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Microwave Transistor Modeling for Time Domain Simulation

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Creating a specific model for a microwave transistor can help achieve accurate circuit simulation in the desired frequency range for the user's application

High frequency models of transistors are of interest because they have applications to computer-aided design of high frequency circuits. When these models are derived, a problem encountered is that measured transistor *S*-parameters do not agree with the hybrid-π model. In this article, a simplified method is described to obtain an optimized classical hybrid-π model that predicts the measured *S*-parameters of the device across the desired frequency band. The modeling capabilities of the CAD program Touchstone (now is incorporated with ADS) were utilized to create such a transistor model. The optimization goal is to minimize the error function between the measured *S*-parameters and those of the RF transistor equivalent circuit. This technique has been implemented to obtain a high frequency circuit model for the RF transistor BFY 90 across the band from 100 MHz to 500 MHz. Such a model can be used in time-domain circuit analysis programs to predict the transistor behavior.

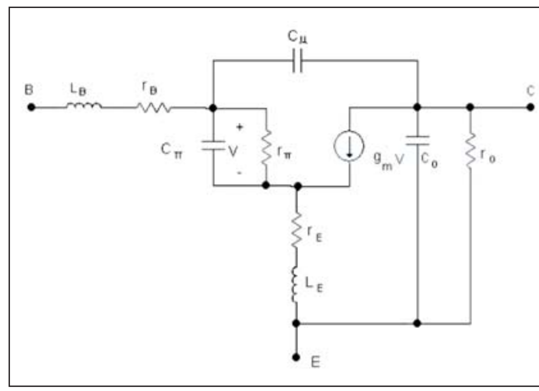

Figure 1 · A simple high frequency transistor model.

Introduction

The characterization of RF transistors is of significant importance at high frequencies. There are, in general, two methods used to model high frequency transistors:

• The first one is achieved using *S*-parameters. In this approach, the transistor is considered as a linear two-port network and is treated as a black box regardless of the internal device elements. The *S*-parameters are based on the incident and reflected waves at the transistor input and output ports and can be measured easily using the network analyzer [1]. Microwave transistor manufacturers usually measure and do provide *S*-parameter sets at different frequencies and DC bias points.

• The second technique, on the other hand, is based on the high frequency equivalent circuit of the transistor. The hybrid-π model is usually used to characterize the RF behavior of the BJT at high frequencies. However, the model parameters are very difficult to measure and obtain accurately at such frequencies. On the other hand, device data sheets rarely provide full set of transistor internal parameters at microwave frequencies. Package parasitic inductances and capacitances should also be considered because their effects may degrade the AC performance of high frequency transistors. High frequency equivalent circuits are, however, very important in circuit analysis programs such as *PSpice* to simulate the transistor's performance both in time and frequency domains.

RF Transistor Models

A simple linear high frequency transistor model is shown in Figure 1. Basically, this is an extension of the hybrid-π model with package lead inductances and resistances at the base and emitter.

The frequency dependence of the short circuit current gain of the transistor is given by [2]:

$$h_{fe}(f) = \frac{h_{fe}}{1 + jf / f_\beta} \quad (1)$$

Where h_{fe} is the low frequency short circuit current gain and f_β is the cut-off frequency. f_β can be estimated from the model parameters:

$$f_\beta \cong \frac{1}{2\pi . r_\pi . C_\pi} \quad (2)$$

The gain-bandwidth frequency f_T can also be estimated by:

$$f_T \cong \frac{g_m}{2\pi . C_\pi} \quad (3)$$

f_β and f_T are related by:

$$f_\beta = \frac{f_T}{h_{fe}} \quad (4)$$

The diffusion capacitance of the emitter-base junction C_π can be approximated by:

$$C_\pi \cong g_m . \tau_F \quad (5)$$

where τ_F is the total forward transit time, which represents the mean time for the minority carriers to cross (diffuse) the base region from the emitter to the collector and is dependent on the collector current.

Replacing equation (5) in (3) yields:

$$f_T \cong \frac{1}{2\pi . \tau_F} \quad (6)$$

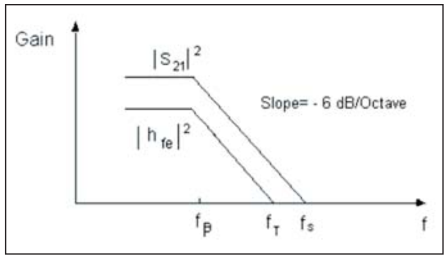

Figure 2 · Frequency characteristics of $|S_{21}|^2$ and $|h_{fe}|^2$.

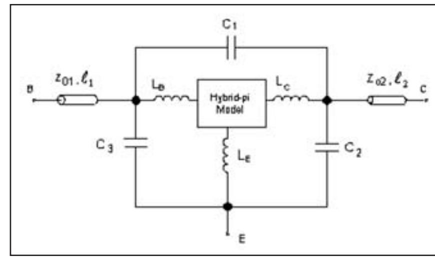

Figure 3 · Typical packaged microwave transistor model.

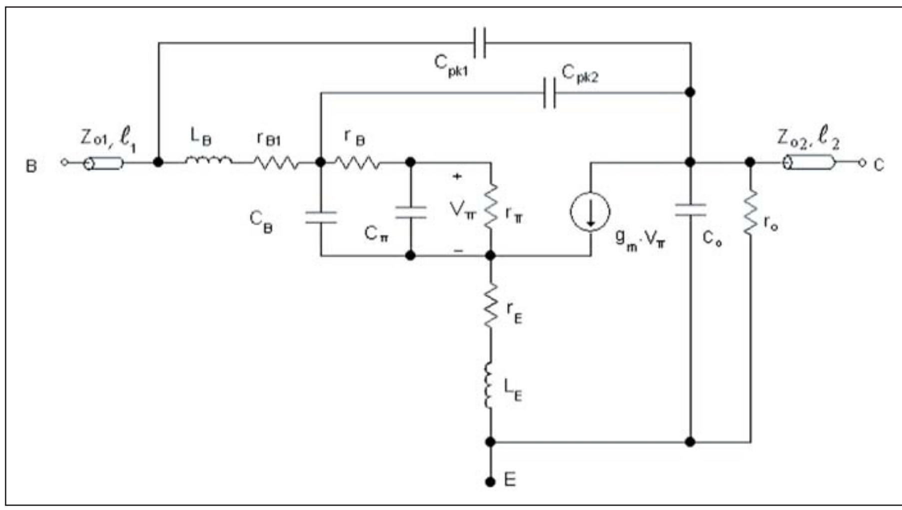

Figure 4 · The modified hybrid-π transistor model used for optimization.

which means that the gain-bandwidth frequency of the transistor is inversely proportional to the forward transit time.

Figure 2 illustrates a comparison between the forward transducer gain $|S_{21}|^2$ and $|h_{fe}|^2$ for the RF transistor.

For packaged microwave transistors, parasitic inductances and capacitances play a significant role at microwave frequencies and should be modeled accurately. Also, pieces of transmission lines should be included to model the delay in time required for signals to travel from the terminals of the transistor package to the transistor chip as shown in Figure 3.

The Simulated Model

In this article, a modified hybrid-π model was adopted for computer simulation and is presented in Figure 4. This model was proposed in a previous work [3] and gave satisfactory results. The model differs from the simplified hybrid-π model of Figure 1 in two things. The first one is the modeling of the emitter-base junction with additional RC section, while the second one is the addition of two transmission lines at the input and output to model the time delay in the signal that propagates from the terminals of the package into the transistor chip.

The Computer Procedure

Prior to computer optimization, an initial circuit model should be created based on the approximate equations stated previously. A good initial circuit model is necessary to ensure quick convergence within a reasonable time and at a reasonable cost. The computer procedure is shown schematically in Figure 5.

The Microwave computer pro-

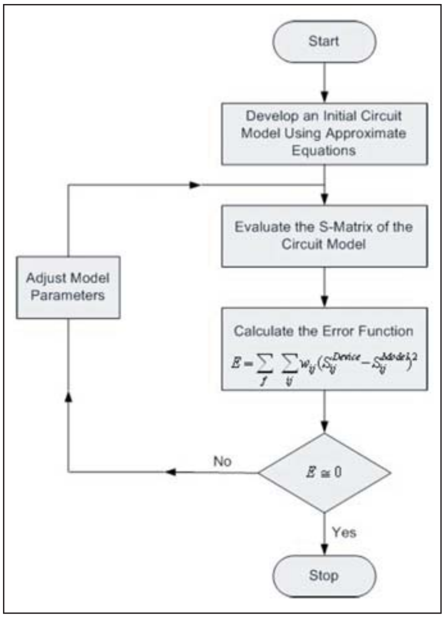

Figure 5 · The computer procedure for model optimization.

$f(MHz)$	$\lvert S_{11}\rvert$	$\angle S_{11}$	$\lvert S_{21}\rvert$	$\angle S_{21}$	$\lvert S_{12}\rvert$	$\angle S_{12}$	$\lvert S_{22}\rvert$	$\angle S_{22}$
100	0.574	–79	10.65	127	0.023	67	0.788	–56
200	0.374	–130	7.01	105	0.036	60	0.682	–97
300	0.292	–172	4.44	97	0.047	66	0.654	–136
400	0.259	142	3.62	92	0.063	63	0.64	–178
500	0.198	96	3.02	88	0.072	60	0.617	140

Table 1 · The *S*-parameters of the transistor BFY 90 @ V_{CE} = 10V, I_C = 8 mA.

gram will first evaluate the S-matrix of the circuit model and compare it with the measured S-parameters of the microwave transistor at each sample frequency within the required band. For this purpose an error function, which is proportional to the difference between the measured S-parameters of the transistor and those of the circuit model, should be formulated and minimized by the microwave circuit optimization and simulation program. This error function may look like:

$$E = \sum_{f} \sum_{ij} w_{ij} \left(S_{ij}^{Device} - S_{ij}^{Model} \right)^2 \qquad (7)$$

Where S_{ij}^{Device} are the S-parameters of the actual transistor, S_{ij}^{Model} are the calculated S-parameters of the model, and w_{ij} are some weighting factors.

The optimization program then systematically attempts to minimize this performance function by varying the values of model parameters according to certain optimization technique. Upper and lower constraints can be imposed on the values of model parameters. Several trials are attempted until a satisfactory value of the error function is reached.

Procedure Application

The computer program Touchstone was used to create a circuit model for the RF transistor BFY 90 in the frequency band from 100 to 500 MHz. This device operates as a small signal amplifier in the VHF/UHF bands. It has a gain-bandwidth product frequency of 1.3 GHz. The manufacturer's S-parameters measured at a bias point of V_{CE} = 10 V, and I_C = 8 mA are shown in Table 1.

Initial model parameters should be estimated prior to computer optimization. These parameters can be calculated as follows:

$g_m = I_C/V_T$ = 8 mA/26 mV = 0.325 mho
β = 100 for this device.
$r_\pi = \beta/g_m$ = 307.7 Ω.
f_T = 1.3 GHz.
$\tau_F = 1/2\pi f_T$ = 122 ps.
$C_\pi = g_m.\tau_F$ = 37 pF.

Two pieces of transmission lines were added at input and output with Z_o = 50 Ω and implemented as coaxial cables. We know that the characteristic impedance of the coaxial cable is:

$$Z_o = \frac{138}{\sqrt{\varepsilon_r}} \log\left(\frac{D_o}{D_i}\right) \qquad (8)$$

Selecting Z_o = 50 Ω, D_o = 8 mm, and D_i = 2 mm results in a value for ε_r of 2.76. Other model parameters

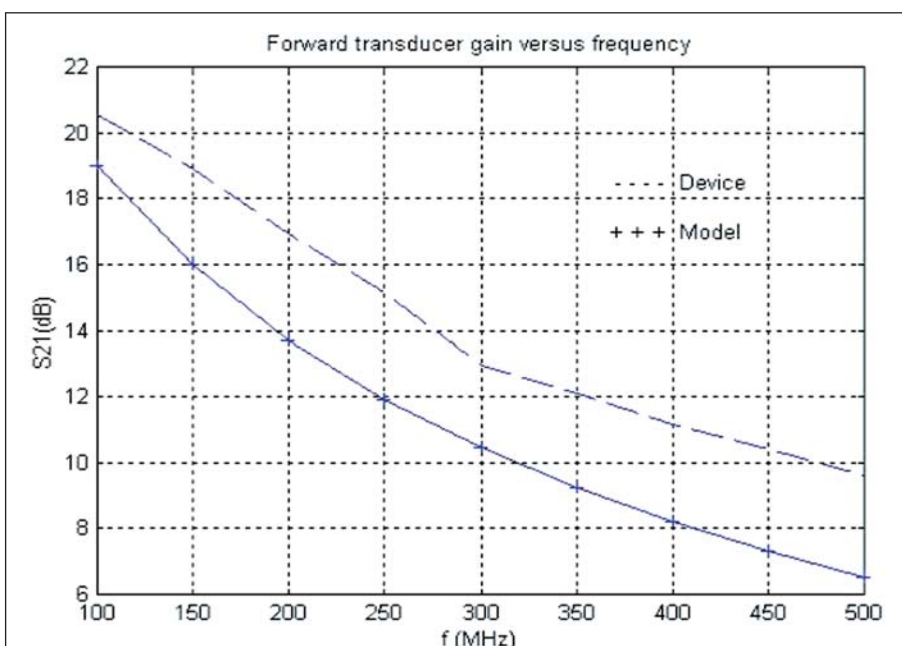

Figure 6 · Graph of S_{21} versus frequency prior to computer optimization.

Parameter	Value	Unit	Parameter	Value	Unit
Z_{o1}	50	Ω	r_B	10	Ω
Z_{o2}	50	Ω	r_{B1}	20	Ω
ℓ_1	1	mm	C_B	2	pF
ℓ_2	0.5	mm	r_E	1.78	Ω
g_m	1	mho	C_{pk1}	0	pF
τ_F	200	ps	C_{pk2}	2.2	pF
C_π	5	pF	L_E	1	nH
r_π	27	Ω	L_B	0.04	nH
r_o	9.3	kΩ	C_o	0.06	pF

Table 2 · The final optimized model parameters.

$f(MHz)$	$\lvert S_{11}\rvert$	$\angle S_{11}$	$\lvert S_{21}\rvert$	$\angle S_{21}$	$\lvert S_{12}\rvert$	$\angle S_{12}$	$\lvert S_{22}\rvert$	$\angle S_{22}$
100	0.286	–87	11.09	127.5	0.051	53	0.740	–82.9
200	0.242	–126.5	6.76	107.3	0.066	46.8	0.591	–122.9
300	0.228	–146.4	4.75	97.4	0.078	48.6	0.542	–144.5
400	0.222	–158.8	3.69	90.93	0.089	51.6	0.526	–158.4
500	0.219	–167.5	3.03	86	0.102	54.3	0.522	–168.5

Table 3 · The simulated *S*-parameters of the optimized model.

were chosen arbitrarily.

After substituting the estimated parameters for the equivalent circuit model, a rough circuit simulation was made to compare its response with the actual device performance. Figure 6 shows a comparison between S_{21} for the circuit model and that of the actual device before computer optimization.

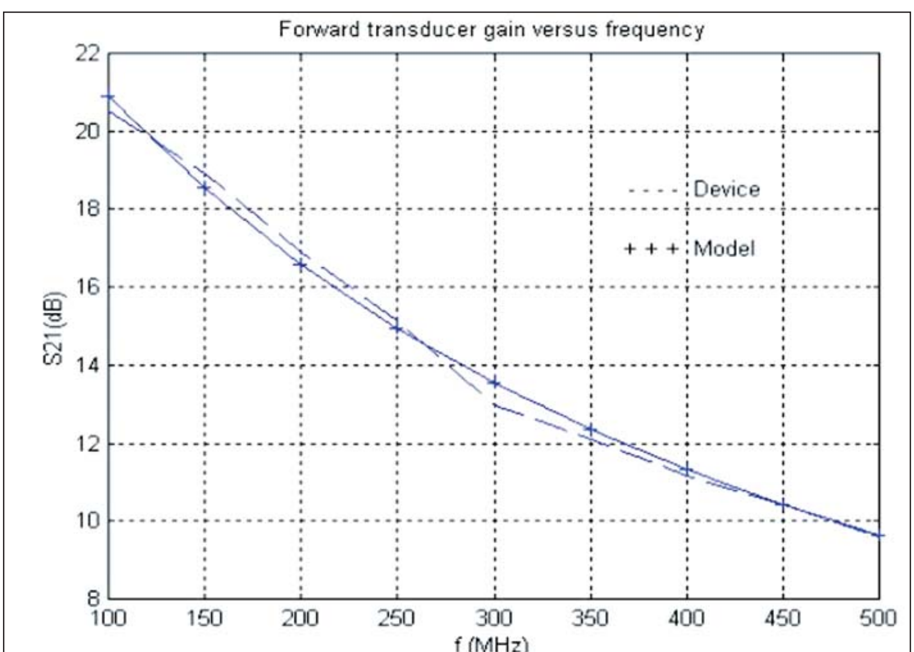

Figure 7 · Graph of S_{21} versus frequency after computer optimization.

The Touchstone circuit file used in the simulation of the transistor model is presented in the appendix. Actually, Touchstone has a built-in simple hybrid-π model for the BJT. This model was modified by adding further elements and neglecting some elements such as R_μ, C_μ, and r_c in order to match the equivalent circuit of Figure 4.

Choosing the least square error function and the gradient optimization technique, a total of 50 iterations were required to reduce the error function from 10.3 to 0.225. The resulting optimized values of the model elements are shown in Table 2.

Figure 7 shows a comparison between the forward transmission coefficient S_{21} of the device and that of the optimized model across the frequency band of interest. The optimized S-parameters of the circuit model are shown in Table 3 and can be compared with those of the device presented in Table 1.

Conclusion

A simple method for creating an equivalent circuit model of high frequency transistors has been described and applied to build a model for the RF transistor BFY 90 across the frequency band from 100 to 500 MHz. Such a model can be used in circuit analysis programs to simulate the behavior of the RF device in the time domain as well as in frequency domain. It was shown that the accuracy of the resulting model depends on the equivalent circuit chosen and on the type of the performance error function to be minimized.

Limitations of the technique stem from the fact that the method adopted is based on the linear assumption of the RF device. If the input signal amplitude increases, some of the internal parameters may vary with signal level. This condition occurs in RF power amplifiers where the signal power level is significantly high. On the other hand, the high frequency model is derived from one set of *S*-parameters at a certain operating DC bias point. This means that if the DC bias point is changed then the model will become invalid.

References

1. R.W. Anderson, "S-Parameter Techniques for Faster, More Accurate Network Design," HP Application Note 95-1, February 1967.

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3. R.G. Gough, "High-Frequency Transistor Modeling for Circuit Simulation," *IEEE J. Solid-State Circuits,* Vol. SC-17, No. 4, August 1982, pp. 666-670.

Author Information

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Appendix

The Touchstone's circuit file written for circuit optimization is shown below:

```
DIM
    RES OH
    CAP pF
    IND nH
    COND /OH
    FREQ MHz
    TIME ps
    LNG mm
CKT
    HYBPI 4 5 6 G#.05 1 1 T#10 200 3000 CPI#0 5 50 &
    RPI#20 27 400 CMU=0 RMU=1E8 RB#1 10 25 RC=0 RE=0
    CAP 4 6 C#.1 2 5 ! CB
    RES 3 4 R#0 20 25 ! rB1
    RES 6 7 R#0 1.78 12 ! rE
    IND 7 0 L#0 1 2 ! LE
    IND 2 3 L#0 0.04 1 ! LB
    CAP 5 0 C#0 .06 5 ! Co
    RES 5 0 R#100 9300 10000 ! ro
    CAP 2 5 C#0 0 4 ! Cpk1
    CAP 4 5 C#0 2.2 4 ! Cpk2
    COAX 1 2 0 0 DI=2 DO=8 L#.5 1 8 ER=2.76 TAND=0 RHO=1
    COAX 5 8 0 0 DI=2 DO=8 L#.5 .5 8 ER=2.76 TAND=0 RHO=1
    DEF2P 1 8 TRMODEL
    S2PA 1 2 0 BFY90
    DEF2P 1 2 DEVICE
OUT
    TRMODEL DB[S21] GR1
    DEVICE DB[S21] GR1
    TRMODEL SPAR
FREQ
    SWEEP 100 500 50
OPT
    TRMODEL MODEL DEVICE
GRID
    RANGE 100 500 50
    GR1 8 22 2
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