Theoretical and Experimental Studies of Gain Compression of Millimeter-Wave Self-Oscillating Mixers

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Abstract —A general theory for a heterodyne Gunn self-oscillating mixer is developed to explain the experimentally observed phenomenon of "beat output power compression," i.e., an increase of down conversion gain with a decrease of millimeter injected power. Adler's general differential equation has been used, with some pertinent modifications and proper boundary conditions. This differential equation has been modified to allow the self-oscillating mixer to be frequency modulated. The solution of the new equation has been obtained through a perturbational technique, where the frequency of the self-oscillating mixer is assumed to be outside the locking range of the injected signal. The theory has been based on the fact that, owing to the bias perturbation of the (voltage tunable) self-oscillating mixer, the oscillator is modulated, both in amplitude and in angle. The functional dependence obtained depends, primarily, on the order of magnitude of the "induced" frequency of modulation. This semi-quantitative theory agrees quite well with experiments performed with both InP and GaAs Gunn diodes in the frequency range 75–100 GHz.

I. Introduction

INTEREST IN millimeter-wave self-oscillating mixers (SOM) 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. The self-oscillating mixer has the advantage of large instantaneous bandwidth of operation [6] and the fact that it does not need a separate local oscillator (LO) and mixer diode. It acts simultaneously as a local oscillator and a mixing element.

There are several potential applications, such as short-range radars, secure communications, electronic seekers, etc., especially for those applications where broad bandwidths are required. Moreover, millimeter waves are particularly advantageous if uses in smoke, dust, fog, or other adverse environments are contemplated where infrared would be absorbed and scattered.

In the present article, results from detailed investigations of heterodyne InP and GaAs SOM's are reported. A semi-quantitative theory for the experimentally observed phenomenon of gain compression is also presented. This phenomenon manifests itself through the increase of down-conversion gain with a decrease of millimeter-wave injected power [1], [7]. In other words, the behavior of power in the beat frequency is related to the millimeter-wave received power, and it is shown that the conversion improves with decreasing millimeter-wave received power.

The theoretical analysis is carried out using the basic Adler's equation [8] in which the pertinent assumptions and boundary conditions are introduced. Such conditions and assumptions are going to be discussed in due course. It is important to note, however, that the theory here developed is to be regarded as a semi-quantitative theory concerned with the general pattern of response of self-oscillating mixers.

The Gunn diodes used in the experiments were rated for maximum output powers around 94 GHz, and the tests were carried out in the frequency range 75–100 GHz. The InP diodes were of two types: either a n^+-n-n^+ sandwich, or n-n^+ with a current-limiting cathode contact. The GaAs diodes used were of the n^+-n-n^+ sandwich structure. Some of the experimental results presented for the types of Gunn diodes were carried out at 94 GHz, thus providing means of a comparative study.

II. Theoretical Analysis

A. RF Voltage Across the Gunn Diode

Fig. 1 presents the experimental setup used and is the basis of the subsequent theoretical analysis. In the presence of an externally injected signal, which is sufficiently small to avoid driven-oscillator instability spectra [9], the effect of the beating millimeter-wave signals across the device can be analyzed in terms of an amplitude-modulated voltage signal together with a frequency-modulated voltage signal *owing to the bias perturbation of the (voltage tunable) Gunn self-oscillating mixer (SOM).*

Therefore, disregarding absolute phase differences (e.g., between the modulating signals), the actual RF voltage across the Gunn diode can be written as

$$v = A(1 + m\cos\omega_m t)\sin\left(\omega_0 t + \frac{\Delta\omega}{\omega_m}\sin\omega_m t\right) \qquad (1)$$

where A is the amplitude of the free-running SOM millimeter-wave signal, m is the amplitude modulation index, ω_m is the "induced" modulation frequency,[1] ω_0 is the free-run-

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[1] i.e., fundamental mixing frequency, defined by $\omega_{inj} - \omega_0$-ω_m, where ω_{inj} is the angular frequency of the injected signal and ω_0 is the free-running SOM frequency.

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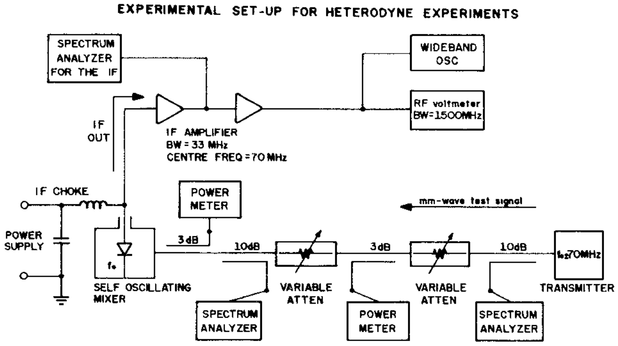

Fig. 1. Experimental test system.

ning SOM frequency, and $\Delta\omega/\omega_m$ is the "induced" modulation frequency index. After a somewhat laborious, but not difficult, algebraic manipulation we can expand (1) in terms of a combination of Bessel functions and trigonometric functions according to [10] and reach an expression which gives the total RF voltage across the device in terms of each frequency component individually, i.e.,

$$\begin{aligned} v = {} & AJ_0\left(\frac{\Delta\omega}{\omega_m}\right)\sin\omega_0 t + \sum_{n=1,2,3,\cdots} AJ_n\left(\frac{\Delta\omega}{\omega_m}\right) \\ & \times\left[1+\frac{mn}{\Delta\omega/\omega_m}\right]\sin(\omega_0 t + n\omega_m t) \\ & + \sum_{n=1,3,5,\cdots} AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[\frac{mn}{\Delta\omega/\omega_m}-1\right]\sin(\omega_0 t - n\omega_m t) \\ & + \sum_{n=2,4,6,\cdots} AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[1-\frac{mn}{\Delta\omega/\omega_m}\right]\sin(\omega_0 t - n\omega_m t) \end{aligned} \tag{2}$$

where the J_k's, $k = 0,1,2,\cdots,n$, are the first-kind Bessel functions of order k and argument $\Delta\omega/\omega_m$.

The right-hand side term of (2) could be put together as

$$\begin{aligned} v = {} & \sum_{n=0,1,2,\cdots} (-1)^n AJ_n\left(\frac{\Delta\omega}{\omega_m}\right) \\ & \cdot\left[1-\frac{mn}{\Delta\omega/\omega_m}\right]\sin(\omega_0 t - n\omega_m t) \\ & + \sum_{n=1,2,\cdots} AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[1+\frac{mn}{\Delta\omega/\omega_m}\right]\sin(\omega_0 t + n\omega_m t). \end{aligned}$$

However, for future use, it is better to preserve (2) as it has been presented previously.

Therefore, (2) represents the instantaneous RF voltage across the Gunn device in terms of each frequency component (provided that the relaxation frequency of the SOM is much higher than ω_m).

B. Derivation of the Intermediate Frequency Output Power

It has been accepted so far (e.g., [11], [12]) that the main nonlinearity in the Gunn diode is its differential negative resistance, and, of course, by the very nature of a nonlinear element, a complete set of terms derived from the mixing between the components (or any other higher order cross-modulation product) are obviously going to be present at the device (SOM) terminals. However, the bias choke of the SOM "prevents" high-frequency radiation leaking out via the bias port and, therefore, only the lower frequency components develop a substantial voltage drop across the load (input impedance of the IF amplifier, in our case). By "substantial" we mean a signal greater than the input noise signal to the amplifier, regardless of the nature of the noise, and a signal which lies within the overall bandwidth of the IF system.

The time varying representation of the IF current is given by [13]

$$i(t) = \sum_n g_n v^n, \qquad n = 0,1,2,\cdots,m \tag{3}$$

where g_n is the nth order conductance. Although a higher order power series can describe more precisely the phenomenon [14], it is sufficient to take the first three terms of the power series given by (3) to achieve a good compromise between simplicity and accuracy for small signal nonlinearity. The first two terms ($n = 0,1$) only yield the average dc term and high-frequency components (even for high values of m). Therefore, it follows that for simple multiplication for smallest signal nonlinearity, the first-order cross-modulation products from (2), which yield frequency components at ω_m, are

$$\begin{aligned} i_{\omega_m} \propto {} & AJ_0\left(\frac{\Delta\omega}{\omega_m}\right)E_1 + AJ_0\left(\frac{\Delta\omega}{\omega_m}\right)W_1 + \sum_{n=1,2,3,\cdots} E_n E_{n+1} \\ & + \sum_{n=1,3,5,\cdots} W_n Z_{n+1} + \sum_{n=2,4,6,\cdots} W_{n+1} Z_n \end{aligned} \tag{4}$$

where

$$E_n = AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[1+\frac{mn}{\Delta\omega/\omega_m}\right], \qquad \text{for } n = 1,2,3,\cdots$$

$$W_n = AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[\frac{mn}{\Delta\omega/\omega_m}-1\right], \qquad \text{for } n = 1,3,5,\cdots$$

$$Z_n = AJ_n\left(\frac{\Delta\omega}{\omega_m}\right)\left[1-\frac{mn}{\Delta\omega/\omega_m}\right], \qquad \text{for } n = 2,4,6,\cdots.$$

Rearranging (4) we have

$$\begin{aligned} i_{\omega_m} \propto {} & A^2 J_0\left(\frac{\Delta\omega}{\omega_m}\right)J_1\left(\frac{\Delta\omega}{\omega_m}\right)\frac{m}{\Delta\omega/\omega_m} \\ & + 2A^2 \sum_{n=1,2,3,\cdots} J_n\left(\frac{\Delta\omega}{\omega_m}\right)J_{n+1}\left(\frac{\Delta\omega}{\omega_m}\right)\left[\frac{m(2n+1)}{\Delta\omega/\omega_m}\right]. \end{aligned} \tag{5}$$

Since

$$\sum_{n=1,2,\cdots} J_n\left(\frac{\Delta\omega}{\omega_m}\right)J_{n+1}\left(\frac{\Delta\omega}{\omega_m}\right)$$

converges very quickly for small arguments $\Delta\omega/\omega_m$, and for simplicity (without losing any essential feature of the process) approximating the Bessel functions by the asymptotical expression for very small arguments [10]

$$J_n\left(\frac{\Delta\omega}{\omega_m}\right) = \frac{\left(\frac{1}{2}\Delta\omega/\omega_m\right)^n}{n!}.$$

Equation (5) is simplified to

$$i_{\omega_m} \approx K_1 m + K_2 m\left(\frac{\Delta\omega}{\omega_m}\right)^2 \quad (6)$$

where K_1 and K_2 are constants.

Therefore, the power at the intermediate frequency ω_m, P_{IF} is

$$P_{IF} \propto \left(i_{\omega_m}\right)^2 \approx K_3 m^2 + K_4 m^2\left(\frac{\Delta\omega}{\omega_m}\right)^2 + K_5 m^2\left(\frac{\Delta\omega}{\omega_m}\right)^4 \quad (7)$$

with the K_n's, $n = 3, 4, 5$, being constants.

Under the small-signal injection analogy (e.g., [15]) we shall now establish the functional dependence of the amplitude modulation index m and the frequency modulation index $\Delta\omega/\omega_m$ with respect to the injected power P_{inj}.

C. Amplitude Modulation Index

For modulation frequencies $f_m > 10$ MHz, the finite time constant of energy storage in the self-oscillating mixer resonator leads to a phase delay of the amplitude modulation, which in turn synthesizes the angle modulation. This synthesis, being essentially a phase shift of the AM sidebands, is adding energy to the carrier (cf., fundamental angle modulation) which satisfies

$$J_0^2(\xi) + 2\sum_{n=1,2,\cdots} J_n^2(\xi) = 1$$

in the Bessel function representation. In other words, the amplitude modulation can be regarded as limited in favor of angle modulation, so that at high-modulation frequencies the effect of the phase delay actually enhances the FM sensitivity [16]. Therefore, it is reasonable to assume that m is a fairly insensitive function of the injected power. The dependence of m with modulation frequency is nearly constant for the modulation frequency range of our concern and it will be neglected.

Hence, we can say that for high-modulation frequencies

$$m = M + \delta(P_{inj}) \approx M \text{ for } P_{inj} > \epsilon_{P_{inj}} \quad (8)$$

where M is a small constant, $\delta(P_{inj})$ is a "zero order" function of the injected power, and $\epsilon_{P_{inj}}$ is a lower limit for injected power such that (8) is still valid.

D. Frequency Modulation Index

Within a fairly wide range of high-modulation frequencies f_m, the peak frequency deviation $\Delta\omega$ can be regarded as independent of f_m, but not independent of P_{inj}. Actually, $\Delta\omega$ is only a strong function of f_m as the modulation frequency approaches the relaxation frequency of RF energy in the self-oscillating mixer, which normally lies around 1 GHz for J-band devices [17]. One would expect the relaxation frequency to increase for higher frequency devices, as has been already reported for Q-band devices [6].

Adler's equation [8] can be extended such as to allow the self-oscillating mixer to be frequency modulated by $\Delta\omega$ by the small injected signal. Under this assumption, we can re-write Adler's equation as

$$\frac{d\phi}{\phi t} = -\frac{(\omega_0 + \Delta\omega \sin\omega_m t)}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}\sin\phi - \Delta\omega_0 \quad (9)$$

where ϕ is the phase difference between injected and outgoing signals, $\Delta\omega_0$ is the free-running frequencies difference, Q_{ext} is the external Q, and ω_0 and P_{out} are the self-oscillating mixer free-running frequency and output power, respectively.

The general form of the differential equation (9) is then

$$\frac{d\phi}{dt} = -A\sin\phi - B\sin(\omega_m t)\sin\phi - C \quad (10)$$

with

$$A = \frac{\omega_0}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}$$

$$B = \frac{\Delta\omega}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}$$

$$C = \Delta\omega_0$$

as compared with Adler's general form differential equation

$$\frac{d\phi}{dt} = -A\sin\phi - C.$$

When in the latter we have

$$\frac{\Delta\omega_0}{\frac{\omega_0}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}} > 1$$

i.e., the injection frequency is outside the locking range, the closed-form solution is given by [8]

$$\tan\frac{\phi}{2} = -\frac{A}{C} - \sqrt{1-\left(\frac{A}{C}\right)^2}\cdot\tan\left[\frac{Ct}{2}\sqrt{1-\left(\frac{A}{C}\right)^2}\right] \quad (11)$$

which shows that ϕ undergoes a periodic variation and does not converge to a constant value. However, for our differential equation (10), the solution is not straightforward, but since

$$\frac{\Delta\omega}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} \ll \frac{\omega_0}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} \qquad \text{(i.e., } B \ll A \text{ in (10))}$$

and

$$\frac{\Delta\omega}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} \ll \Delta\omega_0 \qquad \text{(i.e., } B \ll C \text{ in (10))}$$

we can apply a perturbational technique to solve it.

Therefore, if the solution to Adler's equation is called $\phi_A(t)$, we shall try a solution of the form

$$\phi_T(t) = \phi_A(t) + \phi_p(t) \quad (12)$$

to (10), where $\phi_p(t)$ is just a small perturbation to $\phi_A(t)$. It is necessary, however, that $\phi_p(t)$ as well as $d(\phi_p(t))/dt$ be comparably smaller than $\phi_A(t)$ and $d(\phi_A(t))/dt$, respectively, and that the boundary conditions of interest, i.e., not necessarily every boundary condition, must be verified by $\phi_T(t)$.[2]

Substituting $\phi_T(t)$ into (10) and using the fact that

$$\cos(\phi_p(t)) \approx 1$$

and

$$\sin(\phi_p(t)) \approx \phi_p(t)$$

yields

$$\frac{d}{dt}(\phi_A(t) + \frac{d}{dt}(\phi_p(t)) = -A[\sin(\phi_A(t)) + \phi_p(t)\cos(\phi_A(t))] - B\sin(\omega_m t)[\sin(\phi_A(t)) + \phi_p(t)\cos(\phi_A(t))] - C. \tag{13}$$

Recalling the general form of Adler's differential equation, we can identify

$$\frac{d}{dt}(\phi_A(t)) = -A\sin(\phi_A(t)) - C$$

and, therefore, (13) can be simplified to

$$\frac{d}{dt}(\phi_p(t)) = -A\cos(\phi_A(t))\cdot\phi_p(t) - B\sin(\omega_m t)\sin(\phi_A(t)) - B\sin(\omega_m t)\cos(\phi_A(t))\cdot\phi_p(t).$$

We assume the effect of the perturbation to be very small indeed, such that

$$|\cos(\phi_A(t)\cdot\phi_p(t)[-A - B\sin(\omega_m(t))]| \ll |-B\sin(\omega_m t)\sin(\phi_A(t))|$$

is a valid assumption.

Thus

$$\frac{d}{dt}(\phi_p(t)) \doteqdot -B\sin(\omega_m t)\sin(\phi_A(t)). \tag{14}$$

Since $A \ll C$, from the definitions following (10)

$$\phi_A(t) \doteqdot -Ct \pm 2k\pi, \qquad k = \text{integer}$$

with $-\pi/2 \leqq Ct \pm 2k\pi \leqq \pi/2$ for the principal value.

Substituting the above expression for $\phi_A(t)$ into (14), we have

$$\frac{d}{dt}(\phi_p(t)) \doteqdot -B\sin(\omega_m t)\sin(-Ct)$$

where

$$\pm 2k\pi - \frac{\pi}{2} \leqq 2k - Ct \leqq \pm 2k\pi + \frac{\pi}{2}.$$

As $C = \Delta\omega_0 = \omega_m$, i.e., the beat frequency

$$\phi_p(t) \doteqdot -\frac{B}{2\omega_m}\sin(\omega_m t)\cos(\omega_m t).$$

[2]This ensures the validity of the solution, its "perturbational" nature, and, of course, sets boundaries for validity to the obtained solution $\phi_T(t)$

Therefore, the general approximate solution to (9) is

$$\phi_T(t) = \left[\frac{2\omega_0 t}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} - \omega_m t \pm 2k\pi\right] - \frac{\Delta\omega}{2\omega_m Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}\sin(\omega_m t)\cos(\omega_m t) \tag{15}$$

where use has been made of the fact that $A \ll C$, and the binomial expansion has been applied to the argument of the tangent function appearing in $\phi_A(t)$.

The right-hand term outside the brackets in (15) is the phase difference due to the induced frequency modulation of the self-oscillating mixer. It is worth noticing that the mean phase difference $\langle\phi_p(t)\rangle$ added to the total phase difference is zero over one period of the induced frequency of modulation. This is what one would expect, since the nature of the modulation effect was considered to be symmetrical about the "carrier" ω_0, and, consequently, should have a zero mean value over one modulation cycle.

The frequency difference $F(t)$ is the derivative of the total phase difference $\phi_T(t)$. Therefore

$$F(t) = \frac{d}{dt}(\phi_T(t)) = \frac{2\omega_0}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} - \Delta\omega_0 - \frac{\Delta\omega}{2Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}\cos(2\omega_m t). \tag{16}$$

From the above expression, we can see that the second right-hand term is a constant, independent of P_{inj}. Since we are seeking a relationship between $\Delta\omega$ and P_{inj}, this term is of no consequence to us.

The (maximum) peak frequency deviation can be defined from (16) as

$$\Delta\omega = \frac{2\omega_0}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} + \frac{\Delta\omega}{2Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}$$

which can be re-arranged into a more suitable form, i.e.,

$$\frac{\Delta\omega}{\omega_m} = \frac{\dfrac{2\omega_0}{\omega_m Q_{ext}}\sqrt{\dfrac{P_{inj}}{P_{out}}}}{1 - \dfrac{1}{2Q_{ext}}\sqrt{\dfrac{P_{inj}}{P_{out}}}}$$

where $\Delta\omega/\omega_m$ is, then, the index of frequency modulation.

For a low level of injected power P_{inj}

$$\frac{1}{2Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} \ll 1$$

and we can apply the binomial expansion to the denominator of the expression for $\Delta\omega/\omega_m$, yielding

$$\frac{\Delta\omega}{\omega_m} \doteqdot \frac{2\omega_0}{\omega_m Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}} + \frac{\omega_0}{\omega_m Q_{ext}^2}\frac{P_{inj}}{P_{out}}. \tag{17}$$

For very small values of P_{inj}, i.e., in the limiting case $P_{inj} \to \epsilon$, the first term of the above expression is the dominant term. Thus

$$\lim_{P_{inj} \to \epsilon} \frac{\Delta\omega}{\omega_m} \to \frac{2\omega_0}{\omega_m Q_{ext}} \sqrt{\frac{P_{inj}}{P_{out}}} \Bigg|_{P_{inj} = \epsilon}$$

which is exactly the functional behavior if no induced modulation were present. On the other hand, as physically expected, $\Delta\omega/\omega_m \to 0$ as the injected signal power $P_{inj} \to 0$. Another important feature depicted in the above expression is that $\Delta\omega$ shows an approximately $1/Q_{ext}$ dependence, which is very similar to the characteristic of a direct bias voltage modulated Gunn diode for high f_m [18]. Equation (17) seems to predict fairly well the behavior of $\Delta\omega$ of a self-oscillating mixer when the injected signal is outside the locking region (as defined by Adler's equation), without losing the essential features of the two free-running interacting oscillators. (A study when the injected signal is in the locking region has already been carried out with similarly good results [19], and will be reported later.)

Therefore, the dependence of the index of amplitude modulation and frequency modulation with respect to P_{inj} are, respectively, given by (8) and (17), namely

$$m \div M$$

$$\frac{\Delta\omega}{\omega_m} \div \mu P_{inj}^{\frac{1}{2}} + \delta P_{inj}^{1 \cdot 0}$$

where M, μ, and δ are constants.

Substituting the above expressions into (7) and neglecting the terms whose orders are higher than two in P_{inj}, it yields the power at the intermediate frequency

$$P_{IF} \div \delta_1 + \delta_2 P^{1 \cdot 0} + \delta_3 P^{1 \cdot 5} + \delta_4 P^{2 \cdot 0} \qquad (18)$$

where the δ_n's are constants and P is the injected power P_{inj}. The above equation is valid only for low-level signals and provided that $P > \epsilon_{P_{inj}}$ where, in practice, $\epsilon_{P_{inj}}$ is roughly of the order of the total baseband noise power within the bandwidth considered.

III. Experimental Results

The setup shown in Fig. 1 was used for the experiments with InP and GaAs SOM's. A detailed analysis of the experimental setup is given in [1].

No special adjustments were made to achieve the best performance from the SOM's, and therefore the data shown represent typical results. Best overall noise figures obtained so far are 11.5 dB for the InP (n^+-n-n^+) diodes as compared with ~ 23 dB for the InP (n-n^+) and GaAs diodes, including the IF amplifier noise figure of 4.5 dB (70-MHz IF, 33-MHz IF bandwidth). Fig. 2 shows a typical graph of conversion versus millimeter-wave injected power. Conversion is defined as

$$\text{Conversion (dB)} = 10 \log \frac{P_{IF}}{P_{inj}}$$

where P_{IF} is the power at the intermediate frequency and P_{inj} is the injected millimeter-wave power. The theoretical

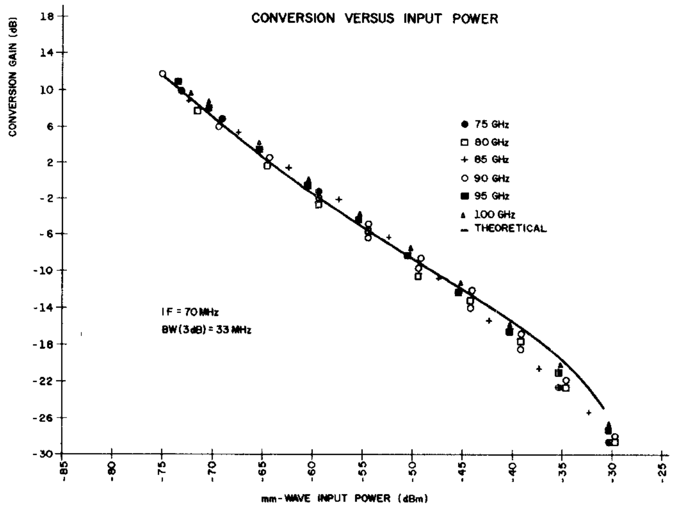

Fig. 2. "Swept" frequency graph of conversion against millimeter-wave input power.

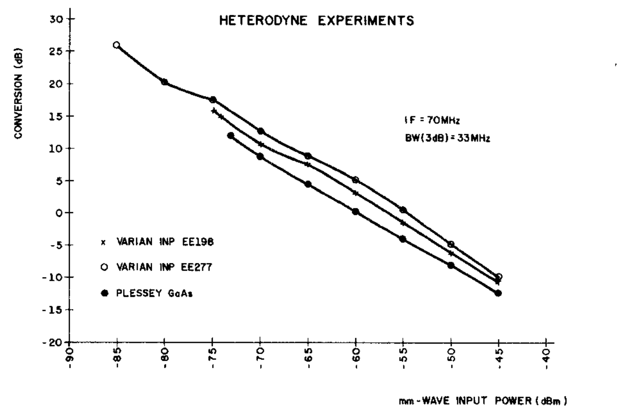

Fig. 3. Graph of conversion against millimeter-wave input power at 94 GHz.

curve was plotted using for P_{IF} the expression given by (18). It is possible to observe that there is no great difference in response (i.e., conversion) in the frequency range 75–100 GHz. The theoretical curve agrees quite well with experimental data.

Fig. 3 shows the conversion versus injected power for the three types of devices tested at 94 GHz, which provides a comparative picture at the 94-GHz window. The theoretical curves are derived from (18). To the authors' knowledge, the data obtained are the best results reported in the literature so far.

IV. Conclusions

A general theory for heterodyne self-oscillating mixers was developed to explain the observed phenomenon of "beat output power compression" (i.e., increase of conversion with decrease of millimeter-wave injected power). This was done using a modified Adler's differential equation with proper boundary conditions. The solution to the new equation was obtained through a perturbational technique, and, basically, all the boundary conditions rely on the fact that the injected signal is outside the locking range of the self-oscillating mixer.

The theory agrees quite well with experimental data acquired with InP (n-n^+), InP (n^+-n-n^+), and GaAs SOM's working from 75 to 100 GHz. Some results have been presented for the 94-GHz window specifically, thus providing a comparative picture of the three types of devices tested. Some of the results obtained can be considered the state-of-the-art for self-oscillating mixers in the millimeter-wave region.

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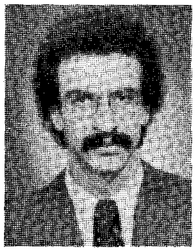

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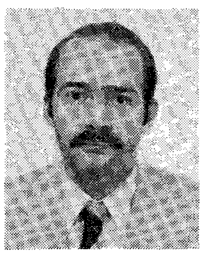

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