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# A MICROWAVE BIASED GaAs SUBMILLIMETER DETECTION SYSTEM

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**Abstract**—Microwave biasing techniques were employed to construct a sensitive, wide bandwidth GaAs submillimeter detection system. Optimum operating conditions and the performance characteristics were determined for three different microwave receiver systems. An NEP of $3{\cdot}2 \times 10^{-10}$ W/Hz$^{1/2}$ and a responsivity of $3 \times 10^3$ V/W was achieved. The bandwidth limitation was found to be the microwave cavity bandwidth of 11 MHz. For comparison, a d.c. biased GaAs detection system was constructed and its performance characteristics evaluated.

## INTRODUCTION

A fast, sensitive submillimeter detection system is required for (a) the study of pulsed submillimeter lasers;(1,2) (b) thermonuclear plasma diagnostics;(3) (c) the development of submillimeter modulators; and (d) submillimeter radar systems. To meet these needs, a microwave biased GaAs detection system was developed and tested. Three different microwave circuits were investigated and the performance characteristics of each presented below. In addition, the performance of the microwave biased systems were compared to that of a d.c. biased detector.

High purity, $n$-type, epitaxial GaAs can be used as a submillimeter detector.(4) When cooled to liquid helium temperatures, GaAs exhibits extrinsic photoconductive response to radiation extending in wavelength from 100 to 350 $\mu$.(5) Illumination of the GaAs induces photothermal ionization of the shallow donor impurity atoms. Very sensitive submillimeter detection systems have been constructed from a d.c.-biased GaAs photoconductive element. Noise-equivalent powers of $1{\cdot}4 \times 10^{-12}$ W/Hz$^{1/2}$ and responsivities of $4 \times 10^4$ V/W have been reported.(4) The applied d.c. bias field in such a device is limited by impact ionization of the shallow donors to approximately 5 V/cm. The lifetime of the donor electrons has been estimated to be $5 \times 10^{-9}$ sec, based on the observed decay time of current pulses produced by impact ionization.(4) Thus, the bandwidth of the material itself should be at least 30 MHz.

A detection system which fully utilizes this 30 MHz bandwidth is difficult to construct. Maximum responsivity is obtained using a load resistance that matches the detector resistance. Device and lead capacitance shunting the high impedances of the detector and the load resistor severely limit the circuit bandwidth. To achieve a larger bandwidth it is necessary to decrease the load resistance. However, this results in a corresponding decrease in responsivity and, consequently, a decrease in sensitivity.

A low capacitance input preamplifier located close to the detector element can ameliorate this problem to some extent. However, excess amplifier noise as well as the difficulty in operating the preamplifier at liquid helium temperatures does not always make this an attractive approach. An alternate solution to the problem of increasing bandwidth and maintaining high sensitivity is the use of a microwave frequency a.c. bias signal on the detector and the utilization of microwave circuitry techniques to achieve a good match between the impedance of the signal line connecting the device to the receiver and the device itself. Such microwave biased photoconductive detection systems have been constructed before at m.m., i.r. and optical wavelengths(6–8) and have exhibited an improvement in both sensitivity and bandwidth.

## MICROWAVE BIASED DETECTION

In order to achieve a bandwidth which was larger than that of d.c. biased GaAs detectors, a microwave biased GaAs detection system was constructed. A 1 × 0·38 cm GaAs detector element was supported by a teflon holder in the high electric field region of a $TE_{111}$ cylindrical microwave cavity (Fig. 1). The cavity was coupled to an X-band waveguide by an adjustable probe to form a reflection cavity. The reflection cavity was submerged in liquid helium. Submillimeter radiation from a 337 $\mu$ HCN laser was transmitted from the top of the LHe cryostat through a $\frac{1}{2}$ in. dia. stainless steel light pipe to a light pipe cone which focused the radiation through a small aperture in the top of the cavity.

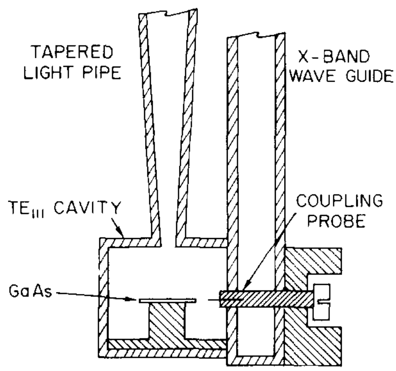


Fig. 1. Cross-sectional view of the reflection microwave cavity.

The detector element consisted of a 100 $\mu$m thick, high purity, $n$-type epitaxial layer of GaAs grown on an insulating GaAs substrate. (The detector element was obtained from Cayuga Associates.) The donor and acceptor concentrations of the epitaxial layer were $N_D = 4{\cdot}61 \times 10^{14}$ cm$^{-3}$ and $N_A = 2{\cdot}45 \times 10^{14}$ cm$^{-3}$, respectively.

A generalized schematic of the microwave biased detection system is shown in Fig. 2. Submillimeter radiation incident on the detector element generated carriers in the GaAs by photoionization of the shallow donor impurities. The increase in conductivity of the GaAs changed the amount of microwave power absorbed in the cavity. This variation in the absorbed power produced a change in the power reflected from the cavity. A microwave receiver was used to monitor the change in the reflected microwave signal.

The fundamental bandwidth limitation of this system could be determined by the ratio of the resonant frequency of the cavity, $f_0$, to the loaded $Q$ of the cavity $Q_L$,

$$\Delta f = f_0/Q_L \tag{1}$$

where $\Delta f$ is the full-width, half-power bandwidth of the cavity.

The optimum operating conditions and the ultimate performance of a microwave biased detection system were strongly dependent on the type of microwave receiver which was utilized to monitor the signal returning from the cavity. Detection systems using three different types of receivers were constructed and evaluated: (a) square-law receiver; (b) homodyne receiver; and (c) heterodyne receiver.

## SQUARE-LAW RECEIVER

The microwave biased GaAs detection system shown in Fig. 3(a) employed a crystal detector as a microwave receiver. The crystal output current was proportional to the square of the amplitude of the microwave electric field. Thus, changes in crystal current were proportional to changes in the microwave power reflected by the cavity.

The detector element and microwave cavity can be modeled with the equivalent circuit of Fig. 3(b). $L$, $C$ and $R_C$ are the equivalent circuit parameters of the empty and unloaded

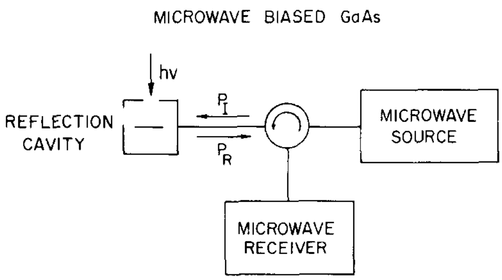


Fig. 2. Generalized representation of a microwave biased detection system.

$TE_{111}$ cylindrical cavity. The probe coupling of the cavity to a transmission line of characteristic impedance $Z_0$ is modeled with the coupling transformer of turns ratio 1:M. $R_D$ represents the losses in the cavity due to the detector element.

In a small signal approximation, the change in reflected power, $\Delta P_R$, due to a change in $R_D$ is given by

$$\Delta P_R = \frac{\partial P_R}{\partial R_D}\Delta R_D = 2\rho P_1 \frac{\partial \rho}{\partial R_D}\Delta R_D \tag{2}$$

where $\rho$ is the voltage reflection coefficient and $P_1$ is the incident microwave power. Near the resonant frequency of the cavity, and with the losses in the cavity dominated by the detector element ($R_D < R_C$), the reflected power is given by

$$\Delta P_R = \pm 4P_1 \frac{(VSWR)^2 - VSWR}{(VSWR+1)^3}\frac{\Delta R_D}{R_D} \tag{3}$$

where a + sign stands for an overcoupled cavity, while a − sign is for the undercoupled case. For a given cavity and detector element, the *VSWR* is determined by the cavity coupling. The response goes to zero as the cavity is critically coupled ($VSWR = 1{\cdot}0$ or $\rho = 0$). Maximum response is predicted at a $VSWR = 3{\cdot}73$ or a voltage reflection coefficient of $\rho = 0{\cdot}58$ for either an overcoupled or an undercoupled cavity.

The experimental data of Fig. 3(c) illustrates the effect of changing the cavity coupling on the performance of the microwave biased GaAs detection system using a square-law receiver. The signal varied qualitatively as the small signal approximation predicted.

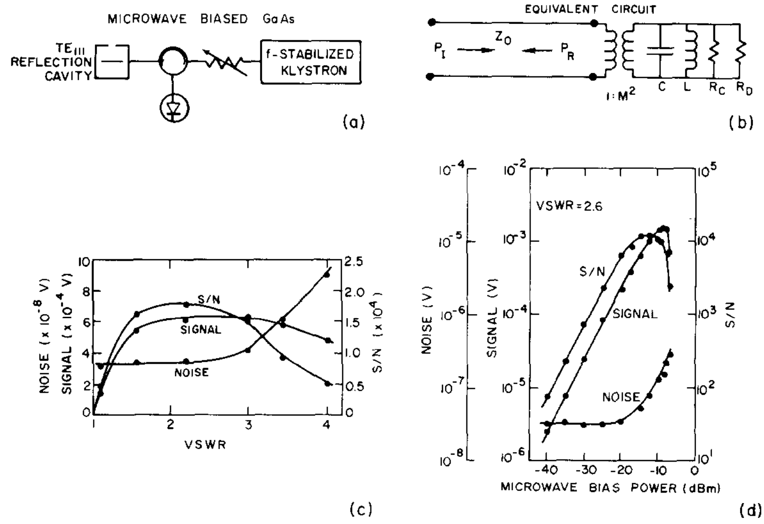


Fig. 3. Square-law receiver system. (a) Schematic of the system; (b) an equivalent circuit representation of the system; (c) performance of the detection system as a function of coupling to the microwave cavity; (d) performance of the system as a function of microwave bias power.

Zero response was measured for a critically coupled cavity; maximum response was measured at a $VSWR = 3{\cdot}0$ or $\rho = 0{\cdot}5$. In the prediction of maximum response at a $VSWR = 3{\cdot}73$ it was assumed the square-law crystal detector characteristics would remain constant as the $VSWR$ was varied. In practice, variation of the $VSWR$ from 1·0 to 4·0 significantly changed the microwave power reflected by the cavity and, therefore, the microwave bias power incident on the crystal detector. The operating point of the crystal detector was shifted from its square-law region as the $VSWR$ became large and the response decreased more sharply than the ideal prediction.

For a $VSWR$ less than about 2·5, the system noise appeared to be due to the Johnson noise of the crystal detector. For a $VSWR$ greater than 2·5, the microwave power incident on the crystal detector was greater than 0·18 of the microwave power incident on the cavity. The observed increase in noise can be attributed to (a) amplitude fluctuations of the klystron and (b) current noise of the crystal detector. The maximum signal-to-noise ratio (S/N) occurred at a $VSWR = 2{\cdot}2$.

The effects of the microwave bias power (power incident on the cavity) on the signal and noise are shown in Fig. 3(d). The cavity coupling was set for a $VSWR = 2{\cdot}6$. The signal increased linearly with bias power until breakdown of the GaAs occurred due to impact ionization. At low bias levels the noise was dominated by the Johnson noise of the crystal detector. At higher bias power, the noise began to increase as the amplitude fluctuations of the klystron and the current noise of the crystal detector became the dominant sources of noise. Maximum S/N was achieved at a bias power of −12·5 DBM.

At a $VSWR = 2{\cdot}2$ and a bias power of −15 DBM, the microwave biased GaAs detection system, using a square-law receiver, had a noise-equivalent-power of $1{\cdot}2 \times 10^{-9}$ W/Hz$^{1/2}$, a responsivity of 12·7 V/W and a bandwidth limit of 120 kHz. The bandwidth of this system was not limited by either the GaAs or the reflection cavity, but simply by the crystal detector video bandwidth of the detector we used.

## HOMODYNE RECEIVER

A microwave biased GaAs detection system using a homodyne receiver is shown in Fig. 4(a). A homodyne receiver is a linear detector. The mixer crystal current was proportional to the microwave electric field, i.e. its output was dependent on the magnitude and the phase of the voltage reflected from the cavity.

In order to calculate the theoretical response from a linear receiver, it is necessary to determine the change in reflected voltage $\Delta V_R$ due to a change in the resistance of the detector element $R_D$. Using the equivalent circuit of Fig. 4(b) and making a small signal analysis, we obtain the following expression:

$$\Delta V_R = \frac{\partial V_R}{\partial R_D}\,\Delta R_D = V_1\,\frac{\partial \rho}{\partial R_D}\,\Delta R_D \tag{4}$$

At the resonant frequency of the cavity and with the losses in the cavity dominated by the detector element ($R_D < R_C$), the response is given by

$$\Delta V_R = 2V_1\,\frac{VSWR}{(VSWR+1)^2}\,\frac{\Delta R_D}{R_D} \tag{5}$$

Maximum response is achieved when the cavity is critically coupled ($VSWR = 1{\cdot}0$). The response decreases as the cavity is either overcoupled or undercoupled.

The signal and noise of the microwave biased GaAs with a homodyne receiver were measured as a function of microwave bias power [Fig. 4(c)]. The cavity coupling was adjusted for $VSWR = 1{\cdot}0$. The signal increased with bias power; in the region between −27 and −12 DBM the signal increased at a rate proportional to the square root of the bias power. At −10 DBM the GaAs began to break down due to impact ionization and the signal decreased sharply.

The reference signal power incident on the mixer crystal was held constant while the microwave power incident on the cavity was varied. Since the cavity was critically

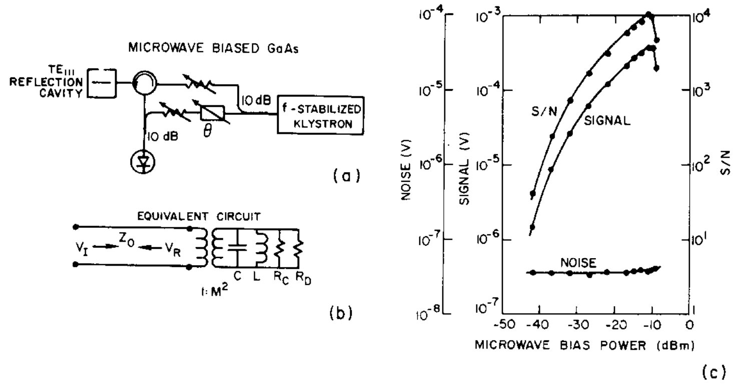


Fig. 4. Homodyne receiver system. (a) Schematic of the system; (b) an equivalent circuit representation of the system; (c) performance of the system as a function of microwave bias power.

coupled, the microwave power incident on the mixer crystal was essentially the reference signal power. The noise was produced by the reference signal power and thus the noise remained constant as the bias power was increased. Maximum S/N was achieved at a bias power of $-11$ DBM.

Unlike the square-law system, maximum signal and minimum noise occurred at the same value of cavity coupling ($VSWR = 1{\cdot}0$) for the homodyne system. Overcoupling or undercoupling the cavity decreased the signal, as predicted by equation (5), and increased the noise. As the $VSWR$ was made greater than 1·0, the power reflected by the cavity increased contributing crystal current noise to that already produced by the reference signal power.

With the homodyne receiver, the microwave biased GaAs detection system had a noise-equivalent-power of $2{\cdot}5 \times 10^{-9}$ W/Hz$^{1/2}$, a responsivity of 6·8 V/W, and a bandwidth limit of 11 MHz. The limitation on the bandwidth was not due to the GaAs nor the mixer crystal, but rather was due to the cavity bandwidth. This will be discussed in detail later.

## HETERODYNE RECEIVER

A microwave biased GaAs detection system using a heterodyne receiver to monitor the microwave signal reflected from the cavity is shown in Fig. 5(a). A bias klystron and a local oscillator klystron were stabilized 60 MHz apart. A balanced mixer generated a 60 MHz difference frequency signal which was amplified by a 60 MHz intermediate frequency amplifier followed by a video detector.

The heterodyne receiver is also a linear detector and, therefore, maximum response was obtained with the cavity critically coupled. The effects of microwave bias power

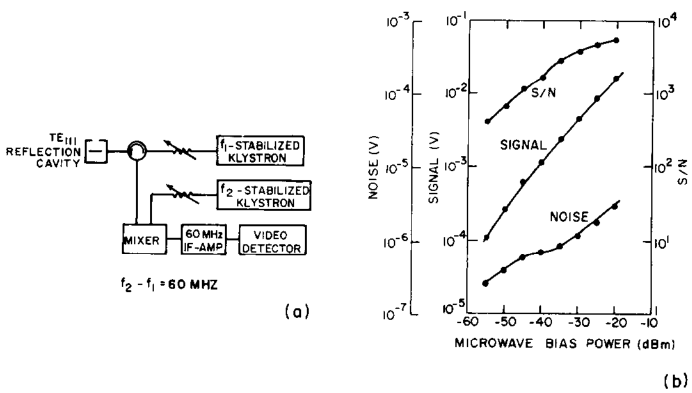


Fig. 5. Heterodyne receiver system. (a) Schematic of the system; (b) performance of the system as a function of microwave bias power.

can be seen from Fig. 5(b). Between −40 and −20 DBM the signal increased at a rate approximately proportional to the square root of the bias power. Above −20 DBM breakdown due to impact ionization began to occur increasing the losses in the GaAs and causing the cavity to become undercoupled. The response decreased and the noise increased sharply.

The noise increased at a slower rate than the signal, producing a maximum S/N at a bias power of −20 DBM. The sources of noise include: (a) amplitude and frequency fluctuations of the bias klystron; (b) circulator leakage; and (c) inability to obtain perfect critical coupling of the cavity.

The microwave biased GaAs detector using a heterodyne receiver had a noise-equivalent-power of $3{\cdot}2 \times 10^{-10}$ W/Hz$^{1/2}$, a responsivity of $3{\cdot}0 \times 10^4$ V/W, and a bandwidth limit of 2·9 MHz. The bandwidth limitation was due to the bandwidth limit of the mixer and not due to the GaAs or the cavity.

## D.C. BIASED DETECTION

For the purpose of comparison, a d.c. biased GaAs detection system was constructed. The detector element was identical in material properties to the one used in the microwave biased systems, i.e. both devices were cut from the same wafer. The detector was 1 cm long, 0·73 cm wide, and had an epitaxial layer thickness of 100 $\mu$m. Wire leads were soldered to evaporated Au–Ge–Ni contacts on the top of the epitaxial layer.

An equivalent circuit is shown in Fig. 6(a). $R_D$ represents the detector element. $C$ represents the capacitance of the leads connecting the detector element to the outside of the cryostat. $R_L$ represents a room temperature load resistor.

Illumination of the detector element with submillimeter radiation produced a change, $\Delta R_D$, in the detector resistance causing a change in the bias current. This change in bias current was measured by monitoring the change in voltage, $\Delta V_L$, across the load resistor. With a small signal approximation, the $\Delta V_L$ due to a $\Delta R_D$ is given by

$$\Delta V_L = \frac{\partial V_L}{\partial R_D} \Delta R_D \tag{6}$$

$$\Delta V_L = \frac{V_B R_L}{(R_D + R_L)^2} \frac{1}{(1 + \omega^2 C^2 R^2)^{1/2}} \tag{7}$$

where $R = R_L R_D/(R_L + R_D)$. The maximum $\Delta V_L$ for a given $\Delta R_D$ occurs for $R_L = R_D$. The bandwidth of this system was limited by the capacitive shunting to

$$\Delta f = \frac{1}{2\pi RC} \tag{8}$$

Experimental curves showing the effect of bias current on the performance of this detection system are shown in Fig. 6(b). The signal increased linearly with bias current

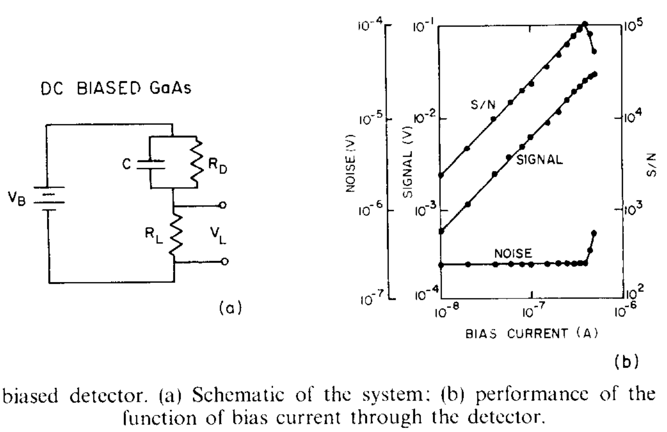


Fig. 6. d.c. biased detector. (a) Schematic of the system; (b) performance of the system as a function of bias current through the detector.

until breakdown due to impact ionization began to occur at a bias current of $4 \times 10^{-7}$ A, or a bias field of 7·5 V/cm. The noise remained constant with bias current since it was mainly determined by the Johnson noise of the room temperature 1 MΩ load resistor. For bias currents above $4 \times 10^{-7}$ A, the noise increased sharply because of breakdown. A maximum S/N occurred at a bias current of $4 \times 10^{-7}$ A.

This d.c. biased GaAs detection system had a noise-equivalent-power of $2 \times 10^{-12}$ W/Hz$^{1/2}$, a responsivity of $5{\cdot}9 \times 10^{4}$ V/W, and a bandwidth limit of 630 Hz. The bandwidth limit was due to the shunting of the high impedance detector and load resistor by the lead capacitance. The chopping frequency was 200 Hz, with a post-detection equivalent noise bandwidth of 6·3 Hz.

## BANDWIDTH LIMITATION

The fundamental bandwidth limitation of the microwave biased GaAs detection system was the bandwidth of the loaded reflection cavity. Of the three microwave systems tested, only the one using the homodyne receiver reached the cavity limit. The square-law and heterodyne systems were limited by the receiver bandwidths.

The reflection cavity full-width, half-maximum (*FWHM*) bandwidth was verified by three different methods: (a) dynamic, (b) decrement, and (c) Ge modulator. The dynamic method consisted of monitoring the reflected power from the cavity while sweeping the microwave frequency through the cavity resonance. The *FWHM* bandwidth was measured to be 10·75 MHz.

The decrement method consisted of applying a microwave pulse to the reflection cavity and monitoring the reflected voltage with the homodyne receiver. The decay time of the reflected voltage was a measure of the time required for the fields in the cavity to decay from steady state. The time required for the reflected voltage to drop to $(1 - 1/e)$ of its initial value was $30 \times 10^{-9}$ sec. The corresponding *FWHM* bandwidth was therefore 10·6 MHz.

The third method utilized a Ge impact ionization modulator[9] to measure the actual rise time of the microwave biased GaAs detection system resulting from very fast changes in the submillimeter radiation intensity. The photograph of Fig. 7 indicates that the time required for the signal to rise to $(1 - 1/e)$ of its final value was $30 \times 10^{-9}$ sec. This corresponds to a *FWHM* bandwidth of 10·6 MHz.

The above three measurements of bandwidth indicate that the bandwidth limitation of this microwave biased detection system was approximately 11 MHz and was limited by the cavity bandwidth, as expressed in equation (1).

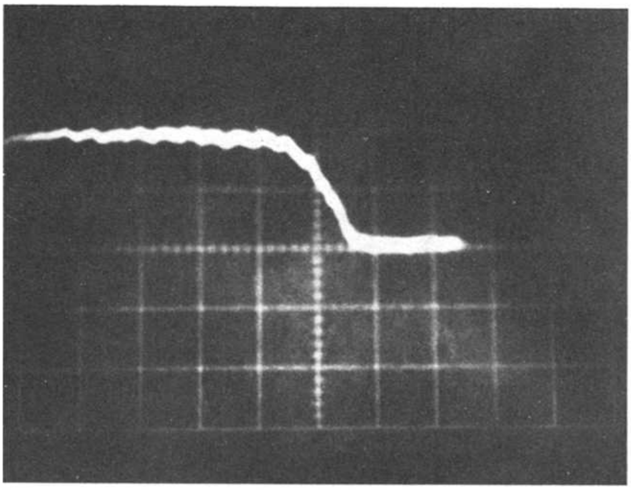

Fig. 7. Time response of the homodyne detector system to a pulsed excitation through a Ge modulator. Vertical scale: 50 mV/div. Horizontal scale: 50 nsec/div.

## CONCLUSIONS

Four different GaAs submillimeter detection systems were constructed and their performances evaluated. Three utilized microwave biasing and the fourth used d.c. biasing. The performance and the optimum operating conditions of a microwave biased detection system depend on the type of microwave receiver employed. With a square-law receiver, maximum signal-to-noise ratio was achieved when the cavity was mismatched to a $VSWR = 2{\cdot}2$. When using a linear detector, either a homodyne receiver or a heterodyne receiver, maximum signal-to-noise ratio was achieved at critical coupling ($VSWR = 1{\cdot}0$).

Table 1.

| | DC BIASED GaAs | MICROWAVE BIASED GaAs | | |
|---|---|---|---|---|
| | | SQUARE-LAW RECEIVER | HOMODYNE RECEIVER | HETERODYNE RECEIVER |
| LENGTH (CM) | 1 | 1 | 1 | 1 |
| WIDTH (CM) | .38 | .19 | .19 | .19 |
| THICKNESS (MICRONS) | 100 | 100 | 100 | 100 |
| RESPONSIVITY (V/W) | $5.9 \times 10^{4}$ | 12.7 | 6.8 | $3.0 \times 10^{3}$ |
| NEP ($W/HZ^{1/2}$) | $2.0 \times 10^{-12}$ | $1.2 \times 10^{-9}$ | $2.5 \times 10^{-9}$ | $3.2 \times 10^{-10}$ |
| BANDWIDTH (HZ) | 630 | $1.2 \times 10^{5}$ | $1.1 \times 10^{7}$ | $2.9 \times 10^{6}$ |

Table 1 lists the dimensions of the detector element, the responsivity, the noise-equivalent-power, and the measured bandwidth limit for each of the four detection systems. Although the d.c. biased GaAs had a noise-equivalent-power which was 160 times less than the most sensitive microwave biased GaAs system, its bandwidth was severely limited to a value almost 5000 times smaller than that of the most sensitive microwave biased system.

In conclusion, the microwave biased GaAs detection system provides a simple means of achieving a wide bandwidth detector. By operating at a higher microwave frequency or redesigning the reflection cavity to have a lower loaded $Q$, the 11 MHz cavity bandwidth could be increased. Thus, using microwave biasing techniques it is possible to construct a fast, sensitive submillimeter detection system which fully utilizes the 30 MHz bandwidth capability of GaAs.

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