GaAs FET Applications for Injection-Locked Oscillators and Self-Oscillating Mixers

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***Abstract*—Injection-locked oscillators (ILO's) using GaAs FET's are described experimentally and theoretically, showing that a wider locking range can be obtained with transmission-type ILO's than with reflection-type, assuming Q_{ext} to the load to be the same in each case. Frequency-stabilized FET oscillators are discussed in terms of the advantages gained by terminating the gate port by a 50-Ω load. Functioning as a self-oscillating mixer, the circuit showed a 9.5-dB (DSB) noise figure.**

I. Introduction

Gallium arsenide FET's show promising features as microwave-power sources, especially because of their high efficiency and available output power level. Those GaAs FET oscillators reported so far have been equipped with one output port in order to replace conventional diode oscillators. But GaAs FET's being three-terminal devices, make it possible to provide two output ports which have directivity between them. We will discuss the applications of two-port GaAs FET oscillators used in injection-locked oscillators (ILO's), self-oscillating mixers, and frequency-stabilized oscillators.

ILO's are commonly used to obtain high gain within a relatively narrow-frequency range by injecting a signal into an oscillator by means of a circulator to isolate input and output power (Fig. 1(a)). Many authors' analyses of this circuit, here called reflection-type ILO, have been fully discussed by Kurokawa [1].

By equipping an oscillator with separate signal-input and power-output ports (Fig. 1(b)) transmission-type ILO's can be realized. This paper explains that when three-terminal devices with a large maximum-stable gain, such as GaAs FET's, are used as oscillating sources, a wider locking range can be achieved with transmission-type ILO's rather than with reflection-type ILO's. A locking range as much as 2.5 times wider was achieved in experiments with the GaAs FET oscillator shown in Fig. 2.

The two-port oscillators also work as self-oscillating mixers when the frequency of the injection signal is out of the locking range due to the mixing function of GaAs FET's. The oscillating frequency is stablized by a dielectric resonator in order to reduce the locking range. Advantages of terminating the gate port of a frequency-stabilized oscillator by a 50-Ω load are discussed.

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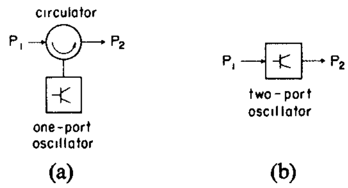

Fig. 1. Injection locking of an oscillator. (a) Reflection type. (b) Transmission type.

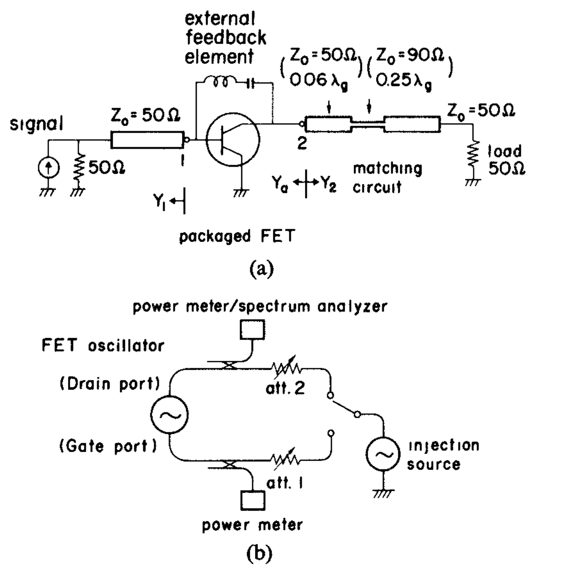

Fig. 2. (a) Injection-locking circuit using a GaAs FET. (b) Diagram of injection-locking experiment.

Experimental results of self-oscillating mixers and frequency-stabilized oscillators are presented.

II. Analysis of Transmission-Type ILO's

Fig. 3 shows an oscillating circuit Y, which includes an active device as well as a feedback circuit, connected to loads Y_1 and Y_2. Here, Y_2 is supposed to be a resonant load to which most of the output power from the device is delivered. Signal current i is injected into port 1 or port 2 according to the type of injection; port 1 when it is transmission type, and port 2 when reflection type. The oscillation condition is derived for the transmission type as

$$[\,Y_a(A)+Y_2(\omega)\,]\,V_2=-\frac{Y_{21}}{Y_{11}+Y_1}\,i \qquad (1)$$

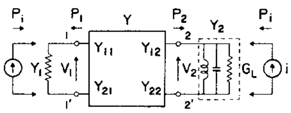

Fig. 3. Two-port oscillator, with an injection source at port 1 when transmission type, and at port 2 when reflection type.

and for the reflection type as

$$[Y_a(A)+Y_2(\omega)]V_2=i \tag{2}$$

where, for each case:

$$Y_a=Y_{22}-\frac{Y_{12}Y_{21}}{Y_{11}+Y_1}.$$

Here, Y_2 is assumed to be dependent on frequency only, while parameters of circuit Y are mainly dependent on the amplitude A of V_2. Equations (1) and (2) show that, with the transmission-type ILO, the injection source is amplified by a factor of $-Y_{21}/(Y_{11}+Y_1)$.

Free-running oscillation ($i=0$) takes place with amplitude A_0 and frequency ω_0, which are determined by the intersection of the loci $Y_2(\omega)$ and $-Y_a(A)$, load and device line, respectively. Kurokawa [1] showed that the locking range of reflection-type ILO's can be obtained from the possible ranges that vector i/V_2 can reach keeping one end on the load line and one on the device line. With transmission-type ILO's, the vector should be multiplied by $-Y_{21}/(Y_{11}+Y_1)$; thus locking range ($\omega_0 \pm \Delta\omega_m$) is obtained straightforwardly, as

$$\frac{\Delta\omega_m}{\omega_0}=\frac{1}{Q_{ext}}\left|\frac{Y_{21}}{Y_{11}+Y_1}\right|\sqrt{\frac{Y_1}{G_L}}\sqrt{\frac{P_i}{P_2}}\frac{1}{|\sin\theta|} \tag{3}$$

where Q_{ext} is the external Q of the load G_L, θ is the angle made by loci $-Y_a$ and Y_2. P_i and P_2 are the available power from the source i and the free-running output power from port 2, respectively, and are given as

$$P_i=|i|^2/8Y_1 \tag{4}$$

$$P_2=\frac{G_L}{2}|V_2|^2=\frac{G_L}{Y_1}\left|\frac{Y_{21}}{Y_{22}+Y_2}\right|^2\cdot P_1 \tag{5}$$

where P_1 is the free-running output power from port 1. Using the free-running condition of the two-port circuit:

$$(Y_1+Y_{11})(Y_2+Y_{22})=Y_{12}Y_{21}. \tag{6}$$

Equation (3) can be modified to

$$\frac{\Delta\omega_m}{\omega_0}=\frac{1}{Q_{ext}}\frac{G_s}{G_p}\sqrt{\frac{P_i}{P_2}}\frac{1}{|\sin\theta|} \tag{7}$$

where $G_s(=|Y_{21}/Y_{12}|)$ is the maximum stable gain of the circuit Y, and G_p is $(P_2/P_1)^{0.5}$. Equation (7) differs from that for the locking range of reflection-type ILO's by a factor of G_s/G_p.

Usually, in oscillator designs the coupling factor to load G_L, $Q_{ext}|\sin\theta|$, cannot be chosen arbitrarily, rather it has the required value for tolerable pushing and pulling figures or the minimum values achievable determined by the device Q of the transistors. Equation (7) shows, however, that even if Q_{ext} and θ are given, locking range can be enlarged by the factor G_s/G_p if the circuit is a transmission type.

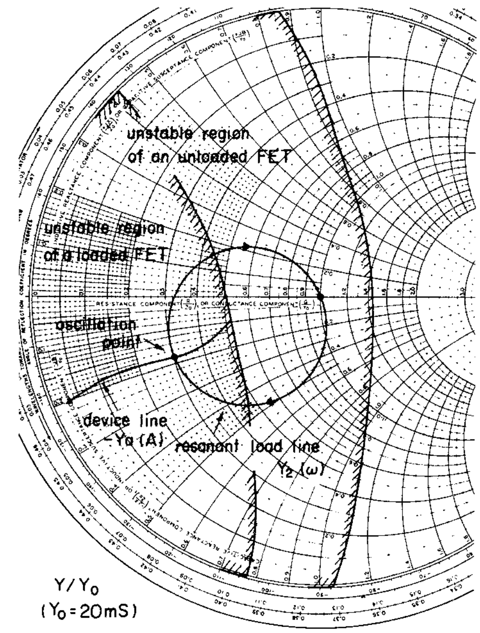

Fig. 4. Unstable region of a loaded FET is smaller than that of an unloaded FET. Resonant load line and a device line are also depicted.

To obtain a high G_s/G_p value, while keeping large G_p in order to extract the most power from port 2, only high-gain devices with large G_s are practical for transmission-type ILO's. Furthermore, a feedback loop must be designed such that it will not reduce G_s too much but still be effective enough to sustain oscillation.

III. ILO Experiments

A transmission-type ILO was fabricated using a GaAs FET (packaged; 10-dB maximum available gain at 10 GHz; common source) with its gate port terminated by a 50-Ω load (Y_1), (Fig. 2(a)). A feedback loop was made by a lead wire in series with a chip capacitor between the gate and drain. Measured device line $-Y_a$ varied along the constant susceptance line with real part diminishing as amplitude A increased as shown in Fig. 4. A low Q_{ext} matching circuit was designed to transform a 50-Ω load to $-Y_a$ at P_{max}.

The oscillator gave a maximum output power of 10 dBm (P_2) at 9.2 GHz, showing no hysteresis at any bias condition. Only 1/7 of the output power P_2 was dissipated at the gate load. Thus $G_p=2.65$. Small signal G_s was also measured as $G_s=3.34$, giving locking range widening factor 1.26. Injection-locking experiments were performed with the circuit shown in Fig. 2(b). For reflection-type experiments the injection source was connected to the drain port and att. 1 was set at maximum, while for the transmission type the injection source was connected

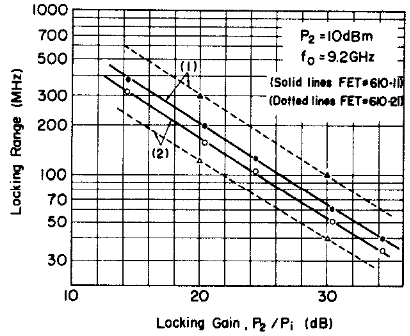

Fig. 5. Locking characteristics of a two-port oscillator. Signal is injected at (1) gate port and (2) drain port.

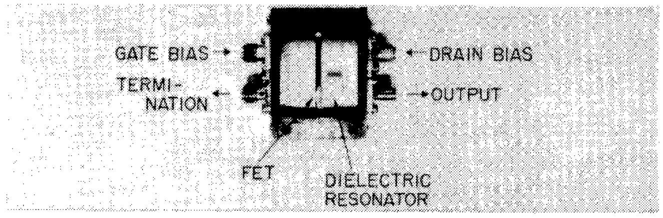

Fig. 6. Stabilized GaAs FET oscillator with its gate port terminated by 50 Ω.

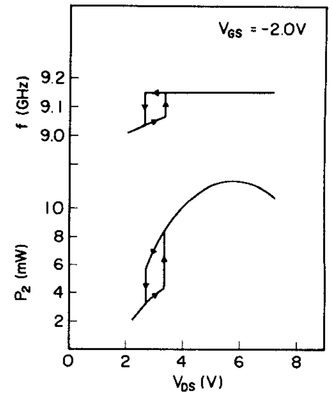

Fig. 7. Oscillating characteristics of a stabilized oscillator.

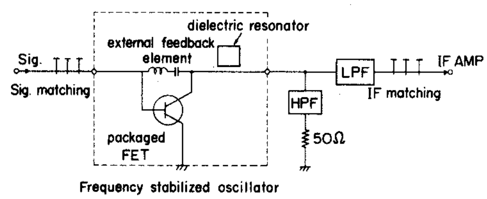

Fig. 8. Self-oscillating mixer.

to the gate port with att. 2 set at maximum. By injecting a signal into the gate port rather than into the drain port, a wider locking range was achieved by a factor of 1.21 (Fig. 5, solid lines), which was very close to the predicted figure. A factor as large as 2.5 was observed in other experiments (dotted lines).

A big advantage of this injection-locking technique is that it does not necessarily require the use of a circulator to isolate the input and output ports, and yet still retains high gain (P_2/P_i) within a locking range which is wider than that of reflection-type ILO's.

IV. Frequency-Stabilized Oscillators

Two-port oscillators can be referred to as loaded oscillators in which extra loss is loaded at the port other than the output port. Because of this loss, device admittance shows smaller unstable region than when it is not loaded. This is a convenient feature in order to stabilize the frequency of the oscillator by a high Q resonator.

Device admittance was measured at the drain looking into the device. Fig. 4 shows the unstable regions for both loaded FET where gate port was terminated by 50 Ω and unloaded FET where a no-loss open-end microstrip was connected to the gate as in [4]. The origin of the chart is excluded in the loaded FET and included in the unloaded FET.

This figure also shows the load-admittance locus which resonates at the resonant frequency of a resonator. With the loaded device, the circuit can be designed to have a single-oscillation condition at the resonant frequency. On the other hand, with the unloaded device, oscillation can take place at the origin as well as at the resonant mode of the resonator, and a big hysteresis in oscillation is inevitable.

An oscillator was frequency-stabilized by coupling a dielectric resonator to the drain port, while terminating the gate port by a 50-Ω load (Fig. 6). A feedback loop was made by a lead wire and a chip capacitor, as before.

Experiments showed a frequency-stabilized region over a wide range of drain-bias voltages, with very little hysteresis compared to the circuit in which the gate was terminated by open-end microstrip. (Fig. 7).

It can be said, that by terminating the gate port with a lossy circuit, the FET is stabilized and oscillation hysteresis is eliminated at the cost of a power loss to the gate load which is about 1/7 of the total ouptut power.

V. Self-Oscillating Mixers

A self-oscillating mixer was also fabricated using the two-port frequency-stabilized oscillator by injecting a signal into the gate port. Special care was taken in designing a feedback loop to have little effect at IF but still be able to sustain the oscillation.

Fig. 8 shows a diagram of a self-oscillating mixer constructed for 500-MHz IF. A minimum noise figure of 9.5 dB (DSB), including a contribution from a 2-dB noise figure IF amplifier, and a maximum conversion gain of 3 dB were obtained. The data are slightly inferior to Pucel *et al.*'s report [2] in which a separate local oscillator was used. The difficulty with self-oscillating mixers is in obtaining sufficient oscillation amplitude at a bias condition where nonlinearity is strongest. The advantage lies in the fact that fewer devices are required to construct a simple receiver front end.

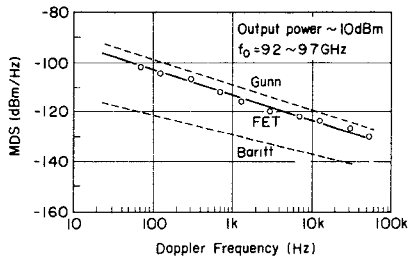

Fig. 9. MDS of FET, Gunn, and Baritt oscillators.

The self-oscillating mixer can also work as a Doppler detector when the circuit is modified to have output and signal ports together at the drain, and IF port at the gate. Minimum detectable signal (MDS) was measured [3] and is shown in Fig. 9 together with that of Gunn and Baritt [3] diodes. The inferiority to Baritt diodes, in spite of good noise performance at higher frequency, is probably due to the large $1/f$ noise near the carrier. With the advance of crystal growth and surface-finishing technique, the sensitivity could be further improved.

VI. Conclusion

Applications of two-port oscillators as transmission-type ILO's, frequency-stabilized oscillators, and self-oscillating mixers were studied.

Analysis of transmission-type ILO's showed that the locking range of transmission types differs from reflection types by a factor of G_s/G_p, where G_s represents the maximum stable gain of the two-port oscillation circuit, and G_p is the square root of the output power ratio of the two ports. Wider locking range was obtained experimentally at X band with transmission types than with reflection types, using a GaAs FET two-port oscillator.

It was also shown that terminating the gate port with a lossy circuit stabilizes the FET at a cost of minimal power loss at the gate. The oscillating frequency was then stabilized, using a dielectric resonator, showing a frequency-stabilized region over a wide range of drain-bias voltage with very little hysteresis.

This frequency-stabilized oscillator works as a self-oscillating mixer when the frequency of the injecting signal is out of the locking range, due to the mixing function of GaAs FET's. A minimum noise figure of 9.5 dB (DSB) was obtained. The difficulty with self-oscillating mixers is in obtaining sufficient oscillation amplitude at a bias condition where nonlinearity is strongest.

An FET self-oscillating mixer can be used as a Doppler detector, although the minimum detectable signal was larger than that of Baritt diodes by approximately 15 dB.

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References

[1] K. Kurokawa, "Injection locking of microwave solid-state oscillators," *Proc. IEEE*, vol. 61, pp. 1386–1410, Oct. 1973.

[2] R. Pucel, D. Masse, and R. Bera, "Performance of GaAs MESFET mixers at X band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 351–360, June 1976.

[3] J. R. East, Hien Nhuyen-Ba, and G. I. Haddad, "Design, fabrication and evaluation of Baritt devices for Doppler applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 943–948, Dec. 1976.

[4] H. Abe, Y. Takayama, A. Higashisaka, and H. Takamizawa, "A high stabilized low-noise GaAs FET integrated oscillator with a dielectric resonator in the C band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 156–162, Mar. 1978.