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Homodyne and Heterodyne Studies of GaAs and InP Millimeter-Wave GUNN Mixers

F.R. PANTOJA

***Abstract*—Detailed investigations of both homodyne and heterodyne self-oscillating mixers have been conducted. The active devices were GaAs and InP Gunn diodes, operating in the frequency region of 94 GHz. In addition to the fourfold comparisons of GaAs and InP homogyne and heterodyne mixers, finer comparisons were made with recently developed diode structures. The InP diodes were of two types: either n^+-n-n^+ sandwich, or n-n^+ with a current-limiting cathode contact. The GaAs diodes were of n^+-n-n^+ sandwich structure.**

Sensitivity of −80 dBm (homodyne) at a few hundred hertz beat frequency was obtained with InP n^+-n-n^+ diodes. These results were of the order of 6 dB better than those with GaAs n^+-n-n^+ and InP n-n^+ diodes. With heterodyne, the InP n^+-n-n^+ gave sensitivity approaching −90 dBm with intermediate frequency at 70 MHz and an IF bandwidth of 33 MHz, which constituted a superiority of 10 dB over the other two diode types.

I. Introduction

Interest in millimeter-wave self-oscillating mixers has been on the increase in recent years [1]–[5] mainly because of the high burn-out power limit, ruggedness, low cost, and comparatively simple circuitry for signal processing. Moreover, the advent of high-frequency GaAs and InP Gunn diodes has brought considerable innovation to the materials technologies and device structures in order to meet the requirements of efficiency and high powers for millimeter-wave generation using solid-state devices [6], [7].

It is, therefore, the main purpose of this paper to report a comparative study of some of the new device features in homodyne and heterodyne self-oscillating mixers around 94 GHz, since it is to be ascertained whether reasonable performances could be achieved with these recent devices.

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II. Gunn Device Characteristics

The GaAs Gunn diodes were made by the vapor-phase epitaxy (VPE) technique using arsenic trichloride, and consisted of three-layer structures: n^+-n-n^+ with integral heat sink. The active region presented a carrier density of 7×10^{15} to 1.2×10^{16} atoms cm^{-3} with an active distance between 2.0 and 3.0 μm. The total GaAs thickness was 10 to 12μm, and a Ni/Ge/Au metal scheme was used to provide the ohmic contacts, with specific resistance within 1 to $3\times10^{-6}\cdot cm^2$ [6], [9].

Measurements carried out of power and conversion efficiency showed that the devices used in the experiments delivered typically 12 mW at about 1 percent efficiency at 94 GHz.

The InP Gunn diodes were of two types: 1) a two-layer structure of n-n^+ with a current limiting cathode contact, and 2) a three-layer structure of n^+-n-n^+. Both types of InP diodes were also fabricated by the VPE process, using phosphorous trichloride, indium, and hydrogen. They were of the integral heat-sink-type. The active regions had carrier concentration of 6 to 8×10^{15} atoms cm^{-3} with active layer thicknesses from 1.5 to 2.5 μm. The total InP thickness was of the order of 20 μm for the InP n-n^+ devices. Contacts for the InP were of a similar metal scheme to those described for the GaAs diodes [10]. The main difference between the two types of InP devices was the presence of a current-limiting cathode contact which controls the injection of carriers into the active layer. The $I-V$ characteristics of the InP n-n^+ devices do not present the familiar drop-back in bias current above threshold. Actually, the bias current increases with voltage due to self heating of the diodes [11].

Evidence is presently being accumulated to establish the function of nonohmic contacts in improving the efficiency of operation of InP devices at higher frequencies. However, for lower frequencies, it is well established that the use of such types of contacts will limit the device average current density to an optimum value. When optimized, the reverse-bias saturation current density at the cathode is slightly greater than that of the saturated drift velocity region of the device. Although this is a necessary condition to improve efficiency, a sufficient condition is that current density at the cathode varies only slightly with the electric field at the cathode [11]–[17].

Measurements carried out showed that the InP n-n^+ diodes used in the experiments delivered typically 25 mW at about 4-percent efficiency at 94 GHz. The InP n^+-n-n^+ devices yielded output powers of the order of 15 mW with conversion efficiency typically around 1.5 percent. Both GaAs and InP diodes were packaged in pico-pill capsules resisting on round flanges on top of threaded studs.

III. *W*-Band Oscillator–Mixer Hardware Configurations

One of the basic advantages of the self-oscillating mixer is the fact that it does not need a separate local oscillator (LO) and mixer diode. It acts simultaneously as an LO and a mixing element because nonlinearities are always present in such a negative differential resistance oscillator. Therefore, with the Gunn diode serving these two functions, design criteria for efficient cavities operating both as an oscillator and mixer must be devised. The more stringent requirement is the performance of the Gunn device in the oscillator mode, since the parallel behavior of the Gunn diode as a mixer in the same circuit is not greatly influenced by the cavity design. For example, in both homodyne and heterodyne detection, the external Q_{ext} or the loaded Q_L affects the mixing process only slightly [18]–[21].[1] In fact, for each particular type of diode tested to date, an optimum oscillator configuration has corresponded with optimum performance as a self-oscillating mixer.

Two distinct types of oscillator/mixer structures were used in the present work, the choice being dictated completely by the devices used. For the InP devices, working in the fundamental mode of oscillation, coaxial-to-waveguide oscillator structures were used. Detailed investigations of some of the fundamental aspects of this kind of structure are presented in [22]. Typical values for Q_{ext} ranged from 150–250, measured by the frequency-pulling technique. The lower values of Q_{ext} corresponded, normally, to bias voltages close to the threshold values, and were associated with very noisy performance, as expected, thus degrading the operation of the self-oscillating mixers (SOM's) as oscillators. For the GaAs diodes, operating in the harmonic mode, the oscillator/mixer circuit consisted of a reduced-height cavity with cutoff frequency ≈ 26.3 Ghz, coupled to a tapered W-band waveguide and having a step transition in the broad width. The plunger was a "contact-sliding" plunger made of phosphor bronze. Typical values for Q_{ext} ranged from 500–650, and these high values can be explained simply because the oscillator is working in a harmonic-extraction mode and, therefore, it is the power at the second harmonic which is pulling the fundamental frequency of oscillation [22].

IV. Measurements and Analysis

In this section, the measurements procedures, hardware, experimental data, and analysis of the results obtained are presented for homodyne and heterodyne self-oscillating mixer receivers. For convenience, a concise presentation of the experimental results is given, pointing out the main characteristics of performance, and, especially, comparing the behavior of the different devices used. In this paper, the results for typical experimental measurements are presented which were among the best performance results for the large sample of devices and circuits evaluated.[2] Whenever necessary, best performance figures will be given.

Since the ultimate goal is a comparative study, the set of curves presented have been arranged so that the performance of the three types of devices can be easily compared and evaluated on each graph.

V. Homodyne Self-Oscillating Mixer System and Results

The experimental setup for the homodyne experiments is shown in Fig 1. The signal from the SOM was fed, after a waveguide run, into a 20-dB gain standard horn, facing the metallized cone

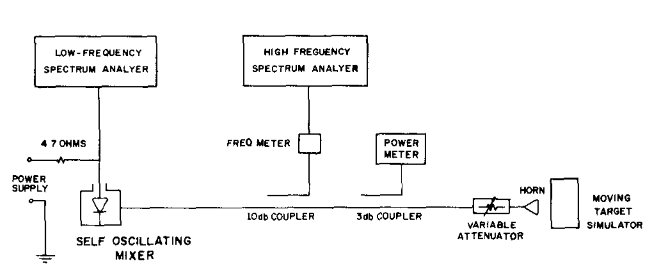

Fig. 1 Experimental setup for the homodyne tests.

of a loudspeaker (moving target simulator). Without any drive current applied to the loudspeaker coil, the overall insertion loss the the system (two-way) was measured. The loss was also measured for several different levels of dc current applied to the coil, yielding a deflection of the cone up to 3 mm from its rest position. The loss measured was identical (within equipment accuracy) to the loss measured with the cone in its rest position. Care was taken to ensure that the vibration of the cone, when the audio signal was applied, was not microphonically transmitted to the circuit under test (self-oscillating mixer) and measuring systems. The dc power supply was connected, as illustrated (with an optimum load of 4.7 Ω), to the Gunn diode inside the cavity.[3] The output from the bias port of the SOM was constantly monitored with a low-frequency spectrum analyzer. A high-frequency spectrum analyzer was used to monitor the millimeter-wave signal spectrum. The output power from the SOM was measured via the 3-dB coupler shown, and facility for measuring power going into the SOM was provided by the "four-port" coupler (10-dB coupler).

The frequency of the audio signal used to drive the loudspeaker was 220 Hz. This low frequency was chosen because it lies well within the "flicker-type" noise of a Gunn oscillator. Therefore, it should provide very reliable data to ascertain the performance and prospects of the homodyne circuit at very low "beat" frequencies such as produced by slow-moving targets.

The measurements were taken through the 1-MΩ input port of the spectrum analyzer, and the beat signal voltage (and noise voltage) can be assumed to be developed across an effective load resistor of 4.7 Ω. Fig. 2 shows the beat output power (4.7-Ω load) against the millimeter-wave return power (reflected from the vibrating loudspeaker). The millimeter-wave signal strength was varied by means of the variable precision attenuator, down to the signal level where the beat signal power was 3 dB above the background noise at 220 Hz (minimum detectable signal). This background noise had been previously recorded and stored at the spectrum analyzer with a very slow time base setting, and with the attenuator setting at 70 dB (140-dB two-way attenuation).

As far as a detection system is concerned, the lowest levels of detection are of primary importance. It is clear from Fig. 2 that the InP (n^+-n-n^+) has (consistently) shown a performance, as homodyne detectors (at beat frequencies of up to 20 KHz[4]), at least 5 dB better than the performance of the other devices. Actually, the best figure for the minimum detectable signal[5] was

[1] In heterodyne detectors, the above-mentioned effect of the Q_{ext} on the performance of self-oscillating mixers, especially for relatively high intermediate frequency, is somewhat more pronounced

[2] This excludes the InP devices type n-n^+. Only three devices were tested, but, in contrast, the variations in performance of these diodes were, indeed, negligible.

[3] This particular value of load was chosen because it seems to be the value that yields the best performance. However, no work was dedicated exclusively to ascertain the actually optimum load value. The reader is, then, referred to [3], [4], [6], [18]–[20] for more information

[4] This higher frequency limit was set because of the "simulator" used.

[5] Minimum detectable signal as defined in the previous paragraph

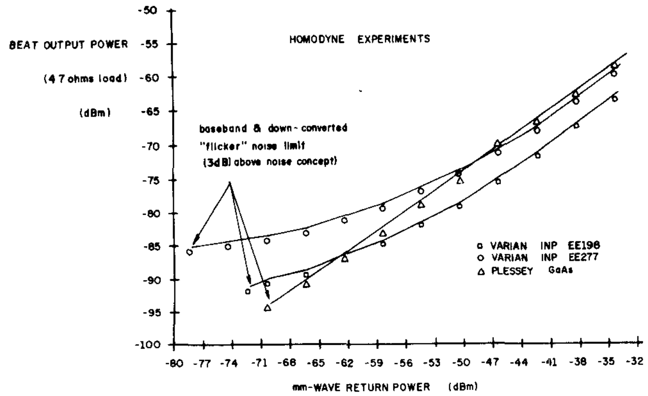

Fig. 2. Beat output power (4.7-Ω load) versus the millimeter-wave return power. (a) Operating frequency ~ 94 GHz. (b) Ratio of operating voltage versus threshold voltage for the devices: b.1) InP n^+-n-n^+ type ~ 2.00:1, b.2) InP n-n^+ type ~ 2.05:1, b.3) GaAs type ~ 1.35:1.

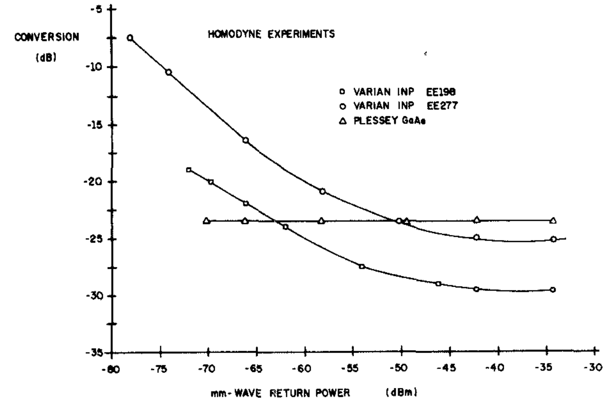

Fig. 4. Conversion versus millimeter-wave return power. Ratio of operating voltage versus threshold voltage for the devices: a.1) InP n^+-n-n^+ type ~ 2.00:1, a.2) InP n-n^+ type ~ 2.05:1, a.3) GaAs type ~ 1.35:1.

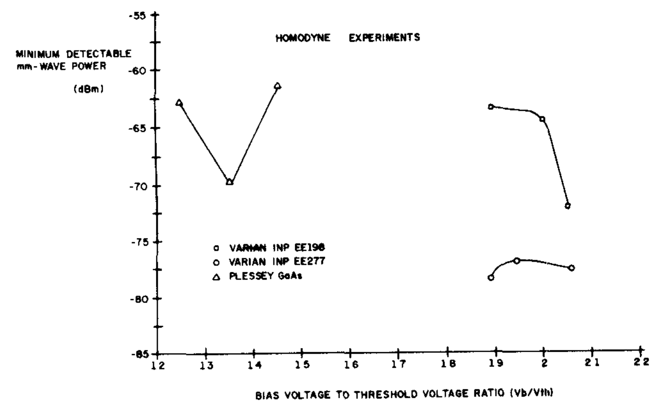

Fig. 3. Minimum detectable signal as function of the bias voltage to threshold voltage ratio. (a) Output powers for the devices: a.1) InP n^+-n-n^+ type ~ 15 mW, a.2) InP n-n^+ type ~ 24 mW, a.3) GaAs type ~ 12 mW. (b) Operating frequency ~ 94 GHz.

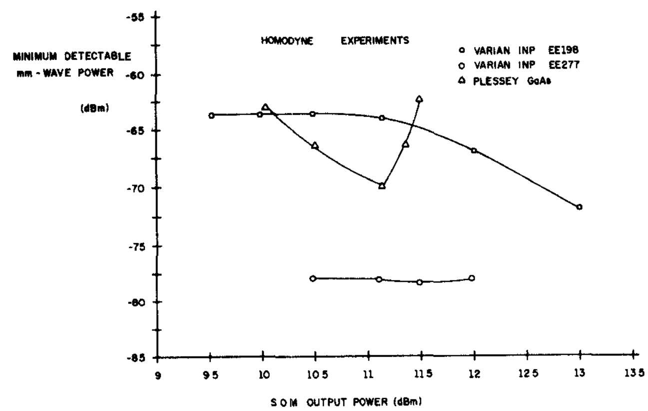

Fig. 5. Minimum detectable signal as function of the self-oscillating mixer output power: Operating frequency ~ 94 Ghz.

achieved with an InP (n^+-n-n^+) device, yielding a detectability down to −83 dBm of millimeter-wave return power and down-conversion loss of 5 dB.

Fig. 3 shows typical measurements of minimum detectable signal as a function of the bias voltage to threshold voltage ratio. The GaAs Gunn diodes presented a much more pronounced dependence on the bias voltage than the InP devices. There was no relationship between "dc to RF conversion" and sensitivity indicated from these measurements.

Down-conversion can be defined for the self-oscillating Gunn mixer as the ratio of the video output power to the received millimeter-wave signal:

$$\text{conversion (dB)} = 10\log\left(\frac{P_{\text{beat}}}{P_{\text{mm-wave}}}\right)$$

with

$$P_{\text{beat}} = \text{beat output power}$$

$$P_{\text{mm-wave}} = \text{mm-wave return power.}$$

In Fig 4, typical measured conversion is plotted against the received millimeter-wave return power for the three types of diodes tested. Theoretical treatment of the behavior of the down-conversion characteristics can be found elsewhere [23].

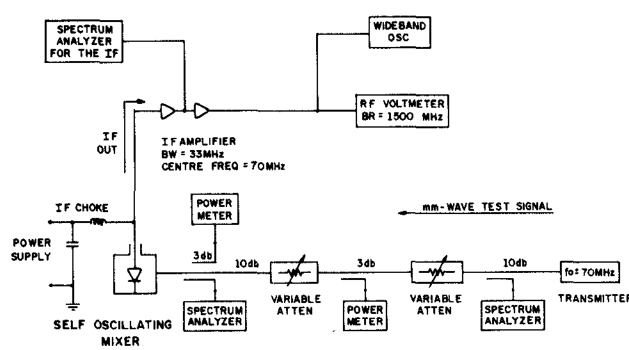

Fig. 6. Experimental setup for the heterodyne tests.

Measured minimum detectable signal as function of the SOM output power is shown in Fig. 5.

VI. Heterodyne Self-Oscillating Mixer System and Results

The experimental test system for the heterodyne experiments is shown in Fig. 6. The millimeter-wave test signal is supplied using a waveguide testline to the self-oscillating mixer receiver. The

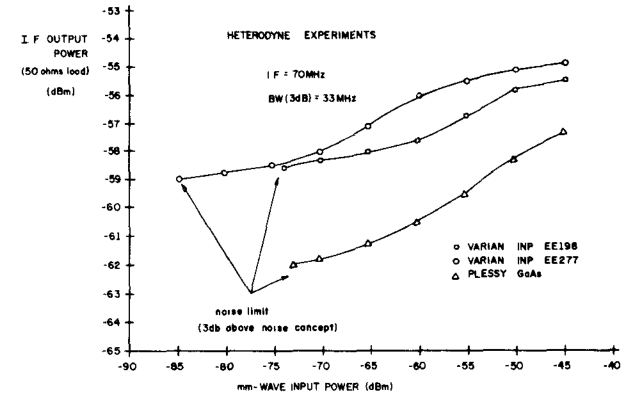

Fig 7. Intermediate frequency signal output power (50-Ω load) versus the millimeter-wave input power Ratio of operating voltage versus threshold voltage for the devices: a 1) InP n^+-n-n^+ type ~ 2.00 : 1, a.2) InP n-n^+ type ~ 2.05 : 1, a.3) GaAs type ~ 1.35 : 1.

transmitter was the same throughout most of the experiments in order to have (nearly) the same signal-to-noise ratio for the test signal at the transmitter port of the test set. The transmitter consisted of a cap-resonator InP Gunn oscillator, where an InP device was specifically chosen because of its low noise and good output power performance. The insertion loss of the waveguide run was measured within a bandwidth of ≃ 800 MHz centered at the self-oscillating mixer free-running frequency, with every attenuator set to the 0-dB reading. The insertion loss measurement showed variation of less than 1 dB with the measuring equipment connected. The transmitter dc bias port was shunted with a 1-μF capacitor to reduce the influence of the mixing products (from the SOM) fed back onto the transmitter.[6] The transmitter frequency was kept, roughly, at 70 MHz above or below the SOM frequency. Both the SOM and the transmitter were thermally stabilized (room temperature) and could be monitored constantly during the experiments.

The intermediate frequency (IF) signal from the self-oscillating mixers was fed to a wide-band pre-amplifier, and then to a band-limiting amplifier with 33-MHz 3-dB bandwidth. After amplification by 70 dB, the IF signal was monitored simultaneously with both the oscilloscope and RF voltmeter thus providing both signal-noise observation together with overall bandpass of ≃ 1500 MHz.[7]

It is worth noticing that no frequency-phase stabilization was applied to the transmitter.

Fig. 7 shows the IF output power (into a 50-Ω load) as a function of the millimeter-wave input power for the three types of devices tested. Clearly seen is the phenomenon of IF compression, i.e., increase in conversion (as defined for the homodyne case) for a decrease in millimeter-wave input power.

The noise limit was established as follows: the IF power was monitored while the input power was decreased, until

$$\frac{P_{IF} + P_N}{P_N} = 2$$

where P_{IF} is the IF output power after the amplifier system and P_N is the output noise power of the amplifier without any millimeter-wave input signal applied. Actually, in Fig. 7 the term "3 dB above noise concept" can be misleading, because in the above definition of minimum detectable signal, the IF signal power is equal to the noise power. However, since the IF power meter reading is, in this situation, 3 dB above the reading of the output power of the amplifier without any millimeter-wave input signal applied, it is justified to use the expression "3 dB above noise."

The sensitivity for the InP (n^+-n-n^+) is of the order of −90 dBm, which constituted a superiority of 10 dB over the other two diode types (minimum detectable signal of the order of −80 dBm). It is interesting to observe that, although the total "baseband" noise power is somewhat less for the GaAs than for the InP (about 5 dB), better sensitivities were achieved with InP devices (a similar situation has appeared in the homodyne tests).

The overall noise figure of the systems tested (including the IF amplifier noise figure of 4.5 dB) can be established by the well-known approximate expression

$$NF(\text{dB}) = P_{MDS}(\text{dBm}) + 174(\text{dBm}) - BW(dB)$$

where P_{MDS} is the minimum detectable signal in dBm, and BW is the bandwidth expressed in dB.

Typical and best figures for the overall noise figure are presented in Fig. 8. The table suggests that the performances of the self-oscillating mixers here reported, although operating at much higher frequencies (94-GHz region) than those in previously reported works (in particular, see [4]) have shown overall noise figures comparable to the lowest noise figures quoted in the literature. In particular, the InP (n^+-n-n^+) devices have shown remarkably low overall noise figures, just a few decibels greater than the NF of balanced mixers.

Typical curves for conversion against the millimeter-wave input power are given in Fig. 9 for the heterodyne mixers. Conversion gains as high as 25 dB were achieved for InP (n^+-n-n^+) devices, in contrast with figures of the order of 10–15 dB for the GaAs and InP (n-n^+) devices.

In Fig. 10, the minimum detectable millimeter-wave powers are plotted as functions of the applied bias voltages. Both the GaAs and InP devices have shown a less pronounced variation of the minimum detectable power with respect to bias voltage as compared with the homodyne test results.

One point regarding the general behavior of the InP devices tested, and, to a lesser degree, the GaAs diodes, is the extreme wide bandwidth capability of operation (i.e., frequency of oscillation) of the devices. The GaAs diodes could work from 60 to 100 GHz without the output power dropping 3 dB down on the manufacture's maximum output power at 94 GHz. After 100 GHz, the output power of the GaAs diodes drops drastically, probably because of the high-frequency "cutoff" limit.[8] However, most of the InP devices could work form 60 GHz to, at least, 130 GHz without reaching power output levels at the fundamental frequency 6 dB down on the manufacture's maximum output power at 94 GHz.

VII. Conclusions

Brief descriptions of the Gunn devices used in the four-fold comparison between InP and GaAs diodes as homodyne and heterodyne detectors have been given. The InP diodes used in the experiments were of two types, namely, the InP sandwich type n^+-n-n^+, and the current limiting cathode InP (n-n^+). The GaAs devices were of the more conventional type n^+-n-n^+.

[6]This step was necessary because of the lack of isolators.

[7]Actually this precision is less than 1500 MHz, since a 500-MHz oscilloscope was connected in parallel with the 1500-MHz RF voltmeter. Nevertheless, the results reported are related to a 33-MHz bandwidth, which is the 70-dB amplifier bandwidth.

[8]We are referring here to the second-harmonic extraction mode of operation.

DIODE TYPE	TYPICAL OVERALL NOISE FIGURE (including 4.5 db noise figure from the IF amplifier)	BEST OVERALL NOISE FIGURE (including 4.5 db noise figure from the IF amplifier)
InP(n^+-n-n^+) EE-277	13.5 db	11.5 db
InP(n-n^+) EE-198	23.5 db	22.5 db
GaAs	25.5 db	22.5 db

Fig. 8. Overall noise figures.

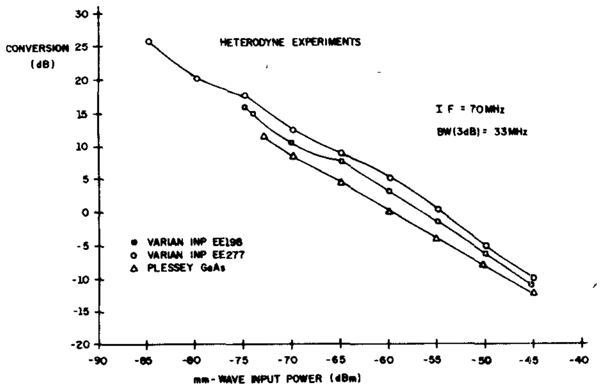

Fig. 9. Conversion versus millimeter-wave input power. Ratio of operating voltage versus threshold voltage for the devices: a.1) InP n^+-n-n^+ type ~ 2.00:1, a.2) InP n-n^+ type ~ 2.05:1, a.3) GaAs type ~ 1.35:1.

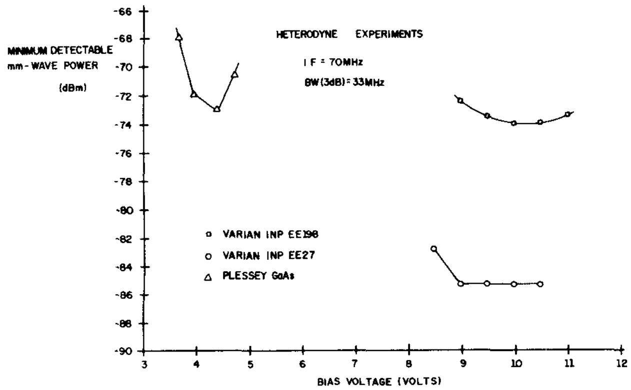

Fig. 10. Minimum detectable millimeter-wave powers as function of the applied bias voltages. (a) Operating frequency ~ 94 GHz. (b) Output powers for the devices: b.1) InP n^+-n-n^+ type ~ 15 mW, b.2) InP n-n^+ type ~ 24 mW, b.3) GaAs type ~ 12 mW.

The measurements were carried out in the 94-GHz frequency region, in order to ascertain that reasonable performance could be achieved with these devices in both homodyne and heterodyne self-oscillating mixer receivers.

For the homodyne self-oscillating mixer receiver, we have particularly chosen a beat frequency well within the flicker-type noise of the oscillator (beat frequency ≃ 220 Hz). Under these circumstances, the results provided can be used to assess the performance of the devices at higher beat frequencies, and therefore, at more realistic doppler shifts.[9]

For the heterodyne self-oscillating mixer receiver, we have achieved noise figures just a few decibels above the noise figure of a well-designed, fixed-tuned GaAs Schottky diode mixer. Improved performance can be expected with the use of frequency-phase stabilization of the receiver.

[9] The reader is referred to [24] for a discussion of the influence of the absolute beat frequency and absolute bandwidth on "close to carrier" Doppler shifts.

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