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A NEW AND EFFICIENT APPROACH TO THE ANALYSIS AND DESIGN OF GAAS MESFET MICROWAVE OSCILLATORS

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ABSTRACT

A new technique for the analysis and design of oscillators is presented. The solution is based on Volterra series and the resulting nonlinear system is solved by an efficient algorithm. The novel feature here is the way in which the oscillator circuit is decomposed so that the determination of the nonlinear kernels can be evaluated much more easily. This method is fast, requires no initial guess, has good convergence properties and can be implemented on a computer in a straightforward manner. Measurements performed on a microwave GaAs oscillator show close agreement with the predicted results.

INTRODUCTION

One of the problems in oscillator circuit design is to obtain at steady state information such as oscillating frequency and output power levels of the fundamental component and harmonics. Previous reports on the design of oscillators are based on small-signal analysis, empirical method or by large signal s-parameters (1-3). The accuracy of these methods is often questionable and there is no information on harmonic content. Time domain simulators enjoy a wide range of applications, but the convergence of the numerical methods is a problem when the circuit contains widely varying time constants or distributed elements, resulting in lengthy computation times. Applying harmonic balance algorithms (4) in oscillator design has several difficulties. An oscillator, being an autonomous system determines its own frequency, power and harmonic content. A good initial guess of voltages and currents is almost impossible in this case. Direct use of harmonic balance techniques regarding frequency as a variable to be optimised, might have severe convergence problems and could be very inefficient. Furthermore, this method includes harmonic balance iteration which is very CPU time intensive. The new method presented here is based on Volterra series theory in the frequency domain which allows rapid computation of harmonic components. Volterra series analysis is more efficient than generalized harmonic balance algorithms because it requires neither Fourier transformation nor iteration [5-7]. An efficient algorithm is proposed to solve the resulting nonlinear equations iteratively. This new technique is highly stable and reliable with respect to convergence properties. A user-friendly CAD package for oscillator design has been developed based on this method.

PROBLEM FORMULATION

A typical oscillator circuit is shown in Figure 1. The method presented here converts the oscillator into a one port network by making a break somewhere in the circuit such as point A. The impedance (or the voltage across the break) looking into this port at the steady state condition has to be zero at the fundamental and at all harmonics. Using small signal analysis, the input impedance would have a negative resistance over a certain range of frequencies.

The next step is to excite the network by a current source at some assumed frequency ωo as in Figure 2. An ideal impedance is connected in parallel with the source. This impedance should have infinite value (open circuit) at the fundamental and zero value (short circuit) at other harmonic frequencies (including D.C.). Due to the presence of nonlinearities inside the circuit, the input impedance is now a function of the driving current level I and the angular frequency of excitation ωo ($2\pi f_o$). The Volterra series representation of this nonlinear impedance can be expressed as,

$$\begin{aligned} Zin(\omega o, I) = \; & Z_1(\omega o) \; + \\ & 0.75\; Z_3(\omega o, \omega o, -\omega o)\, I^2 \; + \\ & 0.625\; Z_5(\omega o, \omega o, \omega o, -\omega o, -\omega o)\, I^4 + \cdots \end{aligned}$$

where Z_1, Z_3, Z_5 are the first-, third- and the fifth-order Volterra kernels in the frequency domain. Note that the first order kernel is simply the input impedance of the linear circuit. The kernels of a system with power-series-type nonlinearity can be obtained very efficiently by the nonlinear current method. This approach is believed to be much more straightforward than the one proposed in (8) which requires the breaking of a single-loop circuit and the description of the high-order nonlinear transfer function of the determining equation in terms of the basic Volterra kernels. Here, the only requirement is to match the nonlinear input impedance of the one-port network to the known impedance (short-circuit). This is achieved by applying a current to the circuit and adjusted both the amplitude and frequency until the voltage is zero.

AN ALGORITHM FOR SOLVING THE PROBLEM

The oscillator problem is now reduced to a nonlinear

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equation with two unknowns (ωo and I). An algorithm has been developed for solving the equation Zin(ωo, I) = 0 and will be described as follows:

1. Set $I_k = 0$ and ωo equal to the resonant frequency of the linear circuit.

2. Search for ωo such that
   Im [Zin (ωo, I_k)] < a pre-defined small value

3. Using the value of ωo obtained in step 2, solve for I_{k+1}

$$I_{k+1}^2 = \frac{-\text{real}\ \{\ Z_1(\omega o) + 0.625\ Z_5(\omega o, \omega o, \omega o, -\omega o, -\omega o)\ I_k^4 + \cdots \}}{0.75\ \text{real}\ \{\ Z_3(\omega o, \omega o, -\omega o)\ \}}$$

4. Update I_k such that

$$I_k = p\, I_{k+1} + (1 - p)\, I_k \qquad \text{where } 0 < p < 1$$

5. Go back to step 2, until
   Zin(ωo, I_k) < a pre-defined small value

6. Compute the output power level of the fundamental and harmonics, etc.

Often the oscillating frequency ωo would be very close to the value of the resonant frequency obtained from linear circuit analysis, therefore computation in step 2 can be achieved quite easily by any iterative method such as the mid-point method. The updating method used in step 4 is especially effective for nonlinear system with only two unknowns. The typical value of p is 0.25 . Once the resonant frequency and the value of I are determined the output power level of the fundamental and the harmonics can be calculated with ease. Another advantage of the proposed method is its reliable convergence nature. Since there are only two variables in the problem, the possibility of convergence to local minima is eliminated. Therefore, when the solution converges, it should always converge to the correct solution. This technique is ideally suited to nonlinear oscillator analysis but is limited in its ability to deal with strong nonlinearities. This limitation is due to the algebraic complexity involved with Volterra nonlinear transfer functions of order greater than three. Therefore, a computer program based on the above method is written which will perform circuit analysis and Volterra kernels computation of any order. The program formulates and solves the circuit numerically using nodal analysis. The user need only write a separate input file which is very similar to a SPICE circuit file. The first-order voltages are simply the response of the linear circuit. The second order nonlinear currents are found from the mixing products of the first-order responses. The second-order node voltages are then obtained by solving the linear network's admittance equations with the second-order source currents used as excitations. The process is repeated to find the third- and higher-order node voltages. One need not evaluate all the harmonic components; it is necessary to evaluate and retain the first few components that are significant. By doing so, the computations can be performed very rapidly.

DESIGN OF GAAS MESFET OSCILLATORS

A nonlinear model for the GaAs MESFET is shown in Figure 3. The values of the linear circuit elements given in Table 1, are determined by optimization using the s-parameters measured over a wide range of frequencies of the device NE71000 at a single bias point. Most of the distortion arises from the nonlinear dependence of the drain current on gate and drain bias; to a lesser extent it stems from the nonlinear bias dependence of the gate diode conduction characteristic and the gate-source capacitance. The nonlinearities of the gate-drain feedback capacitance and the drain-source capacitance are considered to be small compared to the other nonlinearities.

The nonlinear drain current exhibits a significant dependence on the bias voltages and can be expressed as a power series around the operating point. The power series for the drain nonlinearity of the MESFET NE71000 is given by:

$$Ids = 50.1\ vgs + 4.89\ vgs^2 - 28.65\ vgs^3 - 2.13 vgs^4 + 6.75\ vgs^5 \quad (mA)$$

The coefficients of the series are obtained by curve fitting the polynomial to the measured data. The data is taken along the load line as shown in Figure 4. The slope of the load line can be found by linear circuit analysis. In principle, the drain current should be expressed as a function of both gate and drain voltages and resulting in a two-dimensional polynomial equation (5). However, this will increase the program complexity and hence lower computational efficiency.

The forward conduction of the gate diode has a dominant effect on the limiting of voltage swing across the gate diode. The current-voltage characteristic of the gate schottky diode of the MESFET can be expressed as,

$$I_{gs} = I_s \exp(\alpha\ vgs) - I_s$$

where I_s and α are the fitting variables.

The expanded and truncated power series of the above equation is given by,

$$I_{gs} = 0.21\ vgs + 0.441\ vgs^2 + 0.617\ vgs^3 + 0.648 vgs^4 + 0.545\ vgs^5 + 0.381\ vgs^6 + 0.229\ vgs^7 + 0.1201 vgs^8 \quad (mA)$$

EXPERIMENTAL RESULTS

The microwave FET oscillator shown in Figure 5 is used to verify the theoretical predictions. In addition, an optimum design has been realized by suppressing the output power levels of the second and third harmonics. Of course, this can be done in many different ways, in our case, the length of the transmission line has been optimized to achieve low harmonic content. Computer simulations show that the length of the line should be about 0.7 of a quarter wavelength for best suppression of the harmonics. The oscillating frequency and the output power levels of the constructed oscillator are measured using a HP8555A spectrum analyzer and HP5343A frequency counter.

The small discrepancies between the predicted and the experimental results tabulated in Table 2 show that the proposed method provides a powerful tool for the analysis of nearly sinusoidal oscillators. The influence of the nonlinearity in Cgs on the power performance of a circuit, in which a MESFET is terminated in 50 ohms, has been investigated by the authors using a simulator based on the frequency domain(9) harmonic balance technique and also by other researchers (10). The results suggested that the nonlinear capacitor plays an important role in modifying the production of second and third harmonic components, especially at high power levels. This might expain the discrepancies between the computed and measured data of the second and third harmonic power levels. The accuracy we have achieved in the simulations is good enough for most oscillator designs.

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Figure 1 Typical oscillator configuration

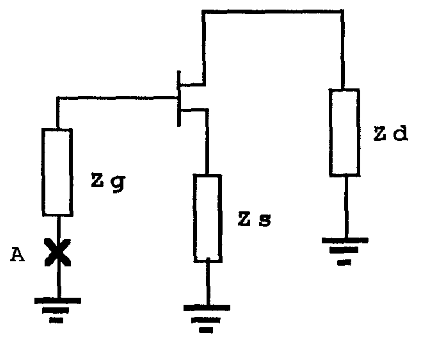

Figure 2 The oscillator is transformed into an one-port network plus an ideal impedance across the port

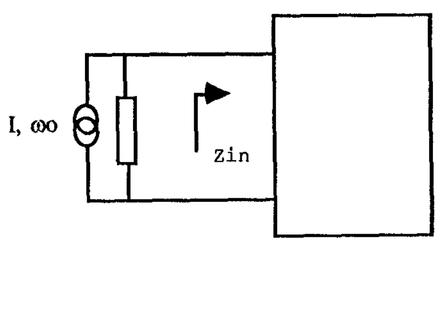

Figure 3 Nonlinear model of MESFET

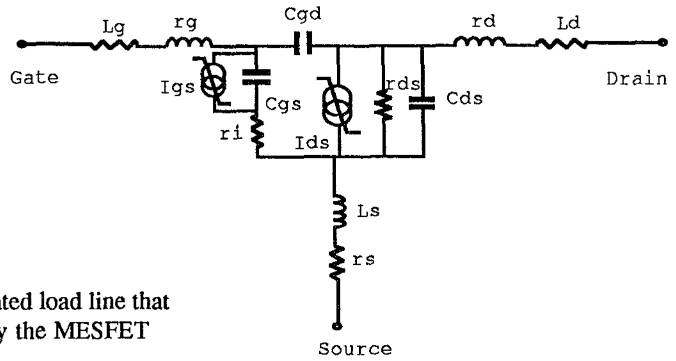

Figure 4 Approximated load line that is taken by the MESFET

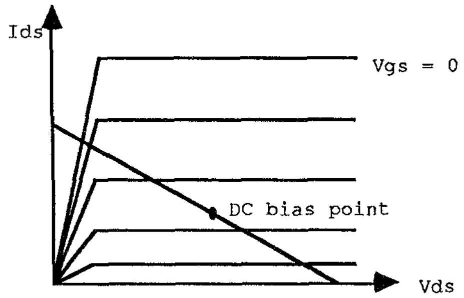

Figure 5 Oscillator Circuit

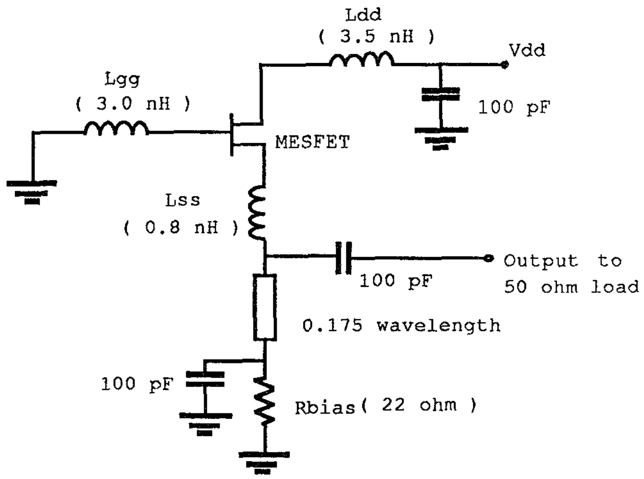

Table 1 Extracted values of linear element

Lg	0.01 nH
Ld	0.01 nH
Ls	0.005 nH
rg	2.0 ohm
rd	2.0 ohm
rs	1.0 ohm
ri	5 ohm
rds	210 ohm
cgd	0.04 pF
cds	0.08 pF

Table 2 Comparision between computed and experimental results

	Predicted	Measured
Resonant Frequency	5.48 GHz	5.41 GHz
Ids	26.5 mA	24.0 mA
Vgs	-0.58 V	-0.53 V
Fundamental	8.3 dBm	8.6 dBm
1 st harmonic	- 15.5 dBm	- 17 dBm
2 nd harmonic	- 22.4 dBm	- 24 dBm