Transmission-Type Injection Locking of GaAs Schottky-Barrier FET Oscillators

YUSUKE TAJIMA AND KATSUHIKO MISHIMA

***Abstract*—Transmission-type injection-locked oscillators equipped with both signal-input and power-output ports are studied. A comparison with traditional reflection-type injection-locked oscillators, in which a signal is injected into the output port of the oscillator, is presented theoretically. It is shown that the locking range of transmission types always differs from the reflection type by a factor of G_s/G_p where G_s represents the maximum stable gain of the two-port oscillator and G_p represents the square root of the output power ratio of the two ports.**

Experiments on common-source injection-locked oscillators using GaAs FET chips are described and show that, with transmission types, a 1.8 times wider locking range can be obtained than with reflection types. Furthermore, investigation of FM noise for both types of injection revealed lower off-carrier FM noise for transmission types than reflection types, even though the locking gain of the transmission types was kept the same as that of reflection types. Thus overall features of transmission-type injection locking were found to be advantageous for FM signal amplification even though there is a minimal power loss at the signal input port.

I. Introduction

LOCKING the frequency of an oscillator by injecting a signal into the output port is a well-known technique which has become especially popular and practical at microwave frequencies with the advent of negative resistance diodes such as Gunn, IMPATT, TRAPATT, and tunnel diodes as reliable and economical microwave sources. Reports on the application of solid-state injection-locked oscillators to FM or PSK signal amplifiers and limiters are numerous [1]–[3].

The phenomenon of injection locking has been studied and discussed by many authors [4], [5] and was described by Slater [6] using the quasi-static analysis in a particularly suitable way for the study of microwave oscillators. Kurokawa [7] extended the discussion into a dynamic analysis which revealed locking-transient and noise behavior. In the circuit that Slater and Kurokawa studied, a signal is injected into the output port of an oscillator by means of a circulator (Fig. 1(a)). This can be called a reflection-type injection, in which the use of a circulator is inevitable in order to isolate input and output power.

Recently, we introduced [8] transmission-type injection locking where an oscillator is equipped with separate signal-input and power-output ports (Fig. 1(b)). In a simple circuit model where only a single resonant circuit was assumed for the load, and frequency insensitivity for the device parameters, the transmission type was shown to be advantageous to the reflection type when the directivity between the two ports is strong. The transmission type can retain high gain within a locking frequency range which is wider than that of reflection types, but does not necessarily require the use of a circulator to isolate the input and output ports.

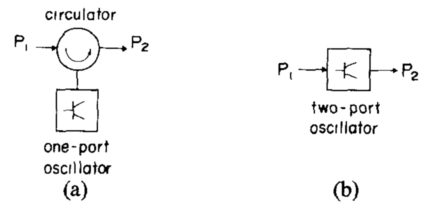

Fig. 1. Two types of injection locking. (a) Reflection type. (b) Transmission type.

This paper further investigates the analysis of transmission-type circuits. We will develop a general theory in which both frequency and terminal voltage amplitude dependency are assumed in the circuit parameters using the quasi-static approximation method [6], [9]. It will be shown that previous results can be applied to any oscillating circuit equipped with two ports.

Experiments are carried out using GaAs FET oscillators in order to find out the feasibility of application of transmission-type injection locking to FM signal amplification. GaAs FET's are used rather than bipolar transistors because of their higher stabilized gain at microwave frequencies. The experiments showed a wider locking range and lower off-carrier FM noise for transmission types than for reflection types.

II. Injection into Two-Port Circuit

In our previous analysis, the RF voltage-amplitude-dependent part of the oscillation circuit was separated from the frequency-dependent part, consisting of a load and parallel resonant circuit. However, this separation is not always possible in actual transistor circuits because, for instance, phase shift in the feedback loop plays an important role in selecting the oscillation frequency, thus always making the oscillating part somewhat frequency-dependent. Here we consider an injection into a general two-port oscillation circuit in which frequency and amplitude dependency are combined. The two-port circuit Y includes an active device, feedback circuit, resonant circuit, and all surrounding parasitics and is connected to loads Y_S and Y_L at ports 1 and 2, respectively. We

Manuscript received May 15, 1978; revised November 27, 1978.
The authors are with the Toshiba Research and Development Center, Toshiba Corporation, Saiwaiku, Kawasaki, Japan.

0018-9480/79/0500-0386$00.75 ©1979 IEEE

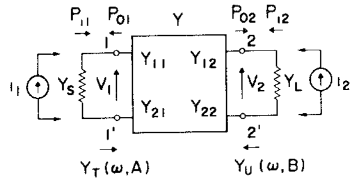

Fig. 2. Injection-locking circuit.

consider loads Y_S and Y_L to be real (Fig. 2). Thus admittance parameters of circuit Y (Y_{11}, Y_{12}, Y_{21}, Y_{22}) are functions of frequency ω and voltage amplitudes at ports 1 and 2, $|V_1|(=A)$ and $|V_2|(=B)$, respectively. However, since A and B are related, the parameters can be expressed as functions of (ω,A) or (ω,B). Injection-current sources i_1 or i_2 will be connected to port 1 or 2 according to the way in which the circuit is injected. When the injection source is connected to the output port, port 2, the circuit is a reflection type, and when connected to the input port, port 1, it is a transmission type.

By representing the admittances, looking into circuit Y from ports 1 and 2, as $Y_T(\omega,A)$ and $Y_U(\omega,B)$, respectively, the oscillating conditions of circuit Y when the injection source is at port 1 is

$$[Y_T(\omega,A)+Y_s]V_1=i_1 \tag{1}$$

and when injection source is at port 2, is

$$[Y_U(\omega,B)+Y_L]V_2=i_2. \tag{2}$$

Here $Y_T(\omega,A)$ and $Y_U(\omega,B)$ are

$$Y_T(\omega,A)=Y_{11}(\omega,A) - Y_{21}(\omega,A)Y_{12}(\omega,A)/(Y_{22}(\omega,A)+Y_L) \tag{3}$$

$$Y_U(\omega,B)=Y_{22}(\omega,A) - Y_{21}(\omega,A)Y_{12}(\omega,A)/(Y_{11}(\omega,A)+Y_S). \tag{4}$$

Free-running oscillation takes place at frequency ω_0 and amplitudes A_0 and B_0 which are derived from (1) and (2), setting $i_1=i_2=0$:

$$Y_T(\omega_0,A_0)+Y_S=0 \tag{5}$$

$$Y_U(\omega_0,B_0)+Y_L=0. \tag{6}$$

When signal $i_1=a_0\exp(j\omega_i t)$ is injected at port 1, locking the oscillation frequency at ω_i, (5) no longer holds. Suppose a_0 is small and amplitude A somehow deviates from its steady-state value A_0 by a small amount ΔA. And also suppose that ω_i is close to ω_0. Then we can express the real and imaginary parts of the parenthetical term in (1), using (5), as

$$Y_s+G_T(\omega_i,A)=\frac{\Delta A}{A}sY_S+G_{T\omega}\cdot(\omega_i-\omega_0) \tag{7}$$

$$B_T(\omega_i,A)=\frac{\Delta A}{A}rY_S+B_{T\omega}\cdot(\omega_i-\omega_0) \tag{8}$$

where G_T and B_T represent the real and imaginary parts of Y_T, sY_S, and rY_S represent $A_0(\partial G_T/\partial A)$ and $A_0(\partial B_T/\partial A)$ at $\omega=\omega_0$ and $A=A_0$, respectively, and suffix ω stands for $(\partial/\partial\omega)$ at $\omega=\omega_0$ and $A=A_0$.

Then the locking range $2\Delta\omega_L$ can be derived from [9] by

$$\frac{a_0}{A_0}=\frac{\mathrm{Im}\left[Y_{T\omega}^*\cdot(s+jr)\right]}{\sqrt{s^2+r^2}}\Delta\omega_L. \tag{9}$$

This relation can be rewritten in terms of the free-running output power at port 2, P_{02}, and the injection power P_{i1} by substituting

$$P_{02}=Y_LB_0^2/2=Y_L|Y_{21}/(Y_{22}+Y_L)|^2A_0^2/2$$

$$P_{i1}=a_0^2/8Y_S.$$

The result is

$$\frac{\Delta\omega_L}{\omega_0}=\frac{1}{Q_{\mathrm{ext}\,1}}\sqrt{\frac{P_{i1}}{P_{02}}} \tag{10}$$

where

$$Q_{\mathrm{ext}\,1}=\frac{\omega_0}{2}\frac{1}{\sqrt{Y_LY_S}}\left|\frac{Y_{22}+Y_L}{Y_{21}}\right|\frac{|\mathrm{Im}\left[Y_{T\omega}^*\cdot(s+jr)\right]|}{\sqrt{s^2+r^2}}. \tag{11}$$

$Q_{\mathrm{ext}\,1}$ is an equivalent external Q that relates locking range $\Delta\omega_L$ to injection power P_{i1}.

Next, we consider injection at port 2. Suppose a small injection signal $i_2=b_0\exp(j\omega_i t)$ at port 2 locks the oscillating frequency at ω_i and induces a deviation of amplitude B from its steady-state value B_0 by a small amount ΔB, the real and imaginary parts of the parenthetical term in (2) can be expressed using (6) as

$$Y_L+G_U(\omega_i,B)=\frac{\Delta B}{B_0}uY_L+G_{U\omega}\cdot(\omega_i-\omega_0) \tag{12}$$

$$B_U(\omega_i,B)=\frac{\Delta B}{B_0}vY_L+B_{U\omega}\cdot(\omega_i-\omega_0) \tag{13}$$

where G_U and B_U represent the real and imaginary parts of Y_U, uY_L, and vY_L represent $B_0(\partial G_U/\partial B)$ and $B_0(\partial B_U/\partial B)$, respectively, at $\omega=\omega_0$ and $A=A_0$.

Locking range is thus obtained as before:

$$\frac{\Delta\omega_L}{\omega_0}=\frac{1}{Q_{\mathrm{ext}\,2}}\sqrt{\frac{P_{i2}}{P_{02}}} \tag{14}$$

where P_{i2} is the injection power $(b_0^2/8Y_L)$ and

$$Q_{\mathrm{ext}\,2}=\frac{\omega_0}{2}\frac{1}{Y_L}\frac{|\mathrm{Im}\left[Y_{U\omega}^*\cdot(u+jv)\right]|}{\sqrt{u^2+v^2}}. \tag{15}$$

From (11) and (15), we can derive (see the Appendix)

$$Q_{\mathrm{ext}\,2}/Q_{\mathrm{ext}\,1}=G_s/G_p \tag{16}$$

where G_s is the maximum stable gain of circuit Y and G_p is the square root of the ratio of the free-running output power at port 2, P_{02}, to that at port 1, $P_{01}=Y_SA_0^2/2$.

Equation (16) shows that the locking range of a transmission-type circuit is different from that of a reflection-type circuit by the factor G_s/G_p. This is consistent with the previous result [8]

$$\frac{\Delta\omega_L}{\omega_0} = \frac{1}{Q_{\text{ext}}} \frac{G_s}{G_p} \sqrt{\frac{P_{i1}}{P_{02}}} \frac{1}{\sin\theta} \tag{17}$$

which was derived assuming a frequency-dependent load-admittance locus and amplitude-dependent device locus. In (17), Q_{ext} is the external Q of the resonant circuit and θ is the angle between the two loci.

In order to obtain a wider locking range with transmission-type injection locking, the circuit must be designed to have large G_s and small G_p. These factors are determined by a feedback circuit, source and load admittances, and Y parameters of the transistor used. It is not only important to use transistors with high G_s but also to design a feedback circuit which will sustain the oscillation without reducing G_s too much. The feedback circuit also affects the output powers P_{01}, P_{02}. The power dissipated at the signal source, P_{01}, should be small; however, as this value decreases, G_p is increased, thus making the factor G_s/G_p smaller. Therefore, minimal power loss at the signal source is inevitable when transmission-type injection is meaningful. It will be necessary for most of the system applications to use an isolator in order to isolate the signal source and oscillator.

III. Experimental Results of Injection Locking

Experiments on injection locking were performed using GaAs FET's with 1-μm gate length and 300-μm gate width. A GaAs FET chip was mounted on a chip carrier and placed between two alumina substrates. Gate and drain electrodes were connected by lead wires to microstrip lines on the alumina substrates, while source contacts were bonded to the chip carrier. Between the two striplines, a feedback circuit was fabricated by a microchip capacitor (1.5 pF) and a 25-μmϕ gold wire (Fig. 3).

The gate port, port 1, was terminated by a 50-Ω load. Device admittance Y_U was measured at reference plane 2 looking into the FET, by changing the measuring frequency and incident power (Fig. 4). The loci of Y_U, device lines, follow almost constant susceptance lines as incident power increases. The output power at port 2, P_{02}, is also plotted, representing equal output power lines by dotted lines. The figure shows that, with this circuit configuration, the circuit has an optimum oscillating condition at around 8 GHz. This optimum oscillation frequency can be varied by changing the length of the feedback lead wire. It should be noted that with FET's, device admittance does not change much from its small signal value until the output power becomes large; whereas, with other negative resistance diodes such as Gunn and IMPATT, the device admittance continues to change from the small output power level.

A matching circuit at the drain was designed to transform a 50-Ω load to optimum device admittance at 9 GHz. Here it was constructed by two 0.12-λ_g open stubs placed 0.22 λ_g away from the FET. With this matching

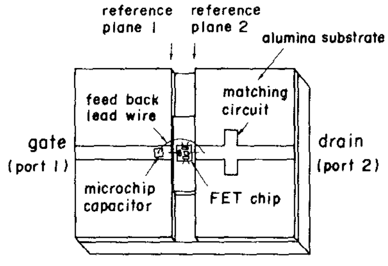

Fig. 3. Two-port GaAs FET oscillator.

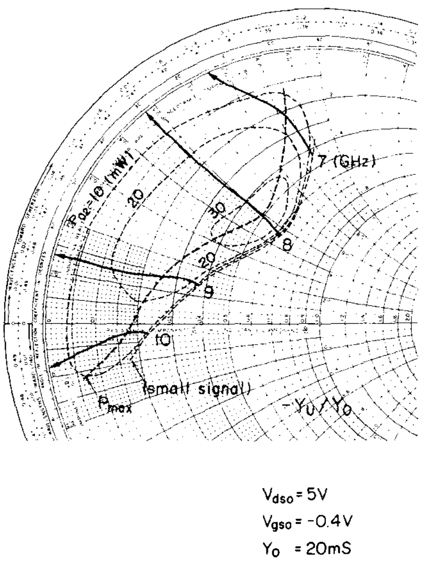

Fig. 4. Device admittance looking into the FET from port 2 at reference plane 2 (solid lines: $-Y_U/Y_0$, $Y_0 = 20$ ms).

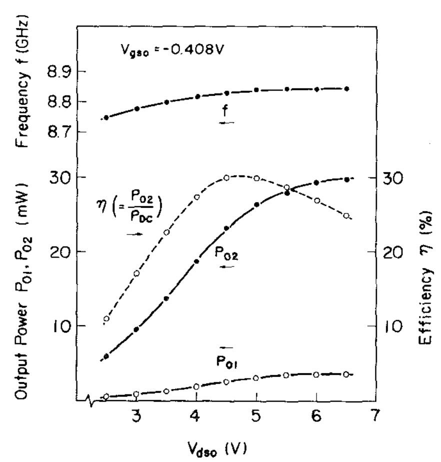

Fig. 5. Oscillating characteristics of the two-port oscillator.

circuit at the drain and a 50-Ω load at the gate, a two-port oscillator was constructed. Oscillator characteristics showed no hysteresis at any bias condition (Fig. 5). Maximum output power of 30 mW was obtained at 8.8 GHz. Maximum efficiency was 30 percent. Only 1/9 of the output power at port 2, P_{02}, was dissipated at the load at port 1.

Both reflection- and transmission-type injection-locking experiments were performed. The relation between locking gain (P_{02}/P_i) and locking range is shown in Fig. 6.

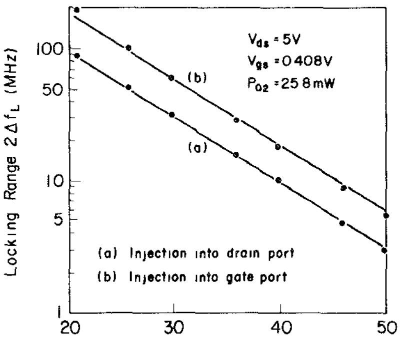

Fig. 6. Locking characteristics of: (a) reflection type and (b) transmission type.

Q_{ext} was found to be 9 when the signal was injected at port 1 (transmission type) and 16 when the signal was injected at port 2 (reflection type). Thus with the same locking gain, the transmission type has more locking range than reflection type by a factor of 1.8, showing its advantage over the latter.

The maximum stable gain of the common source GaAs FET oscillator including feedback circuit was estimated from the power ratio of P_{02} to P_{01} to be 7.3 dB.

IV. FM Noise Measurement of Transmission-Type Injection-Locked Oscillator

When injection locking is applied to the amplification of FM signals, the signal-to-noise ratio of the output signal becomes one of the important factors determining the required input signal level, and thus the maximum locking gain of injection. Here FM noise characteristics of transmission-type injection-locked oscillators used as FM amplifiers are investigated and compared with the reflection type.

Fig. 7 shows the block diagram of a noise measuring system. An output signal of a UHF low-noise synthesizer, up-converted by a mixer with a local oscillator, was used as an injection source. A Gunn oscillator was used as the local oscillator with its oscillating frequency stabilized by a high-Q resonator at 7.6 GHz with root-mean-square FM noise deviation (Δf_{rms}) of less than 0.15 Hz/$\sqrt{\text{Hz}}$. The up-converted signal was injected into the gate port (port 1) of the two-port FET oscillator being tested when the injection was transmission type and into the drain port (port 2) when it was reflection type. Synchronized output from the drain port was down-converted by another mixer using half of the power from the same local oscillator used with the first mixer. Injection signal power was monitored by a spectrum analyzer (SA). The down-converted signal was frequency-demodulated by a UHF high-sensitivity FM linear detector (FLD), and the demodulated signal level was measured by a wave analyzer. The baseband frequency range of the FM linear detector was 0 to 200 kHz and residual FM noise was less than 0.02 Hz/$\sqrt{\text{Hz}}$. The wave analyzer was calibrated by measuring the voltage amplitude of the frequency-demodulated FM signal, having peak frequency deviation of 1 kHz.

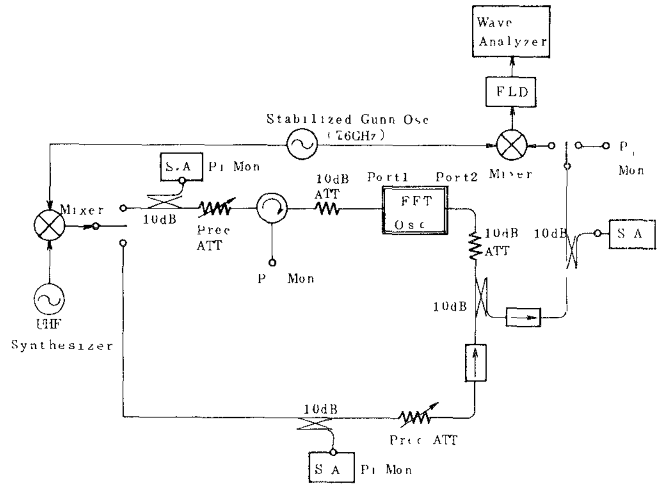

Fig. 7. Block diagram of the circuit used for FM noise measurement.

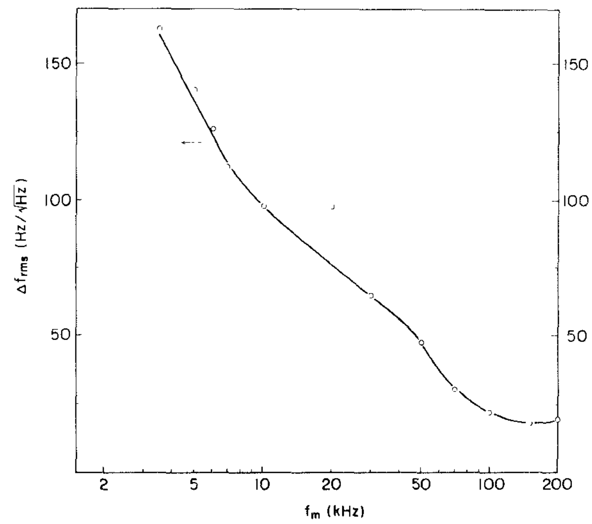

Fig. 8. FM noise of the free-running oscillator.

A GaAs FET oscillator used for measuring FM noise has the same configuration as that described in Section III. The oscillation frequency was varied to 8.1 GHz so that the UHF FM linear detector can be used. The output powers of 4.5 mW at port 1, P_{01} and 18.3 mW at port 2, P_{02} were obtained, respectively. The equivalent external Q's, $Q_{ext\ 1}$ and $Q_{ext\ 2}$, were found to be 10.5 and 15.3, respectively, from the transmission- and reflection-type injection-locking experiments. The temperature coefficient of the oscillation frequency was about 1.4 MHz/°C.

FM noise of the GaAs FET oscillator at free-running operation is shown in Fig. 8. Off-carrier frequency range in this experiment falls in the $1/f$ noise region of GaAs FET's; the value of the noise depends mainly on the material and fabrication process for GaAs FET's. The measured value is essentially the same as results reported [10], [11] for GaAs FET oscillators, taking into account the difference in external Q's.

FM noise of the synchronized output is compared for transmission types and reflection types in Fig. 9. The bottom solid line (x) shows the FM noise level for the UHF synthesizer. The same level was obtained without

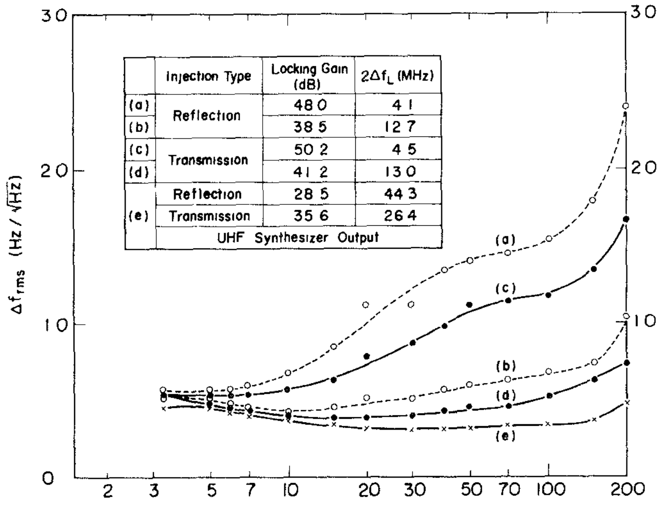

Fig. 9. FM noise of transmission- and reflection-type injection-locked oscillators.

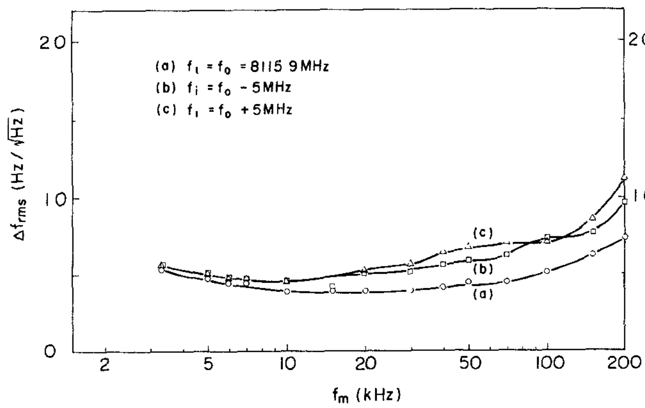

Fig. 10. Variation of FM noise level of transmission-type injection-locked oscillators synchronized at three different frequencies in the locking band.

degradation for the synchronized output of the oscillator, when the injection level P_t was large enough.

When the injection signal level is smaller and the locking gain is higher, the FM noise of synchronized output degrades from that of the injected signal [13]. This degradation was studied by Kurokawa [12] for conventional reflection-type injection and was described as a function of locking range when the oscillator and injection sources were set. In our experiment, the degradation of FM noise of transmission types and reflection types was compared, adjusting the injected signal level to keep the locking range equal for both types (Fig. 9). It is clear from the figure that the degradation of FM noise is less for transmission types even though a smaller injection power, 2–3 dB lower, was used to keep the locking range equal to that of the reflection type.

Fig. 10 shows a variation of FM noise characteristics for transmission-type injection synchronized at three different frequencies in the locking band. Locking gain is kept at 41.2 dB. FM noise degrades when the synchronizing frequency shifts from the free-running frequency of the oscillator, which is the same tendency as Kurokawa predicted and calculated for reflection-type injection [12].

V. Conclusion

Analysis of transmission-type injection-locked oscillators showed that the locking range of transmission types always differ 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 represents the square root of the output power ratio of the two ports.

Common-source two-port oscillators were fabricated using GaAs FET chips. Both reflection- and transmission-type injection-locking experiments were performed. 1.8 times wider locking range was found with a transmission type, while only 1/9 of the output power was dissipated at the signal source.

FM noise for both types of injection was studied. Lower FM noise was observed for transmission types than reflection types even though the locking gain of the transmission types was kept the same as that of reflection types.

Overall features of transmission-type injection locking were found to be advantageous for FM signal amplification. But, because there is a minimal power loss at the signal input port, an isolator might be necessary between the injection port and signal source.

Appendix

The following equations were used to derive (17) from (12) and (16):

$$Y_{T\omega} = Y_{11\omega} - \frac{Y_{21\omega}Y_{12} + Y_{12\omega}Y_{21}}{Y_{22} + Y_L} + \frac{Y_{21}Y_{12}Y_{22\omega}}{(Y_{22}+Y_L)^2}$$

$$\frac{Y_s}{A_0}(s+jr) = Y_{11A} - \frac{Y_{21A}Y_{12} + Y_{12A}Y_{21}}{Y_{22} + Y_L} + \frac{Y_{21}Y_{12}Y_{22A}}{(Y_{22}+Y_L)^2}$$

$$Y_{U\omega} = \frac{Y_{22}+Y_L}{Y_{11}+Y_s}\left[Y_{11\omega} - \frac{Y_{21\omega}Y_{12} + Y_{12\omega}Y_{21}}{Y_{22}+Y_L} + \frac{Y_{21}Y_{12}Y_{22\omega}}{(Y_{22}+Y_L)^2}\right]$$

$$\frac{Y_L}{B_0}(u+jv) = \frac{Y_{22}+Y_L}{Y_{11}+Y_s}\left[Y_{11A} - \frac{Y_{21A}Y_{12} + Y_{12A}Y_{21}}{Y_{22}+Y_L} + \frac{Y_{21}Y_{12}Y_{22A}}{(Y_{22}+Y_L)^2}\right] \frac{dA}{dB}\bigg|_{A=A_0}$$

where suffix A represents $\partial/\partial A|_{A=A_0}$.

References

[1] W. M. Hubbard *et al.*, "A solid-state regenerative repeater for guided millimeter-wave communication systems," *Bell Syst. Tech. J.*, vol. 46, no. 9, pp. 1977–2018, Nov. 1967.

[2] J. W. Amoss and K. E. Gsteiger, "Frequency modulation of avalanche transit time oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 742–747, Dec. 1967.

[3] C. P. L. Ruthroff, "Injection-locked-oscillator FM receiver analysis," *Bell Syst. Tech. J.*, vol. 47, no. 8, pp. 1655–1661, Oct. 1968.

[4] B. Van der Pol, "Forced oscillation in a circuit with nonlinear resistance," *Phil. Mag.*, vol. 3, pp. 65–80, Jan. 1927.

[5] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE*, vol. 34, pp. 351–357, June 1946.

[6] J. C. Slater, *Microwave Electronics*. New York: Van Nostrand, 1950, p. 205.

[7] K. Kurokawa, "Injection locking of microwave solid-state oscillators," *Proc. IEEE*, vol. 61, pp. 1386–1409, Oct. 1973.

[8] Y. Tajima, "GaAs FET applications for injection-locked oscillators and self-oscillating mixers," in *Dig. 1978 Int. Microwave Symp.*, pp. 303–305, June 1978.

[9] K. Kurokawa, "Some basic characteristics of broadband negative resistance oscillator circuits," *Bell Syst. Tech. J.*, vol. 48, pp. 1937–1955, July–Aug. 1969.

[10] M. Maeda *et al.*, "Design and performance of *X*-band oscillator with GaAs Schottky-gate field-effect transistors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 661–667, Aug. 1975.

[11] H. Abe *et al.*, "A highly 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.

[12] K. Kurokawa, "Noise in synchronized oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 234–240, Apr. 1968.

[13] J. R. Ashley *et al.*, "Noise properties and stabilization of Gunn and avalanche diode oscillators and amplifiers," in *Dig. 1970 Int. Microwave Symp.*, pp. 161–164.

Common-Drain Flip-Chip GaAs FET Oscillators

RAYMOND L. CAMISA, MEMBER, IEEE, AND FRANCO N. SECHI, MEMBER, IEEE

***Abstract*—GaAs FET oscillators with flip-chip mounted devices in a novel common-drain configuration are described. It is shown how common-drain oscillators can achieve low thermal resistance while at the same time minimizing parasitics. It is also shown that broad-band negative resistances can be generated without external feedback elements. This paper also reports experimental results where output powers of 390 mW with 22-percent efficiency at 8.5 GHz and 230 mW with 26-percent efficiency at 11.7 GHz have been demonstrated.**

I. Introduction

THE BEST performance reported to date for GaAs FET power oscillators operating above 8 GHz has been achieved using common-gate circuits with devices heat sunk through the SI GaAs substrate [1]–[6]. Typical common-gate single-frequency results are 500 mW at 9.0 GHz with 27-percent efficiency and 210 mW at 11.5 GHz with 17.5-percent efficiency [1]. Common-gate VCO circuits have achieved 40-percent bandwidth with YIG [4], [5] and varactor tuning elements [6]. Since GaAs is a relatively poor heat conductor, for power oscillator applications, the FET was either thinned and plated up with metal, or the device spread out to extract the heat generated. An alternate method for thermal management of power FET's is to operate the devices in a flip-chip format in which heat is removed from the surface of the chip where it is generated. This mounting procedure does not, however, lend itself to a common-gate configuration.

In this paper, GaAs FET oscillators using flip-chip mounted devices in a novel common-drain configuration will be described. This mode of operation has been referred to in the literature as a "reverse channel" circuit [8]. This oscillator type exploits the symmetry of self-aligned gate processing [7] and the performance properties of flip-chip mounted devices [9], [10]. It will be shown how common-drain oscillators can achieve low thermal resistance while at the same time minimizing parasitics which degrade high-frequency performance. It will also be shown that broad-band negative resistances can be generated simply without introducing external feedback elements, which can then be effectively used in oscillator applications. Using this approach, fixed-tuned power oscillators with output powers as high as 390 mW at 8.5 GHz with 22-percent efficiency and 230 mW at 11.7 GHz with 26-percent efficiency have been demonstrated. Varactor-tuned oscillators operating from 10.5 and 12.5 GHz with simple single-tuned networks have also been realized.

II. Flip-Chip FET's

Flip-chip power FET's realize low chip-to-carrier thermal resistance while at the same time minimizing source parasitic inductance. This section will review briefly flip-chip considerations and will show how the same device may be operated in either a common-source or common-drain configuration by simply reversing the source-to-drain bias polarity. Measurements from 4 to 12 GHz

Manuscript received April 25, 1978; revised December 16, 1978. This work was supported by the Air Force Avionics Laboratory under Contract F33615-76-C-1144.

The authors are with the Microwave Technology Center, RCA Laboratories, Princeton, NJ 08540.

0018-9480/79/0500-0391$00.75 ©1979 IEEE