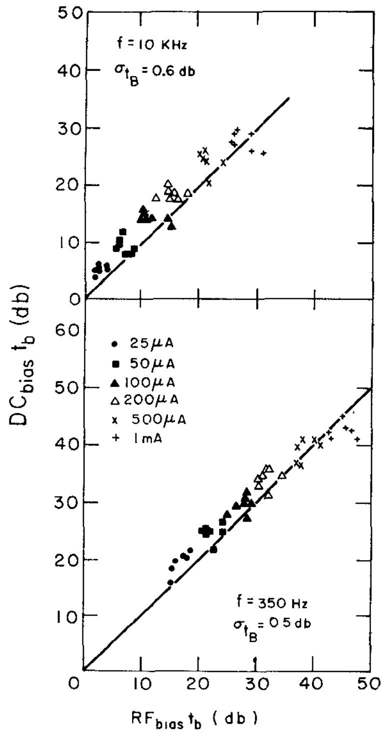

Fig. 6. t_B comparison for RF and dc excitation.

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.

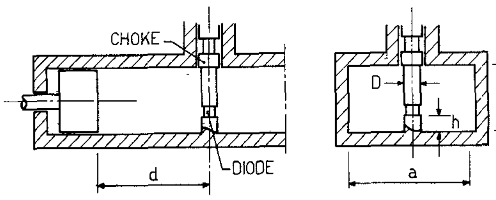

Fig. 1. Post-mounted full-height waveguide-tunable Gunn oscillator.

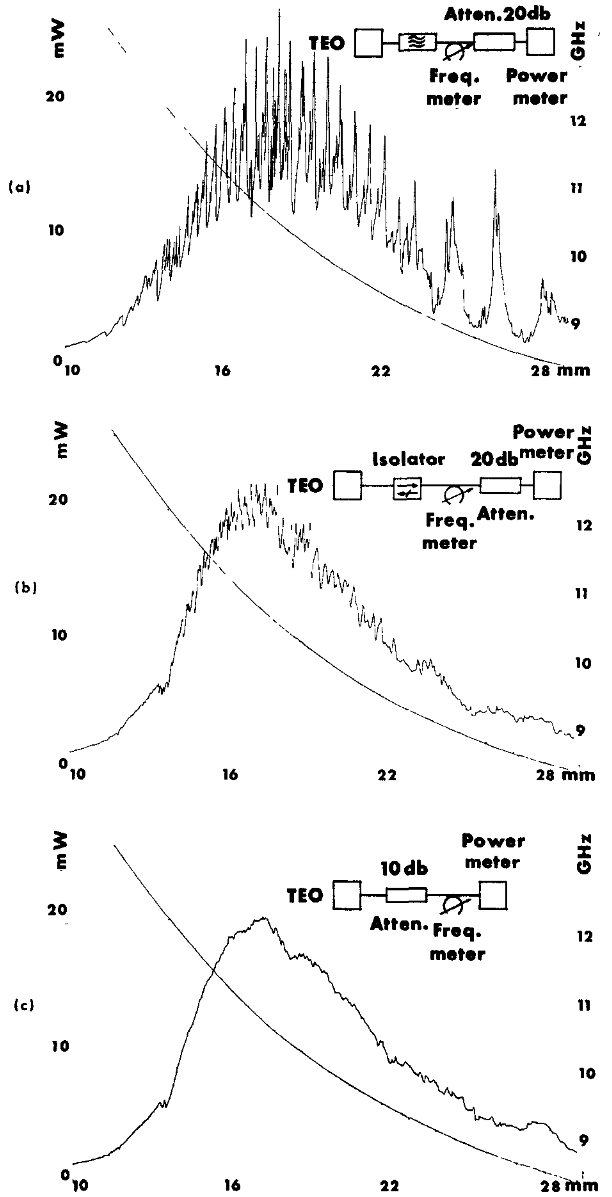

Fig. 2. Power output and oscillating frequency versus tuning-short position for an X-band oscillator, using a CXY11C Mullard device, biased at 8 V. The diode is mounted inside an RG-52 U waveguide, in contact with its wide wall, by means of a 3.2-mm cylindrical post. The three diagrams refer to the circuit condition drawn therein.

which are designed with a view to minimizing their VSWR only in the operating band. Thus resonance phenomena can take place in the volume between the tuning short and the components connected to the oscillator: the larger the number of resonances, the larger the number of the propagating modes and the greater the distance between the short and the reflecting discontinuity. As a consequence, for a given tuning-short position, the impedance seen by the diode in the harmonic frequency range can exhibit a very rapidly varying behavior, with a number of maxima and minima directly dependent on the number of possible resonances. Varying the short position, the distribution of these maxima and minima changes in a rapid and complicated way: thus the set of the impedance values seen by the diode at the harmonics changes, leading to continuous and rapid variations of the amplitudes and phases of the voltage harmonics at the diode. This would determine the observed power fluctuations.

To check the validity of this hypothesis the impedance seen by the diode in the second-harmonic frequency range was evaluated by a computer using the results of the theory developed by Eisenhart and Khan [13]. The geometrical data and the parasitic parameters of the diode package were those of the X-band oscillator described in the Fig. 2 caption. The effect of 150 waveguide modes was taken into account, and the following two extreme ideal load conditions were considered: a) all the modes matched at every frequency (a situation which approximates the attenuator case); and b) all the modes matched in the fundamental frequency range and totally reflected at 8 cm from the diode (reflection coefficient $= -1$) in the second-harmonic frequency range (a situation which approximates the filter case). Furthermore, the post has been considered in short-circuit contact with the guide walls, thus assuming that the choke accomplishes this perfectly at harmonic frequency as well as at the fundamental. In both cases a distance $d = 1.70$ cm between the diode and the tuning short was assumed. The results are plotted in Fig. 3(a) and (b). In Fig. 3(a) the conductance and the susceptance in the fundamental frequency range are given (they are the same for both the a) and b) cases); in Fig. 3(b), which concerns the second-harmonic range, the resistance and the reactance in the a) case and the reactance in the b) case are shown. This last curve indicates that a strong mismatch in the second-harmonic range gives place to a very rapidly varying impedance.

The regularity of the tuning curves in all the experimental situations permits one to infer that harmonics have practically no influence on the oscillating frequency, which, therefore, can be determined by assuming that the diode and the circuit susceptance add to zero. Assuming for simplicity that the diode capacitance C_d is a constant ($C_d \cong 0.2$ pF for the Mullard CXY11C diode [14]), the oscillating frequency f_{osc} can be determined once the susceptance in the fundamental frequency range is known, and the impedance seen by the diode at the frequency $2f_{osc}$ can be found [see Fig. 3(a) and (b)].

When the tuning conditions are varied the diagrams of Fig. 3(a) and (b) move and deform, so that this impedance changes much more rapidly in the b) case than in the a) case. The full-line diagram in Fig. 3(c), shows $X(2f_{osc})$ as a function of d, calculated for tuning-short positions lying in a 1-mm range. $X(2f_{osc})$ diverges two times although the variation of d is very small: this confirms that when strong reflections occur in the second-harmonic range the second-harmonic impedance varies with a rapidity that is comparable to that observed in the output power fluctuations.

To obtain an experimental check of the influence of the harmonics we connected the oscillator to the load through a hybrid T with the E and H arms connected to sliding shorts. The sliding short connected

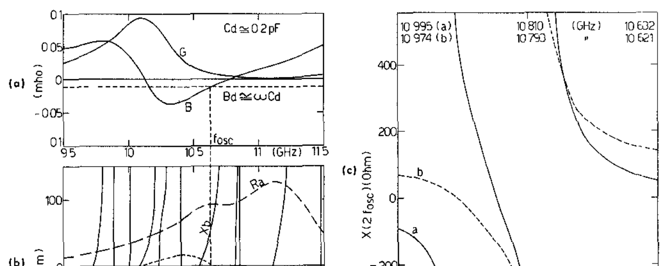

Fig. 3. (a) Conductance and reactance seen by the diode versus frequency in the fundamental band for $d = 1.70$ cm. (b) *Broken line:* resistance and reactance seen by the diode in the second-harmonic frequency range for the same value of d in the hypothesis of perfect matching for all modes; *full line:* reactance in the hypothesis of metallic reflection at 8 cm from the diode, in the same frequency range, and for the same value of d. (c) *Full line:* reactance seen by the diode at the second harmonic as a function of short position, in the case of total reflection of all the modes at the second harmonic. *Broken line:* the same, for the case of a centered diode.

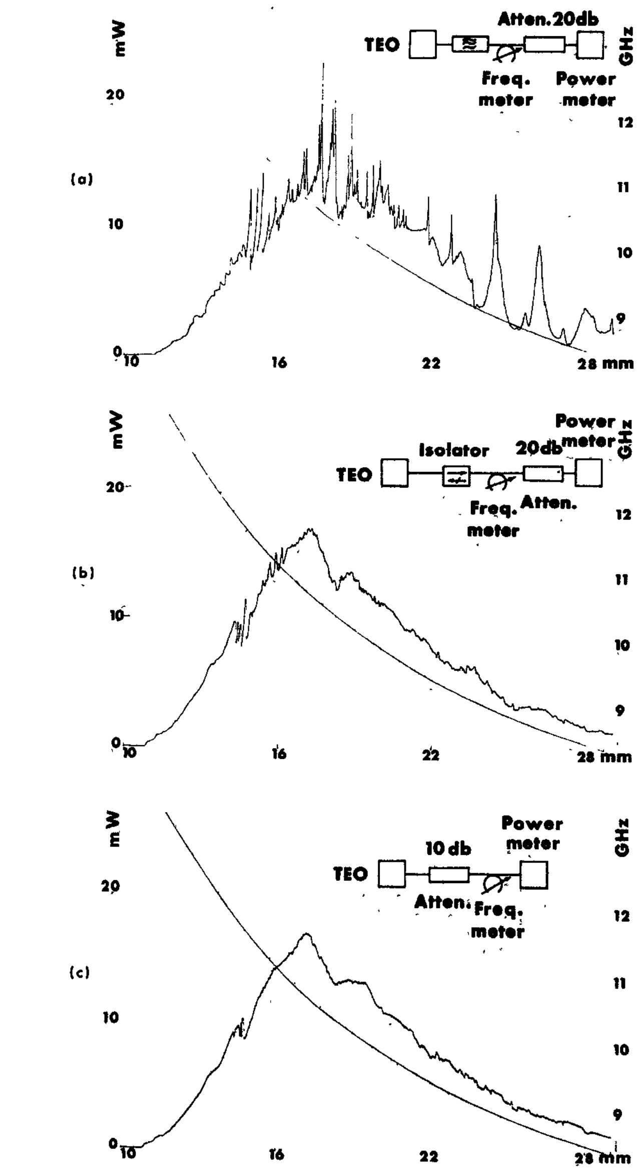

Fig. 4. Diagrams similar to those of Fig. 2, obtained with a centered-diode oscillator. Diode, bias voltage, waveguide, and post diameter are given in Fig. 2 caption.

to the E arm was 90° rotated with respect to its normal position, in such a way that a TE_{10} wave coming from the E arm could not enter the "short" waveguide: thus, moving the plunger could affect only the impedance seen by the diode at the harmonics, but not that at the fundamental. The H-plane short (normally connected) was used to approximately match the oscillator load in the whole X band and its position was fixed.

Power records similar to those shown in Fig. 2 (not reported for conciseness), were obtained for different positions of the rotated short: their average shape was the same, but the amplitude and the position of the power fluctuations changed. For a fixed position of the tuning short, the oscillating frequency was nearly independent of the position of the rotated short (0.01-percent maximum variation): this confirms that its value is practically determined by the susceptance seen by the diode at the fundamental. Furthermore, the output power varied nearly periodically with the position of the rotated short: since the periodicity was $\lambda g/2$ for the TE_{01} mode at the second harmonic, it is possible to infer that the effect of the second harmonic was much more important than the effect of the other harmonics.

Substituting the rotated short with a rotated matched termination the power fluctuation nearly disappeared: this proves that the amplitude of the observed fluctuation depends on the Q factor of the resonance modes excited by the harmonics.

III. INFLUENCE OF THE DIODE POSITION

The excitation of the waveguide modes depends on the diode position, which therefore influences the power fluctuation phenomenon. Off-axis mounting posts should be avoided in order not to excite the TE_{20} mode, which can propagate at the second harmonic. A simple way to reduce the number of excited modes is to mount the diode on a post centered midway between the wide waveguide walls, a disposition which prevents TE_{11} and TM_{11} modes from being excited. Impedance calculations performed under the hypothesis of total reflection for all the modes at the second harmonic show that $X(2f_{osc})$ exhibit a lower number of resonances with respect to the case previously considered [see broken line in Fig. 3(c)]. Experimental results in this case are shown in Fig. 4 (a)–(c). In the filter case it is noted that the number of fluctuations is reduced in comparison with the case of Fig. 2(a). The residual fluctuations are explained as an effect of the resonances due to TE_{10} and TE_{30} modes, which are totally reflected by the filter.

It is interesting to note that in the isolator case [Fig. 4(b)] the fluctuations nearly disappear and the power curve nearly coincides with that of Fig. 4(c) (attenuator case). Further experiments, regarding other components connected to the oscillator, give similar results. This result is ascribed to the fact that the physical constitution of many usual components is such as to not reflect, too much, the TE_{10} and TE_{30} modes at the second harmonic.

IV. CONCLUSIONS

From the previous discussion it is possible to infer that two ways are available to reduce the amplitude and the number of power fluctuations: namely, a) to reduce the number of the propagating modes at the second harmonic; and b) to lower the Q factor of the possible harmonic resonances by suitably designing the oscillator cavity. Anyway, a simple method to minimize the harmonic effect for most practical situations consists simply of mounting the diode at the waveguide center.

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REFERENCES

[1] S. J. Fray and B. C. Taylor, "Frequency-tuning characteristics of waveguide mounted transferred electron oscillators," *Electron. Lett.*, vol. 6, pp. 708–710, Oct. 1970.

[2] W.-C. Tsai, F. J. Rosenbaum, and L. A. MacKenzie, "Circuit analysis of waveguide-cavity Gunn-effect oscillator," *IEEE Trans. Microwave Theory Tech. (Special Issue on Microwave Circuit Aspects of Avalanche-Diode and Transferred Electron Devices)*, vol. MTT-18, pp. 808–817, Nov. 1970.

[3] M. J. Howes, "Circuit considerations in the design of wide-band tunable transferred-electron oscillators," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 1060–1067, Dec. 1970.

[4] C. P. Jethwa and R. L. Gunshor, "An analytical equivalent circuit representation for waveguide-mounted Gunn oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 565–572, Sept. 1972.

[5] R. L. Eisenhart and P. J. Khan, "Some tuning characteristics and oscillation conditions of a waveguide-mounted transferred-electron diode oscillator," *IEEE Trans. Electron Devices*, vol. ED-19, pp. 1050–1055, Sept. 1972.

[6] W.-C. Tsai and F. J. Rosenbaum, "Amplitude and frequency modulation of a waveguide cavity CW Gunn oscillator," *IEEE Trans. Microwave Theory Tech. (Special Issue on Microwave Circuit Aspects of Avalanche-Diode and Transferred Electron Devices)*, vol. MTT-18, pp. 877–884, Nov. 1970.

[7] W. P. N. Court *et al.*, "Reduction of frequency modulation noise from Gunn oscillators," *Electron Lett.*, vol. 3, pp. 567–569, Dec. 1967.

[8] J. E. Carrol, "Resonant-circuit operation of Gunn-diodes: A self-pumped parametric oscillator," *Electron. Lett.*, vol. 2, pp. 215–216, 1966.

[9] G. S. Kino and I. Kuru, "High-efficiency operation of a Gunn oscillator in domain mode," *IEEE Trans. Electron Devices*, vol. ED-16, pp. 735–748, Sept. 1969.

[10] W. Frey, "Influence of a second harmonic voltage component on the operation of a Gunn oscillator," in *Proc. Microwave and Optical Generation and Amplification Conf.* (Amsterdam, The Netherlands), 1970.

[11] M. E. Levinshtein, L. S. Puskaroeva, and M. S. Shur, "Influence of the second harmonic of a resonator on the parameters of a Gunn generator for transit and hybrid modes," *Electron. Lett.*, vol. 8, pp. 31–33, Jan. 1972.

[12] J. F. Reynolds, B. E. Berson, and R. E. Enstrom, "Microwave circuits for high-efficiency operation of transferred electron oscillators," *IEEE Trans. Microwave Theory Tech. (Special Issue on Microwave Circuit Aspects of Avalanche-Diode and Transferred Electron Devices)*, vol. MTT-18, pp. 827–834, Nov. 1970.

[13] R. L. Eisenhart and P. J. Khan, "Theoretical and experimental analysis of a waveguide mounting structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 706–719, Aug. 1971.

[14] K. Wilson, "Gunn effect devices and their applications," Mullard Tech. Commun., vol. 10, pp. 286–293, July 1969.