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RICE UNIVERSITY

SECOND ORDER MIXING AT 311 \mu m

IN POINT CONTACT DIODES

by

PAUL JOEL EPTON

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

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ABSTRACT

SECOND ORDER MIXING AT 311 \( \mu \text{m} \)
IN POINT CONTACT DIODES

by

Paul Joel Epton

An investigation of submillimeter wave point contact diode mixers was made. Tungsten point contacts on nickel, n-type indium antimonide, and p- and n-type germanium were studied. DC I-V characteristics, submillimeter video responsivity, and conversion loss from the 1 THz submillimeter frequency to a 2 GHz intermediate frequency were studied in an attempt to isolate the mechanism of operation of the diodes. The parameters varied were incident submillimeter power, zero-bias contact resistance, and applied DC bias.

The nickel diodes displayed a linear I-V characteristic and the lowest video responsivity, .4 V/W. The indium antimonide and p-type germanium had small but observable nonlinearities, with video responsivities of 1.6 and 4 V/W respectively, while the n-type germanium had the strongest nonlinearity and a 17 V/W responsivity. As mixers, all four materials had approximately the same conversion loss, about 76 dB for an antenna with a gain of 17 and -4 dBm of local oscillator power. The bias dependence of the video and mixing signals was the same and unrelated to the DC I-V characteristic. This implies that tunneling and Schottky barrier rectifier theories cannot explain the detector behavior, and thermoelectric and field emission mechanisms were also unsuccessful. Several studies of MOM diodes in the open
literature have found agreement between tunneling theory and experimental observations, while others have obtained results inconsistent with theory as was the case here. There is a paucity of experimental tests of semiconductor point contact diode mechanisms with which to compare the present results other than the nickel ones.

The mixing signal was utilized to measure a laser line of an optically pumped HCOOH laser that was one of the two submillimeter sources. Based on the known frequency of the HCN line used as the other source, an accurate value for the HCOOH line pumped by the 10R22 CO$_2$ laser line is 962.250 ± .005 GHz (311.554 ± .002 μm). In addition, the tunability of the HCOOH line was determined to be at least 3 MHz with an appropriate output coupler, and the unstabilized linewidth was less than 30 kHz.
ACKNOWLEDGMENTS

Special thanks are due Bill Wilson, for many hours of assistance with both the experimental work and the theory behind it; Frank Titte1, for his continuing support of the project; and the National Science Foundation, for providing the research funds. Additional thanks go to Ken Evenson, for his suggestion of a broadband amplifier: but for that, I might still be hunting a signal. Frank Foote and Dean Hodges provided helpful information on the operation of CO₂ and optically pumped submillimeter lasers, and Lee Aukerman brought the thermoelectric effect to my attention. Jim Chappell's comments about machining small parts and the work of Jim Godwin's staff on the larger ones were also important. Finally, I'd like to thank all of those friends in Houston and elsewhere, who helped me keep my sanity while all of this work took place.
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I. INTRODUCTION

1. Purpose

The purpose of this experiment was to investigate and compare various materials as sensitive point contact diode mixers for the submillimeter wave region. Two submillimeter lasers provided 1 THz signals, which were mixed in the diodes, and the 2 GHz beat signal was observed directly on a microwave spectrum analyzer. Previous experimental work on submillimeter mixers has involved metal-oxide-metal (MOM) diodes and, more extensively, n-GaAs point contact and Schottky barrier diodes [1]. Theoretical [2] and a few experimental papers [3-5, 40] have reported results for other materials as video detectors and mixers.

2. Background

The desirability of fast, sensitive detectors for all regions of the electromagnetic spectrum is unquestioned. In the submillimeter region, various thermal detectors, cooled photoconductors, and non-linear diodes have been used for video detection [6]. Substantial improvement can be achieved by going to mixers. The theoretical sensitivity is independent of the detector; in the submillimeter region, the quantum limit $\hbar \nu$ gives a minimum detectable power of $10^{-21}-10^{-22}$ W/Hz. Recent results with Josephson junction [7], Schottky barrier [8, 9], and InSb photoconductive mixers [10] have approached this result within a few orders of magnitude (Fig. 1). Bandwidth, however,
Figure I-1. Mixer Sensitivity vs. Wavelength.  O = Schottky barrier diode mixer; □ = Josephson junction mixer; △ = Photoconductive mixer. Solid points are for receiver. (after McColl [1]).
still depends on the detector element and is limited to the video bandwidth. For the photoconductors, this range of 2-150 MHz is less than 0.1% of the submillimeter frequency. The nonlinear I-V characteristic of the point contact and Schottky barrier diode detectors is fast enough to follow the incident electric fields directly, and mixing [11] and reradiation experiments [8, 12, 13] have demonstrated the use of the full bandwidth well into the infrared. A hot carrier thermoelectric detector [4] has been demonstrated with an 18 GHz bandwidth, placing it in an intermediate range but still well above the bandwidth required for most applications.

An important application of point contact diodes has been frequency measurement of submillimeter and infrared lasers [14]. Even without sufficient local oscillator power to approach the theoretical mixer sensitivity, beat signals between several sources are large enough to allow accurate determination of difference frequencies. Most measurements have involved one or more submillimeter lasers plus a tunable microwave source, yielding some high order beat note with a frequency in the 0-200 MHz range. Since the S/N ratio falls off almost 9 dB per mixing order [15], high order beats are adequate for only the stronger submillimeter lines. As the number of accurately measured laser lines increases, it becomes feasible to use the lasers themselves as secondary frequency references. An unknown frequency can then be obtained by observing the lowest order beat between the unmeasured line and a conveniently close known one.
3. Present Work

A selection of tungsten-semiconductor diodes were characterized and compared to the more common tungsten-nickel system. DC measurements, video detection of submillimeter radiation, and mixing of two submillimeter sources were utilized in describing the diode behavior. In addition, frequency measurement gave an improved value for the frequency and wavelength of an optically pumped HCOOH laser line near 311 μm.

Chapter II outlines the theory applicable to detection and mixing in point contact diodes. Several mechanisms for low level detection are described. Circuit considerations affecting the sensitivity and frequency response are then discussed. Finally, a treatment of the limits on frequency conversion for a passive mixer is presented.

Chapter III describes the apparatus used in the experiments. A brief review of submillimeter lasers is followed by details of the two lasers used here. Then the diode structure and several mount designs are given. The chapter concludes with a description of the optical coupling to the diode and the electronic circuitry used in measuring the diode characteristics and the detected signals.

In Chapter IV, the principal detector results are presented. After some general comments, the detailed behavior of each diode material is reported. A comparison is then made between the observed performance and the theories presented in Chapter II. An additional comparison is made to other results for point contact diodes reported in the literature.
Chapter V is a short description of the HCOOH laser frequency measurement. Several sources of error were present, but the final frequency value was still much more accurate than any previous reported value for the line measured.

Chapter VI summarizes the detector results. Lack of a good theoretical explanation is noted, as well as the desirability for better control over device preparation.
II. THEORY OF POINT CONTACT MIXERS

1. Introduction

The detectors used in these experiments were metal-metal and metal-semiconductor point contact diodes. Several physical mechanisms for their operation have been proposed in the literature and are described below. A more general circuit treatment is also useful, particularly in understanding the relation between the point contact junction characteristics and those of the network that includes it. Mixing of two different lasers and detection of the beat frequency leads to different problems than simple video detection, and several results can be derived independently of the details of the mixing element.

2. Detector Theory

A. Electron Tunneling - MOM Diodes

The principal explanation for detection in the metal-metal contacts depends on tunneling across a naturally present or grown oxide layer between the two metals [16]. The theory, developed by Simmons [17], is based on a trapezoidal potential barrier plus an image force reduction for the electron in the barrier (Fig. 1). For forward bias, defined as the higher work function metal negative with respect to the lower work function metal, this potential is approximately

\[ \phi_2(x) \approx \phi_2 - (\Delta \phi + eV) \frac{x}{s} - \frac{1.15 \lambda s^2}{x(s-x)} \] (1)
Figure II-1. Potential Energy Diagram for Metal-Oxide-Metal Diode. (after Simmons [17]); $\eta$ = Fermi level, relative to bottom of the conduction band; $\Psi$ = work function; $\Phi$ = potential barrier from Fermi level to bottom of oxide conduction band; $V$ = applied bias; $s$ = oxide thickness; $s_1, s_2$ = classical turning points, where potential barrier equals Fermi level in metal.
where $\phi_2$ = height of oxide conduction band above Fermi level in metal
$\Delta \phi$ = difference in barrier heights $\phi_1$ and $\phi_2$
$s$ = physical thickness of the oxide
$x$ = distance from M2
$\lambda = (e^2 \ln 2)/16\pi \varepsilon_s$
$\varepsilon$ = dielectric constant of the oxide."

The potential is referred to the Fermi level in M2. The terms are respectively the barrier height in M2, the trapezoidal approximation, and the image force correction which is always attractive and lowers the potential. For reverse bias, the potential is referenced to M1, as is the distance, $\phi_1$ replaces $\phi_2$, and the second term becomes positive. For tungsten-nickel, the correct barrier heights are unclear because of uncertainties in the tungsten work function, but in any case the junction is nearly symmetric.

The potential function is substituted in Schrodinger's equation for the insulator; in the metals, the usual free electron approximation applies. With appropriate boundary conditions, expressions for the current density result.

$$J_{F,R} = J_o \left\{ \phi_{2,1} \exp \left[ -A \phi_{2,1}^{1/2} \right] - (\phi_{2,1}^{1+eV}) \exp \left[ -A(\phi_{2,1}+eV)^{1/2} \right] \right\}$$

(2)

where $J_o = e/4\pi^2 \hbar (s_2-s_1)^2$
$A = (2/\hbar) \sqrt{2m} (s_2-s_1)$
$\phi_{2,1} = \int_{s_1}^{s_2} \phi_{2,1}(x) dx / (s_2-s_1) = \text{average barrier height}$
$s_{1,2} = \text{classical turning points, where the local potential equals the particle energy.}$
Expansion of these expressions show that this ideal junction is ohmic for very low voltages and nonlinear but still symmetric up to \( V = \varphi_1/e \). Above this level, the \( \sigma-V \) characteristic becomes asymmetric. Physically, this corresponds to the potential barrier being thinner for one voltage polarity than for the other (Fig. 2).

Since the tunneling process has a time constant on the order of \( 10^{-15} \) sec [18], the diode can behave like a rectifier even at optical frequencies. The detector voltage will be shown in section 2 to be proportional to \(-d^2I/dV^2\). For a tunneling junction, then, the signal is zero at zero bias as long as the applied optical voltage is less than \( \varphi_1/e \). At negative bias the rectification is positive, and vice versa (Fig. 3).

B. Metal-semiconductor Interfaces - Schottky Barrier Diodes

Most metal-semiconductor junctions display a nonlinear I-V characteristic due to the formation of a Schottky barrier [19]. A potential barrier forms because of the presence of surface states on the semiconductor which pin the Fermi level independently of the bulk doping. A bending of the semiconductor band results in a potential barrier (Fig. 4)

\[
\varphi_{BN} = C_2(\varphi_m - \chi) + (1 - C_2)(-\frac{E}{q} - \varphi_0) - \Delta \varphi
\]

where \( C_2 = \frac{\varepsilon_i}{(\varepsilon_i + q^2 \delta D_s)} \)

\( \varepsilon_i \) = permittivity of interfacial layer

\( \delta \) = thickness of interfacial layer \( \sim \) atomic dimensions
Figure II-2. Resistance vs. Bias and Potential Energy Diagram for \( V > \frac{\phi_1}{e} \) for Metal-Oxide-Metal Diode (after Simmons [17]).
Figure II-3. Theoretical I-V Characteristic and Bias Dependence of Second Order Mixing for Metal-Oxide-Metal Diode (after Paris and Gustafson [36]).
Figure II-4. Potential Energy Diagram for Metal-(n-type Semiconductor) Schottky Barrier Diode (after Sze [19]); $\Delta$ = potential energy across interfacial layer; $E_F, E_V, E_C$ = Fermi energy, valence band edge, and conduction band edge. Other terms are defined in the text.
$D_s = \text{density of surface states per eV}$

$\phi_m = \text{metal work function}$

$\chi = \text{semiconductor electron affinity}$

$E_g = \text{semiconductor energy gap}$

$\phi_o = \text{energy level at surface}$

$\Delta \phi = \text{image force lowering}$

This barrier is typically several tenths of a volt high, and the barrier thickness is on the order of 1000 Å, too thick for tunneling to be significant. Conduction occurs instead by a combination of thermionic emission and diffusion, with a current density given by

$$J_F = A^{**} T^2 \exp\left(-q \phi_{Bo}/kT\right) \exp\left(q(\Delta \phi + V)/kT\right)$$

$$J_R = A^{**} T^2 \exp\left(-q \phi_{Bo}/kT\right) \exp\left(q \sqrt{\frac{qE}{4\pi \varepsilon_s}} / kT\right)$$

(4)

where $A^{**} = \text{effective Richardson constant}$

$T = \text{temperature}$

$\phi_{Bo} = \text{zero field asymptotic barrier height}$

$V = \text{applied voltage}$

$\varepsilon_s = \text{permittivity of the semiconductor}$

$N_D = \text{doping density}$

$V_{bi} = \text{built in potential}$

$$E = \left(\frac{2qN_D}{\varepsilon_s} V + V_{bi} - \frac{kT}{q}\right)^{1/2}$$

As with the tunneling junction, the nonlinear I-V characteristic provides rectification of the optical signal with a polarity opposite that of the
second derivative. For an n-type semiconductor Schottky diode, this leads to a negative signal at zero and positive bias, and a weaker positive signal at negative bias (Fig. 5). P-type semiconductors operate best with negative bias and give positive rectification.

C. Thermoelectric Heating - Hot Carrier Detectors

Ohmic metal-semiconductor contacts as well as Schottky barrier diodes can display optical detection [4]. Electron heating in the point contact spreading resistance can produce a thermoelectric voltage with respect to the bulk semiconductor (Fig. 6) [20]. The carrier temperature at a hemispherical point contact is given by

\[ T_e = T_0 + P_{rf} \frac{T_e}{3\pi nkr_1} \]

where \( P_{rf} \) = applied optical power
\( T_e \) = carrier energy relaxation time
\( n \) = carrier density
\( r_1 \) = contact radius
\( k \) = Boltzman's constant
\( T_0 \) = bulk temperature.

This leads to a thermoelectric power for the electrons

\[ Q \approx -\frac{k}{|e|} \left( \frac{3}{2} - \frac{\eta}{kT_e} \right) \]

where \( \eta \) = fermi energy relative to the conduction band. Integrating over temperature between the contact and the bulk, and substituting
Figure II-5. Theoretical I-V Characteristic and Bias Dependence of Detection for n-type Schottky Barrier Diode (after Sze [19] and Tsang and Schwarz [39]).
Figure II-6. Diagram of Hot Carrier Detector Structure (after Harrison and Zucker [20]).
expression (5) for peak temperature gives a steady-state thermoelectric voltage

$$V_{th} = \left( \frac{3}{2} - \frac{n}{kT} \right) \frac{\tau_e}{3\pi n} \frac{P_f}{e|r_1^3}$$  \hspace{1cm} (7)

The thermoelectric power, and thus the voltage, will have a sign opposite that of the carriers and thus opposite that observed with a Schottky diode. The time constant of the detector is simply the relaxation time $\tau_e$: for frequencies above $f = 1/\tau_e$, the detector output is proportional to the rms power but does not follow the signal directly. The hot carrier diode is only indirectly dependent on an applied bias through bias induced heating which may change $n$ or $\tau_e$.

3. Circuit Models

The nonlinear current detectors can be modeled as variable resistances in a circuit which includes an antenna voltage source, a bias supply, and the contact shunt capacitance (Fig. 7a) [21]. The complete current expression is replaced by a Taylor series truncated after the third term,

$$I(V) = I(V_o) + I'(V_o)(V-V_o) + \frac{1}{2} I''(V_o)(V-V_o)^2$$  \hspace{1cm} (8)

where $V_o = \text{bias voltage resulting from bias current } I_o$

$$V = V_o + V_D + V_R$$

= bias voltage + optical frequency voltage across diode +
rectified voltage.
Figure II-7. Circuit Models of (a) nonlinear diode detector, (b) hot carrier detector, and (c) linear approximation to antenna and junction (after Twu and Schwarz [21], Harrison and Zucker [20], and Bradley and Edwards [22]. $v_a$ = antenna source voltage; $R_a$ = antenna impedance; $v_s$ = Thevinin equivalent source voltage; $Z_s$ = Thevinin equivalent source impedance. Other terms are defined in the text.
The circuit equation is then

\[ V = V_o + v_d + V_R = v_s - I_o Z_s - I(V)Z_s \]

\[ = v_s - I_o Z_s - I(V_o)Z_s - I'(V_o)(v_d + V_R)Z_s - \frac{1}{2} I''(V_o)(v_d + V_R)^2 Z_s \]

(9)

where \( v_s \) = Thevinin equivalent source voltage

\( Z_s \) = Thevinin equivalent source impedance

\( I_o \) = bias current.

Taking advantage of the small value of the nonlinearity in typical MOM diodes and the low impedance of the diodes, the expression for the rectified voltage is found to be

\[ V_R \approx -\frac{1}{4} \frac{I''}{I'} \frac{|v_s|^2}{|1 + I'Z_s|^2} \]

(10)

A good diode requires a small \( I' \), i.e. a high impedance, and a large nonlinearity. In the case of the hot carrier diode, the model is considerably simpler, in that there is no bias supply required and the diode is a constant resistance \( R_D \) at the optical frequency (Fig. 7b). Then

\[ v_d = v_s \frac{R_D}{R_D + Z_s} = v_s \frac{1}{1 + I'Z_s} \]

(11)

\[ V_o \propto P_{rf} \]

(12)

\[ = \frac{1}{R_D} \frac{|v_s|^2}{|1 + I'Z_s|^2} \]

The effect of the antenna and of the diode shunt capacitance
can be more explicitly taken into account by approximating the diode as a resistor, \( R_D \) (Fig. 7c) [22]. Then the diode voltage \( v_d \) is determined by the voltage divider equation,

\[
v_d = v_a \left| \frac{R_D |C}{R_A + R_D |C} \right|
\]

(13)

and with \( R_D \gg R_A \) (a high impedance diode), this reduces to

\[
v_d \approx \frac{v_a}{\left[ 1 + (R_A \omega C)^2 \right]^{1/2}}
\]

(14)

For a long wire antenna of length \( \ell \), \( v_d \propto E(\lambda) \sqrt{\lambda \ell} \) and

\[
v_R \propto v_d^2 \propto E^2(\lambda) \lambda \ell / \left[ 1 + R_A^2 \omega^2 C^2 \right]
\]

\[
\rightarrow E^2(\lambda) \lambda \ell / R_A^2 \omega^2 C^2 \quad \omega \gg \frac{1}{R_A C}
\]

(15)

The radiation resistance for a long wire antenna is given by

\[
R_A \approx 60 \left( 1.4 - \ln \frac{2\ell}{\lambda} \right)
\]

(16)

For a 5 \( \lambda \) antenna, the impedance is 220\( \Omega \). A 1000 \( \AA \) radius contact with a 10 \( \AA \) thick layer of dielectric constant 10 has a capacitance of 1.1\( \times 10^{-2} \) pf. Thus the rolloff from the antenna alone is .065 Thz. A diode impedance less than \( R_A \) increases the rolloff frequency but reduces the optical voltage across the diode by \( R_D/R_A \), so nothing is gained. A smaller contact area, however, will lower the capacitance and affect only the rolloff.
4. Frequency Mixing and Conversion Loss

The previous sections have dealt with detection of one submillimeter laser signal. If two lasers, of frequencies \( \omega_{\text{LO}} \) and \( \omega_{\text{SIG}} \), are used to illuminate a detector, the output is more than simply the sum of the single laser outputs. The nonlinearity of the detector couples the electrical signals at the two laser frequencies and generates additional signals at all possible sum and difference frequencies \( |\omega_{\text{LO}} \pm m\omega_{\text{SIG}}| \). In practice, one signal, the local oscillator, is much stronger than the second signal, and only those harmonics with \( m = 0, \pm 1 \) are significant. Additionally, it is usually the intermediate frequency, \( \omega_{\text{IF}} = |\omega_{\text{LO}} - \omega_{\text{SIG}}| \), which is subsequently amplified and detected.

The following analysis is based on a treatment by Kelly [23]. A resistive mixer (one based on a nonlinear resistance) can be modeled as an n-port (Fig. 8). The local oscillator is considered internal to the mixer and the source of a time varying nonlinearity seen by the signal. An incident voltage wave \( V_1^+ \) will generate scattered

\[
V_n^- = \sum_{n1} V_1^+ \text{ at the various frequencies } |\omega_{\text{LO}} \pm \omega_{\text{SIG}}|.
\]

Ideally, all of the incident power would be converted to power at the IF, but in fact some power flow occurs at the signal and image frequencies \( \omega_{\text{SIG}} \) and \( \omega_{\text{IM}} = 2\omega_{\text{LO}} - \omega_{\text{SIG}} \) as well. The higher order signals can be reactively terminated, so that no other power flow occurs. The mixer is then effectively a 3-port; in matrix form the voltages are related as
Figure II-8. Models of a General Mixer. (a) n-port and its frequency spectrum, including LO harmonics and (b) 3-port (after Kelly [23]).
\[
\begin{bmatrix}
V_1^- \\
V_2^- \\
V_3^- \\
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33} \\
\end{bmatrix}
\begin{bmatrix}
V_1^+ \\
V_2^+ \\
V_3^+ \\
\end{bmatrix}
\tag{17}
\]

Port 1 is the signal, port 2 is the image, and port 3 is the IF, with respective admittances \( Y_1, Y_2, \) and \( Y_3 \). Physically, the signal and image ports are identical, since they act at nearly the same frequency which is also approximately the LO frequency. The scattering matrix then simplifies to
\[
[S] =
\begin{bmatrix}
S_{11} & S_{21} & S_{13} \\
S_{21} & S_{11} & S_{13} \\
S_{31} & S_{31} & S_{33} \\
\end{bmatrix}
\tag{18}
\]

and \( Y_1 = Y_2 \). If in addition the mixer is lossless, the matrix equation
\[
[S]^*[Y][S] = [Y] 
\tag{19}
\]

must hold, where
\[
[Y] =
\begin{bmatrix}
Y_1 & 0 & 0 \\
0 & Y_1 & 0 \\
0 & 0 & Y_2 \\
\end{bmatrix}
\]

The mixer power gain from signal to i.f. is given by
\[
G = |S_{31}|^2 \frac{Y_3}{Y_1} 
\tag{20}
\]

Under the constraint of equation (19), the gain can be re-
expressed as

$$G = \frac{1}{2} \left( 1 - |S_{33}|^2 \right) \quad (21)$$

from which it is clear that the best conversion is for $S_{33} = 0$.

The optimum gain is then $1/2$, or the conversion loss is 3dB. Since
the mixer is a passive device (no internal power gain), it can be
further shown that $|S_{11}|_{\text{opt}} = |S_{21}|_{\text{opt}} = \frac{1}{2}$. The lost power is
divided equally between reflection of part of the signal and conver-
sion to the image frequency.

The dependence of the conversion loss on LO power is more
conveniently derived in terms of admittance rather than scattering
parameters. Following the development of Torrey and Whitmer [24],
the voltages and currents are broken up into their various frequency
components.

$$\begin{align*}
i & \quad v \\
i_o & \quad v_o \\
\Sigma \frac{\hat{i}_n e^{jnw}}{n} & \quad \Sigma \frac{\hat{v}_n e^{jnw}}{n} \\& \quad \text{LO and harmonics}
\end{align*} \quad (22)$$

$$\begin{align*}
\delta_i & = \text{Re} \Sigma \frac{\hat{v}_n e^{j\mu t}}{\mu} \\
\delta_v & = \text{Re} \Sigma \frac{\hat{i}_n e^{j\mu t}}{\mu} \\
& \quad \text{IF(β), signal (ω+β),}
& \quad \text{image (ω−β), harmonic}
& \quad \text{sidebands (νω±β)}
\end{align*}$$

Since the LO, harmonics, and DC terms are much larger than the
last set of terms, the latter can be treated mathematically as
variations of the former,

$$\delta_i = \frac{di}{dv} \delta_v \quad (23)$$
where \( \frac{di}{dv} = \sum_{-\infty}^{\infty} y_n e^{j\omega t} \)

Performing the indicated multiplication of equation (23) and collecting terms of the same frequency leads to the result

\[
I_{\beta+n\omega} = \sum_m y_{n-m} v_{\beta+m\omega}
\]  

(24)

Since \( di/dv \) is real, necessarily \( y_{-n} = y_n^* \); leaving out all but the signal, IF, and image terms and again using matrices.

\[
\begin{bmatrix}
  i_{\omega+\beta} \\
  i_{\beta} \\
  i_{\beta-\omega}
\end{bmatrix}
= 
\begin{bmatrix}
  y_0 & y_1 & y_2 \\
  y_1^* & y_0 & y_1 \\
  y_2 & y_1^* & y_0
\end{bmatrix}
\begin{bmatrix}
  v_{\omega+\beta} \\
  v_{\omega} \\
  v_{\beta-\omega}
\end{bmatrix}
\]

(25)

An exponential I-V characteristic

\[
I = A(e^{\alpha v} - 1)
\]

(26)

is appropriate to a Schottky diode. An applied voltage consisting of DC and LO terms,

\[
v = v_0 + v_1 \cos\omega t
\]

(27)

gives a derivative

\[
\frac{di}{dv} = \alpha A e^{\alpha v} = \alpha A e^{0} \sum_n I_n (\alpha v_1) e^{jn\omega t}
\]

(28)

where \( I_n(x) = j^{-n} J_n(jx) \) = modified Bessel functions.

The impedances are then
\[ y_0 = \alpha \text{Ae}^{-\alpha v_1} I_o(\alpha v_1) \]

\[ y_1 = y_1^* = \alpha \text{Ae}^{-\alpha v_1} I_1(\alpha v_1) \]  
(29)

\[ y_2 = y_2^* = \alpha \text{Ae}^{-\alpha v_1} I_2(\alpha v_1) \]

For optimum coupling between the signal generator and the mixer, the admittance-equivalent to the scattering parameter conversion gain, expressed instead as the loss that it really is, is

\[ L = 2 \frac{\frac{y_1}{y_1^*}}{1 + \frac{1}{1 - \eta}} \]

(30)

where \( \eta = 2y_1 y_1^*/y_o(y_o + y_2) \).

Substituting the derived expressions for \( y_0, y_1, \) and \( y_2 \) gives

\[ L = 2 \frac{\frac{1 + 2I_o^2}{I_o(I_o + I_2)}}{1 - \frac{1 + 2I_o^2}{I_o(I_o + I_2)}}^{1/2} \]

(31)

where the argument \( \alpha v_1 \) has been suppressed. This function is plotted in Fig. 9. \( L \) goes as \( \frac{1}{|\alpha v_1|^2} \) \( \propto \frac{1}{\text{P}_{\text{LU}}} \) for \( \alpha v_1 \ll 1 \), while for \( \alpha v_1 \gg 1 \), \( L \) approaches 3 dB, the fundamental limit derived above from the scattering matrix.
Figure II-9. Conversion Loss vs. Normalized Local Oscillator Voltage for a Resistive Mixer (after Torrey and Whitmer [24]).
III. EXPERIMENTAL APPARATUS AND CONFIGURATION

1. Introduction

The experimental work described in Chapters IV and V utilized the apparatus shown in Figures 1a and 1b. The HCN laser could be set to lase at either 891 GHz or 964 GHz (337 \(\mu m\) and 311 \(\mu m\), respectively). The CO\(_2\) laser and the gas in the optically pumped laser could be adjusted to select a line within 2.6 GHz of either HCH line, the limit defined by the IF amplifier. Several candidate lines were determined by a literature search (Fig. 2) [25-27]. Methyl bromide (CH\(_3\)Br), formic acid (HCOOH), and two of the methanol forms (CH\(_3\)OH and CD\(_3\)OD) were tried; of the reported lines, only a 311 \(\mu m\) formic acid line was stable. This line was mixed with the 311 \(\mu m\) HCN line. The lowest order difference frequency, near 2 GHz, was amplified directly and detected with a sensitive microwave spectrum analyzer.

The relative performance of a selection of metal and semiconductor point contact diodes was studied. The ohmeter, bias supply, and oscilloscope aided investigation of the diodes' electrical characteristics and submillimeter response. Both video detection and mixer conversion loss were used to study the dependence on LO power, zero-bias contact resistance, and applied DC bias in an attempt to pin down the detection mechanism. The laser difference frequency was also measured to derive an accurate frequency for the formic acid laser line.
Figure III-1. Overall Experimental Setup. (a) block diagram.
Figure III-1. (b) apparatus.
Figure III-2. Optically Pumped Laser Lines Within 2.6 GHz of HCN Laser Lines. (a) lines near the HCN 311 μm line.
Figure III-2. (b) lines near the HCN 337 μm line.
2. Submillimeter Lasers

A. Background

The two lasers used as signal sources for the detector experiments gave readily measurable powers for mixing at submillimeter wavelengths. This avoided the need for high frequency microwave tubes whose submillimeter harmonics could not be directly measured.

The first submillimeter lasers were based on molecular discharges in H₂O, NH₃, HCN, and H₂S [28]. The number of available lines was limited and the pumping efficiency low. With the demonstration of optically pumped submillimeter lasers in 1970 [29], the situation began to improve rapidly. Some 35 different molecules have already been reported to lase at over 700 different wavelengths [27], and as other molecules and pump lasers are tried, the number will continue to increase. Pumping is via a vibrational absorption, usually in near coincidence with an emission line of a CO₂ laser. The submillimeter output occurs from a pure rotational or rotational-vibrational transition from the excited level. The efficiency can be improved by detuning the CO₂ laser slightly or by Stark-shifting the molecular absorption into coincidence with the pump. Overall efficiencies can be substantially better than for discharge lasers in spite of the extra step of optical pumping.

Both optical resonators and hollow metal or dielectric waveguides have been utilized for optical confinement (Fig. 3). The waveguides lead to higher efficiency and power than the resonators. Because the guides are highly oversized for submillimeter wavelengths, many high
Dielectric or metal waveguide with hole input and output

Waveguide with hybrid output coupler

Stark cell laser

Zig-zag pumping with mesh output coupler

Conventional resonator with Michelson output coupler for discharge pumped laser

Figure III-3. Submillimeter Laser Designs (after Hodges [28] and Yamanaka [28]).
order modes exist and lasing will occur for almost any mirror separation. Resonators, however, can be designed to operate in one or a very few transverse modes, allowing cavity length adjustments to separate the different submillimeter lines pumped by a single CO₂ line.

In the case of optically pumped lasers, a special problem is that of coupling in the pump radiation. The ideal coupler would be transparent at the pump frequency and reflective in the submillimeter region. Only metal mirrors have been found to be good reflectors, however, so the usual coupling scheme is to send the pump through a small hole in one of the mirrors and treat the hole as an additional loss in the submillimeter laser. An alternative pumping scheme is to aim the pump at an angle to the laser axis and let the radiation bounce back and forth across the laser. Unfortunately, this method suffers from a combination of low absorption by the lasing gas and reflection loss as the pump bounces off the walls.

Output coupling also takes several forms. Michelson interferometer couplers allow independent tuning of the laser cavity and the output coupling. The usual polyethylene or Mylar beam splitter absorbs infrared radiation, making this method unacceptable for the optically pumped lasers. Hole coupling is a common, simple alternative. The hole must be backed by a transparent pressure window, and this window must be resistant to IR damage. Additionally, a large hole lowers the number of pump round trips, lowering the overall laser efficiency significantly. The third alternative is the hybrid coupler (Fig. 4), which incorporates a dielectric reflection coating for the pump and either a
Figure III-4. Hybrid Output Couplers for Submillimeter Lasers.
hole or mesh metallization pattern for the submillimeter light. By
reflecting the pump totally, a separate pressure window can be used
that need not be damage resistant. The hole or mesh pattern permits
independent control of the output coupling and additionally allows the
beam to be diffraction limited by the resonator or waveguide diameter.

B. The Optically Pumped Laser

The optically pumped laser was pumped by a CO\textsubscript{2} laser (Fig. 5).
The gain tube of the CO\textsubscript{2} laser was 12 mm in diameter with a 1.1 m dis-
charge length and ZnSe Brewster windows at each end. The overall cavity
length was 1.45 m, and the assembly was stabilized with four Invar rods.
Single line operation was achieved with a 100 lines/mm blazed diffraction
grating with a 97\% first order diffraction efficiency in the 9 \mu m to
11 \mu m region (PTR OPTICS ML-302). The output mirror was ZnSe with a 69\%
reflectivity coating and a 10 m radius of curvature (II-VI Inc.).
grating, output mirror, and gain tube were all water cooled.

Two gas supplies were used. Originally, separate CO\textsubscript{2}, N\textsubscript{2} and He
supplies were mixed in a gas manifold at the time of use. The gas per-
centages could not be measured directly, but the mix could be varied
to peak the laser output and seemed to be sensitive to variations of
a few percent. Pre-mixed gas increased the power several times, and
a mix of 13.9\% CO\textsubscript{2}, 24.0\% N\textsubscript{2}, and 62.1\% He was settled on for later
work (see Appendix 1).

With careful adjustment of the grating and output mirror, any of
the 9 or 10 micron P or R branch lines could be made to lase. Tuning
Figure III-5. Details of Optically Pumped Submillimeter Laser.
could not be accomplished with the grating alone, however, due to the gain of modes bouncing off the tube walls. In addition, a pure TEM\textsubscript{00} mode was rarely obtained. The output beam was reflected toward the submillimeter laser by a coated silicon wafer, and the transmitted power (2-2\%) was measured to monitor the total power. The peak power on the 10P20 line was greater than 40W.‘

The submillimeter laser (Fig. 5) was 2 m long. All of the optics were in vacuum boxes, eliminating the need for internal pressure windows as well as facilitating adjustment. The gas was contained in a 38 mm i.d. Pyrex tube. Pump radiation was focused with a 2-1/2" focal length Ge lens and recollimated with a 1-1/2" lens before entering one vacuum box through an antireflection coated ZnSe window. The laser input was a 4 mm diameter hole in the center of a 4 m radius of curvature copper mirror. The output mirror was a silicon wafer with a ZnSe/Ge dielectric stack (coated by Valpey) to reflect the pump radiation. There was an additional overcoat of gold, either as a 20-40 lines/mm mesh or with a 3-13 mm central hole, which acted as the submillimeter reflector (see Appendix A-2). A polyethylene disc was the pressure seal and submillimeter window in the vacuum box at the output end of the laser.

A gas manifold with several inlets and a needle valve for pressure control facilitated switching between different gases used in the laser. Gas entered the vacuum box at the optical pump input end and flowed through the tube to the submillimeter output box, to which a mechanical vacuum pump was connected. Pressure was measured with a thermocouple
gauge located on the vacuum line, and typical operating pressures ranged from 50 to 200 mT.

Lasing was observed at a variety of submillimeter wavelengths, depending on gas, pump line, and cavity length. The laser was tuned up with the aid of a cooled GaAs photodetector, which had a spectral response from below 100 μm to beyond 400 μm. Power could then be measured with a calibrated thermopile. Milliwatts were obtained on several lines. With the tube diameter and the mirror curvature used, the laser was intermediate between a waveguide and an open resonator. With a flat copper mirror instead of the curved one, somewhat higher power could be obtained. High order transverse modes, however, guaranteed that the strongest submillimeter line for a given pump line could always lase in some mode, and the weaker lines were unobservable. The curved mirror reduced the number of low loss modes substantially, and the different lines could be easily separated by tuning the cavity length. An occasional problem was that for the weakest lines, lasing became very sensitive to the aim of the pump beam as well as to the usual parameters of the submillimeter laser itself. In addition, there was a warmup period of up to an hour as wall absorption of the pump caused the Pyrex to heat and the cavity length to increase.

C. The Discharge Laser

The discharge pumped laser (Fig. 6) was 3.05 m long. The gain tube was 9 cm in diameter and the assembly was stabilized by four Invar rods. One end mirror was a 6.1 m radius of curvature gold coated glass blank.
Figure III-6. Details of Discharge Pumped Submillimeter Laser.
The second cavity mirror was a gold coated flat which also formed part of a Michelson output coupler. The interferometer mirrors each had differential screw translation control. The beam splitter was oriented vertically, giving a horizontally polarized output at right angles to the laser axis. The pressure window and output port was either a flat polyethylene disc or a polyethylene lens used to focus the beam onto a chopper.

This laser used a NH$_3$ : CH$_4$ mix of 9:4 to generate HCN in the discharge. Typical discharge conditions were 3 kV and .7 A at a total gas pressure of 500 mT, and the usual striations were observed. Since HCN lases best if the tube wall is hot (≈100°C), only the cathode was water cooled. This led to a several hour warmup before the cavity length stabilized, after which the laser needed no further tuning.

By adjusting the position of the mirrors of the Michelson output coupler, two different HCN lines could be obtained. Up to 20 mW were observed on the stronger 337 μm line, while the 311 μm line was down by a factor of 4-5 in power. The mode pattern could be observed and adjusted with the aid of a temperature-sensitive liquid crystal. A two-lobed pattern that scanned horizontally as the coupling was adjusted was not uncommon, but a single lobe could be obtained with careful tuning of all three mirrors.

3. Point Contact Diodes

The point contact diodes used in the experiments were tungsten whiskers contacted to nickel or semiconductor base electrodes, similar
to microwave point contact diodes. 1 mil diameter tungsten wire was clamped in .012" i.d. thin wall stainless steel tubing and then bent into shape with a pair of tweezers (Fig. 7). The loop served as a combination spring and high frequency inductor to confine the terahertz currents to the contact region and define a submillimeter antenna [30]. The wire was etched to a 1000–5000 Å point in a 2M solution of KOH (see Appendix 3) and inspected under an 800x optical microscope. Previous checks with a scanning electron microscope demonstrated a positive correlation between optical and SEM observations, with good points distinguishable from marginal or bad ones even though the tips were not actually resolvable. The Ni or semiconductor samples were mechanically polished to an optically reflecting finish, followed by a light chemical etch for some of the semiconductors. Several hours elapsed between polishing and the initial use, allowing natural surface oxides to form; after several months of use, a repolishing caused no observable change in the diodes' characteristics.

The diode mount (Fig. 8) had XYZ translation adjustments to allow positioning of the diode in the two incident laser beams, and a rotational control was included to optimize the orientation of the whisker antenna. Run-in was accomplished with a 2-micrometer system that had a fine sensitivity of 24 Å/degree of rotation. The coarse adjustment was made under a 75x microscope by watching until the wire and its image in the polished base electrode almost met. Then the mount was moved to the submillimeter setup, where the fine
Figure III-7. Point Contact Diode Detail and Photograph of Etched Tungsten Tip.
Figure III-8. Photograph of diode mount, showing the dual micrometer run-in drive, rotation control, XYZ positioner, and monitor tee for electrical connections.
adjustment was monitored electrically (see Appendix 4). Contact resistance, video noise, and video detection could all be used, but the former was eventually found to be the best guide for obtaining a good beat signal. A given point could be run in and withdrawn several times before replacement, and a good contact lasted several hours or overnight if not disturbed.

4. Mount Detail

Several different structures were tried before a good design was reached. In the first version (Fig. 9a), the BNC connector holding the base electrode and the plunger with the whisker were mounted co-axially in the same aluminum block. The whisker was run in with the dual micrometer control. This mount was fairly stable, although there was some rotational backlash in the plunger. The major problem was one of optical coupling. For a high gain, long antenna, the top section of the mount intercepted the principal antenna lobe and optimal coupling could not be achieved.

A second design (Fig. 9b) offset the plunger and placed the whisker on a cantilever. The base electrode was mounted in an SMA connector instead of the BNC for better IF performance. While this mount eliminated the optical problem, it was much less mechanically stable due to the cantilever design.

The final design (Fig. 9c) reversed the role of the whisker and base. The former was attached to the SMA connector, while the latter became the adjustable element. The switch of electrical ground was
Figure III-9. Details of Diode Run-in Schemes. (a) coaxial, (b) cantilver, and (c) substrate run-in.
unimportant. The mechanical stability was greatly increased by eliminating the adjustable cantilever, while the optical path remained clear. In addition, the larger base electrode made a better ground plane for the antenna.

5. Optics and Electronics.

Two different optical configurations are shown in Figure 10. Initially, the diode was placed at the intersection of the two laser outputs, which were separated by 90°. A whisker that was about 1-1/4 wavelengths long was used, with its principal antenna lobe at 45° from the wire axis, according to the long wire antenna formula [30],

$$\theta_{1m} = \cos^{-1}(1-0.371\frac{L}{\lambda})$$

(1)

The detector was more sensitive to parallel polarized light than to the perpendicular polarization, but only by a factor of 3. By orienting the whisker midway between the two laser beams, the lasers were detected on opposite sides of the principal lobe with an antenna gain of 4 relative to an isotropic antenna [31]. This method was rather simple to set up, but there was considerable mismatch between the focused laser beams and the whisker pattern.

A second optical configuration was employed with somewhat better results. A silicon wafer was used as a beam combiner at the laser intersection, and the diode was located where it received the transmitted HCN beam and the reflected HCOOH beam, with efficiencies of about .2 and .5 respectively. The low HCN efficiency included an
Figure III-10. Details of Optical Configurations Near Diode. (a) 45° antenna and (b) high gain antenna with beam combiner.
aperture limiting effect of the wafer mount, as well as reflection and absorption losses. A longer antenna, with a correspondingly higher gain and narrower beam pattern, could be used. The longest one tried was 9-1/4 wavelengths long, with a gain of 19-1/2 and a 15° full beamwidth that nearly matched the laser focusing. After correcting for the beam combiner, the improvement from the antenna gain was confirmed, and even without the correction, a better response was seen for the detection even though the submillimeter power was still not completely absorbed. A lossless beam combiner, such as that described by Fettermen, et. al. [8], would have permitted a direct observation of this improvement. A narrower beam to match a still higher gain antenna was not practical. A longer focal length lens would have been required to reduce the beamwidth, but the spot size would have been larger and the antenna would not have intercepted as much of the radiation.

As noted above, the contact was run in electrically, by watching the voltage generated by a .1 μA current. This measurement circuit, a separate DC bias supply, and an oscilloscope were connected to the diode through a monitor tee (see Fig. 1). This allowed the I-V and low frequency information to be obtained simultaneously with the mixing data without affecting the microwave circuit.

The IF signal was matched to a broadband GaAsFET amplifier (Avantek SD8-0601 M) with a double stub tuner. The tuner compensated for the transmission line length and the IF impedance of the diode mount, giving a 4 dB increase in the signal to the amplifier. The
diode itself was not matched to the mount, but this problem could not be overcome. Following the amplifier was a .9-2 GHz isolator used for noise suppression.

The final detector for the 2 GHz beat signal was a Singer SPA-100 spectrum analyzer. A calibration of the spectrum analyzer local oscillator was performed at X-band, indicating an 18 MHz error in the frequency reading, and a HP 435A/8484A power meter was used with a 1-2 GHz oscillator to determine the absolute power calibration of the display.
IV. DETECTOR CHARACTERISTICS

1. General Behavior

Of the materials tested for video response (Table 1), only the Ni, InSb, n-Ge, and more heavily doped p-Ge also detected a beat between the HCN and HCOOH lasers. Thus a more thorough study of the video detection and I-V characteristics along with the mixing was confined to these materials.

For each sample, the mixer output varied by several tens of dB between contacts or as a given contact was run further in. By careful adjustment, however, a maximum response could be obtained which was uniform within a few dB for a given antenna length and substrate. As will be described below, this maximum generally occurred for the lowest zero-bias resistance obtainable, but it was also dependent on applied DC bias.

2. Noise

The microwave noise was dominated by the amplifier-isolator-spectrum analyzer combination and was completely independent of the mixer diode. By using a second broadband amplifier and a 50Ω resistive load along with the isolator and Avantek amp, the noise source was determined to be a combination of the amplifier and reflection of power from the spectrum analyzer LO near 2 GHz. An upper limit of 6700K was derived for the input noise temperature, corresponding to a minimum detectable power (MDP) of 9x10^{-20} W/Hz. For several
<table>
<thead>
<tr>
<th>Material</th>
<th>Doping</th>
<th>Typical Video Responsivity (V/W)</th>
<th>Mixing 2 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>-</td>
<td>.12</td>
<td>Yes</td>
</tr>
<tr>
<td>n-InSb (polycrystalline)</td>
<td>1E16</td>
<td>.4</td>
<td>Yes</td>
</tr>
<tr>
<td>p-Ge</td>
<td>1E17</td>
<td>.14</td>
<td>HCN laser modes only 250 kHz</td>
</tr>
<tr>
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<td>1E18</td>
<td>.7</td>
<td>Yes</td>
</tr>
<tr>
<td>n-Ge</td>
<td>6E17</td>
<td>2.5</td>
<td>Yes</td>
</tr>
<tr>
<td>n-Si</td>
<td>4E14</td>
<td>.03</td>
<td>No</td>
</tr>
<tr>
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<td>4E16</td>
<td>.04</td>
<td>No</td>
</tr>
<tr>
<td>p-GaAs</td>
<td>2E18</td>
<td>&lt;.01</td>
<td>No</td>
</tr>
</tbody>
</table>

Table IV-1. Materials Tried as Point Contact Diode Detectors
reasons, the results presented below were poorer: the best MDP was $2.5 \times 10^{-12}$ W/Hz (Table 2). At the submillimeter frequency, there was an unknown mismatch between the laser beams and the diode antenna and then between the antenna and the junction. The mixer conversion loss was far from saturated (see Chapter II-4), as will be clear from the linearity of the beat signal with LO power, as shown below. Finally, there were IF mismatches between the diode, its mount, and the amplifier. These mismatches affected the noise as well as the beat signal and explained why the diode noise, both intrinsic and LO induced, was unobservable on the spectrum analyzer.

3. Ni Diodes

The first base electrode investigated, and the one most widely used as a high frequency detector and mixer, was nickel. The I-V characteristic appeared linear (Fig. 1), similar to the results of Nagasima and Tako [32], who directly measured the second derivative and found it to be small.

The dependence of the response on contact resistance is shown in Figure 2. The best responsivity, normalized to an antenna length of 7-3/4 λ, was .44 V/W, corresponding to a video noise equivalent power (NEP) of $2.7 \times 10^{-8}$ W/Hz. This video response was monitored across a 150 kΩ load. For $R_{\text{load}} \gg R_{\text{diode}}$, the circuit acted as a voltage divider and for a given video signal at the diode, $V_{\text{load}} \propto R_{\text{diode}}$. However, the higher resistance also reduced the high frequency cutoff and thus the signal at the diode. In addition, a large mismatch between
<table>
<thead>
<tr>
<th>Material</th>
<th>Antenna Length (Wavelengths)</th>
<th>Video Responsivity (V/W)</th>
<th>Mixing Conversion Loss (dB)</th>
<th>Video NEP x 10^8 (W/Hz)^1/2</th>
<th>Mixing MDP x 10^12 (W/Hz)</th>
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</thead>
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<tr>
<td>Ni</td>
<td>7-3/4</td>
<td>.4±.2</td>
<td>82±4</td>
<td>2.7</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>1-1/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7-3/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-InSb</td>
<td>7-3/4</td>
<td>1.6±.3</td>
<td>81±4</td>
<td>10</td>
<td>4</td>
</tr>
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<td>7-3/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-Ge</td>
<td>7-3/4</td>
<td>4+2</td>
<td>79±7</td>
<td>6.3</td>
<td>2.5</td>
</tr>
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<td></td>
<td>7-3/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Ge</td>
<td>7-3/4</td>
<td>17±4</td>
<td>81±4</td>
<td>.65</td>
<td>5</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td></td>
<td>7-3/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 +2 dBm of LO for 1-1/4 λ antenna; -4 dBm of LO for 7-3/4 λ antenna.
2 Noise was unusually high and may have been instrumental, not detector.

Table IV-2. Video and Mixer Performance of Good Mixer Materials.
Figure IV-1. I-V Characteristic for a Typical W-Ni Diode. R=1.6 kΩ (contact 132). See Figure 3 for video response.
Figure IV-2. Video and Mixer Response vs. Contact Resistance for W-Ni Diodes.
the antenna and the diode occurred. For a whisker between 1-1/4 and 9-1/4 wavelengths long, the antenna impedance ranged from $140\Omega$ to $850\Omega$, vs. diode impedances between $30\Omega$ and $1000\Omega$. The diode capacitance, which could only be approximated from estimates of the contact area and thickness, was also important. For 1 THz frequencies, its reactance was on the order of $10\Omega$. Together, these effects apparently favored a high resistance contact for W-Ni, but the improvement was less than the linear increase from the voltage divider alone.

A small load resistance reversed the dependence on contact resistance. The frequency cutoff and antenna mismatch still favored the low resistance diodes, and the low resistance load favored a small diode resistance as well. The two laser beat signal, which drove the microwave amplifier's small input impedance, decreased at high diode resistance and leveled off at low resistance as the antenna impedance began to dominate. The video signal into a $50\Omega$ load showed a similar behavior but fell off less rapidly than the beat signal at high resistances, perhaps because of the relative effects of the IF and DC mismatch of the mount.

Video detection and mixing as functions of DC bias displayed a more complex behavior. For most contacts, the response at zero bias was nearly as great as the response under optimum bias, and both the video and beat signals displayed the same bias dependence (Fig. 3). At $-0.2V$ to $-0.3V$ bias, depending on the contact, the detected signal reversed polarity (Fig. 4); this was mirrored in the mixing data by a disappearance of the beat note at the same voltage. Lower resist-
Figure IV-3. Video and Mixer Response vs. Bias for W-Ni Diodes. Four different contacts; solid lines are typical behavior; dashed lines observed for only two contacts. (contact 132--video, both polarities; 134--video, one polarity; 135a--mixer, solid line; 135b--mixer, dashed line)
Figure IV-4. Bias Voltage for Polarity Reversal of Video Signal and Disappearance of Mixer Signal vs. Contact Resistance for W-Ni Diodes.
ance contacts required a harder run-in, and the variation in the reversal voltage may have resulted from stress-induced changes in the junction.

Both video detection and mixing were approximately linear with power. The voltage swing caused by the optical signal was apparently much smaller than the bias levels used, as evidenced by the linearity even near the polarity reversal. In addition, the signal was too small to switch the diode strongly enough for good heterodyne detection (see Chapter II-4). The best conversion loss, optimized for bias, was 75 dB with a 7-3/4 \( \lambda \) antenna and a -4 dBm of LO power. The associated sensitivity was \( 2.5 \times 10^{-12} \) W/Hz. As noted in Chapter III-6, the beam combiner limited the available LO power to only one fifth of the laser power.

4. n-InSb Diodes

The next material investigated in detail was a sample of polycrystalline n-InSb with \( n=10^{16} \) cm \(^{-3} \). The I-V characteristic was nearly linear for voltages between -.3V and +.15V; outside of this range it shifted to a rather soft exponential of the form \( I = I_o e^{qV/nkT} \) with \( n \sim 10 \) (Fig. 5). The linear forward current was only 5%-60% more than the reverse current, depending on the contact.

The detected signal displayed a great deal of variability as a function of zero-bias contact resistance (Fig. 6). The video detection for relatively low resistance contacts \( (R \lesssim 10 \text{ k}\Omega) \) scattered from -.27mV to +.015 mV, while higher resistance contacts showed a gradual decrease
Figure IV-5. I-V Characteristic for a Typical W-(n-InSb) Diode. \( R=10 \, k\Omega \) (contact 120). See Figure 7 for video and mixer response.
Figure IV-6. Video Response \textit{vs.} Contact Resistance for W-(n-InSb) Diodes. (3 sets of data).
in absolute value from the peak negative level. The best responsivity was 1.6 V/W, but the diode was quite noisy, so the NEP was only $3 \times 10^{-6}$ W/Hz. Also shown is the signal resulting from the beat of two different HCN laser modes separated by about 200 kHz. This signal was observed with the video detection circuitry and showed a much more rapid decrease at higher contact resistance than did the video signal. In addition, it was found that the two laser beat was observable only if the lower frequency two mode beat was good. In contrast to the W-Ni diodes, the video response fell off at high resistance. The associated resistance values were comparable to the load for the straight video signals, making the load effectively low impedance. The HCN mode beat, however, appeared only for relatively low resistance contacts and continued to improve after the video response leveled off.

Like W-Ni, the video and mixing signals for W-InSb reversed polarity at a finite bias, usually but not always at negative bias. There was a much greater variation between contacts, including an actual switch of the bias polarity for zero detected signal (Fig. 7). The video signal and beat signal showed the same bias dependence for a given contact, as in the case of Ni, but there was no correlation between the bias for zero signal and the peak detected signal. This variation may have been due to the polycrystalline nature of the sample, with the semiconductor band structure and thus the Schottky barrier height being functions of the crystalline orientation. In all cases, the video and beat signals were linear with optical power at all biases checked. The conversion loss, 77 dB, and the mixer sensitivity,
Figure IV-7: Video and Mixer Response vs. Bias for W-(n-InSb) Diodes. (Contact 120—solid lines; 122b—dashed lines).
$4 \times 10^{-12}$ W/Hz, were the same as for Ni within the uncertainty of the data.

5. p-Ge Diodes

The p-Ge diodes showed even more irregular behavior than the InSb ones. Some contacts showed the same linear low voltage and then soft exponential I-V displayed by the InSb (Fig. 8). Others, however, were linear or actually began to saturate above +0.5 V, while the reverse characteristic sometimes included a region between -0.5 V and -1 V where the diode was linear after an initial nonlinearity at lower voltage. A good signal was generally obtained with a low zero-bias contact resistance, but this resistance was a much less meaningful number than for Ni or InSb, in terms of its relation to the overall I-V characteristic. Not surprisingly, there was considerable scatter in the video response as well (Fig. 9). The best video detection was 4.1 V/W, for an NEP of $1 \times 10^{-8}$ W/Hz. High resistance contacts gave a positive rather than a negative signal at zero bias.

The video and mixing signal bias dependence is shown in Figure 10. The video polarity was again negative for large positive bias and reversed polarity at some nonzero bias. The beat signal, however, displayed two zeroes at distinct negative biases, separated by different amounts for different contacts, rather than the single zero seen with the other materials. The video signal was too noisy to measure at the higher bias, so the presence or absence of a polarity reversal at the second zero could not be ascertained. As usual, the diode response was
Figure IV-8. I-V Characteristics for W-(p-Ge) Diodes. (a) Typical diode (contact 148). See Figure 10 for mixer response.
Figure IV-8. (b) Contacts showing saturation at high bias (contacts 3a and 4).
Figure IV-9. Video Response vs. Contact Resistance for W-(p-Ge) Diodes. 
\( \Theta \) = voltage response into 150 k\( \Omega \). \( \circ \) = current response into 50\( \Omega \).
Figure IV-10. Video and Mixer Response vs. Bias for W-(p-Ge) Diodes. (contact 130--video; 148--mixer, dashed line; 149--mixer, solid line).
linear with LO power, and the 75 dB conversion loss and $2.5 \times 10^{-12}$ W/Hz sensitivity were the same as for Ni and InSb.

6. n-Ge Diodes

The last sample that showed good mixing was n-Ge. This material was the only one that had a conventional diode characteristic with a small reverse current and an exponential forward current (Fig. 11). The lowest resistance contact (contact 7), however, would not have been a good detector, based on the contact resistance data (Fig. 12). Repeating the other semiconductor results, a hard run-in to a low contact resistance was favored for both video and beat response, and a somewhat softer I-V characteristic was involved, with the mixer responsivity falling off faster than the video current responsivity. The best n-Ge video responsivity, 17 V/W, was a factor of 40 better than for Ni, but higher noise gave an NEP of $6.5 \times 10^{-9}$ W/Hz, better by only a factor of 5.

The bias dependence of the detector is shown in Figure 13. n-Ge was the only material that always gave a positive signal at zero bias, but effectively this indicated only a positive bias for the usual polarity reversal. The shape of the curves was the same as for the other samples, and the mixing signal followed the video. There was much less scatter in the reversal bias than for InSb or p-Ge, and the signal was linear with power at zero bias and on either side of the reversal. The conversion loss was 78 dB, for a sensitivity of $5 \times 10^{-12}$ W/Hz, the same as for the other diodes despite the factor of 40 in video responsivity.
Figure IV-11. I-V Characteristics for W-(n-Ge) Diodes. (contact 7--solid line; 105--short dashes; 143--long dashes). See Figure 13 for video and mixer response.
Figure IV-12. Video and Mixer Response vs. Contact Resistance for W-(n-Ge) Diodes.
Figure IV-13. Video and Mixer Response vs. Bias for W-(n-Ge) Diodes. (contact 86b--video, solid line, largest signal; 87--video, solid line, smallest signal; 105--mixer, short dashes; 143--video and mixer, long dashes).
7. Comparison to Theory

Where detection depends on a nonlinear current response to an applied voltage, both rectification of one AC signal and mixing of two depend on the second derivative of the I-V curve (see Chapter II-3). For point contact diodes with tunneling or Schottky barrier nonlinearities, which respond well into the infrared, both the video response and mixer output should display the same dependence on bias. At positive bias, where the second derivative is positive, laser illumination should reduce the voltage across the junction (negative rectification), while negative bias and negative derivative should give a less negative voltage under illumination (positive rectification).

All four of the diodes described above had the same qualitative behavior at high bias. With the whisker biased positive, the rectification was negative, while for negative bias, the rectification was positive, consistent with a tunneling or Schottky nonlinearity. Comparison between the detailed bias dependence (Figs. IV-3, 7, 10, and 13) and the experimental I-V curves (Fig. 14), however, reveals weaknesses in interpreting the results in this way. The primary difficulty involves the bias level for zero signal. In the case of the n-InSb and p-Ge diodes, inspection of the I-V curves shows that the second derivative went through zero (the curvature reversed) near zero bias rather than where the video and beat signals went through zero. For n-Ge, the I-V curve implies that there should be no signal for negative bias and certainly no reversal at positive bias. Ni, with no apparent curvature and a theoretically symmetric nonlinearity up to about 4 V
Figure IV-14. I-V Curves of Point Contact Diodes (from Figures IV-1, 5, 8, and 11).
(the metal work function), should likewise have reversed at zero bias if anywhere. From eq. II-10,

$$V_R \approx -\frac{1}{4} \frac{I''}{I^7} \frac{|v_s|^2}{|1+I'Z_s|^2}$$

is is clear that, for a nearly linear diode ($I' \approx$ constant), the detected signal is a direct measure of the bias dependence of $I''$. The video response of Ni, however, is quite unlike the second derivative implied by tunneling theory for a linear diode, as shown in Figure 15.

A combination of the hot carrier effect (Chap. II-2-C) with a non-linear rectification is also insufficient to explain the data. In principle, a thermoelectric voltage could explain the zero-bias detection, with rectification dominating at high bias. A rough extrapolation of Harrison and Zucker's results for 2.5 $\mu$m contacts on 35$\Omega$ -cm p-Ge [20] gives a $10^2$-$10^3$ V/W responsivity for the p-Ge devices used here; 1% antenna efficiency would bring the results into the observed range. The thermoelectric effect, however, predicts that the video signal will have the opposite polarity as the carrier type. While this was generally the case for both Ge samples, the n-InSb showed a negative signal at zero bias most of the time while the p-Ge showed a positive one for light (high resistance) contacts. The thermoelectric effect also favors low carrier concentrations. Of the two p-Ge samples tried as video detectors (see Table 1), the higher carrier concentration material made a better detector, and the much lower concentration n-InSb was less sensitive than either Ge sample. The carrier concentration
Figure IV-15. $d^2I/dV^2$ and $-V_{\text{video}}$ vs. Bias for W-Ni Diode. ($d^2I/dV^2$ after Twu and Schwarz [21]).
in a metal is much too high to explain the responsivity for Ni.

Other explanations for point contact diode detection, proposed in the literature but not presented in Chapter II, are thermally assisted field emission [33] and a geometrical effect [34] to explain the zero-bias signal in MOMs. Both of these theories require electric fields on the order of $10^6$ V/cm, considerably higher than those available from the submilliwatt power levels even with optical focusing and antenna coupling [35].

Another unexplained result is the double zero observed in the beat signal from p-Ge. Tunneling predicts multiple zeroes or sign reversals in the bias dependence of high order beat notes [36], and this phenomenon appears to have been confirmed experimentally [15]. The only prediction of such an effect in the second order mixing investigated here was for MOMs [16], with two additional zeroes, symmetrically placed about the still-present zero-bias crossover.

In addition to the qualitative difficulties related to polarity and bias dependence, there was a quantitative one involving the video and beat signals. All of the theories above have cutoff frequencies well above 2 GHz. A 16 dB difference in the video responsivities, however, disappeared in the mixing conversion loss. Ignoring the uncertainties of the results, the best video detector, n-Ge, was actually a worse mixer than Ni, which had the poorest video behavior (see Table 2). This suggests a detection process with a material-dependent cutoff frequency below 2 GHz, so that the Ge response could have dropped by 19 dB more than the Ni response at 2 GHz. If the rolloff had the usual
1/f form, nearly 2 decades of frequency would have been required, implying a cutoff below 20 MHz for the Ge.

8. Comparison to Other Experiments

Other experiments with point contact diodes, as reported in the literature, are quite varied in their results. With MOM diodes, Twu and Schwarz [21] at 10.6 µm and Faris, et al. [16] at 1.15 µm and 6328 Å observed zeroes in the detected signal near zero bias and symmetric characteristics. Additional zeroes, predicted by tunneling theory for higher resistance contacts, were observed at symmetrically placed non-zero biases. The bias level for the zero signals increased with increasing laser power, however, instead of decreasing as predicted, suggesting that mechanisms other than tunneling were still involved. Yasuoka, et al. [37] interpreted the temperature dependence of an MOM diode as confirmation of the tunneling mechanism. Nagasima and Tako [32] by contrast, used a sensitive circuit to measure the small nonlinearity directly and found that some diodes showed rectification at 10.6 µm that was consistent with $d^2I/dV^2$ but in qualitative disagreement with the tunneling theory predictions of that derivative. Small, et al. [38] note that mechanical contacts could be obtained that had a zero-bias signal nearly as large as the best signal under bias, as observed here. They further point out the value of this behavior in terms of the minimization of the current noise in a detector. The effect was not explained.

Far less applicable work has been done on point contact metal-semi-
conductor diodes, most of the effort having been reserved for plated Schottky diodes on n-GaAs, which are both mechanically and electrically more stable and reproducible. For point contact devices at 10.6 μm, Tsang and Schwarz [39] observed no signal reversal but a bias induced enhancement of about 2-1/2 times for a +.3 V bias on n-Ge, as compared to the signal reversal near +.35 V seen in the present work. McColl, et.al. [9] extrapolate a linear decrease with bias to obtain the Schottky barrier height for Pt--n-GaAs, but the fall-off was due to a decreasing barrier capacitance, which could and did not lead to a sign reversal of the detection.

Payne and Prewer [40], working at 337 μm, found video and superhet sensitivities of 2×10⁻⁸ W and 2×10⁻¹² W (1 Hz bandwidth) for Ge point contact diodes, nearly the same as observed here. GaAs was an order of magnitude worse, the explanation being that a smaller contact could be formed on the harder Ge, offsetting the effect of the higher GaAs mobility. Tsang and Schwarz [39] reported relative video responsivities at 10.6 μm and found no signal at all from GaAs, vs. an inferred S/N of greater than 1000 for n-Ge and Si and 60 for Ni. Zuidberg and Dymanus [3] tested n-Ge, p-Ge, p-Si, and n-GaAs point contact diodes of unspecified carrier concentration. In a mixing experiment at 337 μm, they found behavior within 3 dB for the Ge and Si devices, while the GaAs, with a Au/Cu whisker instead of W, was 16-19 dB better. Kelly and Wrixon [5] have pointed out that InSb, with a mobility even higher than GaAs, should be a good candidate, but that plasma resonance, doping, and dimensional effects offset this advantage.
In the present work, p-Ge, the lowest mobility material of all, was the best detector at zero bias, and the best bias enhancement result with InSb was only 3 dB better than the peak Ge value. This seems to agree with Payne and Prewer's and Tsang and Schwarz's argument in favor of hard materials for point contact diodes, but disagrees with Zuidberg and Dymanus' results.
V. APPLICATION TO FREQUENCY MEASUREMENT

1. HCOOH Laser Lines

Several workers have described HCOOH optically pumped lasers [41-46]. This gas and its isotopes are very attractive submillimeter laser media since they have a large number of relatively powerful lines. Consequently, there is considerable interest in accurate frequency measurement, both to further study the molecular spectroscopy and to allow use of the laser as a reference frequency for other spectroscopic applications. Of the 59 lines reported, 27 have been measured with an accuracy of better than $1 \times 10^{-5}$ by high order mixing with millimeter wave sources [44, 46]. The remainder have either been too weak or not observed at all in the mixing experiments. As described below, use of the spectrum analyzer to directly observe the second order beat between two lasers has permitted measurement of one of these weaker lines, even though the mixer was far from saturation.

The HCOOH line investigated was the 311 μm line pumped by the 10R22 line of the CO$_2$ laser (Table 1). By using the beat signal as a power indicator, the HCOOH laser cavity could be scanned over 20 half-wavelengths and the wavelength determined directly to $< .1\%$. Similarly, the HCN laser could be scanned, providing a quick check that indeed the HCN 311 line was being used, rather than the stronger 337 μm line. The HCN line, known to a relative precision of better than $1 \times 10^{-6}$ [47], was used as the reference frequency.
<table>
<thead>
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<th>Pump Transition</th>
<th>Wavelength</th>
<th>Relative Polarization</th>
<th>Power</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10R22 Pulsed</td>
<td>309±3</td>
<td>±</td>
<td>Medium</td>
<td>Plant, et al (43)</td>
</tr>
<tr>
<td>10R22</td>
<td>311.45±.03</td>
<td>-</td>
<td>-</td>
<td>Wagner, et al (41)</td>
</tr>
<tr>
<td>10R22</td>
<td>311.0±.7</td>
<td>±</td>
<td>Medium</td>
<td>Dyubko, et al (42,44)</td>
</tr>
</tbody>
</table>

Table V-1. HCOOH Optically Pumped Laser Line Reports for CO$_2$ Laser 10R22 Pump Line.
2. Frequency Measurement of the 311 μm HCOOH Line

To perform the frequency measurement, the two lasers were individually peaked for power with the diode, then the spectrum analyzer was tuned to acquire the beat signal (Fig. 1). Each laser was then readjusted to the frequency center of its line by observing the change in beat frequency with cavity length. The HCN laser had a 2-1/2 MHz tuning range, while the HCOOH line tuned between 1 and 3 MHz, depending on the output coupling and pump power. For the HCN laser, the frequency center was at the power peak, but the HCOOH waveguide could support several transverse modes, and the frequency center of the envelope was not always on the peak of a mode. As described below, other measurement errors and uncertainties were larger than the tuning problem, so no attempts were made to improve the laser mode structure.

Several checks were made to insure that the observed beat was in fact the fundamental difference frequency between the two lasers. The aforementioned wavelength measurements determined which range of the spectrum analyzer was applicable as well as eliminated from consideration a spurious signal near 0.95 GHz. By relating the sign of the beat frequency shift to a cavity adjustment within the laser linewidth, the spectrum analyzer image could be rejected as well. The beat frequency was read to be Δf = 2.045 GHz.

Several sources of error were present in the measurement. The uncertainty in setting each laser to the center of its gain curve was ± 1/4 MHz. This was considerably more than the 30 kHz linewidth of the
Figure V-1. Beat Signal Trace on Spectrum Analyzer. Vertical scale: relative power. Horizontal scale: frequency. 3 markers on right separated by 1 MHz; center marker at 2.05 GHz. Beat signal on left.
beat signal, which placed an upper limit on the unstabilized laser linewidths. An additional 1 MHz uncertainty was involved in simply reading the spectrum analyzer dial. The most serious problem, however, was the absolute calibration of the analyzer. Comparison with an X-band source indicated that the dial readings were $18 \pm 3$ MHz low. Taking the $18$ MHz as a systematic error, the final value for the beat frequency was $\Delta f = 2.063 \pm 0.005$ GHz. Combined with the known HCN laser value, this yielded a value for the HCOOH line of $f = 962.250 \pm 0.005$ GHz, or $\lambda = 311.554 \pm 0.002$ μm.
VI. CONCLUSION

Tungsten point contacts on Ni, n-InSb, p-Ge, and n-Ge have been studied as video detectors and mixers at 311 μm. Within the experimental uncertainty, all four materials had the same conversion loss and mixer sensitivity, about 76 dB and $3\times10^{-12}$ W/Hz, respectively, for an antenna with a gain of 17 and -4 dBm of LO power. There was no sign of mixer saturation at this power level, and the three semiconductors showed comparable mixing despite differences in mobility, carrier concentration, and surface hardness. The nickel substrate, with yet different parameters, mixed as well as the semiconductors. For video detection, there was a 16 dB difference between the best (n-Ge) and the worst (Ni) peak responsivities, at odds with the mixer behavior. This result suggests either different processes for video and mixing response or a frequency rolloff well below 2 GHz. The former was unlikely, since the bias dependence of the beat signal was the same as that of the video one, while no mechanism proposed for point contact diode detection has a frequency cutoff even close to the 2 GHz intermediate frequency.

The bias dependence was also qualitatively inconsistent with the proposed theories for low level detection. The usual argument is rectification by a junction nonlinearity. In the case of the MOM diodes, tunneling theory implies a symmetry about zero bias, contrary to what was observed. Transport over a Schottky barrier, appropriate to metal-semiconductor contacts, was inconsistent with the behavior of the InSb and Ge diodes. A non-rectifying mechanism, thermoelectric
heating, also failed to account for the results with respect to both bias dependence and the polarity of the video detection at zero bias. Some reports of MOM diodes have related detection to purely empirical I-V characteristics which have not always agreed with any theoretical prediction. Even this approach, however, failed here, as the I-V characteristics predicted zero signal near maxima in the observed result and strong signals near where the actual response went through zero and reversed polarity.

Lack of an adequate theory notwithstanding, point contact diodes are fairly simple to make and use. A large body of literature attests to their value in direct measurement of frequencies throughout the infrared region. With considerable care in surface preparation, whisker etching, and contacting, it is possible to obtain point contact diodes that do perform in accordance with theory. Alternatively, as photolithographic resolution has improved, it has become possible to prepare planar MOM and Schottky barrier diodes with small enough dimensions to be useful in the submillimeter region. With the more well controlled conditions, various materials can be used and good reproducibility as well as mechanical and electrical stability can be achieved.
VII. REFERENCES


APPENDIX 1. CO₂ LASER MIXED GAS AND DISCHARGE BEHAVIOR

Pre-mixed gas, while ordered to the nearest .1% of the minor components, was shipped ± 5% of the component, e.g. 13.9% ± .7% CO₂. This led to some fluctuation in the gas contents, which in turn allowed optimization of the mix. The range of compositions that were shipped and worked well were 13.6-14.2% CO₂, 23.1-25.3% N₂, and 60.5-63.3% He. Adding separate CO₂, N₂ or He along with the mix indicated that 23.3% N₂ was somewhat low. Cylinders with 12.2% and 11.9% CO₂ lased poorly or not at all, though in the latter case a substantial addition of extra CO₂ brought the power up to the usual 35-40 W level.

In an attempt to conserve the gas, the input flow and pump exhaust were partially closed in such a way as to reduce the flow but maintain the gas pressure and electrical impedance in the discharge. Typical discharge parameters were 28 mA at 18.4kV. On the strong laser lines, the flow could be reduced quite far with only a 5% power loss. In the weaker lines, the same flow led to a severely reduced peak power. In addition, this peak occurred just above the discharge threshold, and increased current caused the laser power to drop precipitously. This close to the electrical threshold, the discharge was also highly sensitive to the optical tuning. By increasing the flow rate, the laser could be brought back to normal operation, with the power showing a broad maximum well above the electrical threshold.

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APPENDIX 2. OPTICALLY PUMPED LASER OUTPUT COUPLERS

Two versions of a hybrid output coupler were used for the optically pumped laser. Both were based on silicon wafers with ZnSe/Ge dielectric coatings for 10 μm reflection; the difference was in the gold overcoat for submillimeter reflection. In the first case, gold was vacuum-deposited through a 20-40 lines/mm electroformed Ni mesh (Buckbee-Mears Company). Deposition was done in an e-beam evaporator rather than a more conventional thermal one (Fig. A-2-1). By using many short evaporations, the grid could be built up without heating the Ni mesh, which tended to buckle. The resultant capacitive grid was a short wavelength reflector, but etalon and dielectric effects from the Si substrate probably led to a very complex transmission spectrum [49]. Experimentally, the reflectivity was very high at the submillimeter wavelengths tested, and the resultant output coupling was too low for useful lasing.

A second coupling scheme utilized a uniform gold coating with a central hole. Gold was thermally evaporated over the whole wafer. A hole was then exposed and developed in a photoresist, and the gold was etched off in a KI-I etch. Some damage occurred to the top Ge layer of the dielectric stack, but the coupler performed well in the laser.

One problem with the gold coatings was heating by the CO₂ radiation. The wafer was poorly heat sunk, and enough power was absorbed from the stronger pump lines to make the wafer and its mount too hot to touch.
Figure A-2-1. Electron-beam Evaporation Setup for Depositing Capacitive Grids.
After several tens of hours, the gold coating turned silver colored and the submillimeter output decayed. One suggested explanation was that the gold had formed a gold-germanium eutectic with the top layer of the dielectric stack. The eutectic was absorptive at both the pump and output wavelengths, and the extra loss was enough to affect the laser. A possible solution, involving more processing steps, was to put an inert dielectric layer such as SiO between the gold and the germanium, but this was not attempted.
APPENDIX 3. TUNGSTEN WHISTER ETCHING

The tungsten wire for the point contact diodes, after being bent into the proper shape, was electrochemically etched to the desired sharp point. The whisker was lowered into a 2M KOH solution containing a small amount of cupric chloride to maintain a meniscus about the wire [50]. An AC voltage was used for the etching. On alternate half cycles, the tungsten passed into the electrolyte, while on the other half cycles, hydrogen was evolved at the wire. The etching occurred most strongly near the liquid surface, the point actually forming when the wire in the solution broke away. The bubbling hydrogen probably helped to mix and replenish the KOH; more importantly, its cessation gave an easy means of determining when the etching was complete. Since the point could still be partly immersed, the current had to be turned off quickly to prevent further etching and dulling. The procedure was therefore done under a microscope to facilitate observation of the bubbling. Twu [51], using a DC etching system, has used an electrical circuit to sense the break and turn off the current.

The etch voltage was adjusted empirically to optimize the tip sharpness. The best value was 1.05 V rms, but there were still variations in both sharpness and angle from tip to tip. Most tips had a cone half angle in the range 5° - 25°. Twu [51] has reported good control over the tip shape by adjustment of the etch concentration, below .75N. His concern was for antennas at 10.6 μm, where the antenna was a coni-
cal one defined by the tip itself. Where the wavelength is much larger than the wire diameter, as in the present work, the detailed shape is unimportant, so this control was not attempted.
APPENDIX 4. CIRCUIT TO MONITOR CONTACTING OF DIODES

The circuit in Figure A-4-1 was used to monitor the contact of the tungsten whisker to the base electrode and also to measure the "zero-bias" resistance. The actual voltage involved was less than .01 V, vs. DC bias levels during the experiment of up to 1 V. The section of the circuit to the left of the dashed line served as a .1 \( \mu \)A current source. The voltage across the diode, less than 10 \( \mu \)V for some of the nickel contacts, was measured to determine the device resistance. The addition of the 150 k\( \Omega \) shunt resistor was related to the initial contacting. Without the resistor, the connecting wires were a capacitor charged up to .15 V, and the peak discharge current upon contacting was enough to burn out the tip. By adding the resistor, the initial voltage was dropped to .015 V and the current surge was within safe limits. Since the diode resistance was usually well below 150 k\( \Omega \), the circuit still behaved as a .1 \( \mu \)A source once the contact was made, and the resistance measurement was relatively unaffected.
Figure A-4-1. Circuit for Monitoring Point Contact Formation and Measuring Resistance at .1 µA of Current.