A NOVEL GaAs FET OSCILLATOR WITH LOW PHASE NOISE

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ABSTRACT

A novel GaAs FET oscillator circuit is presented. This circuit is capable of reducing phase noise up to 20 db. A source-coupled pair of GaAs FETs has a balanced characteristic which can eliminate both the reactive and resistive modulation mechanisms which upconvert 1/f noise. This circuit is inherently broadband and ideal for monolithic implementations.

INTRODUCTION

Low phase noise GaAs FET oscillators are needed in many microwave systems. GaAs FETs have 1/f noise corner frequencies in the range of 1 to 100 MHZ, which is high compared to other devices. This 1/f noise is upconverted by the nonlinearities in the oscillator to form $1/f^3$ sidebands in the phase noise spectrum. The elimination of upconversion can improve the oscillator phase noise by around 20 db. This improvement will significantly advance the state of the art in low noise oscillators. While both FET and bipolar oscillators will benefit from the following circuit technique, FET oscillators should ultimately be quieter than bipolar oscillators.

THEORY

Phase noise dominates the near-carrier spectrum of microwave oscillators. Presently, the phase noise spectrum of GaAs FET and bipolar microwave oscillators is dominated by the 1/f noise of the device. As shown in equation (1), the phase noise of an oscillator contains contributions from the device and circuit at low and high frequencies. For simplicity, this equation assumes the output is taken from the resonator and the low frequency noise sources are uncorrelated.

$$S_\phi(f_m) = \frac{2\,\overline{n(f)^2}}{\omega_m^2 \left|\frac{d\phi}{d\omega}\right|^2 A_o^2}(1+\alpha) + \frac{\overline{\delta\varepsilon_1(fm)^2}}{\omega_m^2} K^2_{\varepsilon_1 FM} + \frac{\overline{\delta\varepsilon_2(fm)^2}}{\omega_m^2} K^2_{\varepsilon_2 FM} \qquad (1)$$

where

$$K^2_{\varepsilon FM} = \frac{\left|\frac{\partial D}{\partial \varepsilon} \times \frac{\partial D}{\partial A}\right|^2}{\frac{\omega_m^2}{A_o^2}\left|\frac{dD}{d\omega}\right|^4 + \left|\frac{\partial D}{\partial A} \times \frac{dD}{d\omega}\right|^2}$$

and

$$D = 1 - KH \text{ or } \frac{Z + Zm}{R_L} \text{ or } 1 - \Gamma_C\Gamma_D.$$

K and H are respectively the amplifier and resonator transfer functions of a feedback oscillator. Z_m and Z are respectively the device and resonator impedances of a negative feedback oscillator. Γ_D and Γ_C are respectively the device and resonator reflection coefficients of a reflection oscillator. Oscillator parameters such as Vgs and Vds are equal to ε_1 and ε_2 respectively. D is a dimensionless quantity that is used to make the noise equations independent of the oscillator realization. The first term in (1) comes out of Kurokawa's theory [1]. This term is proportional to the noise in the device at the oscillation frequency. This term falls off as f_m^2 (the offset frequency) and is inversely proportional to $(d\phi/d\omega)^2$. The α variable relates to the stability of the oscillator. The second and third terms in the phase noise equation describe how low frequency modulations affect the phase noise of an oscillator [2,3]. These terms dominate the near carrier noise in microwave oscillators [4]. Note

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that if ϵ contains 1/f noise the phase noise has an f^{-3} slope. The low frequency noise voltage on the gate of a FET modulates both the gm and the Cgs of the FET. By expanding the K_{FM} term as shown in equation (2), we can see how both these modulations affect the phase noise of the oscillator,

$$K^2_{\epsilon_1 FM} = \frac{\left|\frac{\partial G}{\partial \epsilon}\frac{\partial \phi}{\partial A} - \frac{\partial \phi}{\partial \epsilon}\frac{\partial G}{\partial A}\right|^2}{\frac{\omega_m^2}{A_0^2}\left|\frac{d\phi}{d\omega}\right|^4 + \left|\frac{\partial G}{\partial A}\frac{d\phi}{d\omega} - \frac{\partial \phi}{\partial A}\frac{dG}{d\omega}\right|^2} \qquad (2)$$

where G is the magnitude of the loop gain, ϕ is the loop phase shift in radians, and ϵ_1 is the gate voltage.

By considering noise close to the carrier, we may eliminate the ω_m^2 term in the denominator and simplify the K_{FM} term. For all well designed oscillators, the $(\partial G/\partial A)(d\phi/d\omega)$ term in the denominator is much greater than the $(\partial\phi/\partial A)(dG/d\omega)$ term. Note that the $(\partial G/\partial A)(d\phi/d\omega)$ term amounts to the amplitude saturation factor multiplied by the group delay. The terms in the numerator are dominated by the $(\partial\phi/\partial\epsilon)(\partial G/\partial A)$ term. The $\partial\phi/\partial\epsilon$ term is due to the change in Cgs with gate voltage. If we assume that Cgs changes dominate the FETs modulation, then

$$K^2_{\epsilon 1FM} = \left|\frac{\frac{\partial\phi}{\partial\epsilon}}{\frac{\partial\phi}{\partial\omega}}\right|^2 = \left|\frac{\partial\omega}{\partial\epsilon}\right|^2.$$

As would be expected the frequency modulation coefficient reduces to the change in frequency with respect to voltage. It is important to realize that even if the phase change in the FET due to Vgs changes $(\partial\phi/\partial\epsilon)$ is reduced to zero there will still be 1/f noise modulating the oscillator. Elimination of the $\partial\phi/\partial\epsilon$ term still leaves the $(\partial G/\partial\epsilon)(\partial\phi/\partial A)$ term in (2). This term corresponds to the gm modulation via Vgs changes $(\partial G/\partial\epsilon)$ multiplied by the AM to PM conversion coefficient of the circuit. AM to PM conversion can come from device nonlinearities or slope in the loop transfer function at the operating frequency. This means that operating an oscillator at a frequency other than the center frequency of the resonator creates AM to PM conversion in the oscillator. Other modulation sources, as described by ϵ_2, also limit the phase noise reduction obtained by eliminating $\partial\phi/\partial$ Vgs. In a typical FET oscillator the drain modulation and AM to PM conversion factors may produce phase noise about 20 db below that produced by $\partial\phi/\partial$ Vgs. Therefore, a 20 db reduction in oscillator phase noise may be achieved by eliminating the direct modulation factor, $\partial\phi/\partial$ Vgs. This direct phase modulation may be reduced by using more linear FETs [5] or by circuit techniques [4,6]. To date, the circuit techniques presented for reducing phase noise have been narrow-band and very dependent on the device operating point.

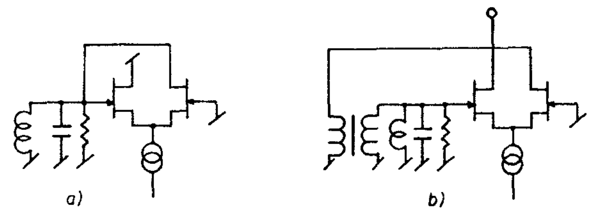

Figure 1. Oscillators using a source-coupled pair: a) negative conductance, b) feedback.

Novel circuits for GaAs FET oscillators consist of the source-coupled pairs shown in Figure 1. A FET pair may be used in a negative conductance or feedback oscillator configuration as shown in Figure 1a) and 1b). These configurations were originally proposed with tubes [7]. These circuit configurations reduce both resistive upconversion and reactive modulation when properly balanced. The reduction in resistive upconversion is due to the cancellation of even order nonlinearities. The reduction in reactive modulation is due to the capacitive compensation of the two FETs.

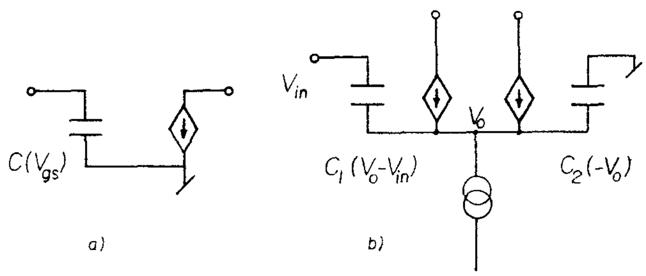

Figure 2. FET models showing Cgs nonlinearity: a) single FET, b) source-coupled pair.

Figure 2a) shows a single FET in a common source configuration. Small variations in Vgs due to low frequency noise produce Cgs variations as given by

$$Cgs(Vgs) = Cgs(Vgso) + \delta Vgs\,\frac{\partial Cgs}{\partial Vgs}. \qquad (3)$$

These Cgs variations change the phase shift through the device and the frequency of the oscillator. The source-coupled configuration of Figure 2b) has an input capacity of

$$C_{in} = \frac{C_1 C_2}{C_1 + C_2}. \quad (4)$$

The variation of C_{in} for small changes in the input voltage can be obtained from Taylor series expansions of C_1 and C_2. A voltage change at the input will cause half that voltage change to be added to V_0. This means that if the input voltage is raised slightly, the voltage across C_1 will be reduced by half that change and the voltage across C_2 will be increased by half that change. These opposing changes will cancel depending on the degree the FETs are matched. A substitution of the Taylor series expansions of C_1 and C_2 into (4) gives

$$C_{in}(\delta V) = \frac{C_{10} C_{20}}{C_{10} + C_{20}} \left[1 + \frac{\delta V}{2(C_{10} + C_{20})} \left(\frac{\partial C_1}{\partial V} - \frac{\partial C_2}{\partial V}\right)\right] \quad (5)$$

if second order terms in δV are ignored. The matching of FET capacitances will cause the voltage dependence to cancel. A comparison of (5) with (3) shows that a capacitance match within 10% will give at least a 20 db reduction in the capacitance sensitivity to voltage variations. Since the $\partial\phi/\partial\varepsilon_1$ term in (2) is directly proportional to $\partial C/\partial V_{gs}$, a 20 db reduction will bring the phase noise down to where other modulation mechanisms will dominate. The use of a well matched pair of source-coupled FETs can therefore reduce the phase noise of broadband oscillators by 20 db.

A monolithic GaAs FET pair is ideal for oscillator realization because of its inherent balance. It is important for the limiting action of an oscillator to not decrease the loaded Q of the resonator. The limiting action in single FET oscillators causes large changes in the impedance presented to the resonator and so results in inferior noise performance. Source-coupled FET oscillators saturate from the limited amount of current available from the current source. This limiting action mainly affects the resistance of the FETs looking into each source. Therefore, this limiting action causes only small changes in the gate and drain impedances and so does not greatly effect the loaded Q.

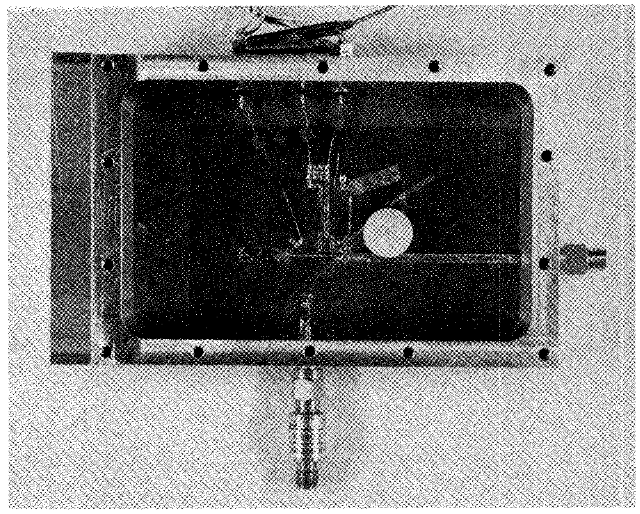

Figure 3. Photograph of 4.5 GHZ dielectric resonator oscillator using a source-coupled pair of discrete FETs.

EXPERIMENT

A balanced pair of FETs at low frequencies have shown up to 39 db of reduction in resistive upconversion. Similar reductions in reactive modulation have also been demonstrated. These promising results led to the construction of the feedback oscillator shown in Figure 3. The discrete pair of FETs used in this oscillator were matched to within 8%. From the previous analysis, this degree of matching should give at least 20 db of reduction in the circuit phase modulation with respect to a single FET. The pair of source-coupled FETs used a dielectric resonator as a feedback element. The feedback configuration was chosen because of its broadband stability.

Figure 4 shows the measured performance of the discrete FET oscillator and the predicted performance of a matched monolithic FET pair in the oscillator. The oscillator had an 8 dbm output power with a single sideband noise-to-carrier ratio ($\mathcal{L}$) of -105 dbc in a 1 Hz bandwidth. This level of phase noise is very good considering the loading on the resonator produced a Q of about 14. The phase noise of the discrete FET oscillator showed no change when the sources were AC coupled or DC coupled. An analysis of the circuit showed that the FET packages and physical separation of the FETs caused an impedance transformation which prevented the cancellation of FET capacitance variations. Matched discrete FETs mounted within the same package or monolithic FET pairs are needed to realize the advantages of this circuit configuration. Oscillators using discrete FET chips in close proximity and monolithic FET pairs are presently under construction.

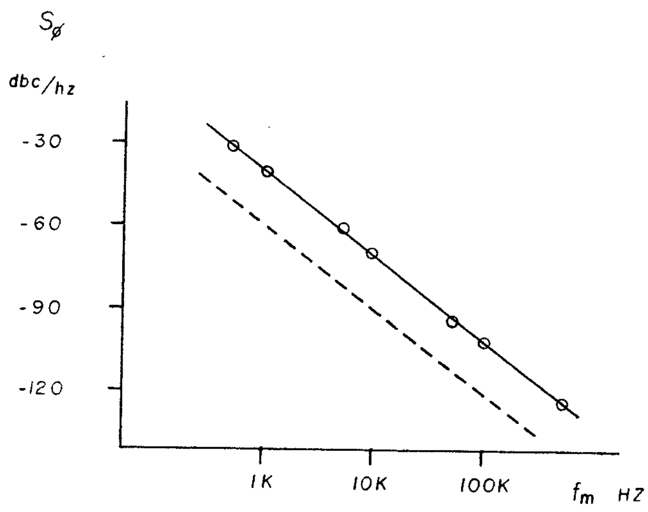

Figure 4. Phase noise spectral density of the 4.5 GHZ oscillator.

——————— measured from discrete FET oscillator

— — — predicted for monolithic FET pair oscillator

CONCLUSION

A novel GaAs FET oscillator circuit has been introduced. Theoretical results show this circuit to be capable of very low phase noise over broad bandwidths. Experimental results have identified some of the problems with realizing this circuit at high frequencies. The importance of contructing the source-coupled pair from matched transistors in close proximity is demonstrated. This circuit configuration is ideal for monolithic implementation, and such an implementation should improve the present state of the art in oscillator phase noise by 20 db.

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