Characterization of RF Power BJT and Improvement of Thermal Stability with Nonlinear Base Ballasting

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Abstract—A novel base ballasting scheme for interdigitated power RF bipolar transistors has demonstrated improved performance and thermal stability. The nonlinear ballast resistor in series with each base finger is implemented using a depletion-mode FET, which requires only minor modification in the fabrication process. Mixed-mode simulation, instead of analytical equations, is used for more accurate device characterization.

Index Terms—Ballasting, parasitic characterization, power BJT.

I. INTRODUCTION

The positive feedback from inhomogeneous temperature distributions in interdigitated power bipolar transistors can cause thermal instability or gain collapse [1], [2]. Usually emitter ballast resistor is used for prevention, and its optimal value needs to be carefully chosen to ensure good instability protection without severe performance degradation [3]. The design of finger spacing is also a tradeoff in view of thermal management, since its reduction can increase thermal coupling between fingers and hence decrease the current hogging effect [4], [5], but this reduction will lead to inefficient head dissipation for the entire cell [5]. We propose to use a new nonlinear base ballasting scheme that is very effective in thermal instability protection with little performance penalty at normal operating conditions. Since the positive feedback from Joule heating can be nearly eliminated, the layout design can also be more aggressive toward handling total heat dissipation.

II. POWER RF DEVICE MODELING

Power RF devices pose significant challenges to modeling strategies, since both thermal and parasitic effects need to be accurately accounted for. For the power bipolar junction transistor (BJT) in this study (Fig. 1), mixed-mode device/circuit simulation which interfaces Stanford’s device simulator PISCES and University of California at Berkeley’s circuit simulator SPICE-3f2 has been demonstrated as an effective method to model the parasitic elements and to link the detailed doping profiles directly with circuit performance [6].

For devices which are fabricated on a monolithic substrate, the circuit often exhibits parasitic behavior due to elements that can be represented by a two-port network configuration as shown in Fig. 2. This T-like topology has been used successfully by many authors [8], [9]. For this network it is assumed that over the frequency range of concern (from 300 MHz to 3 GHz) the equivalent circuit composed of lumped RLC elements, can be described using general interconnect parasitics. In reality, at high frequencies the interconnect circuit parameters such as resistance may vary with frequency, due to skin and other distributive effects. For the frequency range considered here, however, frequency-independent modeling parameters are usually sufficient.

As shown in Fig. 3, construction of the two-port matrices from the inner shell to the outer one or vice versa is straightforward. The extracted parasitics of $C_f$, $Z_e$, $Z_b$, and $Z_c$ are as below [6].
TABLE I
EXTRACTED PARASITIC VALUES FOR
T-NETWORK USING MIXED-MODE SIMULATION

<table>
<thead>
<tr>
<th>C_f</th>
<th>C_C</th>
<th>L_b</th>
<th>L_e</th>
<th>R_b</th>
<th>R_e</th>
<th>R_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3 pF</td>
<td>60 pF</td>
<td>0.7 nH</td>
<td>0.3 nH</td>
<td>0.44Ω</td>
<td>1.20Ω</td>
<td>0.08Ω</td>
</tr>
</tbody>
</table>

Thus by comparing measured \( Z \) parameters and the simulated intrinsic parameters \((Z_{11}, Z_{12}, Z_{21}, \) and \( Z_{22}\)), extrinsic parasitic values \((C_f, Z_e, Z_b, \) and \( Z_c\)) can be obtained. Unlike analytical approaches [3]–[5], the numerical method can capture detailed transistor behaviors and electrical couplings with no operation-mode assumption, and hence has a broader range of applicability. Calibrated Gummel plots to measurements at room temperature are shown in Fig. 4. The measured SRP doping profile is also used for calibration. Extracted values of the parasitic elements are listed in Table I [6]. The emitter ballast resistance is about 110 \( \Omega \) per finger implemented using a p-type diffusion resistor. The \( f_T \) as a function of the collector current \( I_C \) and the \( S \)-parameters are shown in Fig. 5. There is quite good agreement between measurements and simulation.
Fig. 7. Circuit diagram for depletion-mode FET. Each base finger is connected to an FET.

Fig. 8. $I_D$ and $V_{DS}$ characteristics at various temperatures. The operating point should be chosen close to (maximum protection) or below (maximum linearity) the onset of saturating region.

Fig. 9. Gummel plot for BJT with depletion mode MOSFET. $I_{B}$ and $I_C$ are effectively limited by MOSFET at high current level.

Fig. 10. Percentage difference in $I_C$ (hot finger) compared with $I_C$ (cold finger @ $T = 300$ K).

Fig. 11. Transition frequency ($f_T$) versus total $I_C$. BJT with depletion-mode MOSFET has higher $f_T$ (@ $V_{CE} = 5$ V, and $T = 307$ K).

Fig. 12. $S$-parameter comparison between BJT with depletion-mode ballasting and BJT with emitter ballasting.
III. NONLINEAR BASE BALLASTING

It is apparent that a nonlinear ballast resistor will be superior to a linear one, since optimal effective resistance values can be separately designed for operating conditions and instability protection. If the ballast resistor is applied to the base end [5], [7], the equivalent resistance can be obtained by multiplying the emitter resistance with the dc current gain. Although it was argued in [7] that base ballasting can only work for heterojunction bipolar transistor (HBT), not BJT, since current gain increases with temperature for BJT, a more careful analysis in Fig. 6 reveals that the base current still increases with $T_L$, though not as fast as $I_C$. Therefore, base ballasting can still prevent thermal instability in the BJT, just not as effective as emitter ballasting if the equivalent value is used. A nonlinear emitter ballasting is difficult to implement owing to its small $I_{\text{bat}}$ value and limited area. With a nonlinear base resistor implemented by a depletion-mode MOSFET as shown in Figs. 7 and 8, the saturation region of MOSFET will effectively limit the current through hot fingers, while the linear region will hardly affect the normal operating point of cold fingers. The MOSFET has a channel length and width of 3 and 15 $\mu$m, and a threshold voltage of $-0.45$ V. The dimensions of the depletion-mode FET is determined by setting proper $I_{\text{bat}}$ level for optimal circuit performance and instability protection. Other layouts or devices are also applicable as long as the nonlinear resistance values are chosen appropriately (i.e., an enhancement-mode MOSFET with gate connected to $V_{ce}$). Fig. 9 shows improved temperature dependence of the Gummel plot by using the nonlinear ballasting scheme. Different ballasting schemes are compared in Fig. 10 in view of instability protection. Due to increased effective $f_{TM}$ of nonlinear ballasting scheme, higher $f_T$ is resulted as shown in Fig. 11. All coupling capacitances have been taken into account. S-parameters with different ballasting scheme is also compared for high frequency characteristics as shown in Fig. 12. It can be seen that the new ballast scheme is strongly favorable to the conventional emitter ballasting.

IV. HBT APPLICATIONS

The proposed ballast scheme can possibly be applied to power HBT applications, too. The nonlinear resistor can be obtained by MESFET, although more difficult modification.
on fabrication is likely. A computational prototype through mixed-mode simulation is built for illustration. The HBT device follows the specification in [7] and the MESFET has a gate length and width of 2 and 5 μm and a threshold voltage of −0.3 V. As shown in Fig. 13, base ballasting using depletion-mode FET is more efficient in HBT due to decreasing current gain with increasing $T_L$. With proper operating condition, the HBT does not experience current gain collapse since as $T_L$ of the hot finger increases, collector current decreases due to base current is effectively limited by MESFET so that $T_L$ does not increase anymore as illustrated in Fig. 10.

V. CONCLUSION

A new methodology of parasitic extraction and a novel base ballasting scheme for RF power bipolar transistors have been described in this paper. The nonlinear ballast resistor in series with each base finger is implemented using a depletion-mode FET, which prevents from inhomogeneous temperature distribution without sacrificing performance of the power device.

REFERENCES


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