Design and Performance of X-Band Oscillators with GaAs Schottky-Gate Field-Effect Transistors

MINORU MAEDA, MEMBER, IEEE, KATSUHIRO KIMURA, AND HIROSHI KODERA

Abstract—The circuit construction and design of an *X*-band oscillator with a GaAs Schottky-gate FET have been studied. The oscillation characteristics including stability and noise performance have been examined in order to clarify the position of a GaAs FET as a microwave solid-state oscillator device.

The experiments have revealed that 1) the GaAs FET simultaneously possesses the most desirable features of both Gunn and IMPATT oscillators, i.e., low bias voltage operation and fairly high efficiency, and 2) it is situated between Gunn and GaAs IMPATT oscillators with respect to noise properties. The results indicate that the GaAs FET oscillator will soon be joining the family of microwave solid-state oscillators as a promising new member.

I. INTRODUCTION

With recent advances in GaAs material and device technology, it has become possible to realize GaAs Schottky-gate field-effect transistors (GaAs FET's) with noise figures in the order of 3 dB even at 10 GHz [1], [2]. Along with the advent of such low-noise devices, intensive efforts have been devoted to the development of GaAs FET amplifiers and several successful broad-band amplifiers have been reported [3]–[5]. However, only one paper dealing with another application of GaAs FET, i.e., mixer application, has been published so far [6], in spite of the GaAs FET's potential in oscillator and mixer applications.

One of the authors has studied the oscillation characteristics of GaAs FET's and has shown that the GaAs FET possesses some promising features for oscillator application, such as fairly high efficiency, operation at low bias voltage, and so on [7]. Furthermore, the two-dimensional analysis of the GaAs FET has proven that no instability due to the Gunn effect occurs during oscillation [8]. However, there still is a considerable lack of information on the design and behavior of the GaAs FET oscillator.

The purpose of this paper is to present the design procedure and performance of *X*-band GaAs FET oscillators and clarify the position of the GaAs FET as an oscillator device in comparison with other solid-state devices.

II. CHARACTERISTICS OF GaAs FET

The GaAs FET's were fabricated using n-type epitaxial layers. These layers were grown on Cr-doped high-resistivity substrates, with a carrier concentration of 5–8 × 10^{16} cm^{-3} and a thickness of 0.2–0.4 μm. The Schottky-barrier gate was formed by successively evaporating Cr, Mo, and Au. The gate electrode is 1.5 μm in length and 300 μm in width. The source and drain electrodes, chosen so as to make the contact resistance low, are Au–Ge films evaporated and alloyed on an isolated mesa. They are separated from the gate by 1 μm and 2.5 μm, respectively.

The GaAs FET pellet is encapsulated in a ceramic package with a diameter of 1.8 mm, the input capacitance of which is 0.13–0.16 pF. The feedthrough capacitance of the package, about 0.004 pF, is small enough to use at frequencies up to *X* band. Although the details of the fabrication and performance of the device have been discussed elsewhere [9], the device characteristics, including the effect of the package parasitics, can be seen in the polar chart of Fig. 1. Here shown are the *S* parameters of an encapsulated GaAs FET with a saturated drain current of 44 mA and a pinchoff voltage of 3.2 V. The reverse transmission parameter S_{12}, which is known to reduce the stability of the device, is found to be less than 0.05 in the absolute value up to 8 GHz. The value is as small as that of the GaAs FET pellet itself, although the former is slightly higher at frequencies above 8 GHz. Fig. 2 shows the unilateral power gain and stability factor calculated using the

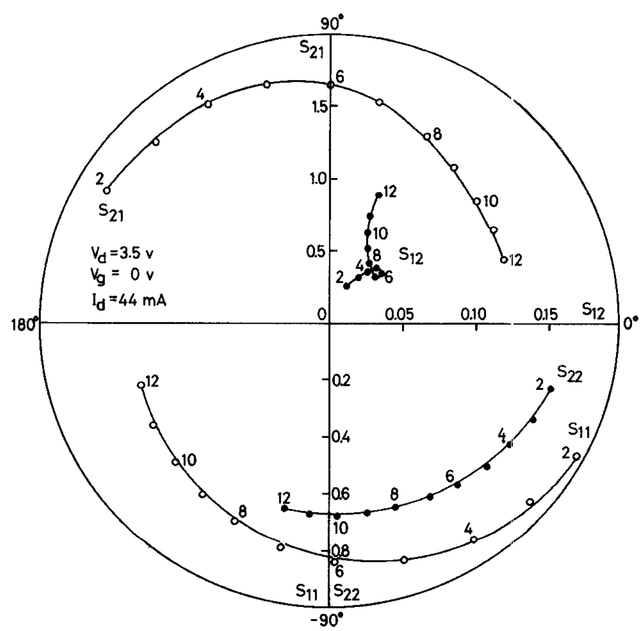

Fig. 1. Small-signal *S* parameters of an encapsulated GaAs FET at the bias condition that yields maximum gain. The saturated drain current I_{ds} and the pinchoff voltage V_p are 44 mA and 3.2 V, respectively.

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The authors are with Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185, Japan.

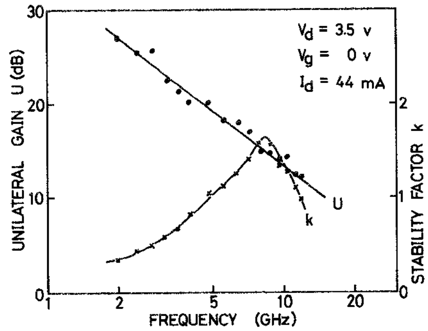

Fig. 2. Unilateral power gain and stability factor calculated using the S parameters of Fig. 1.

S parameters of Fig.1. The unilateral gain drops with a 6-dB/octave slope, and the maximum frequency of oscillation f_{max}, as determined from the extrapolation of the unilateral gain, is 50 GHz. The f_{max} of the samples used in the experiments range from 30 to 50 GHz at the gain maximum bias conditions.

III. CIRCUIT DESIGN OF OSCILLATOR

A. Oscillator Circuit

A microwave transistor oscillator has been constructed by either of two types of equivalent circuits, i.e., circuits with series and parallel feedback elements [10]. Taking into account the package diameter of the GaAs FET, we adopted an oscillator circuit with a feedback element between the source and the ground, as shown in Fig. 3(a). The terminals 1, 2, and 3 correspond to the gate, drain and source, respectively. Shown in Fig. 3(b) is an oscillator circuit with distributed elements. This circuit is proposed here as a practical oscillator circuit realizable with microwave integrated circuit technology.

B. Circuit Design

Although most oscillators operate under large-signal conditions, the large-signal parameters of a GaAs FET have not been clarified so far. Therefore, the small-signal parameters measured by an automatic network analyzer were applied to design of a GaAs FET oscillator. The measured oscillation frequency f_{osc} has been in good agreement with the circuit design, as shown later.

The first step in the design is to determine the optimum combination of reactances X_1 and X_3 at a desired frequency of oscillation. In order for the circuit of Fig. 3(a) to oscillate, the real part of the output impedance Re (Z_{out}), which varies with the combination of X_1 and X_3, should be negative. The optimum combination may be defined as the one that yields maximum absolute value of Re (Z_{out}). This is because the condition will permit oscillation at the largest amplitude; that implies maximum output power. Fig. 4 shows computer-produced contour plots of the real and imaginary parts of Z_{out} calculated using small-signal S parameters. The S parameters were measured at 10 GHz for a GaAs FET with a saturated drain current of 51 mA and an f_{max} of 35 GHz. It can be seen from the

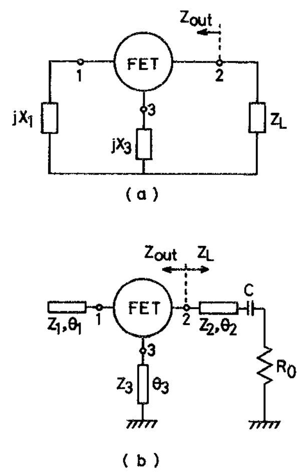

Fig. 3. (a) Simplified equivalent circuit of an FET oscillator. (b) Practical FET oscillator circuit with distributed elements.

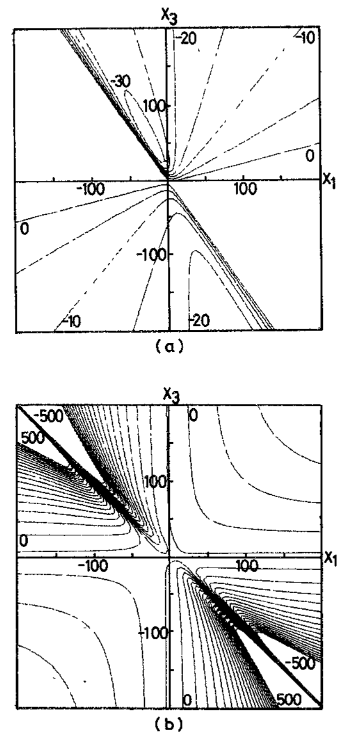

Fig. 4. Computer-produced contour plots of output impedance Z_{out} calculated using measured S parameters at 10 GHz. (a) Contour plot of Re (Z_{out}). The contour lines are drawn at intervals of 5 Ω. (b) Contour plot of Im (Z_{out}). The contour lines are drawn at intervals of 25 Ω.

contour plot of Re (Z_{out}) of Fig. 4(a) that, in the negative regions of Re (Z_{out}), there exist two peak values for the combinations of X_1 and X_3, i.e., one for a negative value of X_3 and another for a positive value of X_3. If the reactance X_3 is positive, it can be realized by a short-circuited line that facilitates the flow of the dc drain current to ground. Therefore, the combination of the negative X_1 and positive X_3 is preferable from the standpoint of the circuit realization. From Fig. 4(a) and (b), the optimum combination and the corresponding output impedance Z_{out} are found as follows:

$$X_1 = -20 \quad X_3 = 44 \quad Z_{out} = -34 - j67.$$

Fig. 5(a) plots the optimum combination of X_1 and X_3 with frequency as a parameter, and Fig. 5(b) shows the corresponding output impedance Z_{out}. It is estimated as the extrapolation of the frequency locus of Fig. 5(b), that the sign of Re (Z_{out}) changes from negative to positive at around 15 GHz. Therefore, an oscillator operated at a frequency up to 15 GHz is realizable with the device and the circuit construction of Fig. 3(a). As a matter of fact, the upper limit of the oscillation frequency can be raised by using a GaAs FET with a higher f_{max}.

The next step is to determine the load impedance Z_L. The imaginary part of the load impedance Im (Z_L) is directly determined by the resonance condition at the desired frequency of oscillation:

$$\text{Im}\,(Z_L) = -\text{Im}\,(Z_{out}). \tag{1}$$

On the other hand, the real part Re (Z_L) is determined by the equation:

$$\text{Re}\,(Z_L) = \tfrac{1}{3}\,|\,\text{Re}\,(Z_{out})\,|. \tag{2}$$

The above condition assures that maximum output power is extracted from the oscillator if the absolute value of Re (Z_{out}) decreases linearly with the amplitude increase of RF drain current [11]. Although the large-signal characteristics of the GaAs FET have never been examined, it is presumed that the absolute value of Re (Z_{out}) decreases monotonically with the RF amplitude increase of drain current. Therefore, (2) gives an approximate condition for maximum output power. Thus, the load impedance, $Z_L = 11 + j67\ \Omega$ for this case, can be determined from (1) and (2). The load impedance is realizable with an arbitrary load resistance R_0, a series capacitance C, and a transmission line which has a characteristic impedance of Z_2 and an electrical length of θ_2, as shown in Fig. 3(b). The series capacitance also acts as a dc block. The element values of the circuit are obtained as follows:

$$Z_1 = 50\ \Omega, \quad \theta_1 = 68^\circ$$

$$Z_2 = 50\ \Omega, \quad \theta_2 = 128^\circ$$

$$Z_3 = 35\ \Omega, \quad \theta_3 = 52^\circ$$

$$R_0 = 50\ \Omega, \quad C = 0.1\ \text{pF}.$$

The design should indicate whether the circuit satisfies the oscillation condition at frequencies other than the desired frequency. Fig. 6 plots Z_t, the sum of Z_{out} and Z_L, of the above example with frequency as a parameter. Since at frequencies other than 10 GHz, Z_t does not satisfy the condition (both Re $(Z_t) < 0$ and Im $(Z_t) = 0$) as shown in Fig. 6, oscillation only at 10 GHz is possible in this circuit.

C. Circuit Construction

The microstrip realization of the oscillator circuit is illustrated in Fig. 7. The circuit is fabricated on an aluminum substrate with a thickness of 0.6 mm. The series capacitance of 0.1 pF is realized by an interdigitated capacitor with a 30-μm gap between the ends of adjacent transmission lines. The drain and gate bias voltages are fed through high-impedance transmission lines, the ends of which are grounded by beam-lead RF bypass capacitors, with an equivalent length of $\lambda_g/4$.

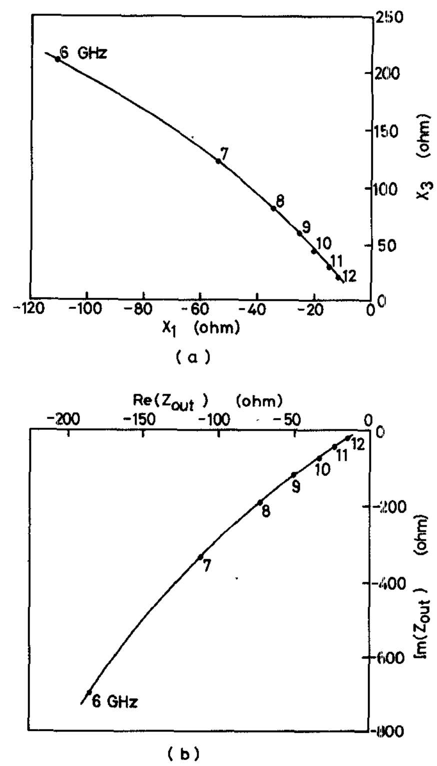

Fig. 5. (a) Optimum combination of reactances X_1 and X_3 that produces a negative peak value of Re (Z_{out}). (b) Frequency locus of the corresponding output impedance Z_{out}.

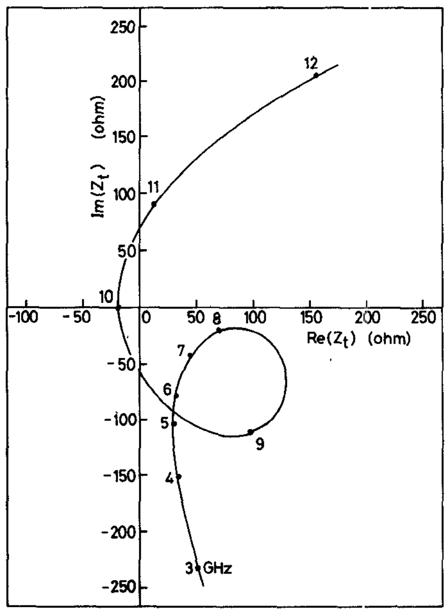

Fig. 6. Frequency locus of $Z_t (= Z_{out} + Z_L)$ of the oscillator shown in Fig. 3(b). Measured S parameters are used to calculate Z_t at each frequency.

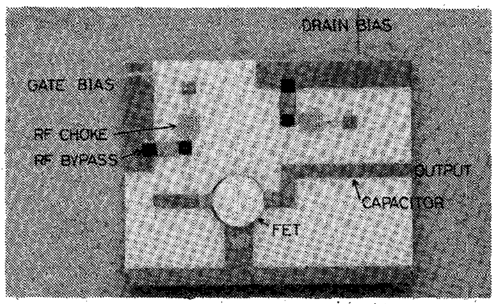

Fig. 7. Photograph of an experimental 10-GHz GaAs FET oscillator realized with microstrip structure.

IV. PERFORMANCE OF *X*-BAND OSCILLATORS

A. Bias Dependance

The experiments were carried out on various samples of GaAs FET with different saturated drain currents. The static transconductances of the samples were in the range from 15 to 23 mmho, and the maximum frequencies of oscillation f_{max} were from 30 to 50 GHz. In these measurements, the oscillator circuits with the same element values were used for all the samples, although the circuit was not necessarily optimized for each sample because of the scattering of the device parameters. Furthermore, no external tuning was applied, and only dc bias voltages were adjusted to study the oscillation characteristics.

Fig. 8(a) and (b) shows typical oscillation characteristics as functions of drain and gate bias voltages, respectively. The saturated drain current and pinchoff voltage of the GaAs FET used are 76 mA and 4.3 V. It is seen from Fig. 8(a) that the oscillation builds up at a drain saturation voltage of 2 V and that the output power increases as the drain bias voltage is raised. Some samples exhibit peak values of output power related to the drain bias voltage. The efficiency also increases with drain bias voltage, but it reaches a peak at around 8 V in this case. Fig. 8(b) shows the gate bias dependence at a fixed drain bias of 8 V. Maximum output power is achieved at a gate bias of -2 V; that corresponds to half the pinchoff voltage. The maximum output power has been obtained at almost the same gate bias condition, i.e., half the pinchoff voltage, for each sample. This condition for the maximum possible oscillation power can be inferred from the fact that the maximum voltage swing from zero to pinchoff voltage is attained at the gate bias voltage. On the other hand, maximum efficiency is achieved by deepening the gate bias voltage by about -1 V compared to that under maximum output operation.

The dependences of oscillation frequency f_{osc} on bias voltages are also shown in Fig. 8. Although the frequency f_{osc} changes with drain bias voltage, its variation is small. On the other hand, f_{osc} rises almost linearly with the deepening of the gate bias voltage. This change is due to the fact that the capacitance of the gate depletion layer varies with gate bias voltage and decreases as gate bias voltage increases. The oscillation frequency in this case is 10.5–10.6 GHz, but has been in the range from 10.0 to 10.6 GHz for other samples used. This is in good agreement with the circuit design.

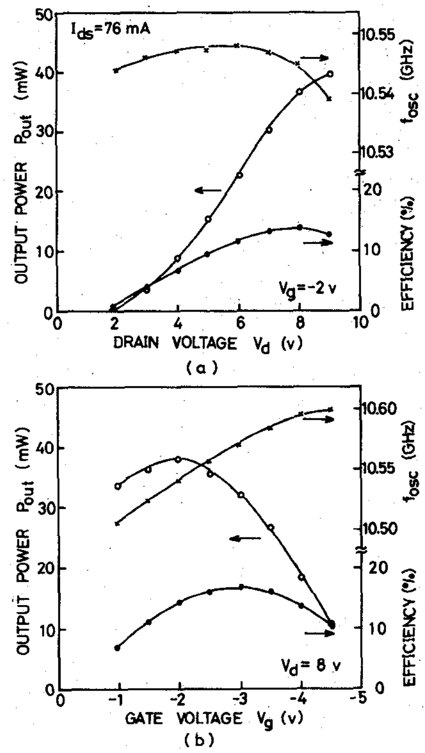

Fig. 8. Bias dependence of a GaAs FET oscillator. The saturated drain current and pinchoff voltage are 76 mA and 4.3 V, respectively. (a) Oscillation characteristics as a function of drain bias voltage at a fixed gate bias voltage that yields maximum output power. (b) Oscillation characteristics as a function of gate bias voltage.

The experiments have also revealed that the maximum output power depends strongly on the saturated drain current among other device parameters and that a higher maximum output power is obtainable using a GaAs FET with a higher saturated drain current. In the preceding example, the maximum output power of 40 mW and the maximum efficiency of 17 percent are obtained using a GaAs FET with a saturated drain current of 76 mA. Although the saturated drain current varies with the device structure such as gate width, channel thickness, and doping density, the gate width primarily determines the saturated drain current without affecting the cutoff frequency of the device. Fig. 9 shows oscillation characteristics of a GaAs FET in a package of which two FET pellets are mounted in parallel. In other words, the GaAs FET is equivalent to one with a gate width of 600 μm. Since the GaAs FET has a saturated drain current of 158 mA, that is twice as large as that of the FET in Fig. 8, and almost the same pinchoff voltage, the maximum output power is expected to be double that of Fig. 8. It can be seen from Fig. 9 that the maximum output power of 79 mW is obtained as predicted above. The maximum efficiency of 16 percent is of the same order as that of Fig. 8. This result implies that the output power can be increased by developing a GaAs FET with a greater gate

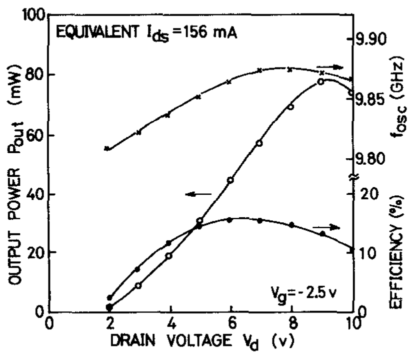

Fig. 9. Oscillation characteristics of an encapsulated GaAs FET in the package of which two FET pellets are mounted in parallel. The equivalent saturated drain current and pinchoff voltage are 156 mA and 4.8 V, respectively.

width and an output power of the order of 1 W at 10 GHz will be attained by a GaAs FET with a gate width of 7500 μm, which is a realizable width [12], [13].

B. Temperature Dependence

Since the temperature stability of an oscillator is one of the primary concerns in the design of communication systems, the dielectric loading technique as well as other stabilizing techniques have been developed to reduce frequency fluctuation induced by changes of ambient temperature [14], [15]. Even if such a stabilizing technique is applied, it is preferable to use a free-running oscillator with a smaller temperature coefficient of oscillation frequency.

In order to examine the stability of a free-running GaAs FET oscillator, the variations in oscillation frequency, output power, and drain bias current were measured with gate bias voltage as a parameter over a temperature range from -20 to $+60$°C. Fig. 10 shows a typical temperature dependence of a free-running GaAs FET oscillator with a saturated drain current of 56 mA and a pinchoff voltage of 4.5 V. The external quality factor Q_{ex} of the oscillator is about 300. In the variation of the oscillation frequency, the effect of the oscillator circuit in addition to the effect of the GaAs FET itself is included. It is evident from Fig. 10(a) that the frequency variation depends on the gate bias voltage and that the temperature slope decreases with the deepening of the gate bias voltage. However, with a deep gate bias voltage the oscillation stops at a high temperature, although the reason for this phenomenon is not yet clear. For example, the oscillator for a gate bias voltage of -3.5 V stops at a temperature of 50°C, as indicated by the mark ↓ in Fig. 8. The best slope obtained is -0.45 MHz/°C for a gate bias voltage of -3.0 V, while the slope for a gate bias of -2.0 V, which satisfies the maximum output condition, is -0.90 MHz/°C. On the other hand, the output power variation due to temperature change is very small at the gate bias condition satisfying the maximum output condition, but it is -0.02 dB/°C at the gate bias voltage that yields the minimum frequency variation slope.

In comparison with other free-running solid-state oscillators, the frequency stability of a free-running GaAs FET

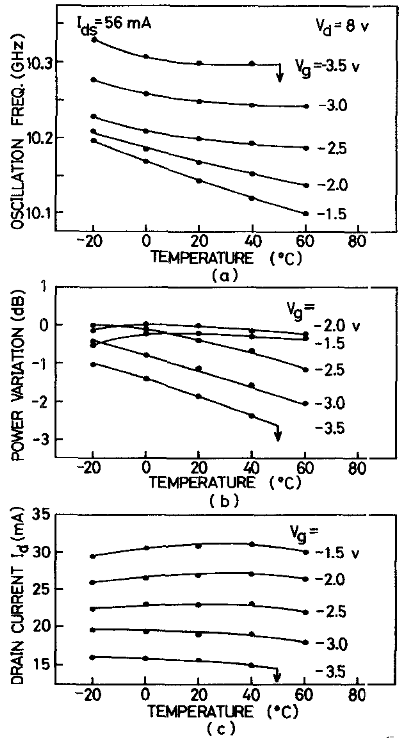

Fig. 10. Temperature stability of a GaAs FET oscillator. The saturated drain current and pinchoff voltage of the FET are 56 mA and 4.5 V, respectively. (a) Oscillation frequency as a function of temperature. (b) Output power as a function of temperature. The 0 dB corresponds to an output power of 23 mW. (c) Drain current.

oscillator is slightly worse than those of GaAs and Si IMPATT oscillators, but of the same order as that of a Gunn oscillator. However, it should be noted that the GaAs FET oscillator used was designed for optimum output power and not for optimum temperature stability.

C. Noise Performance

The noise performance of an oscillator has also become of great interest with respect to system application. Hence, the AM and FM noise spectra of a GaAs FET oscillator were measured and compared with those of other solid-state oscillators. Although many noise measurements have been reported for Gunn and IMPATT oscillators operating at *X* band [16]–[19], the results cannot be directly compared with the noise data measured here because of differences in the noise measuring system and oscillator circuit. Therefore, the noise performance of a Gunn oscillator was also measured using our noise measuring system, which is almost identical to the one reported by Weller [20].

Fig. 11 shows the AM and FM noise of the GaAs FET oscillator which was used in the measurements of temperature stability of Fig. 10, as a function of drain bias voltage. The noise spectra were measured in a 100-Hz bandwidth at 100 kHz off the carrier, and the gate bias voltage was adjusted to give the same oscillation frequency of 10.14 GHz for each drain bias voltage. Also shown in this figure are the corresponding output power

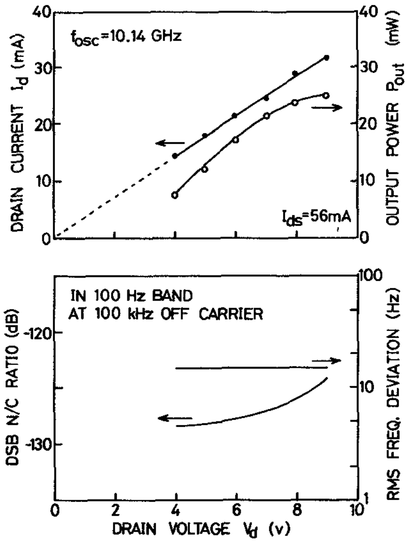

Fig. 11. AM and FM noise of a GaAs FET oscillator as a function of drain bias voltage. The gate bias voltage is adjusted to give the same oscillation frequency for each value of drain voltage. The corresponding output power and drain current are also shown in the top part of the figure. The FET used is the same as that used in Fig. 10.

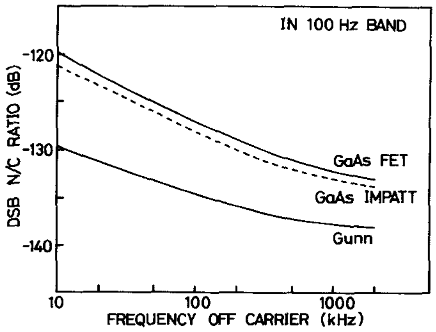

Fig. 12. AM noise of GaAs FET and Gunn oscillators as a function of frequency off the carrier. Also shown, by the dotted curve, is AM noise of GaAs IMPATT oscillator measured by Weller [20].

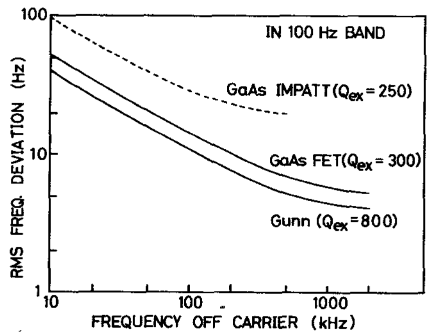

Fig. 13. FM noise of GaAs FET and Gunn oscillators as a function of frequency off the carrier. Also shown, by the dotted curve, is FM noise of GaAs IMPATT oscillator measured by Weller [20].

and drain current. It can be seen from the figure that the AM noise is reduced by decreasing the drain bias voltage, while the FM noise is insensitive to changes in the bias voltage.

Figs. 12 and 13 show AM and FM noise spectra, respectively, for GaAs FET and Gunn oscillators measured as a function of frequency off the carrier. The GaAs FET was biased at a drain voltage of 8 V and a gate voltage of -2 V resulting in an output power of 23 mW. The Gunn diode was biased at a voltage of 7.5 V resulting in an output power of 60 mW. For comparison purposes, the noise spectrum of the GaAs IMPATT oscillator reported by Weller is plotted in both figures, although its oscillation frequency of 30 GHz is different from those of the other two oscillators. From Fig. 12, the AM noise of the GaAs FET oscillator is seen to be higher, e.g., by 8 dB at 100 kHz off the carrier, than that of the Gunn oscillator and comparable to that of the GaAs IMPATT oscillator. On the contrary, the FM noise of the GaAs FET oscillator is lower than that of the Gunn oscillator, taking into account the FM noise dependence on the external quality factor Q_{ex}. This fact can be clarified by computing and comparing the FM noise measures of those oscillators. From Fig. 13, the ratio of the FM noise measure of the GaAs FET oscillator to that of the Gunn oscillator is computed to be about -9 dB at 100 kHz off the carrier. In spite of inaccuracy of the data due to measurement errors as well as insufficiency of data about quantitative differences between the noise spectra of the GaAs FET and Gunn oscillators, these results roughly show that the GaAs FET oscillator is situated between Gunn and GaAs IMPATT oscillators with regard to noise performance. On the other hand, the GaAs FET exhibits much lower noise properties in amplifier operation than other solid-state devices. The gap between noise performance in oscillator and amplifier application should be investigated, although it is presumed to have some relation to large- and small-signal operations.

V. CONCLUSION

GaAs Schottky-gate FET's have so far been developed as low-noise microwave amplifying devices and have been applied exclusively to amplifiers. In this paper, the design and performance of GaAs FET oscillators have been reported, including stability and noise characteristics.

The results of experiments with 10-GHz GaAs FET oscillators have shown that the circuit design using small-signal parameters is in good agreement with the measured oscillation frequency. Furthermore, there exists an optimum bias condition for maximum output power, and another optimum bias condition for maximum efficiency. Higher maximum output power is obtainable using a GaAs FET with a larger saturated drain current, while maximum efficiency is less dependent on the saturated drain current. These experiments have revealed that a GaAs FET oscillator can be operated at a low bias voltage comparable to the bias of a Gunn oscillator, and that the oscillation efficiency compares favorably with a normal IMPATT oscillator. Thus the GaAs FET oscillator simultaneously possesses the most desirable features of both Gunn and IMPATT oscillators. From the standpoint of noise performance, the GaAs FET oscillator is situated between Gunn and GaAs IMPATT oscillators.

At present, the output power is low because of the narrow gate width of the GaAs FET used. However, an output power of 1 W or more is obtainable with improvements in the device in the future. The features described indicate that the GaAs FET oscillator will soon be joining the family of microwave solid-state oscillators as a promising new member.

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REFERENCES

[1] C. A. Liechti, E. Gowen, and J. Cohen, "GaAs microwave Schottky-gate field-effect transistor," in *1972 ISSCC Dig. Tech. Papers*, pp. 158–159, Feb. 1972.
[2] W. Baechtold *et al.*, "Si and GaAs 0.5 μm-gate Schottky-barrier field-effect transistors," *Electron. Lett.*, vol. 9, pp. 232–234, May 1973.
[3] C. A. Liechti and R. L. Tillman, "Design and performance of microwave amplifiers with GaAs Schottky-gate field-effect transistors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 510–517, May 1974.
[4] W. Baechtold, "*X*- and *Ku*-band amplifiers with GaAs Schottky-barriers field-effect transistors," *IEEE J. Solid-State Circuits* (*Special Issue on Microwave Integrated Circuits*), vol. SC-8, pp. 54–58, Feb. 1973.
[5] "A practical 4 to 8 GHz GaAs FET amplifier," *Microwave J.*, vol. 17, p. 26, Feb. 1974.
[6] J. E. Sitch and P. N. Robson, "The performance of GaAs field-effect transistors as microwave mixers," *Proc. IEEE* (Lett.), vol. 61, pp. 399–400, Mar. 1973.
[7] M. Maeda, S. Takahashi, and H. Kodera, "CW oscillation characteristics of GaAs Schottky-barrier gate field-effect transistors," *Proc. IEEE* (Lett.), vol. 63, pp. 320–321, Feb. 1975.
[8] S. Okazaki *et al.*, "Microwave oscillation with GaAs FET," presented at 6th Conf. Solid State Devices, Tokyo, Japan, Aug. 1974.
[9] S. Asai *et al.*, "Single- and dual-gate GaAs Schottky-barrier FET's for microwave frequencies," *Suppl. J. Jap. Soc. Appl. Phys.*, vol. 43, pp. 442–447, 1974.
[10] J. Gonda, "Large signal transistor oscillator design," in *1972 IEEE G-MTT Int. Microwave Symp. Dig. Tech. Papers*, pp. 110–112, May 1972.
[11] J. W. Gewartowski, "The effect of series resistance on avalanche diode (IMPATT) oscillator efficiency," *Proc. IEEE* (Lett.), vol. 56, pp. 1139–1140, June 1968.
[12] L. S. Napoli *et al.*, "High-power GaAs FET amplifier—A multigate structure," in *1973 ISSCC Dig. Tech. Papers*, pp. 82–83, Feb. 1973.
[13] M. Fukuta *et al.*, "Mesh source type microwave power FET," *ibid.*, pp. 84–85, Feb. 1973.
[14] J. Cohen and M. Gilden, "Temperature stability of an MIC Gunn-effect oscillator," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-21, pp. 115–116, Feb. 1973.
[15] C. K. Chan and R. S. Cole, "A stable integrated circuit *X*-band Gunn oscillator," *IEEE Trans. Microwave Theory Tech.* (Lett.), vol. MTT-22, p. 815, Aug. 1974.
[16] J. Josenhans, "Noise spectra of Read diode and Gunn oscillators," *Proc. IEEE* (Lett.), vol. 54, pp. 1478–1479, Oct. 1966.
[17] J. R. Ashley and F. M. Palka, "Noise properties and stabilization of Gunn and avalanche diode oscillators and amplifiers," in *1970 IEEE G-MTT Int. Microwave Symp. Dig. Tech. Papers*, pp. 161–164, May 1970.
[18] P. A. Levine, H. C. Huang, and H. Johnson, "Impatt shoot for Gunn noise levels," *Microwaves*, pp. 52–56, Apr. 1972.
[19] M. Ohtomo, "Experimental evaluation of noise parameters in Gunn and avalanche oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 425–437, July 1972.
[20] K. P. Weller, "A study of millimeter-wave GaAs IMPATT oscillator and amplifier noise," *IEEE Trans. Electron Devices*, vol. ED-20, pp. 517–521, June 1973.

Harmonic Mixing with an Antiparallel Diode Pair

MARVIN COHN, FELLOW, IEEE, JAMES E. DEGENFORD, MEMBER, IEEE, AND BURTON A. NEWMAN, MEMBER, IEEE

***Abstract*—An analytical and experimental investigation of the properties of an antiparallel diode pair is presented. Such a configuration has the following unique and advantageous characteristics as a harmonic mixer: 1) reduced conversion loss by suppressing fundamental mixing products; 2) lower noise figure through suppression of local oscillator noise sidebands; 3) suppression of direct video detection; 4) inherent self protection against large peak inverse voltage burnout. These results are obtained without the use of either filters or balanced circuits employing hybrid junctions.**

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The authors are with the Electromagnetic Technology Laboratory, Westinghouse Defense and Space Center, Advanced Technology Laboratories, Baltimore, Md. 21203.

I. INTRODUCTION

HISTORICALLY harmonic mixing has been used primarily at the higher millimeter wave frequencies where reliable stable LO sources are either unavailable or prohibitively expensive. However, the conversion loss obtained by harmonic mixing has been typically 3 to 5 dB greater than that which could be obtained by fundamental mixing at the same signal frequency [1], [2]. An analysis [3], [4] has shown that such a large degradation should not exist, but it assumes that fundamental mixing between the signal and LO is suppressed. Fundamental mixing