\frac{dI}{dt} R_{e} + I(\frac{1}{C_{e}} + \frac{1}{C}) = \frac{A\lambda}{C_{e}} \frac{d\overline{\theta}}{dt}$$

The solution to this equation is

$$V_{o} = \frac{\lambda}{\rho S \varepsilon} \left( \frac{e^{-\frac{t}{\tau}} - \frac{\tau (C_{e}+C)}{R_{e}C_{e}C}}{1 - \frac{\tau (C_{e}+C)}{R_{e}C_{e}C}} e^{-\frac{t (C_{e}+C)}{R_{e}C_{e}C}} \right) \int_{0}^{t} F(t) dt$$

It can be seen that the maximum of this signal will not be affected by the epoxy layer unless  $\frac{R_e C_e C}{C_e + C}$  approaches the duration of the light pulse whereupon the short pulse approximations used in the formulation break down. Physically this means that the capacitor's charge begins to dissipate through the resistor before the complete charge buildup is accomplished. Therefore if the short pulse approximation still holds then the electrical properties of the epoxy should make no difference to sensitivity or response time.

As can be seen from figures 5 and 6, the pulse shape of both types of detectors were found to be similar.

The sensitivity was found to be about 8 times greater for the electrically conductive epoxy. This could have been due to the very low leakage resistance  $(10^5 \ \Omega)$  of the nonconductive detector due to metallic contamination in the cracks or of course it could be due to a low capacitance value for the epoxy. Since the dielectric constant of epoxy was not known the capacitance cannot be estimated.

The risetime of the thermally conductive epoxied detector was about 20 ms compared to 40 ms for the electrically conductive epoxied detector. This difference was probably due to the difference in heat diffusion rates between the two epoxies.

Over the surface of the detectors, for a constant light pulse size and shape, the voltage output was found to differ by about ±10% for the electrical epoxy and about 20% for the thermal.

From the above data it is clear that either type of epoxy can be used for this detector. The choice should be made on the basis of which will give the flattest and more uniform layer so that optical polishing of the nickel can be done. Polishing was attempted with the thermally conductive epoxied detector and a very uneven surface was the result.

In figures 7, 8 and 9 are illustrated the response times of various other pyroelectric detectors with varying absorbing surfaces.

Using the DREV detector as a standard (.23 V/J) the evaporated nickel surface detector (small diameter) was calibrated to be of sensitivity .11 V/J and the large diameter, electrically cond. epoxied detector .016 V/J.

Piezoelectric oscillations were observed with both the small and large diameter detectors. For the small detector the oscillations corresponded quite closely to the fundamental radial oscillation frequency of the circular ceramic disc. These oscillations could be removed by using an RC filter since the pulse rise and fall times were far removed from the oscillation period. For the large detector several oscillation frequencies were seen, probably due to the cracks in the ceramic.

### Discussion

From the foregoing description of the experimentation with this detector design several problems have become obvious, because of the very porous nature of the pyroelectric element, and its hardness and temperature sensitivity.

The cracking of the ceramic could possibly be overcome by epoxying a larger thickness of ceramic to the aluminum and then grinding it down afterwards.

The most important problem is the quality of the surface obtainable with the epoxied nickel strip. A thicker nickel strip could be used and would tend to keep its own shape rather than being indented during rolling. Also a more dilute epoxy could be tried. It must also be kept in mind that any optically flat surface would be subject to some change due to the strains of the ceramic with temperature changes. The contour of such a large area of pyroelectric changes after it has been polished because of the high temperatures involved in the polishing process.

If a procedure can be found to get an optically finished flat surface with the nickel strip , this detector will prove

sufficiently sensitive and rugged for monitoring the 100 and 600 series laser output energies. If not, then possibly another pyroelectric material should be considered. Since some sensitivity can certainly afford to be lost, perhaps BaTiO<sub>3</sub> or TGS would suffice and at the same time give an optical finish.

The final alternative would of course be to attenuate the beam with a Ge beam splitter with 90-10 reflecting layer on the front surface and an antireflection coating on the back. Then the surface quality of the pyroelectric element would be unimportant and a totally absorbing lampblack or goldblack surface could be used.

## PART B

#### 1. Photon Drag Detectors

#### Introduction

The photon drag effect is due to radiation pressure which drives mobile charge carriers, electrons or holes, in a semiconductor bar down the length of the bar and produces a voltage between opposite ends.

The response of the detector itself is extremely fast. Factors limiting the response will be discussed later, but with a photon drag detector response is sufficient to make laser pulse shape and power measurement possible for sufficiently high powered lasers (since the effect is of quite low sensitivity as will be seen later).

The final big advantage of this effect used in detection is that it is a room temperature effect since only majority carriers are involved. Thus no cooling is necessary.

For 10.6 µm. radiation the material that is used almost exclusively at room temperature is germanium. Some question has been raised however as to whether the response of Ge is in fact as fast as it theoretically should be. Therefore in this report other semiconductors with potentially faster response and comparable sensitivity at room temperature were tested and compared to Ge.

#### Theory

There are several factors affecting the ultimate speed of response of a photon drag detector. The response of individual interactions of photons and electrons and/or holes is limited for electrons by the carrier scattering time of the material, in other words how fast the electrons lose their given momentum. The carrier scattering time is defined by  $\tau = \frac{m_e \mu}{e}$  where  $m_e$  is the effective electron mass,  $\mu$  is the electron mobility and e is the charge of an electron. As an example for n-type InAs this value is  $4.27 \times 10^{-13}$  sec. For holes the controlling factor is the relaxation time from energy conserving intraband hole transitions present in the valence band. This is generally about  $10^{-12}$  sec.

However the response is also governed by the time it takes light to travel down the bar. For Ge and t = 2 cm where t is the length of the bar, this travel time is  $2.67 \times 10^{-10}$  sec. For InAs, it is  $1.0 \times 10^{-10}$  sec. It can be seen then that light travel time is the controlling consideration from a material viewpoint.

Further time response restrictions are imposed by the circuit. Stray capacitance and inductance in the leads can cause problems. Assuming the leads are kept as short as possible and soldered contacts are used to keep unwanted capacitance to a minimum the RC network setup with the element resistance and the oscilloscope input capacitance also presents a time constant to the detector output.

The equivalent circuit of the detector with the oscilloscope is as follows.



Figure 11. Equivalent circuit for photon drag detector

 $C_o$  is the input capacitance of the oscilloscope (about 25 pf. for Tektronix 7703),  $R_o$  is the input resistance of the oscilloscope (1 M $\Omega$  for Tektronix 7703)  $R_p$  is the resistance of the photon drag element, and  $V_p$  is the voltage generated across the photon drag element. Therefore for high frequency signals the reactance  $\frac{1}{\omega C_o}$  approaches  $R_o$ . At this point the  $R_pC_o$  time constant can limit the response time. Therefore a photon drag material which gives a sufficient  $V_p$  and at the same time a low  $R_p$  is clearly desirable from this viewpoint. An  $R_pC_o$  at least as small as the time of light travel limitation discussed above is needed. Once this condition is satisfied then the photon drag material time restrictions will be placed on the circuit of course by the risetimes of the scope, usually 1-3 ns.

The first approximation resistivity for a semiconductor material is:

$$\rho = \frac{1}{ne\mu_e} \text{ for } n-\text{type}$$

$$\rho = \frac{1}{pe\mu_h} \text{ for } p-\text{type}$$

where  $\mu_{e}$  and  $\mu_{h}$  are the electron and hole mobilities respectively,

n and p are the electron and hole carrier concentrations. In order to work out the resistivity the carrier concentration which will give a reasonable sensitivity must first be known.

According to T. S. Moss [3] for short term response where generation and recombination are by comparison long term effects and therefore need not be considered, the open circuit voltage response of a photon drag detector is

$$\mathbf{V}_{oc} = \frac{\mathbf{I}(\mathbf{p}-\mathbf{an}) (1-\mathbf{e}^{-Kt})}{\mathbf{ec}(\mathbf{p}+\mathbf{an}) (\mathbf{n}+\mathbf{p})}$$

Where I is the power density of the radiation, c is the speed of light in vacuum, a is ratio of the force on each electron to the force on each hole, K is the free carrier absorption coefficient.

In the table below is found photon drag data for 4 different semiconductor materials, those found to be the closest to Ge in performance. t is fixed for all the calculations at 2 cm to keep the time of light travel within the desired response time. Thus for each semiconductor analyzed carrier concentrations were chosen to make  $e^{-Kt} \leq .05$  (ie K = 1.31 cm<sup>-1</sup>). Absorption cross-section data was obtained from Moss [3]. All data is for room temperature operation. Commercial availability hinders some of these optimizations, however. p-type InAs is not available in carrier concentrations less than  $10^{16}$  cm<sup>-3</sup>. The limit for p-type InSb is probably  $10^{17}$  cm<sup>-3</sup> and for p-type Te  $2.5 \times 10^{16}$  cm<sup>-3</sup>.

Another semiconductor material, GaSb, is theoretically of interest for photon drag but it is not available in sufficient

Table 1

Material t = 2 cm	Intrinsic carrier conc at 300°K (cm <sup>-3</sup> )	Optimum 'n carrier conc'n (cm <sup>-3</sup> )	$\frac{V_{oc}}{I} \frac{(volts)}{(w/cm^2)}$	p(ohm-cm)
p-type Ge	2.5×10 <sup>13</sup>	1.92×10 <sup>15</sup>	1.08×10 <sup>-7</sup>	1.81
n-type Ge	2.5×10 <sup>13</sup>	3.28×10 <sup>16</sup>	-6.37×10 <sup>-9</sup>	.05
p-type InAs	8 ×10 <sup>14</sup>	2.62×10 <sup>15</sup>	7.96×10 <sup>-8</sup>	1.03
n-type InAs	8 ×10 <sup>14</sup>	2.18×10 <sup>16</sup>	-9.60×10 <sup>-9</sup>	.012
p-type InSb	2 ×10 <sup>16</sup>	2 ×10 <sup>16</sup>	5.20×10 <sup>-9</sup>	.0045
n-type InSb	2 ×10 <sup>16</sup>	10 <sup>18</sup> (1)	-2.08×10 <sup>-10</sup>	8.9×10 <sup>-5</sup>
p-type Te (c-axis along length	4 ×10 <sup>15</sup>	4 ×10 <sup>15</sup>	2.60×10 <sup>-8</sup>	.43

(1) At this concentration 99% of the absorption is by electrons.

purity for serious consideration.

From the above table one can see that the best alternative to Ge for photon drag is n-type InAs because of its low resistivity and relatively high sensitivity. Te is capable of a comparable sensitivity at available carrier concentrations but its resistivity is not as low as that of InAs. If impedance matching is found necessary however, Te offers some advantage.

For a 2 cm. long bar of material with cross-sectional area .25 cm<sup>2</sup>, the resistance of Ge is 14.5  $\Omega$  as opposed to .1  $\Omega$  for InAs and 4  $\Omega$  for Te. Therefore InAs gives a low  $R_pC_0$  time constant at the expense of a factor of 10 in sensitivity compared to Ge.

## Experimental

Pieces of InAs and Te (c-axis along the length) each .5×.5×2 cm. were obtained. The InAs was of carrier concentration  $3 \times 10^{16}$  cm<sup>-3</sup>. The Te was of unknown carrier concentration. These 2 materials were then tested for sensitivity and response time against a similar bar of 1.8  $\Omega$ -cm Ge. The maximum response obtained from the Te was about 1/3 that of InAs. This suggests a very high carrier concentration for Te. The response time could not be analysed because of the small signal obtained (about 3 mV on the oscilloscope). The ratio of sensitivites of InAs to Ge proved to be about 1:10. The rise time of laser pulse signals using both detectors were examined and no difference could be detected. Both detectors could also be used to record the partial mode-locking of the TEA 102 unstable resonator. These mode-locked peaks had a risetime on the order of 1-2 nsec. Partial mode-locking from the Ge detector is shown in figure 12. Due to excessive noise from the unstable resonator the modelocking with InAs was present but not well defined.

## Discussion

There appears to be few advantages to using InAs or Te over Ge at room temperature as a photon drag detector. Te has however been found to have higher sensitivity than Ge at  $77.5^{\circ}$ K [4]. InSb is also a good prospect at lower temperatures where the carrier concentration is not so high. InAs provides a faster (about 3 times) alternative to Ge only if a  $10^{-10}$  sec risetime is desired. For ordinary laser pulses or even modelocked laser pulses the response of Ge is adequate and its much higher sensitivity makes it much more desirable.

## 2, Amplification of the Photon Drag Signal

#### Introduction

Due to the low sensitivity of photon drag detectors, pulse shape detection is very awkward for cases such as  $CO_2$ TEA lasers where a grating is used in the cavity for line tuning. Also the low power levels of CO TEA lasers (5 µm) renders photon drag unsuitable as a power detector. For these applications amplification of the signal is therefore desirable.

A preferable amplification design would be impervious to the large R.F. fields associated with all TEA lasers and would at the same time give a broad band response with the upper limit being close to 1 GHz if mode-locked pulses were to be resolved. For ordinary laser pulses the amplification should be flat from at most 1 MHz to at least 100 MHz.

In view of expected difficulties with saturation due to high peak powers and the R.F. fields an alternative to amplification with active components was sought.

The alternative pursued was to short the ends of the photon drag element and, using a suitable toroidal winding as a current probe, obtain a voltage proportional to the first derivative of the photon drag current. This voltage would then be integrated using an RC combination to obtain a signal proportional to the photon drag current. This method would be especially applicable to InAs where the current is about 10 times the voltage for the element discussed above. This method of amplification has the advantage that all elements used are passive and thus saturation and ultimate blow out will not occur. It still has to be well shielded from R.F. fields however. Such a device has been used with InAs photon drag by Patel [5].

## Theory

In figure 13 is a schematic diagram of the proposed current probe with the photon drag detector.

For the moment, assuming an air core, the probe consists of a small toroidal coil through which the photon drag current flows and produces a magnetic field B. The voltage produced across the coil is proportional to  $\frac{dB}{dt}$  which is proportional to  $\frac{dI}{dt}$  where I is the photon drag current. The equivalent circuit of a magnetic probe has been given by Segre and Allen [6] and is reproduced here.



Figure 14. Equivalent circuit of magnetic probe

V is the voltage generated across the coil, L is the self-inductance of the coil, r is the resistance of the coil, C is the capacitance of the coil, leads and connector. The frequency response of the probe can be analyzed using the following circuit.



Figure 15. Circuit used to analyze frequency response to probe

where R is a matching impedance for the coaxial cable used.

For this circuit it is stated by Segre and Allen [6] that the attenuation |A| and the phase shift  $\phi$  as a function of angular frequency  $\omega$  are

$$|A| = \{ (R+r)^{2} | R^{2} + \Omega^{4} - \Omega^{2} (2 - r^{2} R_{0}^{2} - \frac{R_{0}^{2}}{R^{2}}) \}$$
  
$$\phi = \tan^{-1} \{ \frac{\Omega}{\Omega^{2} - \frac{(r+R)}{R}} (\frac{R_{0}}{R} + \frac{r}{R_{0}}) \}$$

where

$$R_{o} = \sqrt{\frac{1}{C}}, \Omega = \omega \sqrt{LC}$$
.

The resonant frequency is given by  $w^* = \sqrt{LC}$ .

The value of this resonant frequency becomes zero at

$$R = R_{0} (2 - r^{2} / R_{0}^{2})^{-\frac{1}{2}} \sim R_{0}^{2} / \sqrt{2} .$$

Therefore for  $R = R_0/\sqrt{2}$  a quite flat attenuation over a broad frequency range is obtained.

Actually C includes capacitance from both the probe and the oscilloscope (25 pf). The probe capacitance is 10 pf at best. By increasing the value of w\* the bandwidth of the probe can be increased but since C can be reduced only to a certain value L must be reduced. This however is done at the expense of MCMASIER LINWERSITY LIBRARY sensitivity as will be shown.

The magnetic field produced by the photon drag current is

$$B = \frac{\mu I}{2\pi R}$$

where  $\mu$  is the permeability of the core material of the toroid, R is the average radius of the toroid. The voltage produced across the coil is

$$\varepsilon = - \frac{\mu N_a^2}{2R} \frac{dI}{dt}$$

where N is the number of turns, a is the radius of a coil on the toroid.

The above equation dictates that to maximize  $\varepsilon$ ,  $\mu$ , N and a should be large and R small. But

$$L = \frac{\mu a^2 N^2}{2R}$$
 and to

decrease L for increased bandwidth, N and a should be decreased. Therefore a compromise must be made.

Increasing  $\mu$  in order to increase  $\varepsilon$  also has its problems, besides increasing L as well. Materials with the highest  $\mu$ 's also have very narrow band and low frequency response. For example ferrites become extremely lossy much above 25 MHz. But at this frequency their relative permeability is about 125. An air medium gives a good broad band frequency response at the expense of high permeability. Again a trade-off can be made with powdered iron. The relative permeability of this material varies from 4 to 10 but this material will respond to frequencies of 10-200 MHz. The range however is generally only about 25-30 MHz at best. MHz at best.

## Experimental

Some experimentation was done with these powdered iron cores. About 100 turns on a core of about 1/2" diameter and leads connected to a 1 ft long 50  $\Omega$  coaxial cable produced a signal of about 10 times that obtained previously for InAs but its risetime was about 10 times slower than that of the photon drag current. This was due to improper termination of the cable, allowing a resonance signal to build up and take over. Ringing was also observed for about 3 times the actual duration of the pulse. As the value of the termination resistance was lowered, so did the sensitivity but the response time became faster.

From this experiment and the theory, it is concluded that a broadband magnetic probe with response fast enough for a photon drag detector is quite possible to construct but once the desired response time is obtained very little if any amplification will be left.

Another approach, that of the voltage transformer, suffers from the same problem. With it inductance is unavoidably added to the photon drag circuit thus slowing the response. Also reflections would be very difficult to avoid since the device would be impedance matched at one frequency only.

#### PART C

## Pyroelectric Detector Mount

A mount was designed for the proposed 2½" diameter pyroelectric detector. A schematic diagram of the design is shown in figure 10.

With this design, alignment of the pyroelectric element with the incident laser beam is assured since the detector container fits snugly over the snout of the Lumonics 100 series lasers. The light beam is reflected at a 90° angle from the element but the detector can be rotated so that the beam can be directed in any direction in the x-z plane. The mounting platform is anchored securely to one front foot of the laser so that no drilling into the laser cabinet is necessary for installation. The element is mounted in an angled piece of delrin rod. A slot is cut at the back of the rod and close to the back of the element for any desired electrical components. The overall length of the container is 5". The outer aluminum wall of the detector is made from stock thick walled aluminum pipe, which cuts down machine time. All parts are made from aluminum except for the delrin around the detector element. This and an isolated chassis BNC connection provide electromagnetic shielding for the output signal.

The low material cost, ease of fabrication, easy installation and capacity for beam alignment and steering should make this design practical for use with Lumonics pyroelectric detectors and Lumonics 100 series lasers.

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Figure 3. Microscopic photograph of evaporated nickel film on the polished ceramic substrate. 200x.



Figure 5. Pulse shape using thermally conducting epoxy. .lsec/div.



Figure 6. Pulse shape using electrically conducting epoxy. .1 sec/div.



Figure 7. Pulse shape (rise time) of detector with evaporated nickel coating on the 2-1/2" diameter ceramic. 2 ms/div.



Figure 8. Pulse shape (rise time) of the DREV pyroelectric detector. 10 ms/div. (epoxy surface)



Figure 9. Pulse shape (rise time) of the NRC pyroelectric detector. 10 ms/div. (lampblack surface)



Figure 10. Schematic diagram of the pyroelectric detector mount.



Figure 12. Partial mode-locking of Tl02 unstable resonator. 20 ns/div. Detector - 1.8  $\Omega$ -cm Ge photon drag



Figure 13. Schematic diagram of current probe

Design and construction of a modulator for actively mode-locking a 10.6 micron TEA CO<sub>2</sub> laser

by

John W. T. Malcolm

## PART B: MCMASTER (ON-CAMPUS) PROJECT\*

A project report submitted in partial fulfillment of the requirements for the degree of Master of Engineering

Department of Engineering Physics, McMaster University, Hamilton, Ont., 1972

One of two project reports. The other part is designated PART A: INDUSTRIAL PROJECT

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## Abstract

This report deals with the design and construction of a modulator for 10.6 micron wavelength laser radiation with a view to actively mode-locking a  $CO_2$ -He(-N<sub>2</sub>) TEA laser.

First the type of modulating mechanism used, acoustooptic, is justified. Germanium is shown to be the best acoustooptic material, at present, for mode-locking. A theoretical investigation to determine the R.F. voltages required for various modulation depths is undertaken. An R.F. amplifier is described which was built to provide the necessary voltage levels. The development of AgCl as a practical antireflection coating for germanium is discussed. Finally the construction of the modulator itself is described.

## Introduction

The two main types of modulators presently employed for actively mode-locking CO<sub>2</sub> lasers utilize electro-optic and acousto-optic interactions respectively.

In most electro-optic modulators a linear gradient in the dielectric constant is set up from one side of the crystal to the other by an applied voltage between these sides. The time between maximum dielectric constant modulations in the crystal is arranged to coincide with the round trip time of the laser cavity by adjusting the frequency of the applied voltage.

In acousto-optic modulation, when used in mode-locking, acoustic standing waves, set up in the modulating material, modulate the index of refraction at twice the voltage frequency that is applied to the transducer. Mode-locking is obtained when this voltage frequency is adjusted to half the cavity round trip time.

Acousto-optic modulation was the mode-locking mechanism chosen for this work based on various comparisons of efficiencies of the two mechanisms found in the literature, the prime example being the comparison by Henderson and Abrams (1). They found that acousto-optic devices required on the order of 100 times less electrical power for equal large index phase modulation depths.

#### Theory

#### 1. Raman and Nath, and Bragg limits

In order to choose a material for an acousto-optic modulator, the principles behind the modulation of light by acoustic waves in the material must first be considered.

There are two distinct regions of optical interaction with acoustic waves, called the Raman and Nath region and the Bragg region. In the Raman and Nath region the medium is considered as an optical phase grating only, due to a narrow acoustic field. No amplitude modulation of the light occurs on travelling through the acoustic field, only phase modulation. Therefore, in the near field (immediately following the modulator) the phase relationship of the light wave follows the same pattern as the phase of the acoustic wave as is shown in figure 1.



Figure 1. Schematic diagram of Raman and Nath acoustooptic modulation.

In the Bragg limit near field amplitude modulation does occur. Scattering occurs only at the energy and momentum conserving Bragg angle (Bragg angle is  $\theta_0 = \sin^{-1} (\frac{1}{2} \frac{K}{k})$  where K is the wavenumber of the acoustic wave and k is wavenumber of the light in the medium.) This occurs when the diffraction angle of the acoustic beam becomes much less than the Bragg angle due to the increased width of the acoustic beam.

The boundary between the two regions has been defined by Klein and Cook (2) as being

$$Q = 2\pi \frac{\left(\frac{K}{k}\right)}{\left(\frac{S}{L}\right)} = 1$$

where L is the width of the acoustic field, s is the acoustic wavelength in the medium. Q is essentially the ratio between the Bragg angle,  $\frac{K}{K}$ , and the diffraction angle of the acoustic wave,  $\frac{s}{L}$ . For Raman and Nath scattering Q << 1 and for Bragg scattering Q >> 1.

Now for most practical acoustic frequencies (constrained by the length of the cavity), for L of about 1 cm. and at 10.6 microns wavelength of the laser radiation, the values of Q range from about .5 to 5. In other words the operation of most acoustooptic mode-locking devices lies in the transition between the Raman and Nath and the Bragg limits and for this reason theoretical investigations of such devices have not been reported in the literature in any detail. For operation under our chosen conditions, which will be justified later, Q = 2.2. At this value many of the diffraction features of the Raman and Nath limit are still retained. This has been illustrated by Klein and Cook (2). Therefore for purposes of calculating approximate modulation depths the Raman and Nath limit will be used.

# 2. Relation Between Acoustic Power and Modulation Depth

The Raman and Nath theory for various standing wave ratios of ultrasonic waves has been presented by Cook and Hiedemann (3). Assuming a standing wave ratio of 1 (actually about .997 due to acoustic attenuation after one complete pass), the instantaneous pressure in a sinusoidal standing wave is

 $p(x,t) = p \cos Wt \sin Kx.$ 

The far field amplitude distribution for a collimated monochromatic light beam of width 2D at normal incidence to an infinite transmission phase grating is given by

$$A(\theta) = C \exp(i\omega t) \int_{-D}^{D} \exp\{i(kx\sin\theta + v(x,t))\}dx$$
$$v(x,t) = \frac{2\pi Lg}{\lambda} p(x,t)$$

where g is the piezo-optic constant

 $\lambda$  is the wavelength of the light. Now exp(i  $\frac{2\pi Lg}{\lambda}$  pcosWt sin Kx)

$$= \sum_{r=-\infty}^{\infty} J_r \left(\frac{2\pi Lg P}{\lambda} \cos Wt\right) \exp(irKx).$$

Performing the integration it is found that the light is diffracted into discrete orders of amplitude  $A_r$  where

$$A_r = A J_r \left(\frac{2\pi Lg}{\lambda} pcosWt\right) exp(i\omega t).$$

In particular the intensity of the unmodulated light is given by

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$$I_o = I J_o^2 \left(\frac{2\pi Lgp}{\lambda} \cos Wt\right)$$
.

Now

$$\Delta\left(\frac{1}{n^2}\right) = PS$$

where n is the index of refraction,

P is the effective photoelastic coefficient, and S is the local lattice strain. Thus

$$\frac{2}{n^3} \Delta n = PS.$$

But

∆n = gp

and

$$s^2 = \frac{2\phi}{v^3\rho}$$

where  $\phi$  is the acoustic intensity,

V is the velocity of sound in the modulator, and  $\rho$  is the density of the modulator.

Therefore

$$I_{o} = I J_{o}^{2} \left( \sqrt{\frac{2\pi^{2}L^{2}}{\lambda^{2}}} - \frac{(n^{6}P^{2})}{v^{3}\rho} \right) \phi \text{ cosWt} \right).$$

Therefore in choosing a material for maximum modulation depth,  $\frac{n^6 p^2}{v^3 \rho}$  should be maximized. Many materials have been analysed in the literature with respect to this figure of merit. Up to the present time tellurium has been found to have the highest value with germanium second (4). However the material must also have the necessary optical and mechanical properties in order to be used to transmit a 10.6 µm wavelength light beam. Since tellurium has poor mechanical properties (extremely brittle and difficult to polish) and optically is quite highly absorbing in purities presently available, germanium was chosen as the modulator.

Therefore for L = 1 cm, n = 4.0, P = .413 (ref. 4), V =  $5.50 \times 10^5$  cm/sec, and  $\rho = 5.32$  g/cm<sup>3</sup>

$$I_{o} = I J_{o}^{2} (\sqrt{.1745 P_{AC}} \cos Wt)$$

where  $P_{AC}$  is the acoustic power inside the modulator. A plot of  $\frac{I-I_{O}}{I}$  vs.  $P_{AC}$  is shown in figure 2.

# 3. Relation Between R.F. Voltage and Acoustic Power Inside <u>Modulator</u>.

It is now required to know what electrical voltage must be developed across the piezoelectric transducer in order to produce  $P_{AC}$ .

An X-cut quartz crystal with fundamental resonance of 20 MHz was chosen as the piezoelectric element. Quartz was chosen because of its mechanical durability, its ability to withstand relatively high voltages and because it is easily bonded to the modulator. Its disadvantages are its low electromechanical coupling, which means that a high voltage is needed for the required acoustic power, and its high electrical Q which makes tuning to one frequency difficult. A discussion of an alternate transducer will be given later.

The equivalent circuit of a piezoelectric crystal is

as follows.



When operating at its fundamental resonant frequency its

co

equivalent circuit becomes

Figure 4. Equivalent circuit of crystal at fundamental frequency

C is the characteristic static capacitance of the crystal

R

$$C_0 = \frac{A\varepsilon}{e}$$

where A is the electrode surface area,

 $\epsilon$  is the permittivity of the crystal,

and e is the thickness of the crystal.

For X-cut quartz (dielectric constant = 4.41) with fundamental resonance at 20 MHz (e =.0143 cm) and 1 cm. diameter surface area

$$C_{0} = 21.4 \text{ pf.}$$

At 20 MHz, the reactance is 371 ohms.

The value of R is directly dependent on the damping presented to the quartz crystal. When the crystal is backed by air on both sides, the value of R is of the order of 10 ohms. When bonded to the modulator, its value increases considerably. The exact R is difficult to predict theoretically because of this dependence on damping.

In order to make the best use of the electrical voltage available, it is desired that all the power be dissipated across R and not stored across  $C_0$ . Therefore, use of an inductor of  $L_0$  henrys such that  $2\pi f = \left(\frac{1}{L_0C_0}\right)^{\frac{1}{2}}$  will ensure this. Also an impedance transformer from the 50 ohm output of the RF amplifier to R should be used. The following circuit will give optimum performance.



Figure 5. Circuit for electrical coupling to piezoelectric crystal

$$\frac{n_1}{n_2} = \frac{50 \text{ ohms}}{R}$$

 $C_1$  is used to tune the  $L_0C_0$  circuit to a 20 MHz resonance.

Assuming that the effect of the bond between the modulator and the transducer is negligible, the power output for an air-backed fundamental frequency piezoelectric transducer radiating into a loading medium is

$$P_{out} = \frac{16 d^2 \rho_t^2 V_t^2 v^2 f^2 A}{\rho_m V_m}$$

- $\rho_t$  is the density of the transducer (2.65×10<sup>3</sup> kg/m<sup>3</sup> for quartz),
- $V_t$  is velocity of sound in the transducer (5.57×10<sup>3</sup> m/sec for quartz),
  - v is r.m.s. voltage applied to the transducer,
  - f is the frequency,
- $\rho_{\rm m}$  is the density of the modulator (5.32×10  $^3$  kg/m  $^3$  for Ge),
- $V_{\rm m}$  is the velocity of sound in the modulator (5.50×10<sup>3</sup> m/sec for Ge in [111] direction),
- and A is the electrode surface area.

Therefore, for the quartz crystal used,

 $P_{out} = 2.0 \times 10^{-5} v^2$  watts.

This P<sub>out</sub> is the acoustical power entering the Ge modulator at one face. It is desired to get an idea of what power is built up in the centre of the Ge due to the production of standing waves through reflections at both ends. Two important assumptions must first be made to simplify the calculation. First any absorption loss in the quartz or the bonding material is disregarded. Also reflections at the quartz-Ge interface (about 10% for a travelling wave) are also ignored since the Ge to quartz reflection is in phase with the existing standing wave and thus little net loss results. Transmissions of the Ge-air and quartz-air interfaces are negligible.

Therefore the most significant source of loss taken as significant for the acoustic waves is attenuation in the Ge modulator. According to Mason and Bateman (5) the attenuation in Ge is 2.8 dB/cm at 306 MHz. Also the acoustic attenuation varies as  $f^2$  at room temperature. Extrapolating from this information to 20 MHz the attenuation is estimated at .012 dB/cm. or the power transmission of an acoustic travelling wave in  $\frac{1}{2}$  cm is .9985.

Let

$$\alpha = .9985/\frac{1}{2} \text{ cm.}$$

The acoustic power built up in the centre of the modulator then is

$P_{AC} = \alpha P_{out} + \alpha^3 P_{out} + \alpha^5 P_{out} + \cdots$
$=\frac{P_{out \alpha}}{1-\alpha^2}$
2 300 Pout.
But $P_{out} = 2.0 \times 10^{-5} v^2$ watts.
Therefore $P_{AC} = 6 \times 10^{-3} v^2$ watts.
But $I_0 = I J_0^2 (\sqrt{.1745 P_{AC}} \cos Wt)$
Therefore $I_p = I J_0^2 (3.24 \times 10^{-2} \text{ v cosWt})$ .
A plot of $\frac{I-I_0}{I}$ vs v is shown in Figure 6.

Therefore a relation between modulation depth and R.F. voltage required has been obtained. The derivation is intended primarily only as an analysis of the various processes involved in a modulation device. The numerical results obtained are obviously only estimates of what is required but since no similar analysis appears in the literature, it should prove valuable as a quick way to estimate the values required for various parameters of any acousto-optic mode-locking device.

# Experimental

#### 1. AgCl Antireflection Coating

For operation as mode-locking device, the modulator had to be antireflection coated on both sides in order to keep the intra-cavity loss as low as possible. For an optimum single layer coating  $n = (n_1 n_2)^{\frac{1}{2}}$ , where  $n_1$  is the index of refraction of air,  $n_2$  is the index of Ge and n is the index of the AR coating.

Therefore for 10.6 micron radiation n = 2.00 for an ideal AR coating. A compound that was found to fit this prescription very well is AgCl (n = 1.98) (7). Also it was found to exhibit a very high transmission at 10.6 microns (6).

A particular procedure had to be followed in obtaining an optical quality evaporated coating. Since the coating is required to be  $\frac{1}{4}$  wavelength thick (1.325 microns) a large molybdenum boat about lin.  $\times \frac{1}{2}$  in  $\times \frac{1}{4}$  in deep was used as the filament and was filled with reagent grade AgCl particles. Only fine particles were used since larger ones took quite long to melt. A vacuum of .1 microns or less was used. The boat was heated with a 35-40 amp. current for 50-60 minutes with the Ge surface shielded from the boat to ensure that all the AgCl was melted. Failure to do this resulted in splattered particles appearing on the surface of the Ge during melting. After all the AgCl had melted the Ge was exposed to the boat and the current was increased to 60 amps. The film thickness was monitored with a Sloan quartz crystal monitor, placed beside the Ge cube. The resonant frequency of the quartz changed as the thickness of the film deposited on it increased. About 5 or 6 minutes were required to obtain the frequency change calibrated to correspond to 1.325 microns. It was also noticed that if the boat was allowed to empty completely, it glowed very brightly at 60 amps. and gave off excessive ultraviolet radiation. Since AgCl turns dark with overexposure to the ultraviolet, it was ensured that sufficient AgCl was used to avoid it being all evaporated.

To calibrate the Sloan quartz crystal monitor, 3 different frequency changes were recorded for 3 evaporations of AgCl onto portions of glass slides. The monitor and the slides were positioned in the location in the the vaccum chamber where the monitor and Ge would be placed for the final evaporations. These 3 slides were then coated with an evaporated thin film of gold to increase the reflectivity in order to use the Angstrometer for AqCl thickness measurements. This instrument employs a Fizeau flat which forms a wedge with the AgCl coating and also with the glass surface. The step between the AgCl and the glass is then observed as a step in the interference fringes. As each calibration is only good for a particular set-up in the vacuum chamber, it is of no use to present data of the actual calibration except that for this particular set-up, 31,100 Hz frequency change was necessary for a 1.325 micron film thickness.

Three tests were conducted to determine the suitability of the AR film for the high intensity and low loss conditions found inside a laser cavity.

A 1.50 micron thick film on a NaCl substrate was tested for durability under high energy density conditions. About .1 joules of 10.6 micron TEA laser radiation was focused to a spot about 1 mm. in diameter. The coating was then exposed to this spot. No damage to the coating could be observed under the microscope. Assuming an intra-cavity energy of 1 joule and a beam waist of 1 cm diameter, intra-cavity energy densities would be accurately simulated for a spot size of 3 mm diameter.

A reflectance measurement was also carried out for the A.R. coating on two sides of the Ge substrate. Reflected light, incident at an angle of 5°, was collected first from the AR coated Ge and then from a total reflector, by a Audoped Ge detector. Five readings were taken for each target. The reflectance of the AR coated Ge was taken as the ratio of the average voltage readings for the two targets. The average reflectance from the AgCl coated Ge was found to be 1.04%. Theoretically there should be only about .02% reflectance. This discrepancy was probably due to the experimental error involved in placing the correct thickness of AgCl on the substrate. The rather high temperatures subjected to the quartz crystal for the 50 minute melting period affected its resonant frequency to some extent. Also, since so much AgCl had to be evaporated, the directionality and density at the AgCl vapour changed slightly from trial to trial during calibration. Finally the Sloan monitor could only be read to about  $\pm$  200 Å.

A percent transmission measurement was also taken for the AR coated modulator. It was found to be about 75%. This low reading was probably due to absorption of the radiation by the Ge crystal itself. This will be discussed later.

## 2. R.F. Amplifier

In order to deliver the necessary 20 to 40 v to the quartz transducer for a significant modulation depth an R.F. amplifier was built. For the circuit diagram refer to figure 7. The amplifier is a push-pull, tuned grid, tuned plate type with plug-in grid and plate coils and tunable butterfly capacitors. It employs a 5894 tube. It is designed for a maximum output of 100 v across 50 ohms at 20 to 150 MHz.

Tests on the amplifier with a pulsed, 20 MHz, 1 v signal showed that a 20 v peak to peak output was possible with a 400 v and 50 mA plate bias and a rise and fall time of less than 50 nsec.

#### 3. The Modulator

The Ge modulator crystal was cut from a 10 Ω-cm In-doped, p-type ingot with [111] direction along the length. The optimum orientation of the crystal for modulation was

employed, that being acoustic waves travelling in the [111] direction with the electric field of the light parallel to this direction. For the laser mirror configuration used, a plane total reflector, a 10 m partially transmitting and a separation of 3.75 m, the beam waist was .8 cm diameter. The modulator was thus cut as a 1.5 cm cube to accommodate most of the fundamental laser mode. It was polished on four sides to a 1 micron finish with opposite sides kept parallel.

The quartz crystal was bonded to the Ge with a thin layer of stopcock grease. Leads were silver painted to the electrodes on the crystal.

For a similar modulator design see (9).

Preliminary attempts to observe lasing with the modulator placed passively in the cavity were unsuccessful, probably because of the high optical absorption of the 10 Ω-cm Ge crystal.

Attempts at observing modulation outside the cavity were also unsuccessful. This was likely due to improper electrical coupling to the quartz crystal.

### Suggestions For Further Work

Although no modulation was detected with this device several obvious improvements (which were not implemented due to lack of time) can be made which should give positive results.

First, the electrical coupling to the transducer was not adequate and improvement based on the circuit diagram

given in the theory should be made.

Also to obtain the same possible modulation depths with much less required voltage,  $LiNbO_3$  should be used as the piezoelectric transducer. For use with Ge as modulator this transducer is ideal since its characteristic acoustic impedance almost perfectly matches that of Ge. Also the maximum piezoelectric strain constant is  $6.8 \times 10^{-11}$  m/v as compared to  $2.3 \times 10^{-12}$  m/v for quartz.

Finally higher purity Ge should be used in order to cut down optical absorption. The impurity concentration of 10  $\Omega$ -cm Ge is about  $3.5 \times 10^{14}$  cm<sup>-3</sup>. At room temperature for p-type In doped Ge this is also the free carrier concentration. Now according to Moss (8), the energy absorption of Ge is  $B = p(68 \times 10^{-17}) = .238$  cm<sup>-1</sup> for 10  $\Omega$ -cm Ge. This represents about 30% absorption over 1.5 cm.Ge of 30 to 50  $\Omega$ -cm should give a sufficiently low absorption coefficient. 10  $\Omega$ -cm was used in this case because it happened to be available at the time for use in a photon drag detector.

## Summary and Conclusions

The various processes involved in the design and construction of an active mode-locker for 10.6 micron laser radiation were analysed. In particular a Ge acousto-optical modulator was found to be the best for active mode-locking. A theoretical analysis yielded an estimate of the R.F. voltage needed for various modulation depths of such devices. AgCl was found to be ideal (except for a sensitivity to the ultraviolet) as an antireflection coating for Ge and was found to be resistant to damage by 10.6 micron radiation of energy up to 1 joule/cm<sup>2</sup>. The details of the evaporation of AgCl onto Ge were also discussed. An R.F. amplifier for use with the modulator was built. Finally a description of the fabrication of the modulator was given.

The author acknowledges many helpful discussions with B. K. Garside throughout this work.

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