A Physically Based Analytic Model of FET Class-E Power Amplifiers—Designing for Maximum PAE

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Abstract—In this paper, we present a new Class-E power-amplifier model. Through a physically based analysis, our novel approach yields closed-form expressions for input, output, and dc power. These expressions yield the important figures-of-merit [gain, drain efficiency, and power-added efficiency (PAE)]. Using standard device parameters, design optimization for maximum PAE follows directly from the analysis and applies to both integrated and discrete transistor implementations. For integrated designs, the optimal FET aspect ratio can be determined, given the design variables of the Class-E output network (output power, frequency, supply voltage, and loaded-Q of the output resonator). In a discrete transistor application, the Class-E network can be optimized for one of the design variables. The detrimental effects of the device parasitics on the amplifier’s performance at UHF and microwave frequencies are accounted for in the model and explained in this paper. We verified the validity of the model by comparing our computed values against those from simulations using an optimized 0.5 μm CMOS level-3 SPICE model.

Index Terms—CMOS FET power amplifiers, FET amplifiers, microwave power FET amplifiers, MOSFET power amplifiers, switching amplifier, UHF power amplifiers.

I. INTRODUCTION

The recent proliferation of the wireless (cellular) communication industry has rekindled interest in the Class-E tuned power amplifier for high-efficiency transmitter applications. Most of the recent work focuses on practical design issues, but for the most part, neglects theoretical analyses that could explain some of the difficulties encountered at high frequencies.

The lack of new theoretical treatments may be attributable in part to the fact that the switched-mode operation of the Class-E amplifier does not lend itself easily to conventional circuit analysis techniques. Additionally, there exists an extensive collection of theoretical work by Sokal and Sokal [1], Raab and Sokal [2], Kazimierczuk [3], [4], Kazimierczuk and Puczko [5], and Raab [6].

The single-transistor Class-E amplifier topology, shown in Fig. 1, consists of an FET, RF choke, and output network comprised of a shunt capacitor and a series RLC circuit that appears inductive at the driving frequency. Thorough derivations and explanations of the Class-E operation condition (nonsimultaneous high drain current and voltage) exist in the literature [1]–[6]. Waveforms for the drain current and voltage and their associated mathematical expressions are shown in Fig. 2.

Fig. 1. Single-ended FET Class-E resonant tuned power amplifier.

Fig. 2. Class-E drain current and voltage waveforms and equations (Vd and Iq are the duals of those from [3], Vdmin, and Iq(θ)Rd are new in this analysis).

A priori designability (i.e., the Class-E amplifier can be designed without knowledge of the transistor’s characteristics) was shown to be valid at low frequencies (3.9 MHz) [1], but it is not generally realizable. At high frequencies, the device parasitics and resultant degradation in transconductance severely impact the circuit’s performance. Consequently, the ideal switch model of the transistor (which is the foundation of the a priori approach) needs to be reevaluated.

In order to develop an accurate high-frequency model, our approach takes into account the device parasitics and...
II. A NEW CLASS-E AMPLIFIER MODEL

The ideal switch model becomes inadequate to describe the performance of the Class-E amplifier as the operating frequency increases. First, it neglects the input power required to drive the active device. Therefore, in general, the ideal switch model cannot be used to estimate gain. Additionally, it fails to model the transistor’s finite transconductance. This omission leads to inaccurate drain efficiency estimates at high frequencies.

The ideal switch model is based on the premise that the active device has zero resistance while conducting current. The characteristic high transconductance and low-source terminal resistance of a wide channel device allow for low drain voltage during conduction. The a priori approach, therefore, suggests that it is always best to use an FET with an extremely high aspect ratio.

However, as the driving frequency increases, a large FET will require considerable drive power to charge and discharge its substantial input capacitance. Even at high frequencies, a Class-E amplifier using a large device may yield high drain efficiency. The problem is that this amplifier will most likely have low gain.

On the other hand, using a significantly smaller device to drive the same Class-E output network will require less input power and, therefore, may have higher gain. However, its lower transconductance, higher source terminal resistance, and resultant higher drain voltage during conduction will lower its drain efficiency.

Clearly there is a tradeoff between high gain and high drain efficiency. In our analysis, we examine how the transistor’s parasitics and limited transconductance affect gain and drain efficiency. By formulating expressions for input, output, and dc power, we construct a coherent model that allows optimization for maximum PAE.

The following analysis is restricted to FET’s. A detailed analysis for bipolar transistor Class-E amplifiers is the topic of a future paper. In this analysis, we assume that the parasitic capacitances are proportional to channel width and that the resistive parasitics scale inversely with the width dimension. We assume that the length of each gate finger is fixed and that the FET is laid out in an interdigitated structure. Our other assumptions include: ideal load transformation (to meet the Class-E design value, see Table I), 50% duty-cycle, loaded-$Q$ of five, ideal reactive elements, and only linear capacitors.

A. Input Power

The input power derived here is the input power delivered to the input circuit. The source is represented in Figs. 1 and 3(a)–(c) by the ideal voltage source $V_s$.

Table 1: Class-E Output Network Design Equations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{in}$</td>
<td>$\frac{\pi^4 + 4}{8} I_{in} R$</td>
</tr>
<tr>
<td>$R$</td>
<td>$\frac{8V_{in}}{P_{in}(\pi + 4)}$</td>
</tr>
<tr>
<td>$X_{/6}$</td>
<td>$\frac{2\pi V_{in}}{P_{in}(\pi + 4)}$</td>
</tr>
<tr>
<td>$L$</td>
<td>$\frac{8Q V_{in}^2}{\pi P_{in}(\pi + 4)}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$\frac{P_{in}(\pi + 4)}{80V_{in}^2 Q_v}$</td>
</tr>
<tr>
<td>$C_s$</td>
<td>$\frac{P_{in}}{x0V_{in}}$</td>
</tr>
</tbody>
</table>

The source terminal resistance ($R_s$) consists of interconnect resistances (ohmic contact resistance, bond wires, and leads).

The series gate resistance \( R_g \) has the same constituents as the source resistance, but also includes the poly-silicon sheet resistance.

The value of the gate-to-drain bridging capacitance \( C_{gd1} \) depends on the FET’s mode of operation. When the FET is cut off, \( C_{gd1} \) consists of only the overlap capacitance \( C_{gs0} \). When the conductive channel is enhanced between the source and drain, \( C_{gd1} \) consists of \( C_{gd0} \) plus half of \( C_{gs} \).

In order to give a 50% duty-cycle, the device is dc biased at its threshold voltage. Thus, during the positive-going half of the sinusoidal input \( (0 < \theta \leq \pi) \), the FET is active, and during the negative half \( (\pi < \theta \leq 2\pi) \), it is cut off. We perform the input power calculation in separate parts to model the switched-mode operation of the device. Each part of the analysis uses a different equivalent circuit representing either the active or cutoff state of the FET.

1) Positive Half of the Input Cycle \( (0 < \theta \leq \pi) \): For simplicity, we assume that the drain voltage is constant during the positive half of the cycle. This allows us to add \( C_{gs1} \) and \( C_{gs} \) in parallel. The input circuit then simplifies to a series connection of a resistor and capacitor [see Fig. 3(b)]. The power drawn during this interval is as follows:

\[
P_{int1} = \frac{1}{4} \Re \left[ V_s I_s \right] = \frac{V_s^2}{4} \frac{R_g (C_{gs} + C_{gs0})}{1 + \left[ \omega R_g (C_{gs} + C_{gs0}) \right]^2}.
\] (1)

2) Negative Half of the Input Cycle \( (\pi < \theta \leq 2\pi) \): The gate-to-drain bridging capacitance makes this calculation more complicated. While the FET is cut off, no current flows through the device. The current flowing in the shunt capacitor \( C_d \) generates a voltage pulse on the drain (Fig. 2). We approximate the drain voltage with a sinusoidal pulse of amplitude equal to that of the actual pulse. Thus, the impedance looking into the bridging capacitor [see Fig. 3(c)] is given as

\[
Z = \frac{V_{gs}}{I_{DC}} = \frac{V_{gs}}{j \omega C_{gs0} (V_{gs} + V_{dmax})}.
\] (2)

The maximum drain voltage \( V_{dmax} \) can be computed from the voltage equation given in Fig. 2 as follows:

\[
V_{dmax} = 1.13 \frac{I_{DC}}{\omega C_d} + V_{dmin} + 2I_{DC} R_s.
\] (3)

The gate-to-source voltage is written as

\[
V_{gs} = \frac{V_s}{1 + \frac{R_g}{Z} + j \omega R_g C_{gs}}.
\] (4)

Substitution of (2) into (4) yields an expression for \( V_{gs} \) in terms of \( V_s \) and the other quantities. The current \( (I_s) \) flowing into the circuit is simply the difference between \( V_s \) and \( V_{gs} \) divided by \( R_g \) [see Fig. 3(c)]. The power drawn during the negative half-cycle can then be expressed as

\[
P_{int2} = \frac{V_s^2}{4} \frac{\omega^2 R_g (C_{gs} + C_{gs0})}{1 + \left[ \omega R_g (C_{gs} + C_{gs0}) \right]^2} \times \left[ V_s (C_{gs} + C_{gs0}) + V_{dmax} C_{gs0} \right].
\] (5)
Finally, the total power delivered by the source is the sum of (1) and (5) as follows:

\[
P_{in} = \frac{V_s}{4} \left( \frac{\omega^2 R_d (C_{gs} + C_{gdo})}{1 + \left[ \omega R_d (C_{gs} + C_{gdo}) \right]^2} \right) \times \left[ 2V_s (C_{gs} + C_{gdo}) + V_{dmax} C_{gdo} \right].
\]  

Since we assume that the FET has an interdigitated structure, it is more natural to express the resistance and capacitances in (6) as functions of the number of gate fingers \( n \). We define the width and length of a single finger as \( W \) and \( L \), respectively. By doing this, the gate capacitances will be directly proportional to the number of fingers. The gate resistance will be inversely proportional to \( n \), except for the fixed packaging and interconnect resistance \( r_m \). These expressions are given as follows:

\[
R_g = r_m + \frac{1}{n} \left( \frac{\rho_{gate} W}{3L} + r_c \right) = r_m + \frac{r_g}{n},
\]

\[
C_{gs} = \frac{K'(AV^2)}{\mu}, \quad C_{gdo} = \frac{n C_{GDO} W}{n C_{GDO}}.
\]

In (7), \( K'(AV^2) \) and \( \mu (\text{cm}^2/\text{V} \cdot \text{s}) \) are the SPICE model parameters for intrinsic transconductance and bulk carrier mobility, respectively. \( C_{GDO} \) is the SPICE parameter for the gate-to-drain capacitance per unit gate width. The poly-silicon sheet resistance is denoted by \( \rho_{gate} (\Omega/\text{square}) \), and \( r_c (\Omega/\text{finger}) \) is the metal-to-poly contact resistance. The factor of 1/3 for the gate resistance provides an equivalent lumped resistance for the distributed RC network [7]. The values of the parameters above were taken from the optimized level-3 SPICE model, and the measured values of \( \rho_{gate} \), \( r_c \), and \( r_m \) are from MOSIS (Table II).

Now we can re-express the input power in terms of \( n \) as follows:

\[
P_{in} = \frac{n \omega^2 V_s}{4} \left( \frac{r_g(c_{gs} + c_{gdo})}{1 + \left[ \omega r_g (c_{gs} + c_{gdo}) \right]^2} \right) \times \left[ 2V_s (c_{gs} + c_{gdo}) + V_{dmax} c_{gdo} \right].
\]  

In general, the fixed resistance is much smaller than the other components of the gate resistance. By neglecting \( r_m \), the input power can be simplified to a linear function of \( n \) as follows:

\[
P_{in} = \frac{n \omega^2 V_s}{4} \left( \frac{r_g(c_{gs} + c_{gdo})}{1 + \left[ \omega r_g (c_{gs} + c_{gdo}) \right]^2} \right) \times \left[ 2V_s (c_{gs} + c_{gdo}) + V_{dmax} c_{gdo} \right].
\]  

The plots of the simulated and modeled results [from (6)] for input power as a function of the number of fingers are indeed quite linear (Fig. 4). Both here and in what follows, the length and width of each finger will be assumed to be 0.5 and 125 \( \mu \text{m} \), respectively.

### B. DC Current in Terms of \( R_S \)—The Effect of \( R_S \)

In our analysis, we model the transistor as a voltage-controlled current source, where the controlling voltages are the gate-to-source and the drain-to-source voltages. This model allows us to compute the dc current drawn by the circuit as well as the finite drain-to-source voltage during conduction (\( V_{dmax} \)).

Since the drain of the FET is connected to the dc supply by an RF choke, the average drain voltage must equal the supply voltage. Integration of the drain voltage [here, the \( I_d(\theta)R_S \) drop must be included (see Fig. 5)] over one cycle, and some algebraic manipulation yields the following expression for

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**Table II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K' )</td>
<td>2.00 \times 10^{-4} (A/V^2)</td>
</tr>
<tr>
<td>( \mu )</td>
<td>546 (cm^2/Vs)</td>
</tr>
<tr>
<td>( C_{gdo} )</td>
<td>3.05 \times 10^{-11} (F/m)</td>
</tr>
<tr>
<td>( \rho_{c} )</td>
<td>1.9 (\Omega/square)</td>
</tr>
<tr>
<td>( r_m )</td>
<td>0.07 (\Omega/square)</td>
</tr>
<tr>
<td>( r_c )</td>
<td>1.8(\Omega/gate finger)</td>
</tr>
</tbody>
</table>

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This expression shows how the dc current is affected by the source resistance. The plots of the drain current and voltage in Fig. 6(a) and (b) illustrate that the source resistance is not simply a dissipative element, as assumed earlier in the literature [2], [8]. Instead, it also has the effect of limiting the dc current drawn from the supply.

1) Computing $V_{d\text{min}}$: The minimum drain voltage ($V_{d\text{min}}$) remains as an unknown in (10). It can be computed by solving the FET drain current equation for $V_{d\text{min}}$. We defined $V_{d\text{min}}$ as the drain-to-source voltage during conduction; hence,

$$V_{ds}(\pi) = V_{d\text{min}}.$$  \hfill (11)

Assuming that the FET remains in the triode region ($V_{ds} \leq V_{gs} - V_t$), the familiar FET current equation relates the drain current to $V_{gs}$ and $V_{ds}$ as follows:

$$I_d(\pi) = \frac{K'W}{2L} \left[ 2V_{gs}(\pi) V_{ds}(\pi) - V_{ds}(\pi)^2 \right] = 2I_{DC}.$$  \hfill (12)

The amplitude and phase of the gate-to-source voltage relative to the input voltage ($V_s$) can be computed from the equivalent circuit shown in Fig. 5.

$$V_{gs}(\theta) = \frac{V_s}{\sqrt{1 + \left[ \omega (R_g + R_s) (C_{gs} + C_{gd}) \right]^2}} \left[ -\omega (R_g + R_s) (C_{gs} + C_{gd}) \right] \arctan \left[ \frac{\omega (R_g + R_s) (C_{gs} + C_{gd})}{1 + \omega R_g R_s C_d} \right] - I_d(\theta) R_s.$$  \hfill (13)

$$V_{gs}(\theta) = |V_s| \sin(\theta + \chi) - I_d(\theta) R_s.$$  \hfill (14)

Initially, the voltage drop across $R_s$ due to $I_d(\theta)$ is neglected in the derivation of (13), but is later accounted for in (14). After substituting (10), (11), and (14) in (12) and collecting terms, the solution for $V_{d\text{min}}$ is just that of a quadratic as follows:

$$V_{d\text{min}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = 1 - 2\pi\omega R_s C_d$$

$$b = 2\left[ 2\pi\omega R_s C_d [V_s - V_{gs}(\pi)] - 2\pi\omega C_d \frac{L}{K'W} - V_{gs}(\pi) \right]$$

$$c = 4\pi\omega C_d \frac{L}{K'W} V_{dd}.$$  \hfill (15)

2) DC Power: The dc power is simply the product of (10) with the supply voltage

$$P_{DC} = I_{DC} V_{dd} = \frac{\pi \omega C_d (V_{dd} - V_{d\text{min}})}{1 + 2\pi\omega R_s C_d} V_{dd}.$$  \hfill (16)

The plot of (16) in Fig. 7(a) shows how the dc power varies with $\eta$.

C. Output Power

In order to compute the power delivered to the load, we first calculate the output current. The current flowing in the output resonator shown in Fig. 1 is the sum of the FET and shunt capacitor currents minus the dc current. Since we are primarily interested in the fundamental component of the output current, Fourier analysis will produce the desired coefficients.

The output current must be computed in separate parts as well. Again, we will analyze the two regimes corresponding to the active and cutoff modes of the FET.

1) Output Current ($0 < \theta \leq \pi$): During this interval, the device current is described by the equation given in Fig. 2. The current flowing in the shunt drain capacitor is proportional to the derivative of the drain voltage (Fig. 2)

$$I_d(\theta) = \omega C_d \frac{dV_d(\theta)}{d\theta} = \omega C_d I_{DC} R_s \left( \frac{\pi}{2} \cos \theta + \sin \theta \right).$$  \hfill (17)
Using (17), the output current during the first half-cycle becomes

\[ I_{\text{out}}(\theta) = I_0(\theta) + I_c(\theta) - I_{\text{DC}} \]

\[ = I_{\text{DC}} \left( \frac{\pi}{2} + \omega R_s C_d \right) \sin \theta + \left( \frac{\pi \omega R_s C_d}{2} - 1 \right) \cos \theta \]  

(18)

2) Output Current ($\pi < \theta \leq 2\pi$): While the FET is cut off ($\pi < \theta \leq 2\pi$), the device current is zero and, once again, the shunt capacitor current is equal to the derivative of the voltage across the shunt capacitor

\[ I_c(\theta) = I_{\text{DC}} \left( 1 + \frac{\pi}{2} \sin \theta - \cos \theta \right), \quad \pi < \theta \leq 2\pi. \]  

(19)

Here, the output current is

\[ I_{\text{out}}(\theta) = I_0(\theta) - I_{\text{DC}} \]

\[ = I_{\text{DC}} \left( \frac{\pi}{2} \sin \theta - \cos \theta \right), \quad \pi < \theta \leq 2\pi. \]  

(20)

3) Fourier Analysis: The $I_0(\theta)R_s$ voltage drop during the conduction interval introduces a quadrature component to the sinusoidal output current. Therefore, the cosine term should be included in the analysis although its contribution to the output power may be relatively small.

A phase shift ($\phi$) between the switching cycle and the output current arises from derivation of the drain current [6]. This phase must be included in the analysis since it arises from the derivation of Class-E equations [1].

The sine and cosine of this phase angle are the useful quantities in the derivation of the output power expression

\[ \sin \phi = \frac{2}{\pi^2 + 4}, \quad \cos \phi = \frac{\pi}{\pi^2 + 4}. \]  

(21)

Using (18), (20), and (21), we can compute the Fourier integrals.

**Cosine Term**: \[ a_1 = \frac{1}{\pi} \int_0^{2\pi} I_{\text{out}}(\theta) \cos(\theta + \varphi) \, d\theta \]  

\[ = a_1 = \frac{I_{\text{DC}} \omega R_s C_d}{4} \sqrt{\pi^2 + 4}. \]  

(22)

The sine term is calculated in an analogous fashion.

**Sine Term**: \[ b_1 = \frac{1}{\pi} \int_0^{2\pi} I_{\text{out}}(\theta) \sin(\theta + \varphi) \, d\theta \]  

\[ = b_1 = \frac{I_{\text{DC}} \sqrt{\pi^2 + 4}}{2}. \]  

(23)

With these coefficients, the output current at the fundamental is

\[ I_{\text{out}}(\theta)_{\text{fundamental}} = a_1 \cos(\theta + \varphi) + b_1 \sin(\theta + \varphi). \]  

(24)

Finally, the output power becomes

\[ P_{\text{out}} = \frac{1}{2} |I_{\text{out}}(\theta)|^2 R = \frac{\pi^2 + 4}{8} I_{\text{DC}}^2 R \left[ 1 + \left( \frac{\omega R_s C_d}{2} \right)^2 \right]. \]  

(25)

If the source resistance is neglected, the output power reverts back to the form originally derived in [1] (Table 1). The plot of the output power versus the number of gate fingers in Fig. 7(b) shows that, beyond a certain limit, there is little advantage in using larger devices. In fact, since the input power increases almost linearly with the number of gate fingers, using an excessively large FET will adversely affect gain. It is also interesting to note that the inclusion of (10) in (25) eliminates the need for a separate calculation of the power dissipated in $R_s$. This reduction in output power is automatically taken into account in (27).

### III. Design Optimization

Now that the power relationships have been derived, we are prepared to compute gain, drain efficiency, and PAE. As we proceed with the derivations, we will show that an FET that produces high gain may suffer from low drain efficiency and vice versa. Consequently, our methodology entails finding the best compromise between gain and drain efficiency, i.e., we optimize the design for maximum PAE.
A. Gain

To be precise, we are referring to operating power gain since the input power is derived in (6) and the output power in (27) is the power delivered to the load. The operating power gain is, therefore, the ratio of (27) and (6), shown in (28), at the bottom of the page. As would be expected from the plots of input and output power, the plot of gain versus number of MOSFET gate fingers exhibits a definite peak [see Fig. 8(a)].

B. Efficiency

Even for devices with sufficient transconductance, the harmonic distortion, output network losses, and source terminal resistance of the FET prevent the drain efficiency from reaching 100%. Nevertheless, attaining reasonably high drain efficiency (≥ 70%) is not very difficult. It is the difficulty in achieving high gain that is problematic. Therefore, we emphasize the importance of achieving high PAE rather than high drain efficiency.

1) Drain Efficiency: Like output power, drain efficiency increases rapidly with the number of gate fingers, and then levels off [see Fig. 8(b)]. This should not be surprising since, qualitatively, we would expect that the larger the device is, the more closely it approximates an ideal switch. Quantitatively, the drain efficiency is the ratio of the output power to dc power as follows:

\[
\text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{DC}}} = \frac{I_{\text{DC}} R(\pi^2 + 4) \left[ 1 + \left( \frac{\omega R_g C_d}{2} \right)^2 \right]}{8V_{dd}}.
\]

\[
\text{Gain} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{I_{\text{DC}} R(\pi^2 + 4) \left[ 1 + \left( \frac{\omega R_g C_d}{2} \right)^2 \right]}{2V_s \omega^2 R_s (C_{gs} + C_{gs}) \left[ 2V_s (C_{gs} + C_{gs}) + V_{d\text{max}} C_{gs} \right]}.
\]
2) **PAE**: Finally, we compute the PAE using its standard definition, shown in (30), at the top of the page. A comparison [see Fig. 8(a)–(c)] shows that the value of \( \eta \) that will produce maximum PAE lies between the relatively low value for the peak gain and the high value of \( \eta \) where the drain efficiency approaches its limit.

Fig. 8(d) illustrates how (30) can be applied to a device with a fixed number of fingers (the case of a discrete FET). Here, the output power parameter from the Class-E equations (Table I) is the independent variable.

### IV. Practical Design Considerations

It has been suggested previously that the transistor’s parasitic drain-to-source capacitance can be absorbed in the shunt capacitor of the output network [1]. MOSFET devices typically have large gate-to-drain parasitic capacitances as well. The additional contribution to the drain-to-source capacitance made by the gate-to-drain component should be reflected in \( C_d \).

In (31), the shared capacitance \( C_{gs} \) does not appear as part of \( C_d \) since the drain capacitor plays a role in the operation of the Class-E circuit primarily while the device is off.

\[
\begin{align*}
C_d &= C_d - C_{ds} - C_{gsd} \\
&= \frac{P_{out}}{\pi \omega V_{dd}^2} - C_{ds} - C_{gsd}, \quad (31)
\end{align*}
\]

In (31), the shared capacitance \( C_{gs} \) does not appear as part of \( C_{gsd} \) since the drain capacitor plays a role in the operation of the Class-E circuit primarily while the device is off.

### V. Conclusion

Our analysis uses the original design equations for the Class-E output network as a starting point. Our first departure from the *a priori* approach was to model the effects of the input parasitics. This led the way to the formulation of an expression for the input power. We next applied a finite-transconductance model instead of the ideal switch. By using the FET current equation, we established a mathematical relationship between the device terminal voltages and drain current. This was a crucial step in our approach since it provided a way of computing \( I_{DC} \), which strongly affects the output power. Ultimately, we derived an expression for PAE which, in this case, serves as an indicator of how well the active device and Class-E network are suited for one another.

In essence, our design approach is an extension of the *a priori* method. However, our technique insures an optimal design by analyzing how the realistic behavior of the device affects the overall performance of the amplifier.

### APPENDIX

The optimized level-3 SPICE model parameters for the 0.5-\( \mu \)m CMOS devices are as follows.

\[
\begin{align*}
\text{param} \quad & t_{to} \quad 0.6566; \\
\text{param} \quad & t_{ko} \quad 546.2182; \\
\text{param} \quad & \theta \quad 0.2684; \\
\text{param} \quad & \eta \quad 3.000 \times 10^{-3}; \\
\text{param} \quad & l_d \quad 4.700 \times 10^{-8}; \\
\text{param} \quad & \delta \quad 0.6900; \\
\text{param} \quad & n_{fs} \quad 5.900 \times 10^{-1}; \\
\text{param} \quad & \text{tox} \quad 9.600 \times 10^{-9}; \\
\text{param} \quad & c_{gsd} \quad 3.052 \times 10^{-10}; \\
\text{param} \quad & c_{gds} \quad 4.024 \times 10^{-10}; \\
\gamma \quad & 0.5976; \\
\eta_{\text{max}} \quad & 2.000 \times 10^{-5}; \\
\kappa \quad & 2.898 \times 10^{-2}; \\
\tau_{\text{sh}} \quad & 35.001 \times 10^{-1}; \\
\phi \quad & 2.000 \times 10^{-4}; \\
\tau_{\text{hub}} \quad & 2.000 \times 10^{-7}; \\
\gamma_{\text{sh}} \quad & 0.7000; \\
\gamma_{\text{sh}} \quad & 1.000 \times 10^{-4}; \\
\gamma_{\text{sh}} \quad & 3.052 \times 10^{-10}; \\
\gamma_{\text{sh}} \quad & 5.620 \times 10^{-4}.
\end{align*}
\]

### ACKNOWLEDGMENT

The authors thank K. Choi for device measurements and for generating the optimized SPICE model. The authors also recognize Dr. P. Alinikula, Nokia Research Center, Helsinki, Finland, for valuable discussions.

### REFERENCES


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