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NOISE IN OSCILLATORS EMPLOYING SUBMICRON FIELD-EFFECT TRANSISTORS

(Invited Paper)

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Abstract

The various sources of noise in a microwave field-effect transistor are surveyed, and a noise equivalent circuit model for the device is developed. Two alternative methods for the calculation of the oscillator noise spectra are then described, and the factors influencing the FM noise are identified. These factors serve as the basis for classifying the various methods of oscillator FM noise reduction.

I. Introduction

Advances in the technology of submicron device fabrication have made available a number of new active electron devices to circuit designers in the last few years, including the submicron-gate GaAs MESFET, the high electron mobility transistor (HEMT, or MODFET, or TEGFET), the HBT (heterojunction bipolar transistor), the PBT (permeable base transistor), the ballistic transistor, the quantum-well device, and several others exploiting the properties of heterojunctions, superlattices, and submicron dimensions. Of these, the two devices of the field-effect family, the submicron-gate MESFET most commonly fabricated in GaAs, and the high electron mobility transistor (HEMT) most commonly fabricated with AlGaAs/GaAs heterojunction, are well established as low noise devices in linear applications at microwave and millimeter wave frequencies. As preamplifiers, they have the lowest noise figure among all presently known three-terminal active devices, and under cryogenic conditions, their noise figure closely approaches that of masers. In addition, these devices have the advantages of wide frequency range of applicability, high DC-to-RF conversion efficiency, high input--output isolation, suitability for monolithic integration, versatility of circuit applications, simple DC biasing needs, low sensitivity to environmental parameters, and sufficient power output for many applications without post-amplification.

Oscillators designed with MESFETs and HEMTs have not exhibited such outstanding low-noise performance at all [1]. The reason for this disappointing performance is well known : These devices generate high levels of low frequency noise, and this baseband noise modulates the oscillator output due to device nonlinearities, producing large noise sidebands around the carrier frequency. The purpose of this paper is to review our present state of understanding of this subject, and to summarize the available information on the physical origin of the low frequency noise, the influence of the various device and operating parameters on the magnitude of this noise, the mechanism whereby this noise is upconverted to the neighborhood of the carrier frequency, the design variables that govern the magnitude of FM noise spectra, and the state-of-the art reached in low noise oscillator performance.

Three limitations to the scope of the following discussions should be pointed out in advance :

(i) Although most of the following considerations apply to all FET oscillators, the discussions tacitly assume that the oscillators are operated at a microwave frequency and employ the currently available state-of-the-art devices having gate lengths of the order of 0.25 μm.

(ii) There is much more information available in the literature concerning the MESFET oscillators than concerning HEMT oscillators which are of more recent vintage. As a result, the subsequent discussions refer only to MESFETs, although there is no reason to expect any different behavior from HEMTs except in the numerical values of some parameters.

(iii) The present discussion will be confined to the FM noise of oscillators, both due to the focus of this symposium, and due to the fact that the AM noise of oscillators employing field-effect transistors is small and has not been a handicap in any significant system applications of these oscillators. The FM noise of the oscillator can be expressed either as the ratio of the FM sideband noise power, in a unit bandwidth at a specified offset frequency f_m from the carrier frequency, to the carrier power, or as the rms value of the corresponding frequency deviation.

II. Physical Sources of Noise in MESFETs

The purpose of this section is to describe, for each of the various sources of noise in a field-effect transistor, the physical mechanism of noise generation, the region of the device in which the generation of noise takes place, the power spectral density of the noise current component contributed by the noise source, and the factors influencing the magnitude of noise. Since devices with a variety of different structures have been fabricated, the generic version of the MESFET structure, schematically shown in Fig. 1, will be used as the basis for the present discussion. The following are the principal sources of noise in this device :

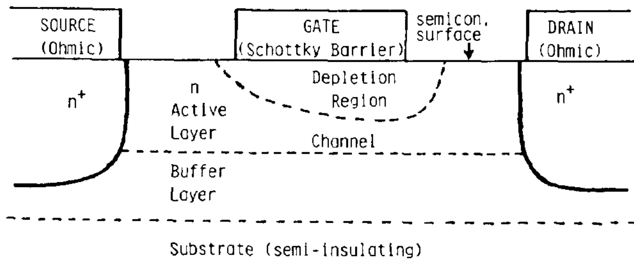

Fig. 1. Schematic Representation of the MESFET Structure.

1. Diffusion (or Velocity Fluctuation) Noise

Diffusion noise arises in the MESFET due to the fact that the majority carriers drifting in the channel in a direction parallel to the electric field have a randomly distributed velocity component in the longitudinal direction due to a finite carrier temperature. The source of this noise is therefore spatially distributed throughout the conducting part of the channel, and its net effect at the device terminals must be found by adding the contributions from all parts of the channel.

The highly conducting source and drain contact regions of the channel, which are outside the region of influence of the gate, contribute essentially a parasitic resistance to the channel; since the electric field in these regions is small and therefore the carriers are in near thermal equilibrium, the diffusion noise in this part of the channel is the same as the thermal noise in the parasitic resistances, and is easily calculated by Nyquist's thermal noise formula. By contrast, the channel region under the gate is a region where the electric field is high, the carrier drift velocity is saturated over some part of the region, and the carriers are far from equilibrium; the power spectral density of the total drain short-circuit noise current at the device terminals due to the diffusion noise arising in this active region alone can be written in a form which mimics the thermal noise formula :

$$S_i(f) = 4\ k\ T\ g_m\ P \tag{1}$$

The similarity of this expression to Nyquist formula for thermal noise is a little contrived; in this expression, g_m is the transconductance of the device, rather than the conductance of a dissipative two-terminal element, and T is the lattice temperature in the channel region rather than the temperature of the carriers having the velocity fluctuations among them. Finally, P is a correction factor that must be introduced in order to make this expression valid; i.e., Eqn. (1) is only the definition of P, and is not a "result". What make Eqn. (1) useful are the results of actual diffusion noise calculations in MESFET channels from first principles, which show that the correction factor P is of the order of unity, and is only a slowly varying function of the DC bias of the MESFET.

The noise power spectrum in Eqn. (1) is frequency-independent; this is an approximation which is valid for all frequencies small compared to the inverse of the correlation time of the carrier velocity fluctuations. Therefore, diffusion noise may be treated as white noise for all frequencies upto about 10^{11} Hz, above which the noise power spectrum must roll-off. This roll-off is theoretically essential, but has not been experimentally explored.

The most important parameter influencing the magnitude of diffusion noise is obviously the electric field profile in the channel region, since the electric field determines the extent of carrier heating. The diffusion noise is therefore determined by DC bias, channel dimensions, doping, and the rate of carrier scattering (since scattering allows the carriers to loose energy by interaction with the lattice, and thus cools them down).

2. Avalanche Noise

When the electric field produced in the channel is high, the impact ionization due to field-accelerated carriers drifting in the channel causes the generation of secondary carriers. This avalanche generation process, being random, is accompanied by a form of shot noise called avalanche noise. The avalanche-generated majority carriers drift along the channel, and contribute an additional component to the drain current. The minority carriers on the other hand can either be collected by the gate terminal, leading to an increase in the gate current, or can drift along the channel, so that the avalanching is caused by carriers of both species. The region of the device where this avalanching is most likely to occur is one where the electric field is the highest; for depletion-mode devices in which the gate voltage is negative, the drain end of the channel region is therefore the principal source of avalanche noise.

The magnitude and the spectrum of the output noise current due to avalanching will depend on whether avalanching is caused by one or both species of carriers. For the special case when both species ionize, the current multiplication factor M is not small, steady-state ionization occurs, and the ionization rate is spatially uniform, the noise power spectrum of short-circuit drain noise current contributed by avalanching can be written as :

$$S_i(f) = \frac{2\ q\ I_P\ M^3}{1 + (\omega M \tau_a\ /\ 2)^2} \tag{2}$$

where I_P is the primary current causing avalanching, and τ_a is the avalanche response time. Other expressions must be used in situations where any of the several restrictive conditions for the validity of Eqn. (2) do not hold.

The power spectrum of avalanche-generated noise is white for frequencies small compared to the inverse of the avalanche-response time. For typical device dimensions, this spectrum is therefore white over the microwave frequency range.

Clearly, the factor having the largest influence on the magnitude of the avalanche noise is the electric field reached in the channel, and this, in turn, is influenced by parameters like DC bias, channel length, and doping density.

3. Shot Noise

Shot noise accompanies any current composed of carriers crossing a potential barrier. As the current flow in the channel

in due to conduction, there is no shot noise associated with drain current. But the gate current consists of carriers crossing the Schottky-barrier between the gate and the channel; therefore the gate current can be expected to be accompanied with full shot noise.

The power spectrum of the gate noise current can be written with the help of Schottky's formula as :

$$S_i(f) = 2\, q\, I_G \tag{3}$$

where q is the magnitude of the charge of an electron, and I_G is the gate current. It is apparent from Schottky's formula that the noise power spectrum is independent of frequency, a consequence of the assumption that the transit-time of the carrier through the barrier is negligible. The shot noise can therefore be taken as white noise for frequencies small compared to the inverse of this transit time, and therefore for all frequencies upto the millimeter wave range.

It also appearent from Schottky's formula that the only parameter determining the magnitude of shot noise is the gate current; therefore the shot noise will be influenced by such factors as the temperature and the doping density in the MESFET active layer. For well-designed MESFETs, and under most reasonable operating conditions, the gate current is small, so that the gate shot noise is very small and can be ignored in many applications. However, there are applications, such as transimpedance amplifiers following optical receivers, in which the shot noise in the gate current is a significant contributor to the device noise performance.

4. 1/f Noise.

Although there is considerable debate concerning the physical origin of 1/f noise, it is generally believed that this noise arises from resistance fluctuations, which are in turn caused either by the fluctuations in the number of carriers or by the fluctuations in mobility. Experimental studies to determine the region of origin of this noise within the device are not entirely unanimous, but 1/f noise is believed to originate primarily at the channel--substrate interface, the semiconductor surfaces, the contacts, and in the active layer itself.

The power spectrum of the drain noise current component due to 1/f noise can be expressed by the empirical formula :

$$S_i(f) = \frac{I_D^2\, \alpha_H}{N\, f^a} \tag{4}$$

where α_H is an empirical parameter, called Hooge's parameter, N is the number of carriers participating in the flow of the drain curent I_D, and therefore depends both on the carrier density and the volume of the active region of the device under the gate, and the exponent a is also an empirical constant, approximately equal to 1.

The factors most influencial in determining the magnitude of 1/f noise are the quality of the buffer layer between the substrate and the active layer, the surface treatment or passivation, and the density of defects in the active region. In addition, empirical studies have shown that many other factors such as the gate leakage current and the external circuit impedance may also influence the magnitude of 1/f noise, but these results cannot be viewed as definitive because there are also reports of other devices where such effects are not observed.

5. Generation-Recombination (g-r) Noise.

Generation-recombination noise arises in MESFETs due to the trapping and release of carriers by the generation-recombination centers (so called traps) which causes random fluctuations in the free carrier density, and thus contributes a noise component to the current. Since the traps are most effective in carrier trapping and release when the Fermi level is close to the trap energy level, those regions of the device where Fermi level is varying are most likely to contribute to g-r noise. As a result, the g-r noise arises primarily in the space-charge regions in the device, including those (i) at the interface of the channel and the substrate layer, (ii) under the gate in the depletion region, and (iii) at the semiconductor surfaces.

The power spectrum of the noise current contribution due to each type of the traps can be written as :

$$S_i(f) = \frac{C}{1 + \omega^2\, \tau_l^2} \tag{5}$$

where τ_l is the lifetime of the carriers in the trap. The constant C is directly proportional to the trap density , and also depends on the trap energy level, and the applied voltages which influence the Fermi level. The power spectrum is therefore of the form of the frequency response of a single-pole low-pass filter, often called the "Lorentzian" spectrum. It is therefore white at frequencies small compared to $1/\tau_l$, and decreases with frequency at higher frequencies at the rate of 20 dB/decade.

Typically, several types of traps will be present simultaneously, and therefore the total g-r noise spectrum will be a superposition of several spectra of the form of Eqn. (5), each having its own magnitude and corner frequency. It is apparent that the total g-r noise spectrum will not have the simple frequency dependence expressed in Eqn. (5). Indeed, if the trap lifetimes are distributed over a wide range of values, extensive and careful measurements are required to separate g-r noise from 1/f noise, and to distinguish the contribution of individual types of traps.

III. Noise Model of the Device

The individual components of the power spectral density of the drain noise current due to the above mentioned noise sources are shown together in Fig. 2. The figure is only illustrative, since the relative magnitudes and the corner frequencies of the various noise sources will be different in different types of devices, and for a given device, with vary with DC bias. Shot noise is not included in this figure, since it is small compared to the the noise contributions shown.

NOISE POWER SPECTRUM OF SHORT-CIRCUIT OUTPUT CURRENT

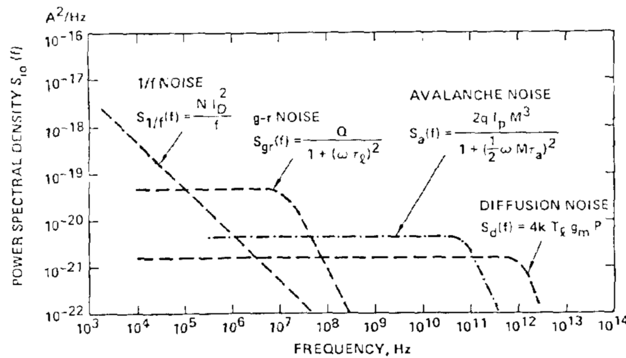

Fig. 2. Power Spectral Density of the Various Components of the Drain Noise Current.

Two conclusions can be drawn from this figure. First, the most significant noise sources at low frequencies (1/f noise and g-r noise) are different from those at high frequencies (diffusion and avalanche noise). Second, the noise produced in the device can be significantly larger at low freqeuncies, typically below 1 MHz, than that at higher frequencies. In nonlinear applications of the device, such as in oscillators, the low frequency noise can modulate signals and generate noise at higher frequencies, thereby deteriorating the noise performance. These two observations explain why the MESFETs are a low-noise device in linear amplifier applications, and yet have a poor noise performance in oscillator circuits.

In linear circuit applications, a MESFET can be represented by a linear (small-signal) circuit model at the desired DC bias conditions, and a noisy linear twoport can always be represented by a noiseless version of the same twoport along with two noise sources, which are partially correlated in general. This is the so called Rothe-Dahlke representation of linear noisy twoports. For nonlinear circuits, there are no such rigorous equivalent-circuit representations of guaranteed validity, and a noise model must be found by inductive methods.

Since quasi-linear models of MESFETs have had some success in describing the op ation of MESFET oscillators, one possible model to consider is a Rothe-Dahlke type model. Such a model is shown in Fig. 3 (a), in which the MESFET is represented by a very simple signal model, consisting of just four noiseless circuit elements : the total input resistance R_T, the gate-to-source capacitance C_{gs}, the output resistance R_o, and the voltage-controlled current source g_m v, controlled by the voltage v across C_{gs}, where g_m is the transconductance of the MESFET. To this are added the two noise sources e_n and i_o at the input and the output respectively, which will be partially correlated in general.

When the equivalent circuit elements are nonlinear, the foregoing simplified noise equivalent-circuit model is still too complex, due to the presence of two separate noise sources. All MESFET oscillator noise analyses to date have therefore introduced further simplification in the noise model by transforming all noise sources inherent in the device to only one of the two noise sources e_n and i_o, and setting the other source to zero. The circuit models of Fig. 3 (b) and (c) show these two possibilities. The first of these models, in Fig. 3(b), is useful in characterization of the baseband noise generation in the device by experimental measurements, and allows the device noise measurements to be carried out at the output (drain-source) port of the device in the form of output current fluctuations. The second model, in Fig. 3 (c) is more convenient for calculating the oscillator noise spectra, as will be seen shortly.

DEVICE NOISE MODEL

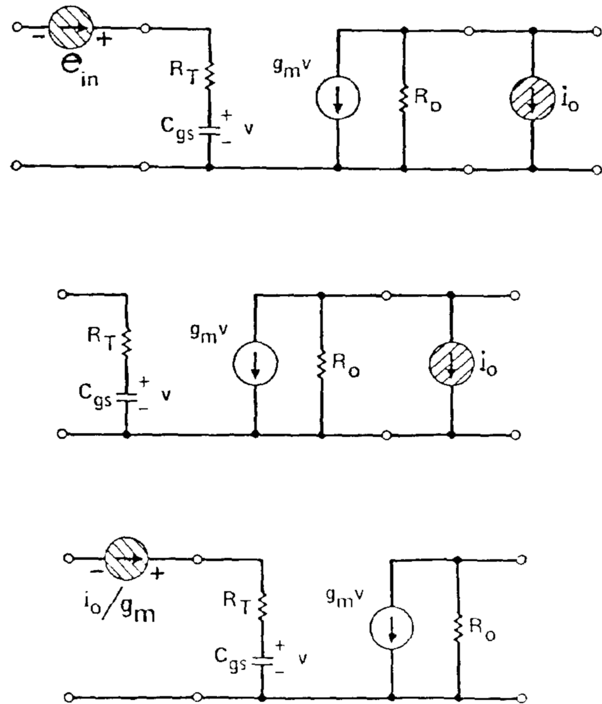

Fig. 3. Noise Equivalent Circuit Models for a MESFET.

The power spectral density of the noise source e_n can be measured in the laboratory as follows. With the device DC biased at the desired operating point, the input (gate-to-source) port is short-circuited at the frequency of measurement, and the output noise power is measured by a narrow-band low-noise receiver. The power spectral density $S_i(f)$ of the output noise current source is thus found. This can be transformed to the input port as a voltage through the intervening circuit model of the device, treated as a linear circuit. At low frequencies, where $\omega C_{gs} R_T << 1$, the transformation involves only the device transconductance, so that the spectral density of the noise voltage source e_n is given by :

$$S_e(f) = S_i(f) / g_m^2 \qquad (6)$$

IV. Noise Model of the Oscillator

Many different kinds of oscillator circuits, based on different device configurations, feedback arrangements, resonator connections, and load coupling, have been designed. All such oscillators employing only one MESFET device as the active device can be represented by the circuit model of Fig. 4 (a). The noise spectrum of such a noisy oscillator can be analyzed in one of two different ways :

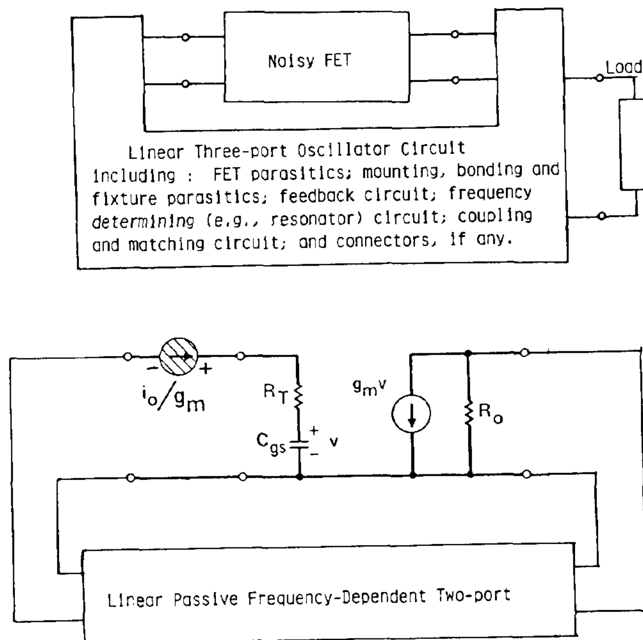

Fig. 4. Circuit Representations of a Noisy FET Oscillator.

1. As an active one-port (negative-resistance) device oscillator

As seen from the load port and looking back towards the oscillator, the MESFET along with its feedback circuit must appear as an active one-port device. More generally, since a field-effect transistor is a two-port active device, the oscillator circuits must use feedback to induce oscillations, so that one port of the device is used for introducing feedback, and the other port serves to deliver the output oscillations to the remainder of the circuit and load. Therefore, the transistor together with its feedback is reduced to a one-port active network, which contains all of the nonlinearity in the oscillator circuit, while the remainder of the circuit is reduced to a linear, passive one-port "load". The active oneport including the device can be represented as a frequency and signal-amplitude dependent large-signal impedance $Z(\omega,V_{RF})$ having a negative real part, which is connected across the load (including any other linear circuit elements), having a frequency dependent circuit impedance $Z_c(\omega)$.

The calculation of the noise spectra of such negative-resistance oscillators has been well-established for a long time, and has been summarized by Kurokawa [2]. In order to use the results of Kurokawa, it is only necessary to transform the noise source e_n present in the device to the terminals of the impedance $Z(\omega,V_{RF})$. To a first approximation, the MESFET may be treated as a linear circuit in carrying out this transformation, and the power spectrum of the new noise source e_t is thus determined. For the low frequency noise sources of interest here, it may be possible to simplify the transformation considerably. The oscillator noise spectra are thus found in terms of the impedance of the one-port device and circuit, their sensitivities to frequency and signal amplitude, and the power spectrum of the noise source connected between Z and Z_c.

The one-port model can be used to represent many different types of oscillator circuits, merely by a suitable choice of a reference plane dividing the oscillator circuit into two parts : an active device and a load. For example, Joshi and Debney [3] designed a common-source FET oscillator, and used the drain--ground port as the dividing plane, while Sechi and Brown [4] designed a common-drain FET oscillator and used the gate--drain port as the dividing plane. If the port used as dividing plane is externally accessible, so that the "device" and "load" impedances can be experimentally measured at this port looking on the two sides, an optimization of the oscillator design can be carried out for minimization of noise spectra. Sechi and Brown [4] show the results of such measurements.

2. As a feedback oscillator using a twoport active device.

Alternatively, the oscillator may be represented as in Fig. 4 (b), wherein the oscillator continues to be treated as a feedback circuit around a twoport active device, which is perturbed by the presence of the noise source e_n. It is clear that if the MESFET model was strictly linear, the frequency at which the condition of oscillations is satisfied in this oscillator circuit would not be influenced by the presence of the noise voltage e_n. The nonlinearity of the MESFET allows the noise voltage e_n to influence the oscillation frequency f_o and thereby produce FM noise sidebands.

Perhaps the simplest method of accounting for the nonlinearity of the device is to allow some of the elements in the equivalent circuit of the device to be nonlinear. The principal nonlinear elements in the MESFET are the three elements C_{gs}, g_m, and R_o, and each of these is influenced by e_n in general. The oscillator noise spectra can therefore be calculated in terms of the oscillator circuit elements, the nonlinearity of the above three elements, and the power spectrum of the noise source e_n in the circuit. Such an analysis is presented by Siweris and Schiek [5].

For the present purposes, the FM noise spectrum of the oscillator will be expressed in less detail, in terms of some composite parameters, rather than in terms of the individual circuit elements of a particular implementation of the oscillator circuit. One of the conclusions from the detailed analysis of Siweris and Scheik [5] is that, of the three equivalent circuit elements, only C_{gs} influences f_o to a first order. Therefore, the calculation of FM noise spectra is reduced to the determination of the sensitivity of f_o to e_n via C_{gs}. In the following, this observation allows the identification of the factors that influence the FM noise spectrum.

V. Factors Influencing the FM Noise Spectrum

The small change in the frequency of oscillations due to the noise voltage e_n can be expressed as follows :

$$\Delta f = \frac{\partial f_o}{\partial e_n} e_n \tag{7}$$

Therefore the FM noise spectrum, expressed in rms frequency deviation at an offset frequency f_m away from the carrier frequency f_o, can be written as :

$$\left[\Delta f_{rms}(f)\right]^2 = \left|\frac{\partial f_o}{\partial e_n}\right|^2 S_e(f_m) \tag{8}$$

The frequency sensitivity to noise voltage can, in turn, be expressed in terms of the factors that influence it :

$$\left|\frac{\partial f_o}{e_n}\right| = \left|\frac{\partial f_o}{\partial C_{gs}}\right| \cdot \left|\frac{\partial C_{gs}}{\partial e_n}\right| \tag{9}$$

Since the gate-to-source capacitance C_{gs} is the capacitance of a Schottky-barrier metal-semiconductor junction, its dependence on the gate-to-source voltage is known from the following equation applicable to abrupt junctions :

$$C_{gs} = \frac{C_o}{\sqrt{1 - v_{gs}/\phi_{bi}}} \tag{10}$$

Therefore, Eqn. (9) can be written as

$$\left|\frac{\partial f_o}{e_n}\right| = \left|\frac{\partial f_o}{\partial C_{gs}}\right| \cdot \left|\frac{\partial C_{gs}}{\partial v_{gs}}\right| \cdot \left|\frac{\partial v_{gs}}{\partial e_n}\right| \tag{11}$$

The set of equations (8) and (11) places into evidence all of the factors that influence the FM noise spectrum of a MESFET oscillator. Furthermore, all of the methods of FM noise reduction that have been proposed can now be placed in perspective.

There are four groups of parameters that are instrumental in determining the FM noise of the MESFET oscillator :

(1) The power spectrum $S_e(f_m)$ of the baseband noise generated in the device, and referred to the gate voltage, at the offset frequency f_m. One obvious method of FM noise reduction is therefore to employ a MESFET with a lower level of 1/f noise or g-r noise, whichever is dominant at the frequency equal to the offset frequency of interest.

(2) The sensitivity of the oscillation frequency to the MESFET gate-to source capacitance, $|\partial f_o/\partial C_{gs}|$. This is dependent on the frequency-determining RF circuit of the oscillator. Thus the choice of the FET configuration, feedback circuit, and resonator coupling should be made to minimize this sensitivity in order to reduce FM noise.

(3) The nonlinearity of the device input capacitance, represented by $|\partial C_{gs}/\partial v_{gs}|$. This is an intrinsic property of the gate junction, and its intrinsic value is determined by the nature of the doping profile. Its effective value can be reduced by diluting the effect of C_{gs} (item 2 above), or diluting the effect of v_{gs} (item 4 below), by introducing other reactive and voltage-dividing circuit elements respectively.

(4) The sensitivity $|\partial v_{gs}/\partial e_n|$. This can be influenced by the low-frequency impedances in the DC gate bias circuit.

The optimization of the FM noise spectrum of the oscillator can be carried out experimentally if each of the above parameters can be measured, and if the effect of the design variables on the values of these parameters can be estimated. It is also possible to measure the two parameters appearing in Eqn. (8) directly. The baseband noise generated in the device at low frquencies can be measured by a low-noise amplifier and a wave analyzer. The oscillator frequency sensitivity to gate noise voltage can be measured by introducing a signal at the gate and measuring the change in oscillator frequency [6]. Thus the device and the circuit can each be selected for minimum FM noise.

VI. Device Selection

The device specifications in the manufacturer's data sheet for a MESFET or HEMT typically include small-signal S-parameters, broadband linear equivalent circuit parameters, DC characteristics, and some large-signal parameters, such as 1 dB gain compression point. The various procedures found in the literature for designing oscillators with these devices are therefore also based on these and other parameters in terms of which the device is characterized. By contrast, the device noise specifications supplied in the data sheets usually consist of the minimum noise figure of the device as a linear amplifier at some microwave frequencies. This information is of no use to the circuit designer wishing to design a low-noise oscillator; given two devices, the one with the lower noise figure may well lead to an oscillator with a higher noise spectrum close to the carrier frequency. The analysis carried out above has identified a small set of parameters which can be conveniently measured for a given device, serve as a specification of the device noise capability in oscillator applications, are useful for comparing two devices in respect of their noise performance as oscillator, can be used to estimate the magnitude of the expected oscillator noise, and thus assist in optimizing the oscillator design for low noise performance.

A number of circuit techniques [7-11] have been proposed in the literature in recent years for lowering the noise in FET oscillators. Each of these techniques, when viewed in isolation, appears as an independent, clever idea. A general analysis of the FM noise in MESFET oscillators, given above in a form which is independent of the specific circuit implementation, has the further advantage that it provides a systematic classification of the various circuit techniques of oscillator noise reduction based on the variable through which the reduction is achieved, so as to put the various methods in proper perspective and understand the relationship between them, and to estimate the level of noise reduction achievable by each technique.

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