A DESIGN TECHNIQUE FOR MESFET MIXERS BASED ON SPICE PROGRAM

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ABSTRACT

A design technique for MESFET mixers is described. This technique is based on a mixer analysis program (MIXAN) developed to obtain the value of conversion gain and optimum source and load impedances for any local oscillator power and DC bias. (MIXAN) program uses SPICE as a "subrotine" to determine large-signal current and voltage waveforms. In accordance, with MIXAN program is possible to obtain the operating conditions for maximum conversion gain. The good agreement between experimental and theoretical values for X band drain and gate mixers prove the validity of the design technique.

INTRODUCTION

A design procedure for MESFET mixers based on the non-linear/linear analysis technique [1] is presented. The approach is similar to the design technique previously proposed by the authors for diode mixers [2], which led to the implementation of a first version of the MIXAN program (MIXers ANalysis).

The non-linear analysis is based on the wide-spread non-linear CAD program SPICE. The time domain analysis of the circuit is called to obtain the voltage and current waveforms when the MESFET is pumped by the local oscillator (LO).

The global mixer characteristics, such as conversion gain (G_c), input impedance (Z_{in}) at radio-frequency (RF) and output impedance (Z_{out}) at intermediate-frequency (IF), are then calculated by the program MIXAN. More elaborated auxiliary routines had to be developed and added to the MIXAN program, in order to accommodate the two port configuration of MESFETs.

Based on the results produced by the program a design technique was developed for the two most common MESFET mixer topologies: **gate-mixer** (local oscillator connected between gate and source) based on the $i_D(v_{GS})$ non-linear characteristic at saturation region ($v_{DS}>v_{DSS}$); and **drain-mixer** (local oscillator connected between drain and source) based on the $i_D(v_{DS})$ non-linear characteristic at triode region, near the knee (low v_{DS}).

In order to acertain the validity of the mixers analysis two 11GHz - 1GHz converters were designed and implemented in microstrip technology with soft substrate. The comparison between measured and theoretical results of the two prototypes, one of each MESFET mixer topology, shows a good agreement what proves the usefulness of the propose method as a design aid.

MESFET MODEL AND NONLINEAR ANALYSIS

For the non-linear analysis of the circuit the Curtice quasi-static large-signal model of the intrinsic MESFET [3], shown in Fig. 1, is used. This model is resident on several versions of SPICE available for PCs, as PSpice version 3.08 [4]. The model parameters are obtained by fitting the device characteristics to experimental data [5], namely DC output $I_D(V_{DS})_{V_{GS}}$ and transfer characteristics $I_D(V_{GS})$, and small signal S-parameters at three bias conditions choosen in accordance with the mixer topology. The nonlinear DC current source parameters are obtained from the DC characteristics and the S parameters are used to obtain the AC intrinsic capacitances and the parasitic elements of the packaged MESFET.

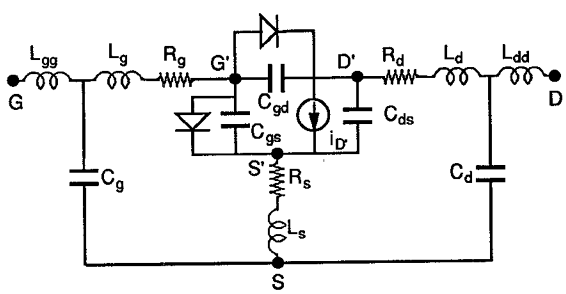

Fig. 1: MESFET nonlinear model.

In order to reduce computation time and avoid convergence problems, we have reduced, within the required accuracy, the number of non-linear elements in the model. For drain mixers, only the feedback capacitance C_{gd}, and the voltage dependent current source $i_{D'}(v_{G'S'}, v_{D'S'})$ were considered as non-linear. The input capacitance C_{gs}, the output conductance g_{ds} and the voltage dependent current source $i_{D'}(v_{G'S'}, v_{D'S'})$ were assumed as the only non-linear elements, for the gate mixer.

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According to the non-linear/linear analysis only the LO excitation is considered to obtain the waveforms of the control variables of the model non-linear elements ($v_{G'S'}$, $v_{D'S'}$).

Under RF small-signal conditions, the current source $i_{D'}$ is modeled by a voltage dependent current source $g_m v_{G'S'}$ and a conductance $g_{d's'}$. Since $i_{D'}(v_{G'S'},v_{D'S'})$ is a non-linear element both g_m and $g_{d's'}$ parameters are time dependent.

From the known waveforms of all control variable, we can write for each non-linear element (C_{gd}, C_{gs}, g_m and $g_{d's'}$) a time varying function, that can be described by its Fourier series:

$$x(t) = \sum_{n=-\infty}^{\infty} X_n \exp(jn\omega_0 t) \quad (1)$$

where

$$X_n = 1/2\pi \int_0^{2\pi} X(t) \exp(-jn\omega_0 t)\, d\omega_0 t \quad (2)$$

We assume that, the frequencies present in the mixer are given by

$$f_{n,m} = nf_0 + mf_s \quad (3)$$

where $-\infty \leq n \leq \infty$, m=0, ±1, and f_0 and f_s are the LO and RF frequencies, respectively.

According to this, all the magnitudes of currents and voltages in the circuit are of the form

$$x(t) = \sum_{m=-\infty}^{+\infty} \sum_{m=-1}^{+1} X_{n,m} \exp[j(n\omega_0 + m\omega_s)t] \quad (4)$$
$$= x_{LO}(t) + x_{MX}(t)$$

where $x_{LO}(t)$ is the local oscillator component of x(t),

$$x_{LO}(t) = \sum_{n=-\infty}^{+\infty} X_{n,0} \exp(jnw_0 t) \quad (5)$$

and $x_{MX}(t)$ denotes the small-signal mixing products

$$x_{MX}(t) = \sum_{n=-\infty}^{+\infty} \sum_{m=-1}^{+1} X_{n,m} \exp[j(n\omega_0 + m\omega_s)t] \quad (m \neq 0) \quad (6)$$

Since all the magnitudes x(t) involved in the above expressions are real,

$$X_{n,m} = (X_{-n,-m})^* \quad (7)$$

and it is only necessary to calculate one of these two complex coefficients.

LINEAR ANALYSIS

Among the set of mixing products are the intermediate frequency (IF) and the image frequency (IM). Only these frequencies, together with RF, are considered in this study. However the MIXAN program can suport higher number of mixing products at the cost of computer time. Following, the complete mixer equivalent network can have the configuration of Fig. 2, in which the mixer is considered as a multiport with each port tuned to a single frequency. All the other mixing products are assumed to be suppressed by the filters F_K, k=1 ... 6, where the index k holds for theRF (k=1, k=4), IF (k=2, k=5) and IM (k=3, k=6). The FET is loaded with complex impedances Z_K, with k denoted as above.

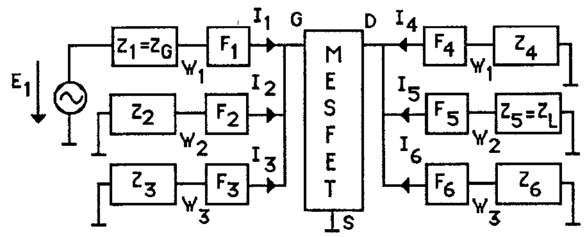

Fig 2 - Mixer configuration as a multiport

Conversion matrices, relate the flowing current and applied voltage components, at different mixing frequencies in each harmonically time-varying circuit element are defined. The matrices elements are the Fourier coefficients obtained on the non-linear analysis, according (1) and (2). For a time-varying circuit resistance, the V-I relation is as follows [6], [7].

$$V_K = [R]\, I_K. \quad (8)$$

Similary, for a capacitor we have

$$I_K = j[\Omega][C]V_K \quad (9)$$

where I_K and V_K are the current and voltage components for the mixing product frequency ω_K. The elements of the conversion matrix [C] are the Fourier components of the time-varying capacitance and [Ω] is a diagonal matrix whose elements are the radian frequencies of the mixing products.

Since Kirchoff's laws hold for the the frequency vectors in (8) and (9), we can write loop or node equations for the circuit of Fig. 2. In a way which is similar to that used for constant coefficient circuits we can write the Z matrix description of the multiport behaviour of the mixer as follows:

$$\begin{bmatrix} E_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_T \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_3^* \\ I_4 \\ I_5 \\ I_6^* \end{bmatrix}$$

where the conversion matrix Z_T can be partitioned as:

$$[Z_T] = \begin{bmatrix} [Z_{11}] & [Z_{12}] \\ [Z_{21}] & [Z_{22}] \end{bmatrix}$$

The four sub-matrices in this partition are functions of the element conversion matrices of the model :

$$
\begin{aligned}
[Z_{11}] &= [Z_1] - [R]\,[Z_3]^{-1}\,[Z_4] \\
[Z_{12}] &= [Z_2] + [R]\,[Z_3]^{-1}\,[R_{ds}] \\
[Z_{21}] &= [Z_6] + [Z_7]\,[Z_3]^{-1}\,[Z_4] \\
[Z_{22}] &= [Z_5] - [Z_7]\,[Z_3]^{-1}\,[R_{ds}]
\end{aligned} \qquad (10b)
$$

where

$$
\begin{aligned}
[R] &= R_i\,[\,I\,] + [C_{gs}]^{-1} \\
[Z_1] &= [Z_{ni}] + [C_{gs}]^{-1} \\
[Z_2] &= R_s\,[\,I\,] + j\,[\Omega]L_s \\
[Z_3] &= [R_{ds}] + R_i\,[\,I\,] + [C_{gd}]^{-1} + ([\,I\,] + [g_m]\,[R_{ds}])\,[C_{gs}]^{-1} \qquad (10c) \\
[Z_4] &= R_i\,[\,I\,] + ([\,I\,] + [g_m]\,[R_{ds}])\,[C_{gs}]^{-1} \\
[Z_5] &= [Z_{no}] + [R_{ds}] + (R_s)\,[\,I\,] \\
[Z_6] &= R_s\,[\,I\,] + j\,[\Omega]\,L_s - [g_m]\,[R_{ds}]\,[C_{gs}]^{-1} \\
[Z_7] &= [R_{ds}]\,([\,I\,] + [g_m]\,[C_{gs}]^{-1})
\end{aligned}
$$

In the above expressions, we have used of the following definitions:

$$
\begin{aligned}
[Z_{ni}] &= \text{diag}\,[Z_g(\omega_k) + Z_{Pi}(\omega_k)] \\
[Z_{no}] &= \text{diag}\,[Z_L(\omega_k)] + Z_{Po}(\omega_k)]
\end{aligned} \qquad (10d)
$$

$[R_{ds}]$, $[g_m]$, $[C_{gd}]$ and $[C_{gs}]$ are the matrix conversion for $R_{ds}(t)$, $\mu(t)$, $C_{gd}(t)$ and $C_{gs}(t)$. $[\,I\,]$ is the identity matrix. $Z_{Pi}(\omega_k)$ and $Z_{Po}(\omega_k)$ are the impedances of the parasitic elements in the model.

From expressions (10) the conversion gain G_c, the input impedance Z_{in} (RF) and the output impedance Z_{out} (IF) are

$$G_c = 4\,|y_{51}|^2\,\text{Re}\{Z_G\}\,\text{Re}\{Z_L\} \qquad (11)$$

$$Z_{in} = 1/y_{11} - Z_G \qquad (12)$$

$$Z_{out} = 1/y_{55} - Z_L \qquad (13)$$

where the yy` are elements of the admittance matrix

$$[Y_T] = [Z_T]^{-1} \qquad (14)$$

DESIGN TECHNIQUE

Under large signal operation, the non-linear device behaviour is strongly dependent on the embedding network, due to its frequency selectivity. However, in order to optimize the mixer performance the embedding network must be designed taking into account the device external characteristics. Accordingly, an iterative method for the design is required.

The MESFET mixers design procedure can be summarized, as follows:

1. Measure the MESFET DC characteristics and the small-signal S - parameters.
2. Fit the large-signal model parameters to the experimental data obtained in step 1 [5].
3. Obtain the 3 mixer parameters, Z_{in1}, Z_{out1} and G_{C1}, with the MIXAN program, for the following terminations: 50Ω generator and a 50Ω load with a SC (short circuit) for the LO frequency .
4. Design the input coupling network in order to obtain impedance matching ($50\Omega \leftrightarrow Z_{in1}$) at RF, to introduce a SC or OC (open circuit) at IF and no filtering, or SC, or OC at IM (six combinations); design the output coupling network in order to match the impedance ($Z_{out1} \leftrightarrow 50\Omega$) at IF, and to introduce a SC or OC at IM and RF (four combinations).
5. For all possible combinations of input and output coupling networks, the 3 mixer parameters are obtained with the MIXAN program: Z_{in2},Z_{out2}, G_{c2}.
6. For the best of these configurations (the one leading to high gain with accepted values for Z_{in} and Z_{out}), design a new set of input and output coupling networks, if $Z_{in2} \neq Z_{in1}$ and $Z_{out2} \neq Z_{out1}$.
7. For the new set of input and output coupling networks the 3 mixer parameters are obtained with the MIXAN program.
8. Step 6 and 7 are repeated until $Z_{inj+1} \approx Z_{inj}$ and $Z_{outj+1} = Z_{outj}$. We have noticed that, usually, j=1 for the input network and j=2 for the output network , are sufficient.

Following this procedure for different LO levels and MESFET bias conditions, the conversion gain can be optimized.

EXPERIMENTAL RESULTS AND CONCLUSION

Figures 3 and 4 present the comparison between measured and computed data for a commercially available MESFET. Good accuracy is obtained.

Two prototypes, one for each MESFET mixer topology were designed, mounted and measured. Figures 5 and 6 present the comparison between theoretical and experimental values for conversion gain

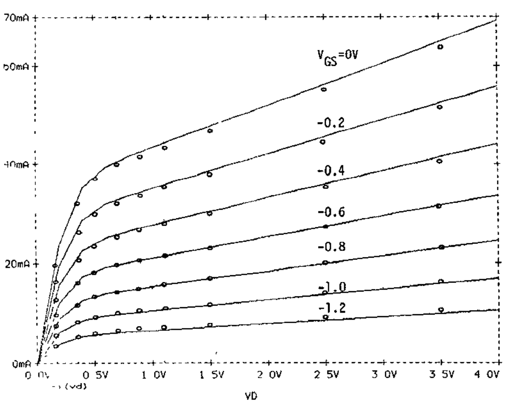

Fig. 3 - DC output characteristics

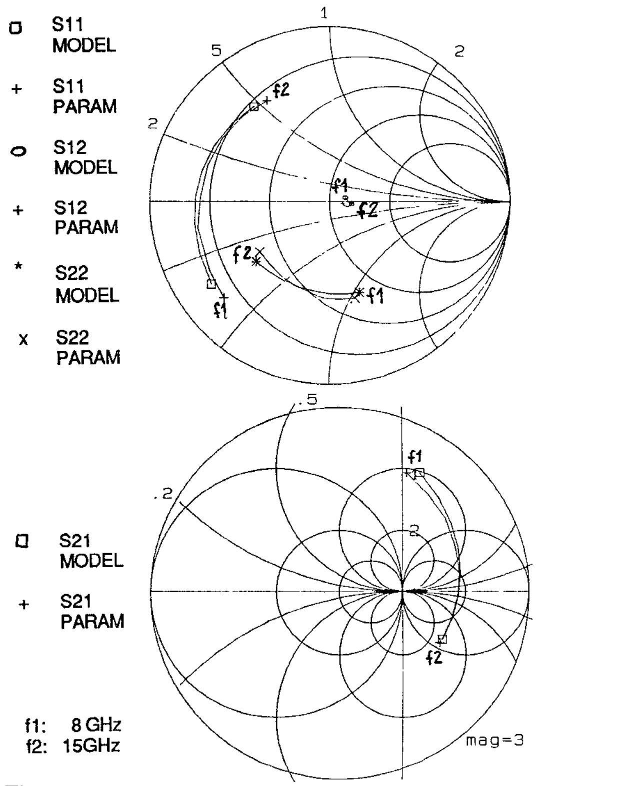

Fig. 4: S parameters comparison for V_{DS}=3V, I_D=10mA

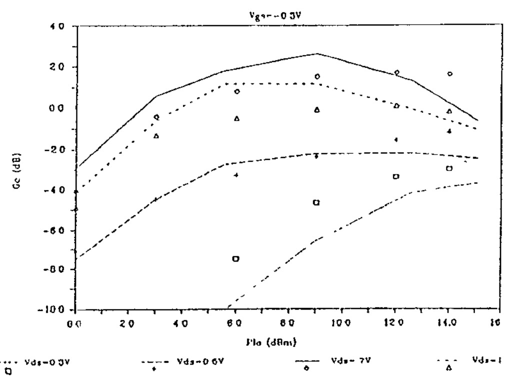

Fig. 5: Measured (symbols) and simulated (lines) conversion gain versus P_{LO} for several values of V_{DS}.

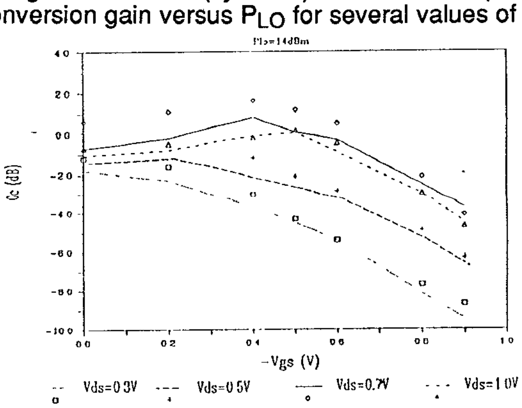

Fig. 6: Measured (symbols) and simulated (lines) conversion gain versus V_{GS} for maximum P_{LO}.

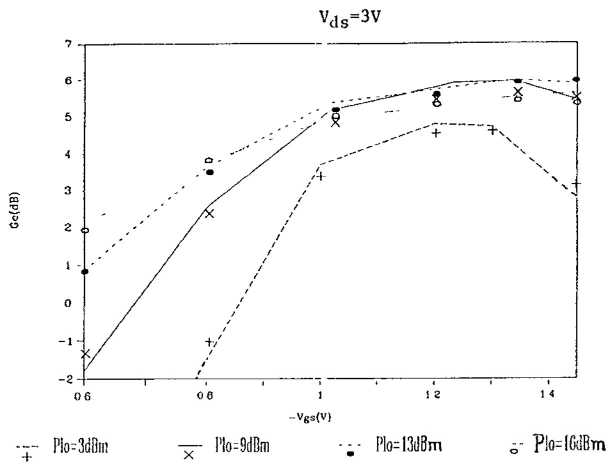

Fig. 7: Measured (symbols) and simulated (lines) conversion gain versus V_{GS} for several values of P_{LO}.

in a drain mixer and figure 7 for a gate mixer. The experimental values are very close to the predicted ones, mainly the LO level and DC bias conditions for optimum performance.

These results confirm the accuracy and usefulness of the technique for mixers design presented. The optimum operating conditions are obtained by an iterative method. In each step different MESFET loading conditions for RF, IF and higher mixing products are tested. Due to the loading condition proposed the convergence was achieved after 2 iterations.

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