Radio Frequency Power Bipolar Transistor Modeling and Simulation

Iliya N. Nemigenchev[1], Pesha D. Petrova[2], Boyan D. Karapenev[3]

Abstract – **A radio frequency power bipolar junction transistor /BJT/ is modelled. A small-signal and a large-signal high frequency models are shown. A procedure for model parameters determining from data sheets is proposed. The effect of the collector current operating point, as well as of the base – spreading resistance, on the transistor characteristics is simulated. Simulation results are presented and discussed.**

Keywords – **BJT high-frequency large-signal model, BJT high-frequency small-signal model, Miller effect, simulation.**

I. Introduction

Normally, for accurate power amplifier design and simulation in a frequency bandwidth and over high dynamic range of the output power, it is necessary to represent an active device in the form of the nonlinear equivalent circuit, which can adequately describe the electrical behavior of the power amplifier closed to the device transition frequency f_T and maximum frequency $f_{\max}$, to take into account the sufficient number of harmonic components. Accurate device modeling is extremely important to develop electronic circuits. Better approximations of the final design can only be achieved if the device behavior is described accurately. For this reason, it is very important to develop and study appropriate high frequency power transistor models. If it is necessary to study power transistor amplifiers in terms of the physical phenomena, some complicated models, such as VBIC, HICUM, or MEXTRAM [1], [2], [3], [4], [5], [6] can be used. But for computer-aided design and simulation purposes, some simplified models are more appropriated. However, they should depend on the mode of the device operation. Since there are two general types of BJT, and three principle modes operation (active mode, saturation mode and cut-off mode) for each, different models of the BJT are required in order to address the common applications.

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II. Nonlinear Model of High-Frequency Power Bipolar Transistor

The modified Gummel-Poon nonlinear model of the bipolar transistor with extrinsic parasitic elements [7], [8] is shown in Fig. 1

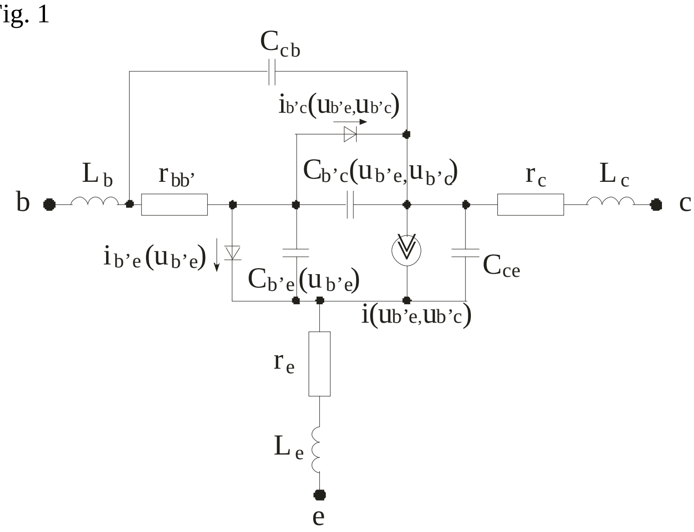

Fig.1. Nonlinear BJT model with extrinsic linear elements.

The hybrid – π equivalent circuit can model the nonlinear electrical behavior of bipolar transistors with sufficient accuracy up to about 20 GHz. The intrinsic model is described by the dynamic resistance diode $r_{b'e}$, the total base emitter junction capacitance $C_{b'e}$, the base-collector diode required to account for the nonlinear effects at the saturation, the internal collector – base junction capacitance $C_{b'c}$, the external distributed collector – base capacitance C_{cb}, the collector – emitter capacitance C_{ce}, and the nonlinear current source $i(u_{b'e}, u_{b'c})$. The lateral resistance and the base semiconductor resistance underneath the emitter are combined into a base-spreading resistance $r_{bb'}$. The extrinsic parasitic elements are represented by the base bondwire and lead inductance L_b, the emitter ohmic resistance r_e, the emitter lead inductance L_e, the collector ohmic resistance r_c and the collector bondwire L_c. The model in Fig. 1 describes accurately the electrical behavior of the transistor over its entire operating frequency range. Nevertheless, this model is difficult to use because of the deficit of manufacturer's data sheet information that is necessary to determine the model parameter values.

III. Linear High-Frequency Power Bipolar Transistor Models

A. High – Frequency Small - Signal Models

The bipolar transistor linear operation at high frequencies can be adequately characterized by a Giacoletto equivalent circuit shown in Fig. 2.

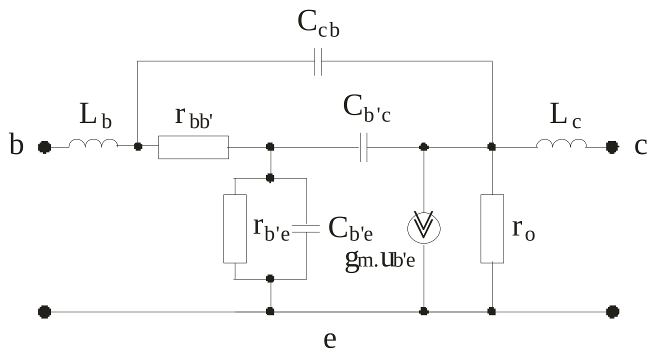

Fig. 2. Giacoletto high-frequency small-signal model for bipolar transistor

In a linear small – signal mode, all elements of the transistor equivalent circuit are considered constant, including the base-emitter diffusion capacitance and differential resistance $r_{b'e}$. The model parameters which are functions of the operating point can be obtained using commonly - available transistor data sheet information. The following procedure gives the values of the parameters for a model in Fig. 2:

1. Choose the base – spreading resistance $r_{bb'}$
Depending on the transistor power it is recommended [9], [10] to choose $r_{bb'} = (1 \div 10)\,\Omega$.

2. Compute the base-emitter resistance $r_{b'e}$ at the operating point from

$$r_{b'e} = \frac{U_T}{I_C} h_{FE} \tag{1}$$

where U_T is the thermal voltage, I_C the collector current at the operating point, and h_{FE} is the dc current gain.

3. Determine the transconductance g_m using

$$g_m = \frac{h_{FE}}{r_{b'e}} . \tag{2}$$

4. Compute the capacitance $C_{b'e}$ across the base-emitter junction by equation

$$C_{b'e} = \frac{1}{r_{b'e}\omega_T} . \tag{3}$$

5. The internal part $C_{b'c}$, and the external part C_{bc} of the collector – base capacitance, are available on manufacturer's data sheets.

6. Use

$$r_o = \frac{U_A}{I_C} \tag{4}$$

to find the output resistance r_o. In the above equation U_A is the forward Early voltage.

7. Choose the base and collector inductances
The values recommended for L_b and L_c are up to 10 nH [11].

Applying the Miller effect [12] for the bipolar transistor the simplified model shown in Fig. 3 can be synthesized.

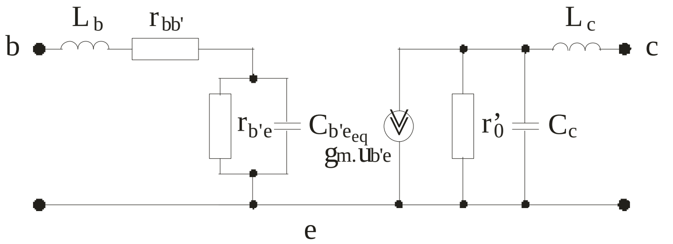

Fig. 3. Simplified high-frequency small-signal model for bipolar transistor

The following sequence can be applied to find the values of the equivalent circuit elements:

- Compute the total collector-base capacitance C_c by

$$C_c = C_{b'c} + C_{cb} . \tag{5}$$

- Determine the output resistance r_o' using

$$r_o' = \frac{1}{\omega_T C_c} . \tag{6}$$

- Compute the equivalent capacitance $C_{b'e_{eq}}$ from

$$C_{b'e_{eq}} = C_{b'e} + C_c\left(1 + g_m r_o'\right) . \tag{7}$$

The values of the remaining elements are identical with the corresponding Giacoletto equivalent circuit elements.

B. High – Frequency Large - Signal Model

To analyze transistor behavior in a large - signal mode it is assumed in the next considerations that the saturation mode of operation is unallowable. When the transistor is operated in the cut - off and active regions, it is necessary to compose two equivalent circuits: the first should correspond to a linear – active region, and the other corresponding to a cut – off region. By using the voltage-controlled switches, two separated circuits can be united in a common model as it is shown in Fig. 4.

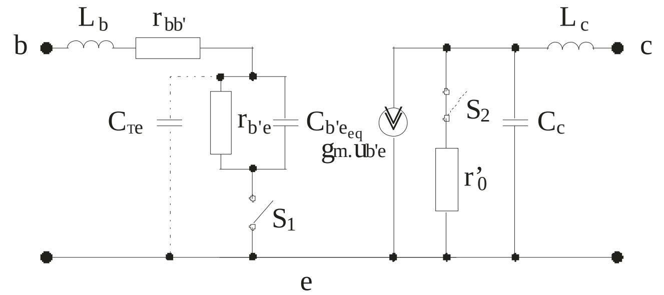

Fig. 4. High-frequency large-signal bipolar transistor model

By applying a piecewise – linear approximation of the transistor transfer current-voltage characteristic, the current $i = g_m u_{b'e}$ as a function of the driving junction voltage $u_{b'e}$ can be written as

$$i\left(u_{b'e}\right) = \begin{cases} g_m\left(u_{b'e} - U_{BE(on)}\right) & u_{b'e} \geq U_{BE(on)} \\ 0 & u_{b'e} < U_{BE(on)} \end{cases}, \quad (8)$$

where $U_{BE(on)} = const = 0{,}7V$.

In the active region the driving voltage $u_{b'e} \geq U_{BE(on)}$ (S_1 – on, S_2 – on), and in the cut-off region, $u_{b'e} < U_{BE(on)}$ (S_1 – off, S_2 – on), respectively. At the boundary of active region and saturation $U_{CE} = U_{BE(on)}$. In practice, most applications of BJT in saturation involve sufficiently large forward currents through each of the junctions that the linearized large-signal model for the diodes (e.g., Constant-Voltage-Drop) is adequate. This leads to the equivalent circuit composed of two dc voltage sources $u_{b'e} = U_{BE(on)}$ and $U_{CE} = U_{CE(sat)} \approx 0{,}5V$.

It is necessary to take into account that the diffusion capacitance $C_{b'e}$ and resistance $r_{b'e}$ depend significantly on the driving signal amplitude by setting their averaged values in an active mode. The $r_{b'e}$, g_m and $C_{b'e_{eq}}$ values for linear active region can be obtained using Eqs. (1), (2), and (7). For cut-off region of operation these parameter values are as follows: $r_{b'e} = 0$, $g_m = \infty$, $C_{b'e_{eq}} = 0$. The capacitance C_{Te} corresponds to the depletion capacitance of the reverse biased base-emitter junction and it is added to improve the model accuracy.

The models in Figs. 3 and 4 are vastly simplified in comparison with the well-known models such as Ebers-Moll and Gommel-Poon models and their modifications. In addition, since the large-signal equivalent circuit includes voltage-controlled switches, it can be successfully used for three principal regions of operation. In order to raise the computation efficiency a suitable MATLAB code for model parameters determination is created. The implemented PSPICE BJT subcircuits, based on MATLAB calculation parameter values, can automatically be adapted to the mode of operation.

IV. Simulation Results

The model parameter's values of the circuits shown in Figs. 2, 3 and 4 have been computed for 10 radio frequency power bipolar transistors. Moreover, the parameter values at different operating points of the transistors have been obtained. Some bipolar transistor characteristics have been simulated using PSPICE and MATLAB simulators.

Simulation results of transistor voltage gain and upper cutoff frequency at different operating points and $r_{bb'} = 1\Omega$ are presented in Table I.

TABLE I
SIMULATION RESULTS WITH OPERATING POINT CURRENT VARYING

Transistor	Model	Ic, A	Au	fh, MHz
BLW86	Fig.2	0,100	6,856	59,768
		2,110	16,744	24,450
		2,600	16,969	24,450
	Fig.4	0,100	6,856	74,230
		2,110	16,744	28,000
		2,600	16,969	26,910
BLV21	Fig.2	0,100	6,358	138,400
		0,600	13,779	55,100
		0,885	14,899	50,800
	Fig.4	0,100	6,358	80,500
		0,600	13,779	33,840
		0,885	14,899	30,900
2N3553	Fig.2	0,100	7,865	127,600
		0,196	11,386	82,730
	Fig.4	0,100	7,865	60,000
		0,196	11,386	39,800

The simulation results of Table I are related to the small-signal model shown in Fig. 2 and to the large-signal model shown in Fig. 4. The results show the following general trends. For the same transistor at the same operating point the voltage gain for the models shown in Figs. 2 and 4 is identical. For both equivalent circuits, in Figs. 2 and 4, respectively the upper cutoff frequency decreases with the collector current operating point increasing. The results for the equivalent circuit in Fig. 3 coincide with the results for a large-signal model in an active mode of operation. It follows from the results that for larger power transistors the model taking into account a Miller effect should be preferred.

Since the base – spreading resistance $r_{bb'}$ can be chosen in the range $r_{bb'} = \left(1 \div 10\right)\Omega$, it is of interest to analyze how this resistance change effects on the bipolar transistor characteristics. Fig. 5 presents the BLW86 transistor output voltage as a function of the frequency with varying value of base – spreading resistance $r_{bb'}$. The results are identical for small - signal and large-signal in an active region models. It follows from Fig. 5 that the voltage gain decreases with base – spreading resistance increase. For example, if the resistance increases from 1Ω to 10Ω the output voltage decreases 1,477 times.

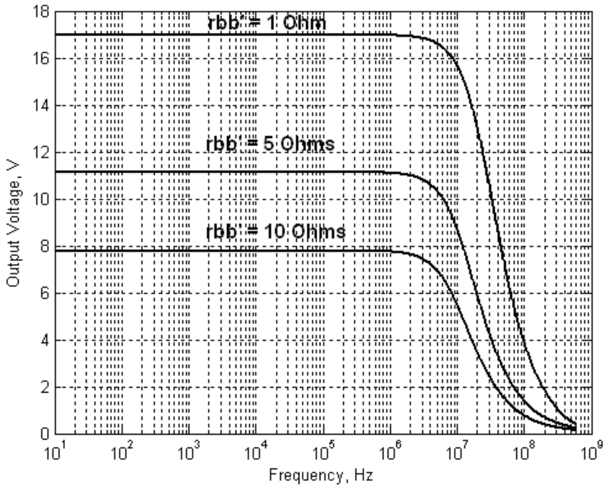

Fig. 5. Transistor output voltage as a function of frequency and base – spreading resistance

Furthermore, the resistance value effects on the upper cutoff frequency. The upper cutoff frequency varying for three transistors as a function of the base-spreading resistance value is presented in Fig. 6. The simulation results in Fig.6 correspond to the transistor models in Figs.3 and 4. It can be concluded from the results that as the base resistance value is increased, the upper cutoff frequency is decreased, i.e. the frequency bandwidth narrows. The increase resistance values from 1Ω to 10Ω causes the upper cutoff frequency decrease of 4,684 times for BLW86 transistor, of 4,811 times for BLY21 transistor and of 5,24 times for 2N3553 transistor, respectively.

In order to evaluate the large-signal model in Table II data sheet and simulated values for current gain are presented.

TABLE II
DATA SHEET AND SIMULATED CURRENT GAIN

Transistor	Ic, A	h_{FE}	
		data sheet	simulated
BLW86	0,1	55	54,3
	2,8	68	68,7
BLV21	0,1	49	49,8
	0,9	51	50,6
2N3553	0,1	46	45,7
	0,2	48	48,3

It is clear that the current gain values are almost the same.

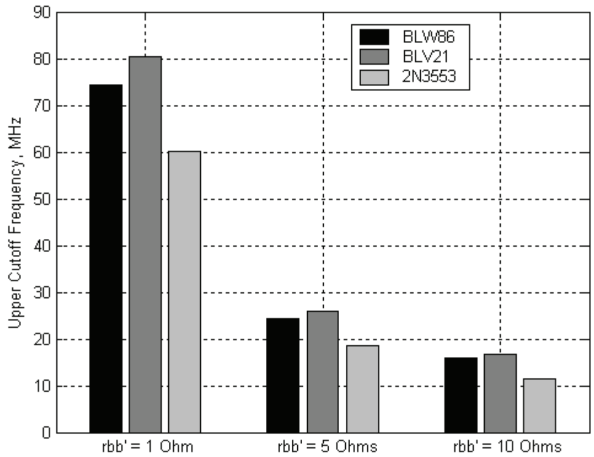

Fig. 6. Plot of upper cutoff frequency versus base – spreading resistance

V. CONCLUSION

The radio frequency power bipolar transistor models for use in CAD tools and procedure for determination of model parameters are proposed. The effect of the operating point, as well as, of the base-spreading resistance on the transistor characteristics is studied. The simulation results support an availability of the modeling approach proposed. The results allow the designers to estimate the effect of the model parameters on the BJT operation in difference regions and to take a correct decision.

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