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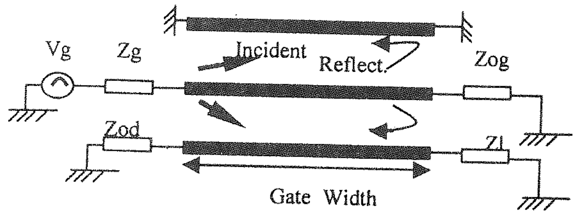

Figure (10) The configuration (excitation, extraction and loading) of a travelling wave FET.

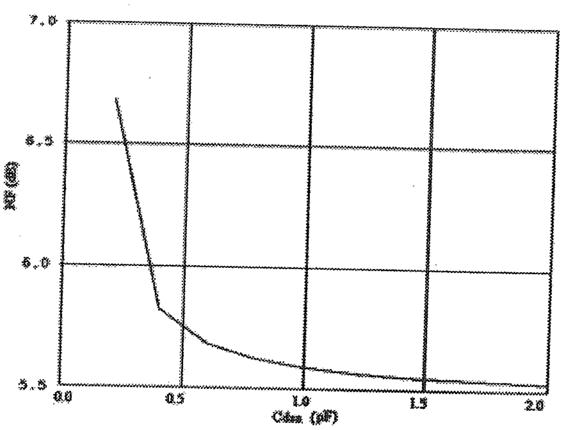

Figure (13) The influence of the added capacitance on the noise figure of the mixer

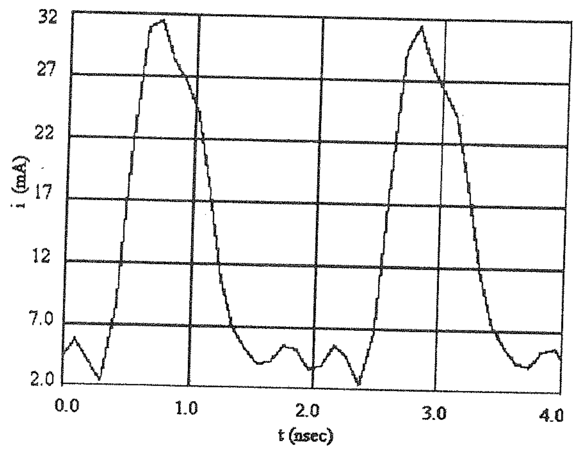

Figure (11) The drain current wavefrom of the last slice before filltering.

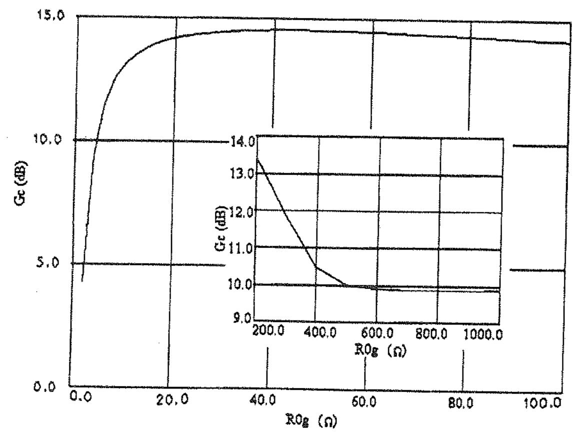

Figure (14) The influence of the gate load on the conversion gain of the mixer

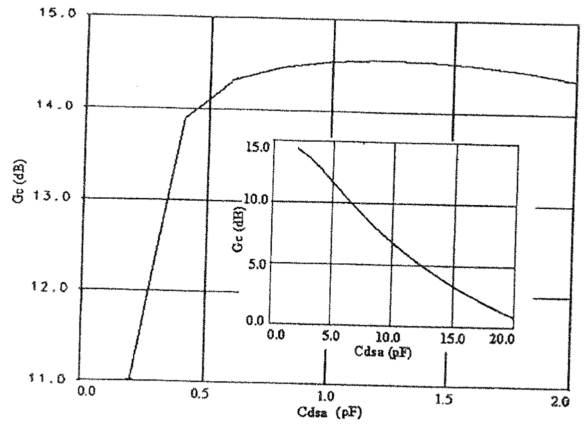

Figure (12) The influence of the added drain-source capacitance on the conversion gain of the mixer

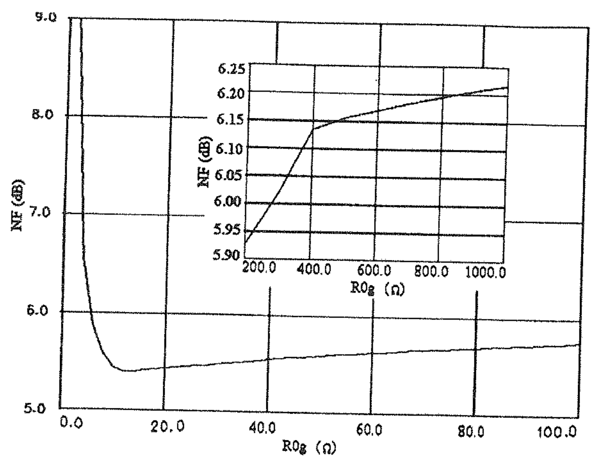

Figure (15) The influence of the gate load on the noise figure of the mixer.

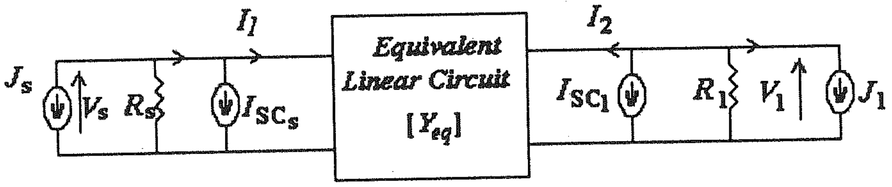

Figure (7) The equivalent circuit of the nonlinear noisy circuit.

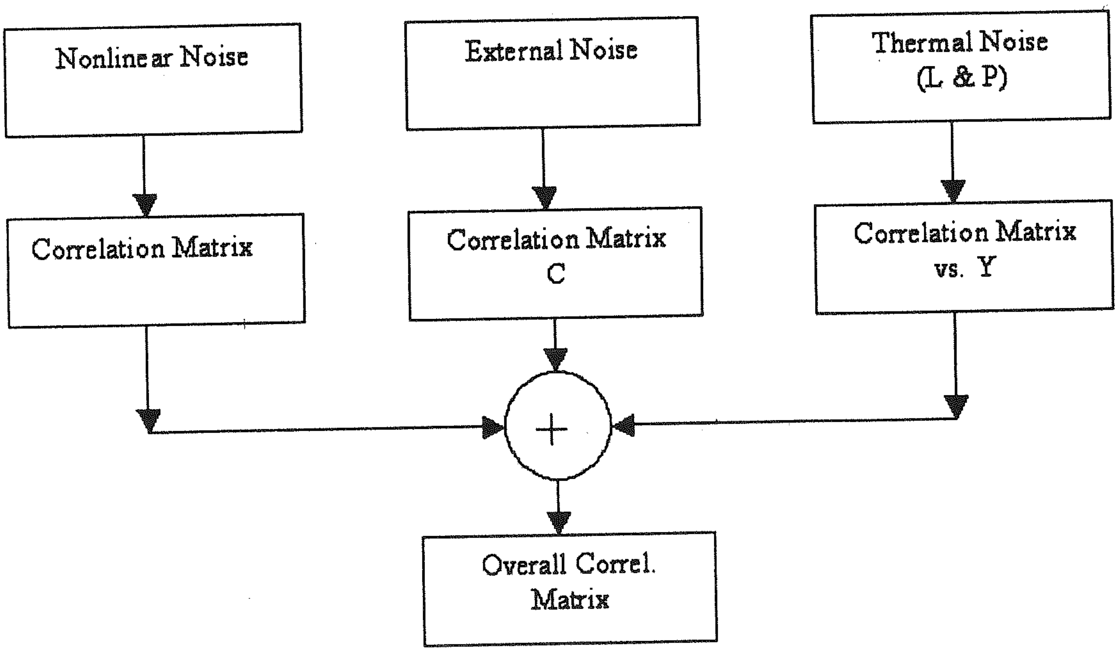

Figure (8) The flowchart for calculation of the noise correlation matrix (NCM).

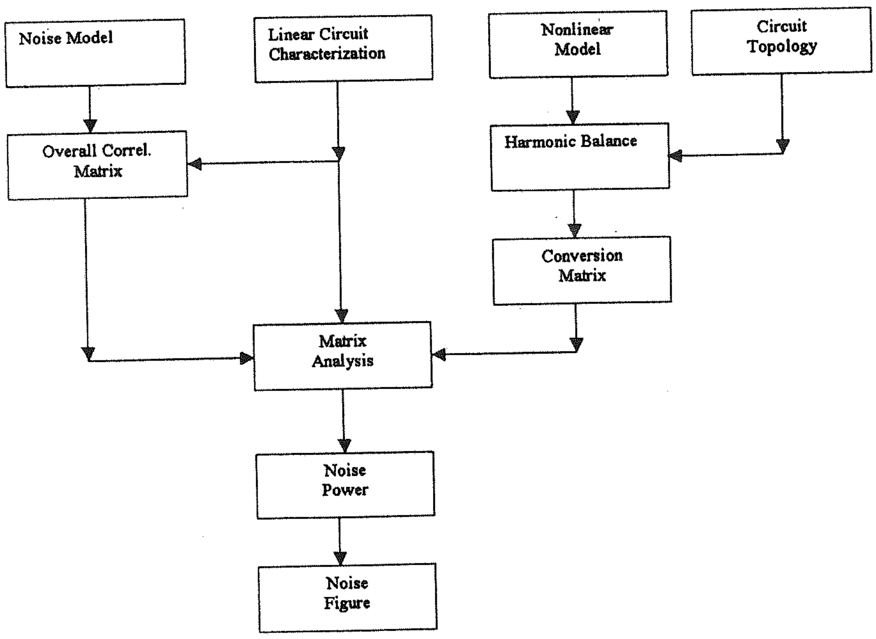

Fig. 9

Figure (9) The flowchart for calculation of the noise figure.

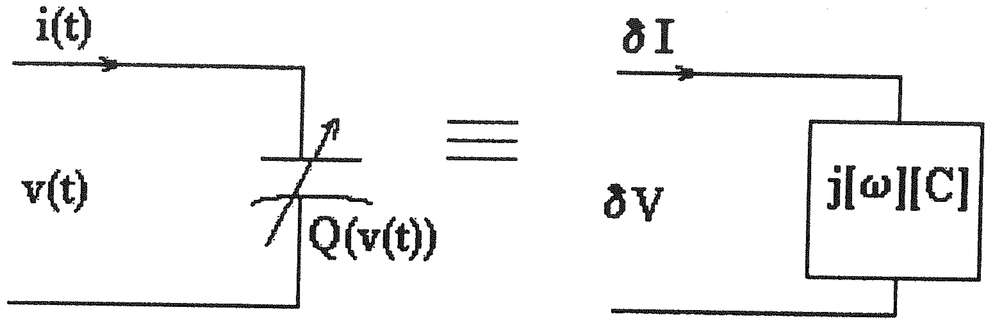

Figure (4) The parametric model of a nonlinear capacitor.

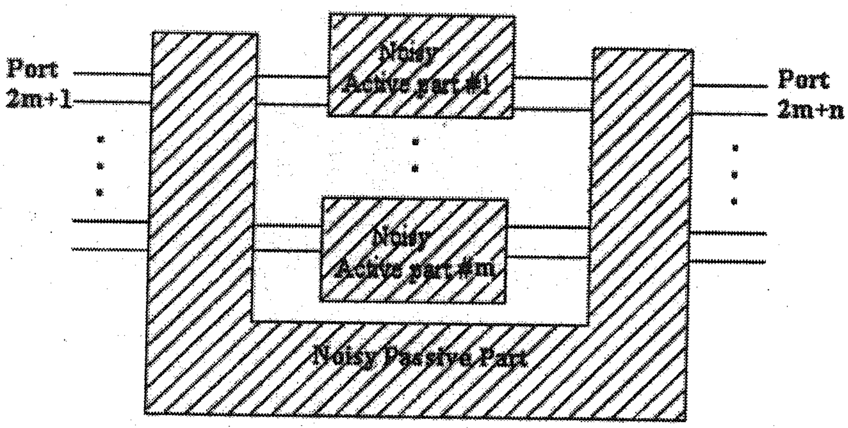

Figure (5) A general noisy nonlinear circuit containing both passive and active devices.

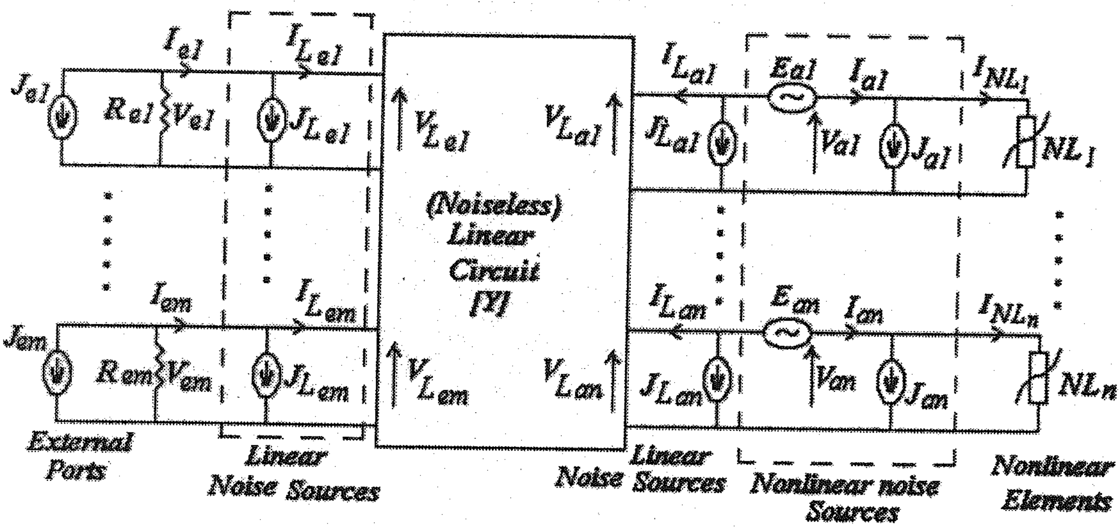

Figure (6) Simplified and rearranged model of Fig. 5.

mode conditions for FETs has been studied, which shows that phase synchronisation is approached by properly increasing the drain capacitance. Finally, the effect of matching of the FET electrodes in mixer application has been discussed. Using the sliced modelling of an FET, it has been shown that proper loading of the electrodes in the travelling wave mode excitation improves both signal and noise performances of a mm-wave FET mixer.

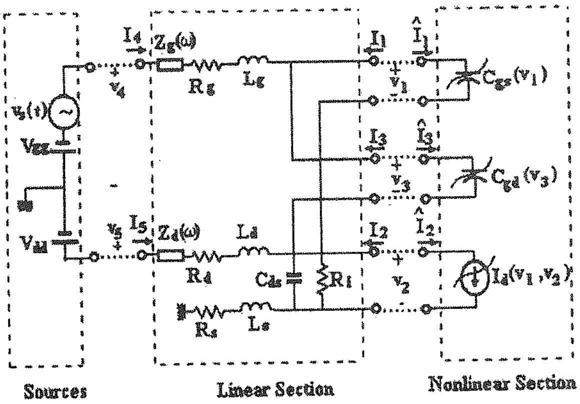

Figure (3) A simple FET model (together with the sources and loads) rearranged for applying the harmonic balance approach.

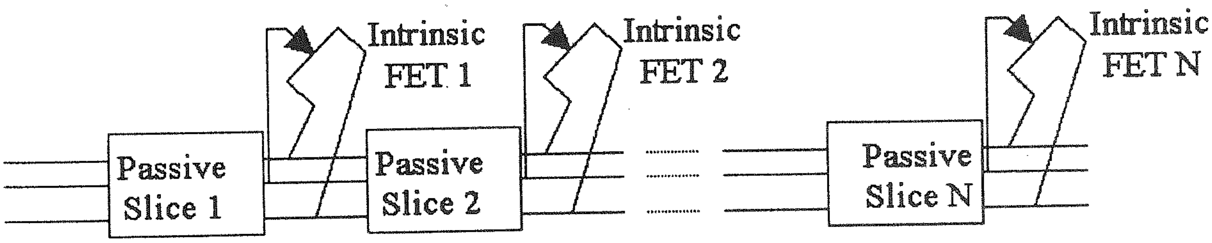

Figure (1) The sliced model of a (travelling wave) FET.

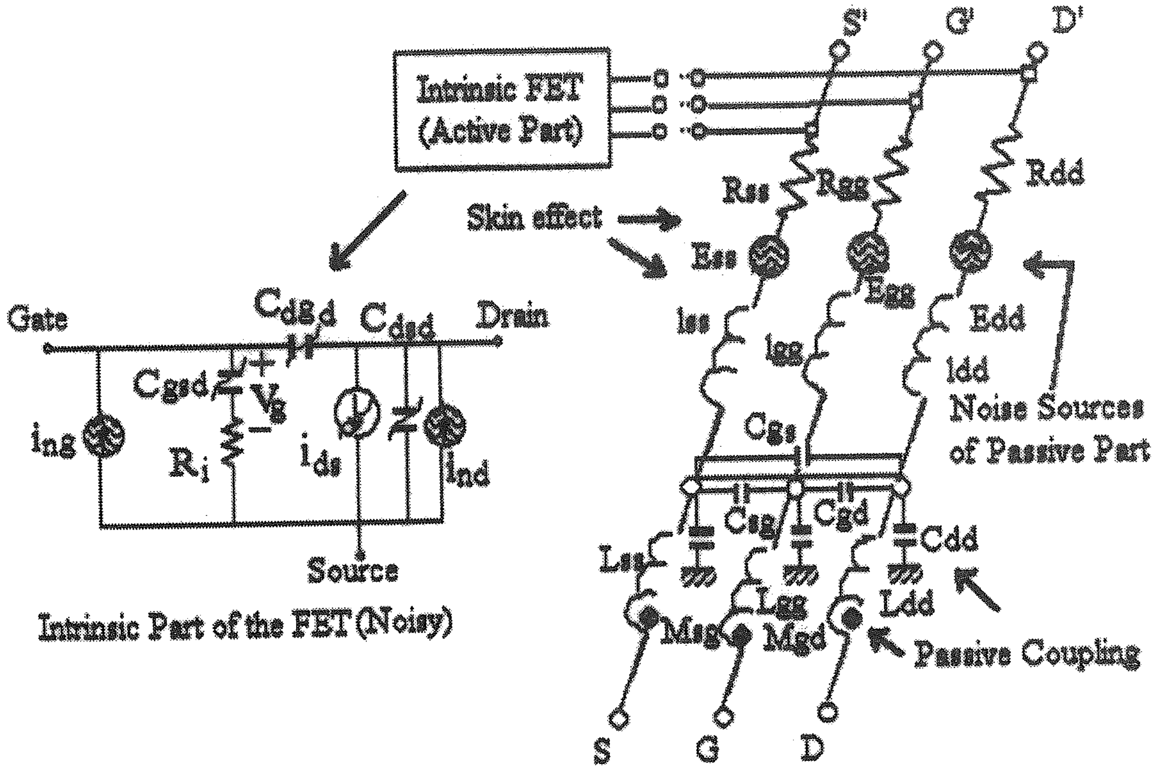

Figure (2) The lumped model for each slice of a noisy FET.

This, in turn, will degrade the device performances. To overcome the problem, the capactiance of the drain-source must be increased. This value is called the *added drain-source capacitance (Cdsa)* in this paper. By using the proper value of *Cdsa*, a travelling wave FET is obtained. In the continuation of the paper, the advantages of this device (i.e. travelling wave FET) in mixer application will be considered.

There are two ways for increasing the drain capacitance. In the general application of mm-wave circuits, the added capacitance is very small so that the capacitor can be implemented in the manufacturing process. This technique is suitable for the millimeter wave integrated circuits (MMWIC). Fortunately, in the most microwave mixer application, the necessary value of the added drain-source capacitance is large. This means that the capacitance can be externally increased between the drain and the source. Fortunately, this technique is applicable for usual (not travelling wave) mixers.

8-Results

Using the proposed model, the influence of added drain-source capacitance in the signal and noise performances of a mm-wave HEMT gate mixer is analysed. The RF frequency is 10.0 GHz, and the IF frequency is 0.5 GHz. Figure. 11 shows the drain current waveform of the last stage. Our study shows that the drain currents in different slices don't have great differences. However, exciting / extracting the signals from the middle of the FET electrodes lead to a considerable discrepancy among the currents of the different slices. Figure. 12 presents the main advantage of the travelling wave mixer. As it is shown, the conversion gain will be maximum for a proper increment in the drain source capacitance. By the rule of thumb, it is seen that for this value of the capacitance, the phase velocity of the drain is approached to the similar value of the gate. Fig. 13 shows the noise figure of the device versus added drain source capacitance, which introduces the improvement of the noise characteristics of the travelling wave mixer.

Besides, we have analysed the influence of proper electrode loading on the device perfomances. Figure. 14 shows the conversion gain of the device versus the value of the gate load, which clearly introduces the improvement of the signal characteristics of the travelling wave mixer. As it is obvious, because of short circuiting the signal by the small values of Rog (Zog in Fig. 10), the conversion gain will be decreased. For large values of the loads, as anybody anticipates, changing the load value does not have any effect on the device performances. The noise figure versus different values of the gate load is shown in Figure. 15, which proves that in spite of using an additional noisy device, the matching condition has improved the noise performances of the mixer.

At last, it is noticeable that the improvement of signal and noise performances of FET mixers has been proved practically for usual mixers, and is going to be performed for travelling wave mixers.

9-Conclusion

A novel sliced model for studying the performances of wide gate FET mixers has been discussed. Also a method for improving the simultaneous signal and noise performances of mm-wave mixers has been introduced. It has been shown that increasing the output capacitance of the FET in mixer application improves the conversion gain and the noise figure of the mixer. Travelling wave

Due to un-correlation of the linear noise sources, the previous equation can be reduced as:

$$C_{I_{sc}} = H_a C_{J_a} H_a^{*t} + H_a C_{JaEa} T_a^{*t} + T_a C_{EaJa} H_a^{*t} + T_a C_{Ea} T_a^{*t} + H_L C_L H_L^{*t} \tag{35}$$

in which C_x and C_{XY} refer to the autocorrelation function of X and cross-correlation function of X and Y, respectively. Besides, there is a relation between the output voltage and the short circuit current as:

$$V_e = - Z_L I_{SC} - Z_L J_e \tag{36}$$

which leads to the following relation for the noise correlation matrix of the output voltage:

$$<V_e V_e^{*t}> = Z_L C_{I_{sc}} Z_L^{*t} + Z_L C Z_L^{*t} \tag{37}$$

Since there are two external ports i.e. the source and the load ones, we can express the previous equation as:

$$<V_e V_e^{*t}> = < \begin{bmatrix} V_s \\ V_l \end{bmatrix} [V_s^{*t} \quad V_l^{*t}]> = \begin{bmatrix} \overline{|V_s|^2} & \overline{V_s V_l^{*t}} \\ V_l V_s^{*t} & |V_l|^2 \end{bmatrix} \tag{38}$$

Note that each element of the matrix by itself has 2N+1 elements as:

$$<V_l V_l^{*t}> = <[V_{l_{-N}}^*, V_{l_{-N+1}}^*, \ldots, V_{l_{-1}}^*, V_{l_0}, \ldots, V_{l_N}]^t [V_{l_{-N}}, V_{l_{-N+1}}, \ldots, V_{l_{-1}}, V_{l_0}^*, \ldots, V_{l_N}^*]> \tag{39}$$

In which:

$$V_{l_{-N}} = V_l^* (N\omega_0 - \Omega) \tag{40}$$

$$V_{l_{+N}} = V_l (N\omega_0 - \Omega) \tag{41}$$

$$V_{l_0} = V_l (N\omega_0) \tag{42}$$

At last the noise figure of the circuit for mixer application is calculated as:

$$F(\omega_{IF}) = \frac{|V_U(\omega_0 - \Omega)|^2}{4K T_0 G_c(\omega_{RF}) R_0} \tag{43}$$

The flowcharts for calculation of the noise correlation matrix and the noise figure are shown in Figs. 8 and 9.

In the continuation of the paper, the illustrated procedure will be applied to the sliced model of travelling wave FET in mixer application.

7-Travelling Wave Mixers

In the slice model, there is this capability that the excitation of the gate can be applied from any point on it. Besides, it can be excited from several points. The same argument is valid for extraction of signal from the drain. Besides, any desired element can be added to each point on the gate or the drain. It is obvious that in usual microwave FETs, the input/output signal is entered/extracted from the middle of the gate/drain. However, in the travelling wave FETs [12-13] the input signal is applied from one end of the gate and the output is extracted from the opposite end of the drain as shown in transmission line model of the FET in Fig. 10.

Besides, for the efficient power transmission, the lines must be matched, i.e. the unused ends of the gate and the drain must be properly terminated. There is another necessity for the efficient performances of a travelling wave FET. Since the gate capacitance is much more than that of the drain, the phase velocity of the wave under the gate is different from the phase velocity of the drain. This imbalance in the phase velocity leads to dispersion and reflection.

voltage at sideband no. q to the current at sidband number p. The indices p and q refer to the number of the active device and the number of the command signal. A matrix representation of the above equation is given by:

$$I_a = M_T \cdot V_a + J_a \tag{20}$$

in which M_T is the global conversion matrix of the nonlinear circuit and $I_a = [I_{a1}, I_{a2}, \ldots, I_{an}]^t$. Since we are searching for the noise response of the circuit, the short circuit current ($I_e = I_{SC}$) in the external port (s) can be calculated by setting Ve=0. Now the relations (17) and (18) can be rewritten as:

$$-I_a = [Y_{aa}]V_a - [Y_{aa}]E_a + J_{La} \tag{21}$$

$$I_{SC} = I_e = [Y_{ea}]V_a - [Y_{ea}]E_a + J_{Le} \tag{22}$$

From (20) and (21), the voltage vector of active part i.e. V_a is expressed as:

$$V_a = -[[MT] + [Y_{aa}]]^{-1}(J_a + J_{La} - Y_{aa}E_a) \tag{23}$$

Putting this equation into (22) leads to the output short circuit current:

$$I_{SC} = [H_a]J_a + [H_L]J_L + [T_a]E_a \tag{24}$$

In which we have:

$$[H_a] = -[Y_{ea}][[MT] + [Y_{aa}]]^{-1} \tag{25}$$

$$[T_a] = -[Y_{ea}]\{[[MT] + [Y_{aa}]]^{-1}[Y_{aa}] - I_m\} \tag{26}$$

$$[H_L] = [H_a \;\; | I_m] \tag{27}$$

For calculating the equivalent admittance matrix (Yeq) seen from the output, we have to null the sources i.e. $J_{le}=0$, $J_a=0$, $J_{la}=0$ and $E_a=0$. Rewriting equations (17), (18) and (20) yields:

$$-I_a = [Y_{aa}]V_a + [Y_{ae}]V_e \tag{28}$$

$$I_e = [Y_{ea}]V_a + [Y_{ee}]V_e \tag{29}$$

$$I_a = M_T \cdot V_a \tag{30}$$

From (29) and (31) we obtain:

$$[V_a] = -[[MT] + [Y_{aa}]]^{-1}\, Y_{ae}\, V_e \tag{31}$$

Using (30) and (32), the equivalent admittance (m x m) matrix is calculated as:

$$Y_{eq} = H_a\, Y_{ae} + Y_{ee} \tag{32}$$

The equivalent circuit of the system is shown in Fig. 7.

g- Calculate the noise correlation matrix of the output current and the noise figure. Due to statistical nature of noise sources, we must calculate the noise correlation matrix, which interprets the correlation among the different noise sources.

For the linear subcircuit, there is a simple relation between the noise correlation matrix and the signal matrix (e.g. admittance matrix) as:

$$C_J = \langle J_L\, J_J^{*t} \rangle = 2KT\Delta f\,([Y] + [Y]^{*t}) = \begin{bmatrix} C_{Ja} & C_{Jae} \\ C_{Jea} & C_{Je} \end{bmatrix} \tag{33}$$

For the circuit containing nonlinear parts, the noise correlation matrix for the equivalent short circuit currents can be calculated by:

$$C_{I_{sc}} = \langle I_{SC}\, I_{SC}^{*t} \rangle = (H_a J_a + H_L J_{La} + T_a E_a)(H_a J_a + H_L J_{La} + T_a E_a)^{*t} \tag{34}$$

signal in frequency domain.

b- Calculate xc(t) using the inverse Fourier transform of Xc(f)

c- Calculate the time-varying equivalent circuit of the nonlinear elements.

d- Calculate the coefficients of Fourier series of g(t) (found in the last step), which are called g_n's.

e- Characterize the linear subcircuit. For linear analysis, several equivalent representations such as impedance, admittance and scattering approach can be used. Taking admittance approach, we will continue the procedure. The relation between the current and voltage vectors is as:

$$I_L = [Y]\, V_L \tag{8}$$

in which I_L can be divided into two active and external parts as:

$$I_L = [I_{La1}, I_{La2}, \dots I_{Lan} \,/\, I_{Le1}, I_{Le2}\,, \dots I_{Lem}]^t = \left(\frac{I_{La}}{I_{Le}}\right) \tag{9}$$

A similar expression is valid for V_L. Each element of I_L (and similarly of V_L) by itself is a vector containing the currents in all desired frequencies. For the port number i, the current vector of active (x=a) or external (x=e) ports can be expressed as:

$$I_{Lxi} = \begin{bmatrix} I_{Lxi}(N_{\omega_0} - \Omega) \\ \vdots \\ I_{Lxi}(\Omega) \\ \vdots \\ I_{Lxi}(N_{\omega_0} + \Omega) \end{bmatrix} \tag{10}$$

in which ω_0 and Ω are the signal and noise frequencies, respectively.

The admittance matrix can be straightforwardly expressed as:

$$Y = \begin{bmatrix} Y_{aa} & Y_{ae} \\ Y_{ea} & Y_{ee} \end{bmatrix} \tag{11}$$

In this matrix, Y_{aa}, Y_{ae}, Y_{ea} and Y_{ee} are submatrices of dimension nxn, nxm, mxn and mxm, respetively.

f- Derive the system equations. Here we are searching for equivalent admittance matrix and following it the noise correlation matrix for noise analysis. These equations are directly extracted from the basic circuit equations and the conversion matrix. For the linear part, from (8), (9) and (11) we have:

$$\begin{bmatrix} I_{La} \\ I_{Le} \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ae} \\ Y_{ea} & Y_{ee} \end{bmatrix} \begin{bmatrix} V_{La} \\ V_{Le} \end{bmatrix} \tag{12}$$

By a glance to the Fig. 6, the following Khirchoffs equations can be obtained:

$$V_{La} + E_a = V_a \tag{13}$$

$$V_{La} = V_e \tag{14}$$

$$- I_a - J_{La} = I_{La} \tag{15}$$

$$I_e - J_{Le} = I_{Le} \tag{16}$$

Combining equations (12) thru (16) leads to:

$$- I_a = [Y_{aa}]\, V_a + [Y_{ae}]\, V_e - [Y_{aa}]\, E_a + J_{La} \tag{17}$$

$$I_e = [Y_{ea}]\, V_a + [Y_{ee}]\, V_e - [Y_{ea}]\, E_a + J_{Le} \tag{18}$$

For the nonlinear part, the current in each frequency is a function of the current in other frequencies i.e.:

$$I_{ap} = \sum_q M_{pq}\, V_{aq} + J_{ap} \tag{19}$$

Mpq is the conversion function from the

will be stopped and the harmonic balance approach will be finished. The signals in the last iteration are used to calculate any desired signal in the circuit.

5-Conversion Matrix Approach

The most common approach for analysis of nonlinear circuits which pumped with one large sinusoidal signal and one small signal is large-signal-small-signal analysis. In this method, at first, the small signal excitation is ignored, and the large signal regime is analyzed using a suitable method such as the harmonic balance approach. Then the nonlinear elements are converted to time-dependent quasi-linear small signal elements. At the next step, the small signal analysis is performed by ignoring the large signal excitation.

Obtaining the time varying relation is done by a perturbation analysis. Here as the most usual case, the procedure is presented for a nonlinear capacitor. If the nonlinear capacitor is introduced by:

$$Q(t) + \delta q(t) = f(v(t) + \delta v(t)) \tag{4}$$

It is easily seen that:

$$\delta q(t) = C(t).\ \delta v(t) \tag{5}$$

In which $C(t) = \frac{\partial f}{\partial v} |_{v(t)}$ shows a linear time-varying capacitor used for modeling the nonlinear capacitor under small perturbation. Since we are interested to the I-V relation of the different elements, we must change q(t) to i(t) which leads to the following equation:

$$\delta i(t) = C(t) \frac{\partial(\delta v(t))}{\partial t} + \delta v(t) \frac{\partial C(t)}{\partial t} \tag{6}$$

Applying Fourier approach to this equation, the vectors of frequency domain currents and voltages are related together as:

$$[\delta I] = j[\omega]\ [C]\ [\delta V] \tag{7}$$

[C] is the conversion matrix of C(t) and containing its Fourier coefficients. As a result, the time-varying capacitor is modeled by a linear multifrequency admittance as shown in Fig. 4.

Applying a similar procedure for each nonlinear element leads to a linear multifrequency equivalent circuit known as the parametric model of the nonlinear circuit. The solution procedure is just similar to the solution method of linear circutis.

By combining the results of large signal and small signal analysis, we can obtain any desired signal at each side-band frequency. Therefore different signal characteristics such as conversion gain can be calculated. More details of this method can be found in [2, 3].

6-Noise Analysis of the mixer

Noise analysis of the nonlinear circuit is performed after signal analysis and calculation of the conversion matrix. Fig. 5 shows a noisy nonlinear circuit containing both passive and active devices. The noise sources can be transferred to the external ports as shown in Fig. 6. Note that in some cases, it is necessary to add additional ports for noise sources. In Fig. 6. J and E refer to the noise current and noise voltage sources, respectively. The subscripts e, a, N and NL refer to the external ports, active deviec, linear part and nonlinear elements, respectively. The subscripts m and n shows the number of the external ports and the number of nonlinear elements, respectively. Obviously m is usually equal 2.

Now, the procedure can be stated in several steps.

a- Consider Xc(f) as the initial command

In the next sections of this paper, we will follow an algorithm for analysing both signal and noise performances of the sliced FET in mixer application.

4-Harmonic Balance Approach

There are several time and frequency domain methods to analyze a nonlinear circuit. The harmonic balance approach is the most powerful method in which the combination of both time and frequency domain techniques is used [2, 3]. In this method, the circuit is divided into two subcircuits, which one of them includes all nonlinear devices, and the other one is completely linear. These two subcircuits have N common ports. If one determines the signals on the common ports, other signals can be straightforwardly calculated. The linear circuit is analyzed using frequency domain methods, and the nonlinear part is analyzed in time domain. For conversion between time and frequency domain signals, the Fourier transform relations can be applied.

To have a better understanding of the harmonic balance approach, consider the sample circuit of a single FET bisected in two linear and nonlinear parts (Fig. 3.)

For the linear section, we have a simple relation between the vector of the currents (I's) and the vector the voltages (V's) in the common section, which is the Norton equivalent relation I=YV+Is. Y is the admittance matrix of the linear section, and Is is the vector of equivalent current sources. It is noticeable that these signal vectors i.e. V's and I's are calculated in all harmonics of the large signal frequency.

For the nonlinear section we have a time domain relation as $i_{NL}=f\ (v(t))$. This can be converted using Fourier transform to $I_{NL}=YeqV$. It must be emphasized that this equation is in matrix from i.e. we have a set of relations for each frequency. Due to KCL in the interconnection of the linear and the nonlinear parts, we must have:

$$F\ (V) = I_L\ (V) + I_{NL}\ (V) = 0 \qquad (1)$$

which can be written in a detailed form as [3]:

$$F(V) = Is + YV + j\Omega Q + I_G = 0 \qquad (2)$$

F(V) is known as the error function because the solution will be obtained if F(V) is zero. In the previous equation, Q is the charge vector of the common port signals, which is used to model the nonlinear capacitors, and Ω is the diagonal matrix of the harmonics of the large signal frequency. I_G is the current vector of the nonlinear conductances calculated using the Fourier transform of the known equivalent temporal relation.

Equation (2) is solved using an iteration method. One of the most suitable solution methods is the Newton's approach containing the following iteration formula:

$$V^{p+1} = V^P - \left(J_F\ (V^P)\right)^{-1}\ F\ (V^P) = 0 \qquad (3)$$

In this equation, $J_F(V^P)$ is the Jocobian of F(V) and its elements can be seen in [3].

For the first trial or iteration of the solution, we set an initial estimate for the signals of the common ports. Having v(t), we can calculate the Fourier domain voltages and also both the frequency and time domain currents of the linear and nonlinear parts. Then after calculating the Jocobian, the next iteration of (3) will be done. The error function (2) in each step is calculated and compared to a pre-set value. If the error is small enough, the iteration the travelling wave structure, one must take into account the wave propagation effect. In other words, a transmission line modelling must be applied to the device analysis to increase the accuracy. There are a few works on distributed modelling of FETs in linear regime [14], and fewer papers on nonlinear distributed modelling [15-16], which none of them considers the travelling wave mode.

Using a distributed model for a FET, we have analysed simultaneous signal and noise modelling of a distributed FET mixer. We have focused on the role of increasing the capacitance of the drain electrode on the device performances. The results show improvement in conversion gain and noise figure of the mixer. Also, we have considered the effect of electrode loading in the device characteristics. It is noticeable that, in our model, the excitation of the FET is from one end of the gate and the extraction of the signal is from the opposite end of the drain. The other ends of the electrodes have been terminated with proper loads to make the device a travelling wave structure. Due to decreasing the reflections of signals from the electrode loads, good stabillity is obtained. Finally, since the gate width can be large, the mixer can tolerate higher power than usual FETs. In the next sections, we will briefly argue on distributed modelling. Then the basic procedures for harmonic balance approach will be discussed. Simultaneous signal and noise analysis of a nonlinear circuit will be presented. And finally the idea of a travelling wave mixer and some results on its performances will be proposed.

2-Necessity of the Distributed Modelling

From the classical transmission line theory, one knows that usual circuit laws and models are applicable for the lumped elements. For FET analysis, if the gate width is comparable to the opearating wavelength, the distributed model must be used. The maximum gate width in usual FETs is up to 200 microns. Therefore, the lumped model seems to be sufficiently accurate up to the mm-wave range. However, for a nonlinear device this is not true, because the generation of higher frequencies makes the device size comparable to the wavelength. Therefore, the distributed modelling seems to be necessary. In the following sections, we will apply the sliced model to the device.

3-The Distributed Modelling

Similar to the linear distributed modelling [14], we can consider the FET electrodes as transmission lines, which have both passive and active couplings. The FET is cut into small pieces, so that in each section, the lumped modelling can be used. The sliced model can be expressed as a cascade connection of passive and active devices as shown in Fig. 1. The simple equivalent circuit of each slice is shown in Fig. 2. Each slice has a passive part including the coupling elements and the skin effect elements. Besides, each slice contains an intrinsic part, which is both active and nonlinear. Meanwhile, both the passive and the active parts are noisy. Noise sources of resistors in passive parts are thermal, which can be easily expressed by their Norton equivalent noise sources. For active part, the equivalent noise sources at the ports of each slice can be considered. Calculation of the passive elements of each slice is performed using the scaling rule [14] for linear part, and following [15, 16] for the nonlinear part. Of course, the idea expressed in [16] for the Tajima model, can also be applied for the Curtice model [1].

Simultaneous Signal and Noise Analysis of a Travelling wave FET Mixer

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Abstract

A novel kind of microwave mixer is introduced which its operation is based on travelling wave mode. It is shown that increasing the drain-source capacitance of a FET will simultaneously improve the conversion gain and the noise figure of the mixer. Besides, It is shown that exciting the input signal from one end of the gate electrode and extracting the output signal from the opposite end of the drain electrode can improve the device performances, provided that two remaining ends of the gate and the drain are properly loaded. The analysis is performed using sliced modeling of active circuits. This structure can be used in high power application because it is specially used for FETs with large gate width. Also due to the travelling wave structure, it is useful for wideband circuits. This idea can also be applied to analyse and improve the signal and noise performances of other microwave and mm-wave integrated circuits.

KeyWords

FET Mixer, Nonlinear Signal and Noise Modelling, Travelling Wave FET, mm-Wave Analysis Techniques

1- Introduction

An active mixer has been used as one of the main parts of modern microwave and millimeter wave systems such as mobile and satellite communication circits. The need for better performances of these systems demands for accurate design and analysis of the subcircuits especially for the nonlinear parts such as mixers. Active mixers are usually designed by GaAs MESFETs and HEMTs. There are several works on signal analysis (e. g. the conversion gain and stability) of FET mixers [1- 4]. However, there are fewer works on noise analysis of FET mixers [5-10], that the best ones belong to Rizzoli and his co-workers [6-8]. Their method is based on the noise correlation matrix. They define a modulation function relating the DC noise measurements to obtain some noise parameters. Besides, there are a few papers on approximate analytical methods for noise analysis of active mixers [11].

The upper mentioned works focus on usual application of FET mixers. For mm-wave, high power and wide band applications of FETs, the idea of travelling wave transistors [12-13] has been introduced and the measurements have shown some better capabilities of this device [13]. To consider