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# NEAR-CARRIER NOISE IN FET OSCILLATORS*

M-3894

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ABSTRACT

An exhaustive study is presented of the relation of near-carrier FM noise of FET oscillators to baseband noise, gate technology, surface passivation, channel formation, and traps. FM noise performance of an FET oscillator will be presented which is over 20 dB better than heretofore reported.

## 1.0 INTRODUCTION

The performance of the voltage-controlled oscillator (VCO) is critical to the success of many radar systems, especially electronic countermeasure systems. Until recently, the only viable solid-state sources were the bipolar transistor for the lower microwave frequencies (L- to S-bands) and the Gunn and IMPATT diodes for higher frequencies.

In recent years, however, the gallium arsenide field-effect transistor (GaAs FET) has demonstrated its superiority as a low-noise amplifying element at microwave frequencies. The intrinsic noise mechanisms responsible for its extremely good noise performance are well-understood. Because of its remarkable noise performance as an amplifier, this device shows promise as a versatile wide-band voltage-controlled oscillator. It is now evident that octave-tuned GaAs FET oscillators, operating up to and above 20 GHz are realizable with usable power output.

The GaAs FET has one major drawback as an oscillating device which makes it unacceptable for many systems applications, namely, its rather high level of near-carrier "1/f" noise, especially in the FM spectrum. In all cases where oscillator noise spectra have been reported, the near-carrier FM noise level of GaAs FET oscillators has been higher than that for comparable Gunn and avalanche diode oscillators, unless extreme measures were invoked (such as the use of temperature-compensated high-K dielectric stabilizing cavities (1,2,3). Therefore, reduction of the noise level of the FET oscillator is highly desirable, because this device has many attractive features: its inherent wide-band performance; its variety of possible operating modes, e.g., grounded gate, grounded source, etc.; and its ease of design, to name a few.

The need for reduction of the near-carrier noise is becoming evident in another important application of FETs, namely microwave monolithic circuits. Here, ultra-broadband monolithic amplifiers (dc-to-microwave) are exhibiting very poor noise figures at the lower end of the band, principally because of "1/f" baseband noise.

If the origin of this noise can be identified and either eliminated or at least controlled or reduced, it is believed that FETs can become important candidates for low-noise VCOs and mixers and low-frequency monolithic amplifiers. The availability of low-noise devices would open the possibility of construction of low-noise front ends in monolithic form, based on FET circuitry.

This paper is a report of research pertaining to the understanding and modeling of baseband and near-carrier noise in FETs, its measurement, and its relation to FET technology.

## 2.0 BACKGROUND

All existing theories of electronic oscillators reduce the problem of analysis to that of a one-port admittance (impedance) with a negative real port.

The FET oscillator, with is associated feedback circuitry, Figure 1(a), therefore can be represented by the one-port equivalent circuit shown in Figure 1(b). Shown is a nonlinear device admittance Y, a function of oscillator amplitude A and frequency $\omega$, with a negative real part in shunt with the frequency-dependent load $Y_L$ and a conductance $G_c$ representing circuit losses.

For stable oscillations, the negative real part of the device admittance must be a decreasing function of the signal amplitude A, where A may represent some current or voltage signal. A necessary condition for oscillation is that

$$G_c(\omega_o) + Y(A_o, \omega_o) + Y_L(\omega_o) = 0 \qquad (1)$$

at some frequency $\omega = \omega_o$, where $A = A_o$ is the resulting oscillation amplitude.

* This research was sponsored by the Air Force Office of Scientific Research under contract F49620-81-C-0052.

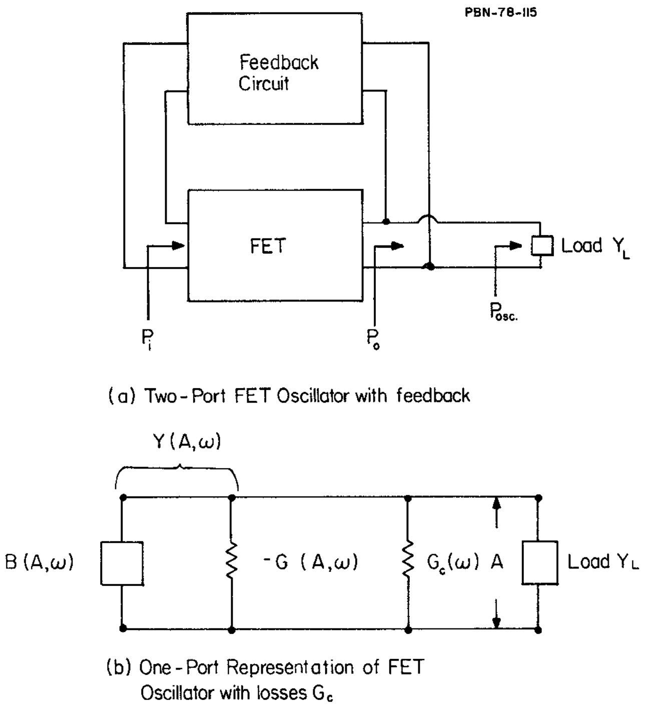



Figure 1. Large-Signal Model of an FET Oscillator.

The predominant sources of nonlinearity in the FET, relevant to oscillator analysis, are the transconductance $g_m$ and the source-gate capacitance $C_{sg}$. Thus, in the representation of Figure 1, $g_m$ contributes to -G(a,ω ) and $C_{sg}$ contributes to B(A,ω ).

There are two types of noise sources in an FET oscillator, (1) white or background noise generated within the channel region or in the parasitic resistances associated with the FET and, (2) low-frequency (baseband) non-white noise associated with defects or traps within the active semiconductor region of the FET. This latter noise, generally speaking, is a decreasing function of baseband frequency. Baseband noise can arise from traps within the active (channel) region or on the semiconductor surface, or at the interface between the active region and the buffer layer or substrate. Both classes of noise can be represented as a current noise source for analysis purposes as illustrated in Figure 2.

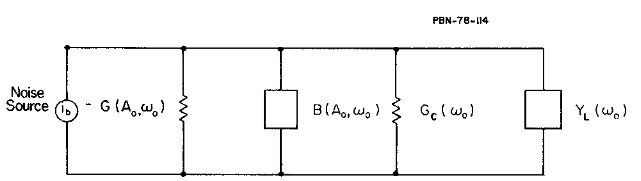



Figure 2. Noise Equivalent Circuit for FET Oscillator.

The white noise is simply an additive type noise which is present within the oscillator band. This noise contributes to the oscillator spectrum in a well understood manner and is not the subject of this paper (4). In FET oscillators, the white noise contribution to near-carrier oscillator noise, generally speaking, is negligible, especially for FM noise. We are concerned here, only with the baseband noise, which by virtue of the nonlinearity in the device admittance, especially the imaginary part, is translated into the oscillator band as near-carrier noise by a "mixing" process. This source of noise is particularly troublesome because it leads to a high level of FM noise which makes the FET unattractive for many radar applications.

At baseband, the mean power spectrum of this source of the noise is usually of the form

$$<i_b^2>/H_Z = \frac{F(T)I^{\alpha}}{f^{\beta}} \qquad (2)$$

over a finite frequency range, where I is the source-drain current, $\alpha \sim 2$, and $\beta \sim 1\text{-}2$, depending on the distribution of traps spatially or in energy level. F(T) is a function of temperature.

## 3.0 EXPERIMENTAL RESULTS

In this paper we shall show that the mechanism of frequency upconversion of the baseband noise is via the modulation of the source-gate capacitance by trap-generated noise in the channel. Figure 3 illustrates this upconversion process. Shown are three curves. The lower curve is the mean-square fluctuation of the drain current, that is, baseband noise as a function of baseband frequency. The middle curve is the measured mean-squared frequency deviation of the oscillator. The upper curve is the predicted frequency deviation based on the measured baseband noise and the upconversion model. Note the good agreement.

The relation of bias circuit performance to this modulation process will be illustrated with experimental data. The effect of circuit Q and phase-locking on this FM noise will be demonstrated and shown to follow the classical oscillator theory as derived for background noise.

Both temperature and laser illumination change the magnitude of baseband noise. A tentative qualitative trap model will be proposed that the most likely sources of baseband noise are surface and possibly bulk traps, but not interface traps. The role of buffer layers will be described.

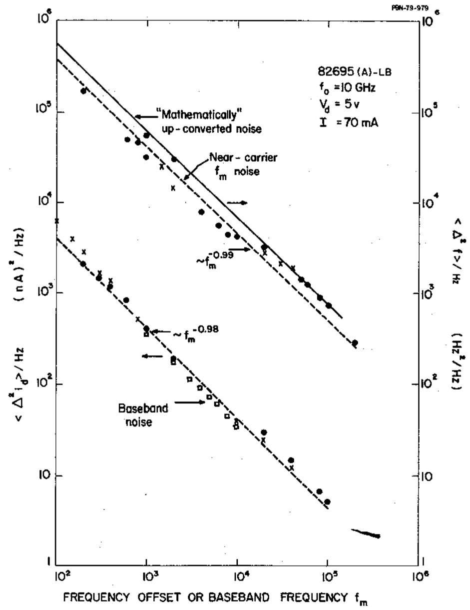


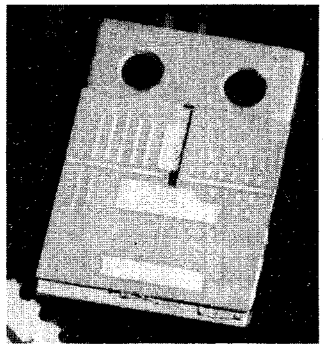

Figure 3. Baseband and FM Noise as a Function of Frequency.

A variety of technologies for making FETs will be discussed, including three gate metal systems, and three surface passivations. It will be shown that gate technology does not play a role in baseband noise, hence oscillator noise, whereas surface passivation does. In particular, it will be shown that for some passivants, the near-carrier noise is increased, whereas for others it remains the same as before passivation. Three passivants were studied, namely, $SiO_X$, $Si_3N_4$, and polyimide.

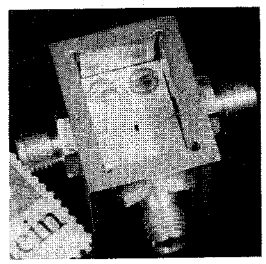
The near-carrier FM noise of a large number of X-band oscillators was measured to illustrate the effect of technology. These oscillators were fabricated in hybrid integrated circuit form as shown in Figure 4. Figure 5 displays the measured results for an epitaxial channel device passivated with $Si_3N_4$. Observe the close adherence to the 1/f law. (Note: the N/C ratio varies as $1/f^3$ when the baseband noise varies as 1/f.) Also observe the low level of this noise. We believe this FM noise is over 20 db lower than any reported heretofore for an X-band FET oscillator with a comparable loaded Q.

## 4.0 SUMMARY

Near-carrier FM noise in an FET oscillator arises from baseband channel noise which is upconverted by depletion layer modulation of the carrier frequency. A model for this process will be presented and demonstrated with experimental results.



(a) Oscillator circuit on alumina substrate.



(b) Oscillator circuit mounted in test jig.

Figure 4. Oscillator Test Circuit.

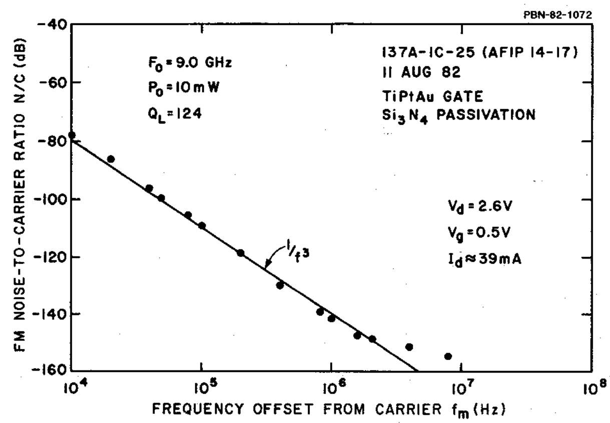



Figure 5. Measured FM Noise of an FET Oscillator.

The major sources of baseband noise are traps located within the active channel region or at the surface of the FET. Gate technology does not appear to affect the near-carrier FM noise but the type of surface passivation does. Some common passivants, however, do not degrade the FM noise performance.

## REFERENCES

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