(a) (b) (c) (d)

Fig. 6. Photographs of adult *Tenebrio molitor* showing normal adult and damaged specimens. (a) Normal adult. (b) $G1$. (c) $G2$. (d) $G3$. Note the presence of a hole in the elytra.

wave is noted whose maximum value is 20 percent greater than the corresponding intensity in the empty guide. The apparent normalized guided wavelength, with respect to the empty guide, is $\lambda_g'/\lambda_g \approx 0.72$. The maximum intensity is 415 V/m and occurs midway along the pupa.

It should be noted that many of the $G3$ category defects (small holes in the elytra) in the adult beetles were observed in this region. Photographs of adult beetles exhibiting the various defects are shown in Fig. 6. Notice that the material of the elytra in the $G3$ defect is deformed around the hole, indicating that this is a growth defect rather than a mechanical one.

VI. DISCUSSION

We confirm the finding that microwave radiation at the 10-mW level in WR-90 waveguide causes teratological damage in insects. This damage is not due to handling of the insects by the experimenter nor is it induced by a slow increase in the ambient temperature. However, transient heating effects, even at these low microwave power levels, cannot be ruled out.

The experiments do not show the incidence of damage to be dependent on the orientation of the specimen in the electric field or on the microwave power level. This suggests that the levels used exceed that needed to induce the damage. The incidence of damage does depend on the amount of energy absorbed by the pupa and it may depend on its age when irradiated. For this reason the data of Table I have been combined and presented graphically in Fig. 7. The controls have been lumped to form a single group. Similarly, all one-day-old specimens exposed to a total energy of 72 W·s (Section III-A–C, and E) for the second group. The third group comprises those one-day-old specimens exposed to a total energy of 36 W·s (Section III-F). The figure shows the increased incidence of damage due to irradiation and the dependence on absorbed energy. The increase in the number of dead pupae at the 36-W·s level has not been explained.

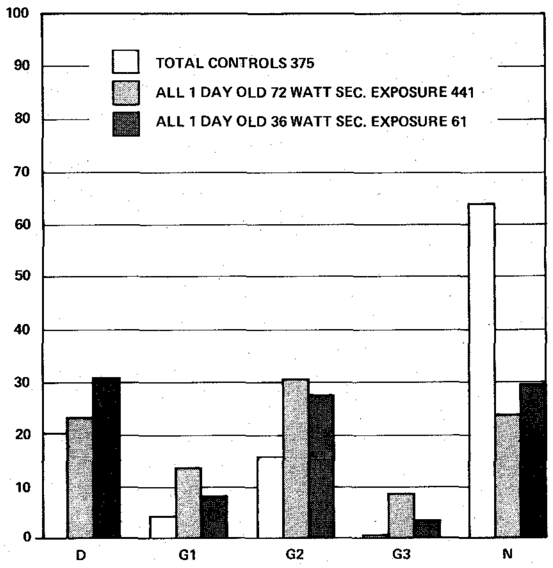

Fig. 7. Effect of 9-GHz radiation in percent of specimens showing given type of damage, compared to the total number exposed.

Experiments conducted to date have not shown the incidence of damage to be dependent on whether the microwave power is pulsed or CW. It must be pointed out, however, that only a small range of pulse repetition frequencies was used in our experiments. Effects with characteristic times shorter than 250-ns pulsewidth or longer than 100-ms repetition period would not have been detected.

ACKNOWLEDGMENT

The authors wish to thank Dr. R. Goldstein of the Department of Psychology, and Dr. W. F. Pickard of the Biomedical Engineering Department, Washington University, St. Louis, Mo.

REFERENCES

[1] R. L. Carpenter and E. L. Livstone, "Evidence for nonthermal effects of microwave radiation: Abnormal development of irradiated insect pupae," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Biological Effects of Microwaves*), vol. MTT-19, pp. 173–178, Feb. 1971.

[2] R. M. Arnold and F. J. Rosenbaum, "Nonreciprocal wave propagation in semiconductor loaded waveguides in the presence of a transverse magnetic field," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 57–65, Jan. 1971.

[3] V. R. Bui and R. R. J. Gagné, "Dielectric losses in an *H*-plane-loaded rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 621–623, Sept. 1972.

[4] F. E. Gardiol and O. Parriaux, "Excess losses in *H*-plane loaded waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 457–461, July 1973.

[5] V. B. Wigglesworth, *Insect Physiology*, 6th ed. New York: Wiley, 1967, p. 112.

[6] L. A. Van Ummerson, "The effect of 2450 Mc radiation on the development of the chick embryo," in *Proc. 4th Tri-Service Conf. Biological Effects of Microwave Radiation*, vol. 1, 1961, pp. 201–219.

[7] ——, "An experimental study of developmental abnormalities induced in the chick embryo by exposure to radio-frequency waves," Ph.D. dissertation, Dep. Biology, Tufts Univ., Medford, Mass., 1963.

[8] B. W. Lindgren, *Statistical Theory*, 2nd ed. New York: Macmillan, 1962.

[9] A. R. von Hippel, *Dielectrics and Waves*. Cambridge, Mass.: M.I.T. Press, 1954, pp. 73–77.

[10] W. R. Tinga and S. O. Nelson, "Dielectric properties of materials for microwave processing—tabulated," *J. Microwave Power*, vol. 8, pp. 23–65, 1973.

Comparison of Diode Noise Under RF and DC Excitations

Y. LIPKIN AND S. MANIV

***Abstract*—Comparison between the low-frequency noise spectra measurements in microwave diodes under RF and dc excitations are reported. The frequency-dependent noise temperature ratio t measured over a range of low frequencies was approximately 3 dB less with RF excitation than with dc excitation, when the dc bias level was identical in the two cases.**

INTRODUCTION

The work described in this short paper was undertaken in an attempt to determine if a useful empirical relationship could be found relating diode flicker ($1/f$) noise under dc and RF excitation. To estimate the flicker noise, we were faced with the need to make use of flicker noise data on available devices under dc excitation only, which is apparently an industry standard.

A search of the literature indicated that the direct comparison of dc-excited and RF-excited flicker noise at low frequencies had not been investigated and very little work at all on flicker noise measurements under RF excitation [1], [2].

The measurement procedure employed was standard [3]. The results obtained indicate that the noise spectra yielded under dc excitation are somewhat more (3 dB) intense than that yielded

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under RF drive, when the dc component of the diode current is kept the same in the two cases.

The measurements were performed at S band and X band, on point contact diodes types 1N21EM and 1N23EM, respectively. Noise power was measured between 150 Hz and 10 kHz. The data obtained for the S-band 1N21EM diode were in all cases similar to that of the X-band 1N23EM diode, hence only the second diode type is considered.

The frequency-dependent noise temperature ratio data were fitted with a $(1/f)$ noise function $t = t_0 + aI^2/f^n$ by means of the least squares technique; the result for the parameters n and a were as expected ($n \simeq 1$ and $a \simeq 130$ dB) [5].

THE EXPERIMENTAL TECHNIQUES

A diode is placed in a diode holder equipped for dc or RF bias, and with provisions for measuring the bias current under both types of excitations (Fig. 1). The diode was followed by a transformer-coupled low-noise audio amplifier and variable bandpass filter. The low-noise amplifier has an input impedance of 1.5 MΩ and a flat frequency response from 50 Hz to 15 kHz.

The noise power at the filter output was measured with a true rms voltmeter. Measurements were made of the output noise power density as a function of frequency under dc and RF excitation, adjusting the RF input power to result in the same dc bias current as with the dc excitation. These measurements were performed at a number of bias levels for several diodes. The noise contributed by the measurement system was determined by measuring the output noise spectra with the diode replaced by resistors of equivalent IF resistance. Additional measurements were made of audio amplifier noise figure, system gain, bandpass filter noise bandwidth for each filter segment used in the measurements, and the diode IF resistance was measured by the small signal method (see Fig. 2). The small signal was of 10-mV rms and 5 kHz. The R_x obtained found to be independent of the signal frequency between 50 Hz to 20 kHz.

The total set of diode and system measurements permitted the determination of diode noise temperature ratio as a function of IF frequency.

To determine if the Gunn oscillator contributed significant noise, measurements were performed with matched diodes in a balanced configuration. It was established that the oscillator noise contributions were insignificant.

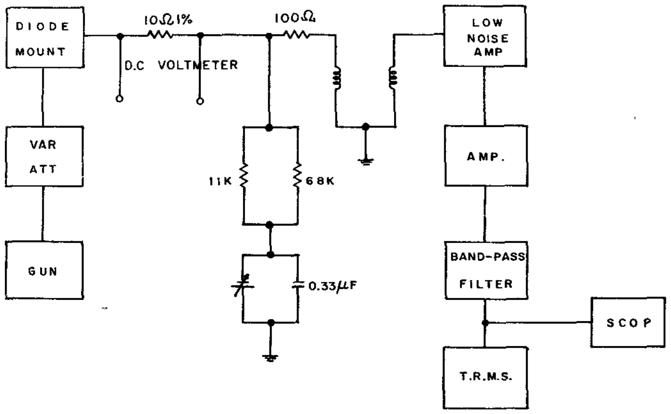

Fig. 1. Noise measurement system.

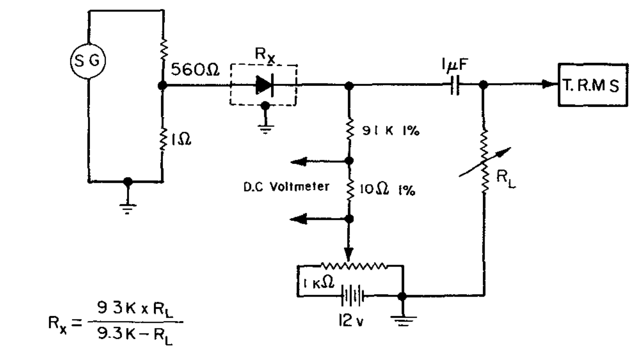

Fig. 2. IF resistance measurement system. (R_L defined as the output resistance corresponding to the maximum output voltage.)

EXPERIMENTS AND RESULTS

The equivalent circuit of the measurement system, from the standpoint of noise is shown in Fig. 3. Here v is the rms IF noise voltage referred to the diode output, v_o is the rms IF noise voltage output of the system, v_{or} is the rms IF noise voltage output of the system when the diode is replaced by a resistance equal to its IF resistance placed in the diode mount. We have two equations for the two cases, with diode and without diode, as follows:

$$4KT_0B\,R_{\mathrm{IF}}(t + F_{\mathrm{IF}} - 1) = \frac{v_o^2}{G_{\mathrm{IF}}} \tag{1}$$

$$4KT_0B\,R_{\mathrm{IF}}(1 + F_{\mathrm{IF}} - 1) = \frac{v_{or}^2}{G_{\mathrm{IF}}}. \tag{2}$$

In the above, K is Boltzmann's constant, B is the noise bandwidth, T_0 is the room temperature, t is the noise temperature ratio of the diode, F_{IF} is the noise figure of the portion of the system following the diode, and G_{IF} is the square of its voltage gain.

v_o and v_{or} can be measured by a true rms voltmeter. It is convenient to divide the squared voltage gain into two components, $G_{\mathrm{IF}} = G_1G_2$, where G_2 is the squared voltage gain of the bandpass filter, and G_1 that of the remainder of the system. We have for the unknown t

$$t = \frac{v_o^2 - v_{or}^2}{4KT_0(BG_2)G_1R_{\mathrm{IF}}} + 1. \tag{3}$$

BG_2 is given by

$$BG_2 = \int_0^\infty |A(f)|^2\,df$$

where the integration is performed over the frequency band of the bandpass filter, and $A(f) = V(f)_{\mathrm{out}}/V(f)_{\mathrm{in}}$. The noise temperature ratio of the diode barrier t_B relates to the measured noise temperature ratio t, $t = (R_Bt_B + R_S)/(R_B + R_S)$ where R_B and R_S are the diode barrier resistance and series spreading resistance, respectively, R_{IF} is the sum of R_B and R_S. The technique employed for measuring these resistance components [3] relies upon the assumption that the barrier forward current is $I = I_0[\exp((qV)/(PKT)) - 1]$ where I_0 is the saturation current extrapolated to zero applied voltage, and P is called the diode "ideality factor," and will normally be 1.5 for silicon point contact diodes [5]. The total IF resistance R_{IF} of the diode is then

$$R_{\mathrm{IF}} = R_S + \frac{PKT}{q}\frac{1}{I + I_0}. \tag{4}$$

The R_{IF} was measured by a small signal method over the frequency range of interest and no significant variation was found. In Fig. 4, R_{IF} is plotted as a function of $(I + I_0)^{-1}$. We found that the R_{IF} versus $(I + I_0)^{-1}$ data fell on a straight line [Fig. 4], and we conclude from this that both P and R_S are constants ($P = 1.5 \pm 0.1$ and $R_S = 45 \pm 10\ \Omega$ for the 1N23EM diodes) within experimental error, over the range of bias currents used for the noise measurements.

The frequency-dependent noise temperature ratio data were fitted with a

$$t_B = t_0 + \frac{A}{f^n} \tag{5}$$

function, by means of the least squares technique. For the cases of $t_B \gg t_0$ we can write $t_B(\mathrm{dB}) = A(\mathrm{dB}) - nf(\mathrm{dB})$ where the dB sign indicates that the parameters concerned are measured in decibel (dB) units ($x(\mathrm{dB}) = 10\log_{10} x$). The parameters n and $A(\mathrm{dB})$ were determined from the above formula by means of the least squares technique. The parameter t_0 is obtained by substitution of these numerical parameters in (5).

The experimental data and the straight line of the best fit are given in Fig. 5 for a typical diode. The errors in n, $A(\mathrm{dB})$, and t_0 were estimated by means of the following [6]:

$$\sigma_n = \left[\frac{12\sigma_T^2}{(\Delta F)^2N}\right]^{1/2} \qquad \sigma_A(\mathrm{dB}) = \left[\frac{4\sigma_T^2}{N}\right]^{1/2}$$

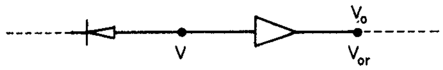

Fig. 3. Equivalent circuit of the measurement system.

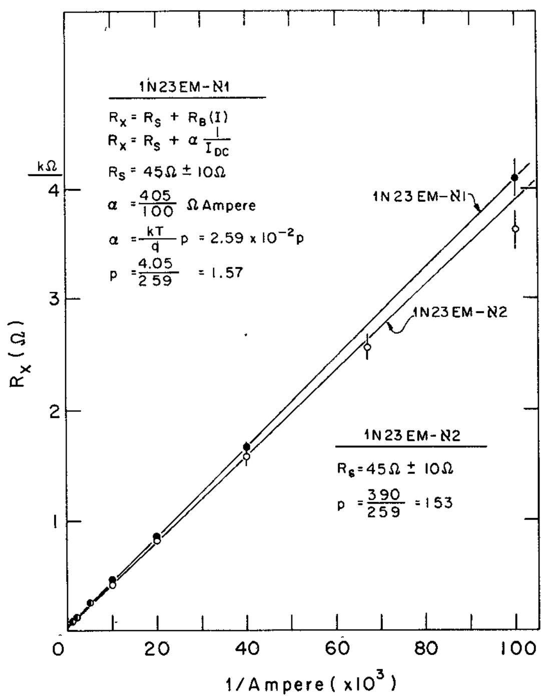

Fig. 4. R_{IF} as a function of $(I + I_0)^{-1}$.

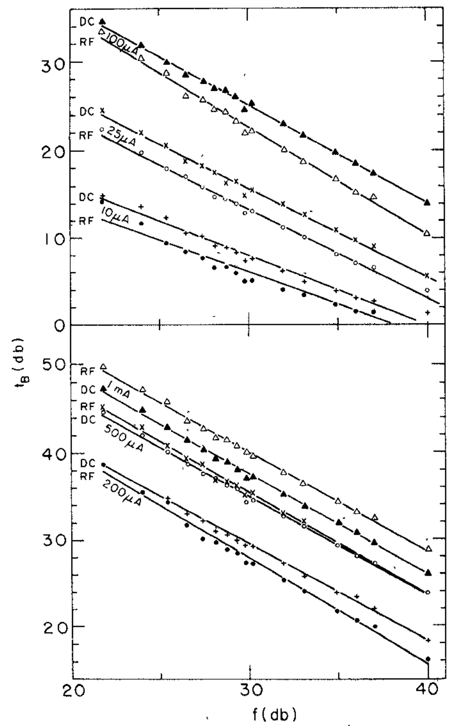

Fig. 5. t_B as a function of frequency (f(dB) = 10 log f).

TABLE I.
THE PARAMETERS n, A, AND a OF A TYPICAL 1N23E DIODE OBTAINED BY THE BEST FITTING OF THE FREQUENCY-DEPENDENCE NOISE TEMPERATURE RATIO t_B TO THE $t_0 + aI^2/f^n$ FUNCTION BY THE BEST FITTING

dc Current	RF Excitation n	RF Excitation σ_n	RF Excitation A(dB)	RF Excitation $\sigma_{A(\text{dB})}$	RF Excitation a(dB)	dc Excitation n	dc Excitation σ_n	dc Excitation A(dB)	dc Excitation $\sigma_{A(\text{dB})}$	dc Excitation a(dB)
10 μA	0.74	0.40	28.3	1.1	128	0.80	0.23	31.9	0.6	132
25 μA	1.02	0.16	43.8	0.4	136	1.02	0.17	46.1	0.4	138
50 μA	1.16	0.24	53.0	0.6	139	1.17	0.15	55.4	0.4	141
100 μA	1.23	0.20	59.5	0.5	140	1.11	0.13	58.2	0.3	138
200 μA	1.22	0.22	64.6	0.6	139	1.12	0.17	63.1	0.4	137
400 μA	1.17	0.16	67.3	0.4	135	1.12	0.17	66.3	0.4	134
500 μA	1.17	0.15	70.5	0.4	137	1.13	0.13	68.9	0.4	135
1 mA	1.14	0.14	74.2	0.4	134	1.15	0.12	72.0	0.3	132

Note: A is the corner frequency $A = aI^2$.

$$\sigma_{t_0} = \frac{\sigma_T}{N^{3/2}} \left[N \sum_{i=1}^{N} t_{Bi}^2 + 4A^2 \sum_{i=1}^{N} \left(\frac{1}{f_i^n} \right)^2 + \frac{12}{(\Delta F)^2} \sum_{i=1}^{N} \left(\frac{A \ln f_i}{f_i^n} \right)^2 \right]^{1/2}$$

$$\sigma_T^2 = \frac{1}{N} \sum_{i=1}^{N} (\Delta T_i(\text{dB}))^2$$

where σ_x is the variance of the random variable x, N is the number of the experimental points on the straight line of $t_B(\text{dB}) = A(\text{dB}) - nf(\text{dB})$, $\Delta F = \ln f_{\max} - \ln f_{\min} = \ln 100$, and $\Delta T_i(\text{dB})$ is the observed deviation of each data point from the best least squares estimate.

The measured values of the parameters n and A agreed with well-known results [5]. The values obtained for the parameter t_0 differ considerably from unity, but are within the range of experimental error from the value unity. Thus the large deviation of t_0 from unity has no physical meaning. Results for a typical diode are shown in Table I. Note that there are no significant differences between the various parameters that are dependent upon the form of the bias. In the case of the parameter t_B, this is not quite the case (see Fig. 5). For t_B, there appears to be a difference of about 3 dB that is dependent upon the form of the bias, t_B being approximately 3 dB greater for dc bias than for RF.

DISCUSSION

The measurements of noise temperature ratio t_B of silicon point contact diodes (1N23E) showed that the value of t_B depends upon the source of the diode bias, whether dc or RF (see Fig. 6). This difference does not depend on other diode parameters.

An attempt of explaining this noise temperature behavior can be done by substituting different values of I in the equation $t_B = t_0 + aI^2/f^n$ for the two following cases. In the first case I is taken equal to the I_{dc} of the dc excitation and in the second case I is taken equal to the constant current component in the expansion of $I = I_0 [\exp(qv/PKT) - 1]$, $V = V_o \cos \omega t$, as a Fourier series. The main problem is the exact mathematical relation between the I

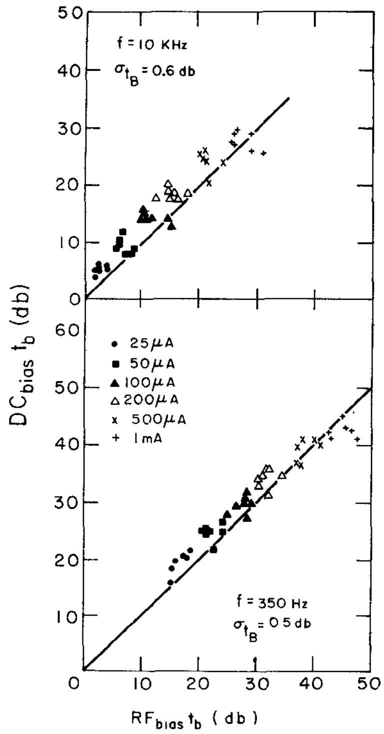

Fig. 6. t_B comparison for RF and dc excitation.

values used in the two cases. This depends critically on the assumed physical model.

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REFERENCES

[1] Y. Anand, "Low-frequency noise in Schottky-barrier diodes," *Proc. IEEE* (Lett.), vol 57, pp. 855–856, May 1969.

[2] G. R. Nicoll, "Noise in silicon microwave diodes," *Proc. Inst. Elec. Eng.*, vol. 101, p. 317, 1954.

[3] A. M. Cowley and R. A. Zettler, "Shot noise in silicon Schottky barrier diodes," *IEEE Trans Electron Devices*, vol. ED-15, pp. 761–769, Oct. 1968.

[4] H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers*, M.I.T. Rad. Lab. Series. New York: McGraw-Hill, 1948, p. 30.

[5] A. M. Cowley and H. O. Sorensen, "Quantitative comparison of solid-state microwave detectors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 588–602, Dec. 1966.

[6] K. R. Johnson, "Optimum, linear, discrete filtering of signals containing a nonrandom component," *IRE Trans. Inform. Theory*, vol. IT-2, pp. 49–55, June 1956.

Influence of the Harmonics on the Power Generated by Waveguide-Tunable Gunn Oscillators

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***Abstract*—It has been observed that in many cases the power generated by waveguide-tunable Gunn oscillators varies irregularly and rapidly with the tuning. These power variations, which are not to be confused with those deriving from mode switching, markedly depend on the components connected to the oscillator, and are present in spite of their good matching in the operating band. Theoretical evaluations and an experimental test have been performed which allows one to ascribe this phenomenon to the interaction between the fundamental and harmonic signals due to the diode nonlinearity. The understanding of this phenomenon allows one to design the oscillator in such a way as to reduce its effects.**

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I. INTRODUCTION

Full-height waveguide-tunable Gunn oscillators, as that shown in Fig. 1, have been widely studied and used in the past few years. In particular, some subjects as tuning features, frequency saturation, mode switching, modulation capability, and noise have been considered in detail [1]–[7].

In this work we put into evidence and discuss some experimental results concerning the output power, which, to our knowledge, have not been reported previously:[1] we observed that, in many cases, the output power goes up and down very rapidly and irregularly when the tuning conditions are varied; furthermore, these power variations strongly depend on the microwave circuit connected to the oscillator. This phenomenon is not to be confused with mode switching, since in our case the frequency varies very regularly and continuously.

We observed such a behavior in many experimental situations where the oscillator was coupled to the load through the usual components, such as a ferrite isolator, a circulator, a filter, a directional coupler, etc. Typical experimental results are given in Fig. 2(a)–(c), which show the output power and the oscillating frequency versus the distance d between the tuning short and the diode. They were obtained in the cases of a waffle-iron HP-X362A harmonic filter, a displacement ferrite isolator, and a flap attenuator with an X-band oscillator using a Mullard CXY11C device, placed on the bottom end of the post, in contact with the waveguide wall. Similar behavior was observed in commercial waveguide X-band oscillators, such as the Varian VSX9001CM.

It is noted that the tuning curve is nearly the same in every case, whereas the power curves differ from each other in the amplitude and the position of fluctuations. The number of fluctuations is very large and two subsequent power maxima take place for very small frequency variations.

It is apparent that this phenomenon, which depends on the circuit connected to the oscillator in a practically unforeseeable way, substantially limits the device performance: in the case of a CW oscillator, for particular circuit and frequency conditions, the output power may be noticeably lower than that available from the device; furthermore, for an electronically frequency-modulated oscillator, an undesirable amplitude modulation can arise.

II. EXPLANATION OF THE PHENOMENON

In all the cases we considered, the circuit dimensions and the very low VSWR of the used components did not permit us to explain the power fluctuations as a long-line effect. The observation that fluctuations are very large in the harmonic filter case [Fig. 2(a)] and nearly absent in the attenuator case [Fig. 2(c)] led us to ascribe the phenomenon to the interaction between the fundamental and harmonic signals due to the diode nonlinearity.

The second-harmonic effect has been studied recently by many authors [8]–[11] with particular emphasis on the possibility of maximizing the efficiency for a fixed-frequency oscillator by properly terminating the diode at the second harmonic [12]. In particular, it has been shown that the power generated at the fundamental frequency strongly depends on the amplitude and phase of the second-harmonic voltage applied to the diode [11]. For a waveguide oscillator the harmonic components of the diode current can excite a number of propagating higher modes besides the fundamental one. These may be reflected by the standard waveguide components,

[1] After the submission of the manuscript we became aware that a study on the behavior of the output power in one of the experimental situations which we consider was carried out by Wu in the thesis work, "Second harmonic characteristics of waveguide cavity CW Gunn oscillators," presented to the Sever Institute of Washington University, St. Louis, Mo., in June 1970.