A Novel Direct Extraction Method for Internal Equivalent Circuit Parameters of HBT Small-Signal Hybrid-Pi Model

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ABSTRACT

A novel and accurate method for the direct extraction of HBT small-signal hybrid-Pi model parameters is proposed. The main feature of this method is that a unique set of intrinsic parameters is calculated for the whole frequency range of operation using a least-squares data fitting algorithm. This algorithm consists of an estimation from measured S-parameters of a set of new analytical equations derived from the intrinsic HBT equivalent-circuit Y-parameters. Experimental validation on an HBT device with a 2x25 μm emitter was carried out, and excellent results were obtained up to 30 GHz.

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) have emerged as popular devices in high speed digital and analog circuit applications. Determination of small-signal equivalent circuit elements of HBT devices is a very useful tool for microwave circuit design and for device process optimization [2]-[9]. Most of the conventional techniques to extract the small-signal HBT model elements are based on numerical global optimization methods that aim to calculate the values of these elements by fitting calculated S-parameters to measured ones. However, it is well known that the main drawback of these techniques is the convergence to nonphysical element values due to the multiple local solutions of the optimized objective function. In order to avoid this problem, we report a novel direct extraction method that fully exploits the frequency dependence of the HBT intrinsic equivalent-circuit Y-parameters. This method is fast, accurate, easy to implement, and does not require special test structures.

II. METHOD

The HBT small-signal equivalent circuit is shown in Figure 1. This circuit is divided into two parts, the outer part contains the extrinsic elements, considered as bias-independent, and the inner part (in the dashed box) contains the intrinsic elements, supposed to be bias-dependent. The extrinsic elements are determined from open collector and off-state measurements [1]. Firstly the device is biased in forward operation mode (high base current I_b) in order to extract the parasitic resistances (R_c, R_e, R_b) and inductances (L_c, L_e, L_b). And in a second time the device is biased in cut-off operation mode thus permitting the extraction of the parasitic capacitances (C_{bep}, C_{bcp}, C_{cep}).

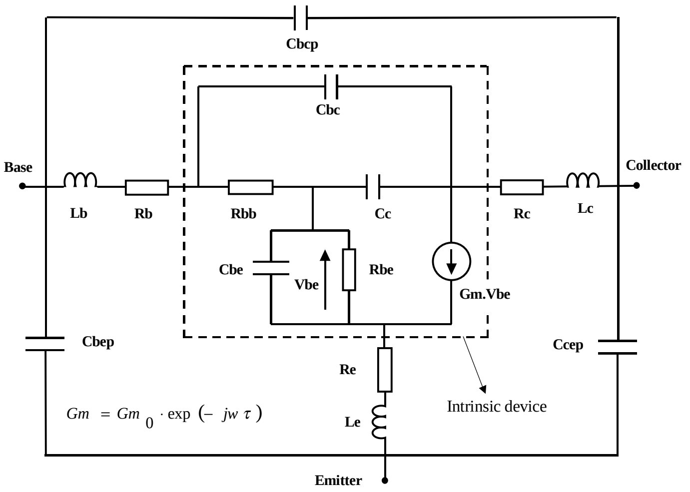

Fig. 1. HBT device small-signal equivalent circuit

The determined values of the extrinsic parameters are then used to de-embed the measured S-parameters of the device and to deduce the intrinsic equivalent-circuit Y-parameters. The next step is to calculate the intrinsic parameters as follows:

- The base-emitter junction resistance is calculated for each bias point from the well-known relation:

$$R_{be} = \frac{n_{be}KT}{qI_b} \qquad (1).$$

  This expression allows for the calculation of a consistent *DC*/*RF* value of this parameter.

- The product of the two parameters R_{bb} and C_c is calculated by means of a linear least-squares fitting routine that minimizes the following function for the *N* measured frequency points:

$$\min\left(\sum_{n=1}^{N}\left|im\left(\omega_n R_{bb}C_c - \frac{(Y_{22}+Y_{12})}{(Y_{21}+Y_{11})}\right)_n\right|^2\right) \qquad (2).$$

- The parameter C_{be} is determined by minimizing the following function in the nonlinear least-squares sense for the *N* measured frequency points:

$$\min\left(\sum_{n=1}^{N}\left|im\left(\frac{1}{Y_{11}+Y_{12}}\right)_n(1+(\omega_n C_{be}R_{be})^2)+R_{be}\left(R_{be}\omega_n C_{be}-\left(\frac{Y_{22}+Y_{12}}{Y_{21}+Y_{11}}\right)_n\right)\right|^2\right) \qquad (3).$$

- Considering that

$$real\left(\frac{1}{Y_{11}+Y_{12}}\right)=\frac{R_{bb}(1+(C_{be}R_{be}\omega)^2)+R_{be}+R_{bb}C_c(\omega R_{be})^2 C_{be}}{(1+(C_{be}R_{be}\omega)^2)} \qquad (4).$$

  One can see that at low frequencies this expression tends asymptotically to the value of R_{bb}+R_{be}, and at high frequencies tends to the value of R_{bb} (Figure 2). Knowing the values of R_{be}, $R_{bb}C_c$, and C_{be}, the value of R_{bb} is then calculated by minimizing the following function in the linear least-squares sense for the N measured frequency points:

$$\min\Big(\sum_{n=1}^{N}\Big|real\Big(\frac{1}{Y_{11}+Y_{12}}\Big)_n\big(1+\left(C_{be}R_{be}\omega_n\right)^2\big)-\big(R_{bb}\big(1+\left(C_{be}R_{be}\omega_n\right)^2\big)+R_{be}+R_{bb}C_c\left(\omega_n R_{be}\right)^2 C_{be}\big)\Big|^2\Big) \qquad (5).$$

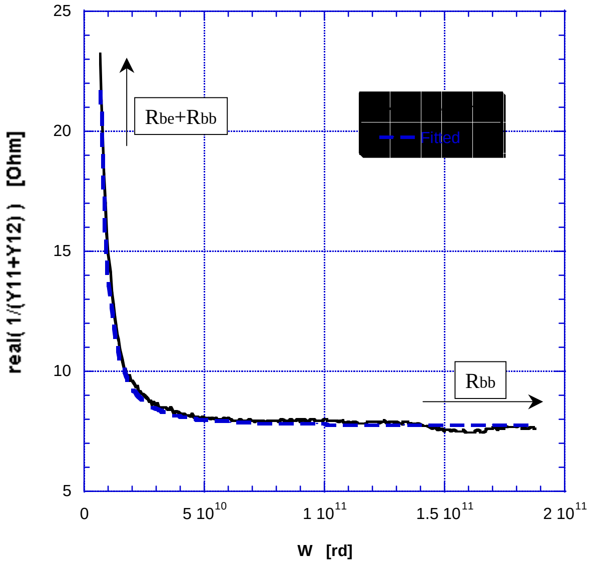

Fig. 2. Plot of *real(1/(*$Y_{11}+Y_{12}$*))* versus *W*
(1-30 GHz, V_{ce} = 3V, I_c = 10 mA, I_b = 50 µA)

- Knowing the previously calculated values of parameters R_{be}, R_{bb}, C_{c} and C_{be}, one can easily determine the value of the extrinsic base-collector junction capacitance C_{bc} by minimizing the following function in the linear least-squares sense for the N measured frequency points :

$$\min\Big(\sum_{n=1}^{N}\Big|\big(\omega_n C_{bc}+im\left(Y_{12}\right)_n\big)\big(R_{bb}^2R_{be}^2\left(C_c+C_{be}\right)^2\omega_n^2+\left(R_{bb}+R_{be}\right)^2\big)+R_{be}\omega_n C_c\left(R_{bb}+R_{be}\right)\Big|^2\Big) \qquad (6).$$

- Parameters G_{m0} and • can be calculated respectively from the magnitude and angle of the following expression:

$$G_{m0}\exp(-j\omega\tau)=\Big(Y_{22}+Y_{12}-\frac{(Y_{11}+Y_{12})(Y_{22}+Y_{12})}{Y_{21}+Y_{11}}\Big)\Big(1+\frac{(1+j\omega R_{be}C_{be})}{j\omega R_{be}C_c}+\frac{1}{j\omega R_{bb}C_c}\Big) \qquad (7).$$

III. RESULTS

In order to validate and to assess the accuracy of the proposed extraction technique, we investigated several 2x25 µm common emitter GaInP/GaAs HBT devices. The measurements were performed with a microwave probing system and a VNA over the frequency range 1 to 30 GHz. Figure 3 shows a comparison between measured and model-calculated S-parameters for the bias point V_{ce} = 3V, I_{c} = 10 mA, and I_{b} = 50 µA. Excellent agreement over the whole frequency range was obtained.

IV. CONCLUSIONS

A new direct method for extracting the HBT small-signal hybrid-Pi model is presented. In this method, new analytical equations are derived for the extraction of the intrinsic model parameters. The extraction procedure is based on a least-squares data-fitting algorithm that allows for the calculation of a physically meaningful set of parameters without using global optimization techniques. This method is fast, accurate, and is easy to implement for automatic device characterization.

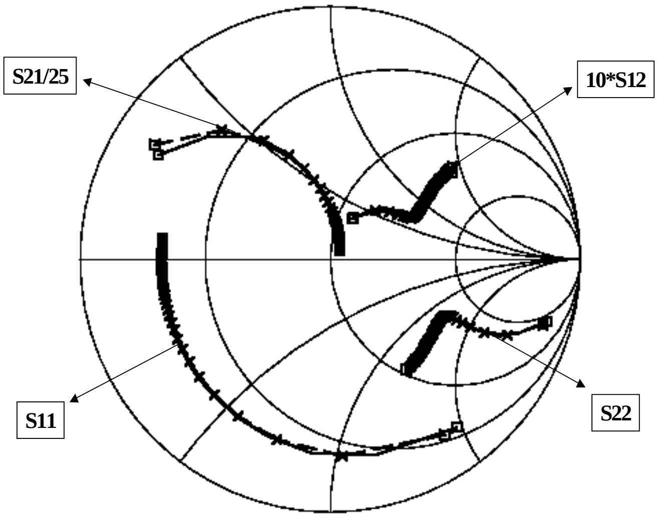

Fig. 3. Measured (-) and model-calculated (-x-) S-parameter of a 2x25 µm common emitter HBT device, (1-30 GHz, *V*ce = 3 V, *I*c = 10 mA, *I*b = 50 µA).

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