A STUDY OF THE RELATION BETWEEN DEVICE LOW-FREQUENCY NOISE AND OSCILLATOR PHASE NOISE FOR GaAs MESFETs

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ABSTRACT

An analytical model for oscillator noise resulting from active device LF noise is presented. We apply it to a number of GaAs MESFET oscillators finding good quantitative agreement, and demonstrating several ways of reducing the phase noise. We show evidence that after having reduced the effect of the normally dominant device LF noise source, a residual LF noise source starts to dominate the phase noise. The best phase noise result for the 5GHz oscillators is $S_\phi(1\text{kHz}) = -75\text{dB/Hz}$.

INTRODUCTION

The work reported here is a continuation of a recent study of the origin of low-frequency (LF) noise in GaAs MESFETs [1]. There it was shown that the major source is trap generation-recombination in a depletion region. In this paper we address the problem of how the GaAs MESFET LF noise is related to the phase noise of oscillators using these devices, and if the reduction in LF noise translates into a reduction in phase noise. For this purpose we have developed an analytical model and applied it to a variety of GaAs MESFET oscillators with a wide spread in phase noise.

THEORY

We take the Kurokawa approach [2] and extend it to include LF noise. It is assumed that the device LF noise can be represented by a small fluctuation, ε, in some device parameter, E. It is also assumed that E has the effect of modulating the device impedance and thus its reflection coefficient. This appears to be a reasonable assumption to make, since ε is a low-frequency fluctuation and is the driving force for the amplitude (A) and phase (ϕ) fluctuations which, in the original Kurokawa approach, are assumed to have a modulating effect. We can solve for the spectral densities of the amplitude ($a=\delta A/A_0$) and phase fluctuations, as well as for their cross-spectral density:

$$S_a(\omega) = S_\varepsilon(\omega)\frac{1}{1+(\omega/\omega_1)^2}\left(k\frac{\partial P_0}{\partial E_0}\right)^2 \tag{1}$$

$$S_\phi(\omega) = S_\varepsilon(\omega)\left[\frac{1}{\omega^2}\left(\frac{\partial\omega_0}{\partial E_0}\right)^2 + \frac{1}{1+(\omega/\omega_1)^2}\left[2\frac{\xi}{\omega_1}\left(\frac{\partial\omega_0}{\partial E_0}\right)\left(k\frac{\partial P_0}{\partial E_0}\right) + \xi^2\left(k\frac{\partial P_0}{\partial E_0}\right)^2\right]\right] \tag{2}$$

$$2\mathrm{Im}\{S_{a\phi}(\omega)\} = S_\varepsilon(\omega)\frac{2}{\omega(1+(\omega/\omega_1)^2)}\left(k\frac{\partial P_0}{\partial E_0}\right)\left(\frac{\partial\omega_0}{\partial E_0}\right) \tag{3}$$

where $k=\ln(10)/20$; P_0 is the output power of the oscillator in dBm; E_0 is the stationary value of E; S_ε is the noise spectral density of E; ω is the modulation frequency; and ω_0 is frequency of oscillation. The four parameters entering in these equations are given below in terms of various derivatives of the device and resonator reflection coefficients Γ_d and Γ_r, respectively.

$$\frac{\partial\omega_0}{\partial E_0} = \left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\times\left(\frac{\partial\Gamma_d^{-1}}{\partial E}\right)\right]\div\left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\times\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right] \tag{4}$$

$$k\frac{\partial P_0}{\partial E_0} = -\left[\left(\frac{\partial\Gamma_d^{-1}}{\partial E}\right)\times\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right]\div\left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\times\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right] \tag{5}$$

$$\omega_1 = -\left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\times\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right]\div\left[\left|\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right|^2\right] \tag{6}$$

$$\xi = \left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\cdot\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right]\div\left[\left(A\frac{\partial\Gamma_d^{-1}}{\partial A}\right)\times\left(\frac{d\Gamma_r}{d\omega}-\frac{\partial\Gamma_d^{-1}}{\partial\omega}\right)\right] \tag{7}$$

The derivatives are evaluated at the operating point, and $\times$ and $\cdot$ stand for vector and scalar product in the complex Γ-plane, respectively.

For GaAs MESFETs we assume $E=V_{gs}$. This makes it easy to test the model since (1) the measured LF noise is represented as an equivalent input (gate) noise voltage $e_g(\omega)$ [1]; (2) V_{gs} is easy to modulate; and (3) the sensitivity $\partial P_0/\partial V_{gs}$ of the output power with respect to the gate bias is negligible for typical GaAs MESFET oscillators. Thus the amplitude noise is negligible, and we can focus on the phase noise, which, to a good approximation, will be given by

$$S_\phi(\omega) = \left[\frac{e_g(\omega)}{\omega}\frac{\partial\omega_0}{\partial V_{gs}}\right]^2 \tag{8}$$

The phase noise can thus be predicted from the LF noise spectral density measured in [1], and the easily measured sensitivity, $\partial\omega_0/\partial V_{gs}$, of the carrier frequency with respect to the gate bias. The analytical expession for the latter is given in equation (4). There are four ways to reduce the phase noise: (1) reduce the device LF noise; (2) use an improved device structure to minimize $\partial\Gamma_d^{-1}/\partial E$; (3) make $d\Gamma_r/d\omega$ as large as possible, i.e. use a resonator with large Q; and (4) use a large signal design and optimize the intersection of the device and resonator trajectories at the operating point. In our experiments we exploited the first three.

EXPERIMENTAL

In Fig. 1 the phase noise, S_ϕ, of three simple microstrip oscillators ($f_0 \approx 5$GHz) using devices with varying magnitude and slope of the LF noise is shown. The sloped lines are the predicted phase noise using a straight line fit to the measured LF noise, and the easily measured carrier frequency sensitivity with respect to the gate bias. Equation (8) predicts the phase noise, and the differences in magnitude and slope of the LF noise are reflected in the phase noise. This gives us confidence in the model, and supports the conclusion in [1] concerning the origin of LF noise, indicating that the charge fluctuation occurs in the gate depletion region.

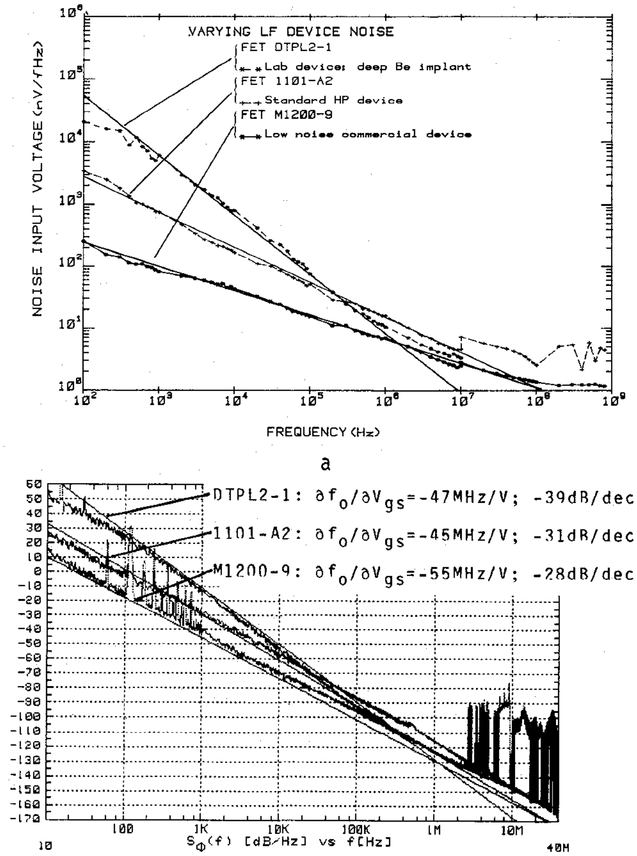

Fig. 1. (a) Equivalent input noise voltage of three very different devices; and (b) phase noise of microstrip oscillators using these devices. The slope lines are related through equation (8).

Fig. 2 illustrates how a reduction in device LF noise translates into, in this case, a 10 dB improvement in phase noise relative to a device with typical level of LF noise. The reduction is predicted well by the model.

Fig. 3 illustrates how improving the device structure can lead to a 15dB reduction in phase

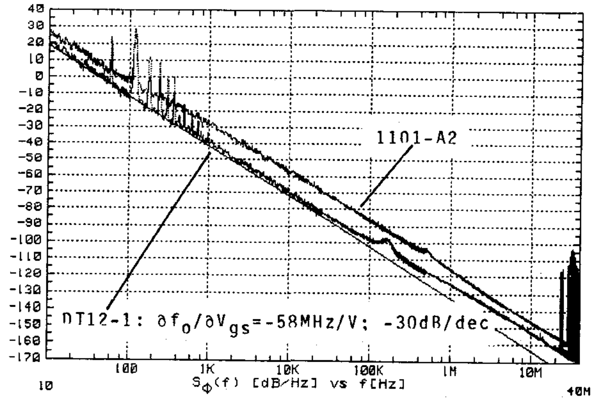

Fig. 2. The effect on the phase noise of reducing the device LF noise (DT12-1). The slope line is the predicted phase noise.

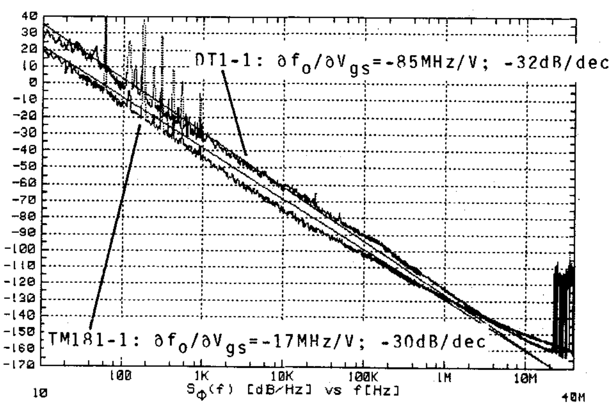

Fig. 3. The effect on the phase noise of using a device (TM181-1) with improved structure, versus using a standard device (DT1-1).

noise compared to a typical device. This is accomplished, in spite of a fairly large device LF noise, by a substantial reduction in $\partial\omega_0/\partial V_{gs}$.

The third way to lower the phase noise is to use a resonator with higher Q than that of simple microstrip matching. We chose to use a 5GHz dielectric resonator for this purpose, and positioned this close to the output microstrip line of the oscillator at a position where oscillation occurs, and where the sensitivity factor in equation (8) is minimized, typically to ~1MHz/V. The phase noise of three such oscillators; using a standard device, a low noise device and a device with improved structure, is shown in Fig. 4. There is a significant reduction in phase noise (20-30dB) to a limit that appears to be typical for GaAs FET dielectric resonator oscillators. There is very little difference in phase noise between the oscillators. Furthermore, using equation (8), the predictions are considerably lower than the experimental values. After evaluating possible reasons for this descrepancy, including possible violations of the assumptions made, we hypothesize that a residual LF noise source must start to dominate the phase noise once the normally dominant charge fluctuation in the gate depletion has been neutralized by sufficiently reducing $\partial\omega_0/\partial V_{gs}$.

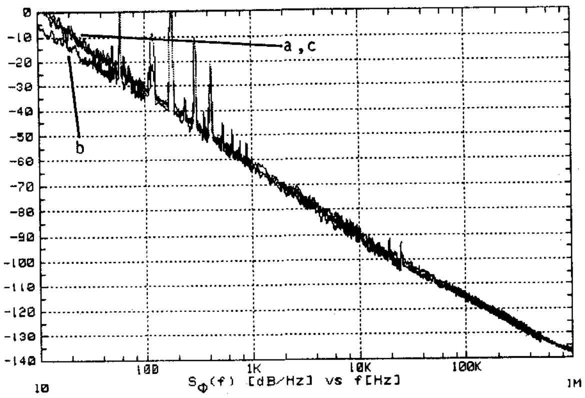

Fig. 4. The phase noise of a 5GHz dielectric resonator oscillator using a (a) standard device; (b) low-noise device; and (c) device with improved structure.

Since the effect of a residual noise source may differ with oscillator configuration we studied a modified version of the 5GHz dielectric resonator oscillator. In Fig. 5 the phase noise of such oscillators, using three different devices, is shown. The phase noise is lower than the limit reached earlier, and the predictions are much better, except for device (c) where there is significant phase noise in spite of a zero sensitivity factor. The phase noise of the oscillator using device (b) and (c) (S_ϕ(1kHz) = -75dB/Hz) is as low as the best result [3] we have seen in the literature for GaAs MESFET oscillators.

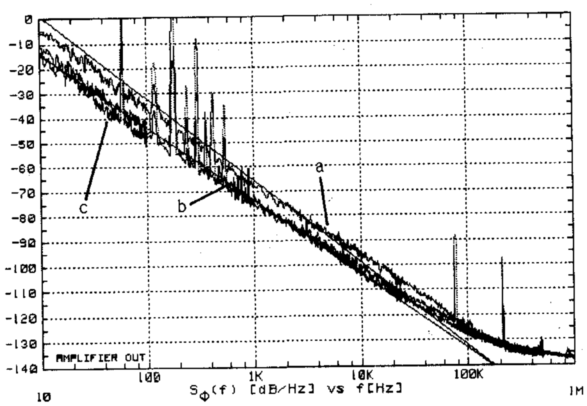

Fig. 5. Same as Fig. 4 but with a modified oscillator configuration.

The case of device (c) in Fig. 5 illustrates that we still reach a limit below which we cannot lower the phase noise by merely decreasing $\partial\omega_0/\partial V_{gs}$. This phenomenon is illustrated more effectively in Fig. 6, where the FM noise Δf_{rms} (directly related to the phase noise S_ϕ by $\Delta f_{rms}=2\Pi\omega\sqrt{S_\phi}$) of an oscillator using a device with very interesting structure in the LF noise is shown. In Fig. 6a the device is biased for non-zero sensitivity factor. The predictions (the dots) are very good, and the structure in the device LF noise is reproduced in the phase noise. Compare this to Fig 6b where we have biased the device for zero sensitivity factor. The phase noise is reduced (but not zero!) and the structure

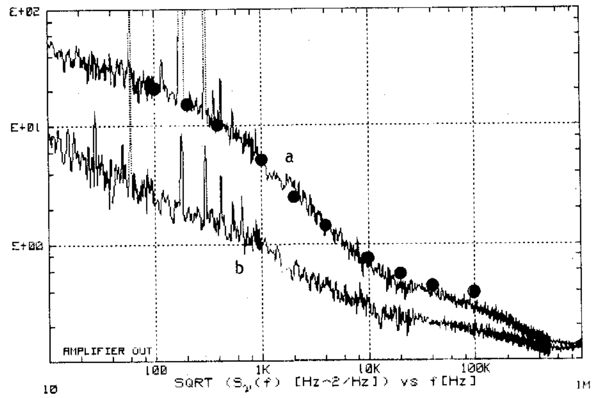

Fig. 6. The FM noise of a 5GHz dielectric resonator oscillator using a device with pronounced structure in the LF noise, biased for (a) non-zero and (b) zero $\partial f_0/\partial V_{gs}$. The dots are the predicted values.

has all but disappeared, indicating that a new LF noise source with, in this case, a different spectrum takes over.

SUMMARY AND CONCLUSIONS

We have presented an analytical model for the oscillator noise resulting from LF device noise. Applied to GaAs MESFETs, it gives clear guidelines for low-noise design. The model has been experimentally verified for a number of GaAs MESFET oscillators. We have demonstrated reduced phase noise by reducing the device LF noise, and by reducing the sensitivity factor $\partial\omega_0/\partial V_{gs}$. The latter was accomplished by improving device structure and by using high-Q dielectric resonators. The results are consistent with the device LF noise being mainly due to trap generation-recombination in the gate depletion region. However, we have presented evidence that once the effect of this noise source has been neutralized by proper design, a secondary LF noise source determines the phase noise. Using devices with reduced LF noise and improved structure, we have demonstrated phase noise as low as S_ϕ(1kHz) = -75dB/Hz, corresponding to £(1kHz) = -78dBc/Hz.

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