Better Predictions of Microwave Amplifier Small Signal Performances with FEM Simulator

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Abstract – This paper provides an alternative and highly accurate method in predicting Small Signal Performance of Microwave Amplifier. An Electromagnetic (EM) simulator that based on Finite Element Method (FEM) was used in combination with the conventional SPICE-based microwave circuit simulator in order to demonstrate the superiority in performance outcome such as Return Loss and Small Signal Gain. The method known as EM/Circuit Co-Simulation assures a microwave amplifier that functions with the first PCB tape-out, therefore multiple PCB layouts can be avoided, which not only reduce development time but also design and manufacturing cost respectively. The method and performance comparisons with the conventional simulator are systematically demonstrated through the design and EM analysis of IEEE 802.16e Mobile WiMAX Power Amplifier (PA).

Index Term – Microwave Amplifier, Small Signal Performance, Electromagnetic Simulator, EM/Circuit Co-Simulation, Finite Element Method (FEM), IEEE 802.16e Mobile WiMAX

I. INTRODUCTION

Computer methods in analyzing Electromagnetics (EM) problems in general fall into one of three following categories; analytical techniques, numerical techniques, and expert systems. Analytical techniques simplify the assumptions about the geometry of a problem in order to apply a closed-form or look-up table solution. Numerical techniques on the other hand, intend to solve fundamental field equations directly but subject to the boundary constraints posed by the geometry. Whereas, expert systems do not actually calculate the field directly, but instead estimate values for the parameters of interest based on a rules of database.

Techniques in Comparisons

Analytical techniques can be a useful tool when the important EM interactions of the configuration can be forecasted. Expert systems solve a problem in same way as a “quick-thinking method” where experienced Microwave or EMC engineer with a calculator would approach it. Numerical techniques as the name implies require more computation than the analytical techniques or the expert systems; however the technique is proven to be very powerful EM analysis tools since it analyze the entire geometry provided as input and calculate the solution to a problem based on a full-wave analysis. A number of different numerical techniques for solving EM problems are available and each technique can be tailored and well-suited for the analysis of a particular type of problem.

Numerical Techniques

As narrowing down to the most widely used method, numerical techniques can be categorized into two groups; differential and integral. Both methods discretized the problematic region and transform the field equations into a system of linear equations. Differential methods such as Finite Element Methods (FEM), Finite-Difference Time-Domain (FDTD) and Transmission Line Matrix (TLM) require the entire problem region to be discretized.

Finite Element Method (FEM)

The Finite Element Method (FEM) or Finite Element Analysis (FEA) is based on the idea of building a complicated object with simpler blocks, or dividing a complicated object into small and manageable pieces. FEM/FEA is the most widely applied computer simulation method in engineering currently and closely integrated with CAD/CAM applications.

Structural Analysis Procedure using FEM

Following are the typical process in structural analysis utilizing FEM/FEA:

i. The structure was divided into smaller homogeneous elements with the corner of the elements called nodes.
ii. The behavior of the physical quantities on each element was described.
iii. Elements at the nodes were connected and assembled in order to form an approximate system of equations for the entire structure.
iv. System of equations involving the unknown quantities at the nodes i.e. displacements were solved.
v. The desired quantities such as strains and stresses at selected elements were calculated.

The elements are not uniform in size where it can be small where geometric details exist and much larger elsewhere. In each finite element, a simple variation (which is usually linear) of the field quantity is assumed. The goal of the FEM/FEA is to determine the field quantities at the nodes. Most FEM/FEA is variational techniques which the methods functions by minimizing or maximizing an expression that is known to be stationary about the true solution. Generally, FEM/FEA solve for the unknown field quantities by minimizing energy functional. The energy functional is an expression describing all the energy associated with the configuration being analyzed. As for 3-Dimensional (3D), time-harmonic problems this functional may be represented as:
The first two terms in the integrand represent the energy stored in the magnetic and electric fields and the third term is the energy dissipated or supplied by conduction currents. Expressing $\mathbf{H}$ in terms of $\mathbf{E}$ and setting the derivative of this functional with respect to $\mathbf{E}$ equal to zero, an equation of the form $J(\mathbf{E}) = 0$ is obtained. A $k$th-order approximation of the function $f$ is then applied at each of the $N$ nodes and boundary conditions are enforced, resulting in the system of equations:

$$
\begin{bmatrix}
J_1 \\
J_2 \\
\vdots \\
J_n \\
\end{bmatrix} = 
\begin{bmatrix}
y_{11} & y_{12} & \cdots & E_1 \\
y_{21} & y_{22} & \cdots & E_2 \\
\vdots & \vdots & \ddots & \vdots \\
y_{mn} & \cdots & y_{nn} & E_n \\
\end{bmatrix}
$$

The values of $\mathbf{J}$ on the left-hand side of this equation are referred to as the source terms. They represent the known excitations. The elements of the Y-matrix are functions of the problem geometry and boundary constraints. Since each element only interacts with elements in its own neighborhood, the Y-matrix is generally sparse. The terms of the vector on the right-hand side represent the unknown electric field at each node. These values are obtained by solving the system of equations. Other parameters, such as the magnetic field, induced currents, and power loss can be obtained from the electric field values.

In order to obtain a unique solution, it is necessary to constrain the values of the field at all boundary nodes. A major weakness of the finite element method is that it is relatively difficult to model open configurations i.e. configurations where the fields are not known at every point on a closed boundary. Various techniques such as ballooning and absorbing boundaries are used in practice to overcome this deficiency. These techniques work reasonably well for 2-dimensional (2D) problems, but so far they are not very effective for 3-dimensional electromagnetic radiation problems.

The major advantage of FEM/FEA over other EM modeling techniques stems from the fact that the electrical and geometric properties of each element can be independently defined. This permits the problem to be set up with a large number of small elements in regions of complex geometry and fewer, larger elements in relatively open regions. Thus it is possible to model configurations that have complicated geometries and many arbitrarily shaped dielectric regions in a relatively efficient manner. Commercial FEM simulators [13, 14] that have graphical user interfaces and can determine the optimum placement of node points for a given geometry automatically are available. These codes are used to model a wide variety of electromagnetic devices such as spark plugs, transformers, waveguides, and integrated circuits.

Specific implementations of three-dimensional electromagnetic finite element codes are described in Ph.D. dissertations by Maile [8] and Webb [11]. Silvester and Ferrari [17] have written an excellent text on this subject for electrical engineers.

II. METHODOLOGY

Evaluation Board Design

In order to demonstrate the accuracy of the EM/Circuit Co-Simulation, 2.5GHz PA was designed as well as the construction of an evaluation board. Biased with +4.8V of Supply Voltage ($V_{dd}$) and 300mA of Total Current ($I_{dd}$), the PA capable to deliver an Input and Output Return Loss (IRL & ORL) that are better than 10dB, Small Signal Gain (SSGain) of 12dB, Third-Order Intercept Point (OIP3) of 44dBm and Output 1-dB Gain Compression (OP1B) of 27dBm at 2.5GHz.

The evaluation board was designed with the material cost and practical limitations i.e. board space constraints were taken into considerations. The evaluation board equipped with 0.031inch (31mils) of FR4 dielectric and populated with 0603 size SMD components. RF connections to the evaluation board were made through PCB edge-mounted microstrip to SMA coax transitions, $J_1$ and $J_2$ as exemplified in Fig. 1.

![Evaluation Board for 2.5GHz Mobile WiMAX PA](image)

The evaluation board requires a single 4.8V voltage supply. The relatively high current (≥300mA) drawn by the evaluation board can result in significant voltage drop over a long $V_{dd}$ supply wires and therefore 4-pin connector, $J_3$, permits 4-wire “Kelvin contact” to be used to compensate any voltage drop in conjunction with power supplies that support such function.

The EM/Circuit Co-Simulation feature in Agilent ADS software was then manipulated to integrate the EM results into the circuit simulator. LineCalc is used to design the input and output 50Ω microstrip transmission lines.

Given:

- **Characteristic Impedance ($Z_c$)** = 50Ω
- **Dielectric constant ($\varepsilon_r$) of FR-4** = 4.6
- **Operating Frequency** = 2.5GHz
- **Conductor Thickness ($T$)** = 0.7mils
- **Substrate Height ($H$)** = 31mils

Substrate Height ($H$) = 31mils
Transmission Line Length (L) = 500mils
Microstrip line (W) width = 55mils

The width calculated is sufficient to accommodate the size of the center pin of the SMA connector. Fig. 2 illustrates the complete evaluation board layout that has been generated using FEM-based EM simulator, Electromagnetic Design System (EMDS) from Agilent Technologies.

As referring to Fig. 2, the red dots are the simulation ports inserted to the evaluation board layout to accommodate all possible components intended to be placed in actual evaluation board. Ideally, in order to obtain a highly accurate simulation results, the entire evaluation board structure have to be modeled and generated. However due to the time constraint and workstation capability, only a very critical evaluation board section was selected to be analyzed as can be seen from Fig. 3. The critical sections are such as 50Ω microstrip transmission line, DC feed traces including the bypass-decoupling networks/traces that would have a huge impact on stability especially at low frequency.

The evaluation board layout was then transferred to a typical microwave schematic simulator (SPICE-based) and actual lumped component model was inserted to imitate the real evaluation board configuration as presented in Fig. 4. With EM/Circuit Co-Simulation, not only the electrical component behavior is analyzed but also the entire structure of the evaluation board including the parasitic capacitance and inductance i.e. the inductance of the via holes.

EM/Circuit Co-Simulation design method is considered successful even if some of the lumped component values have to be slightly adjusted to achieve the desired RF performance, as long as the layout does not have to be modified. It is also considered a successful method even if the model prediction does not exactly agree with measured performance, but the end amplifier performance still meets the initial design criteria and specifications.

III. RESULT AND DISCUSSIONS

Performance Comparisons

The evaluation board performance was measured under the following test conditions: V_{dd} of 4.5V, I_{ds} of 280mA and operating frequency f_{c} of 2.5GHz. In the following discussion, the EM/Circuit Co-Simulation performance which represented by the blue curve will be compared with the actual evaluation board performance symbolized by the red curve.

Fig. 5 expose the performance comparison between evaluation board and the EM/Circuit Co-Simulation in term of Input Return Loss (IRL). Clearly at the desired operating frequency, (f_{c}) which is 2.5GHz, the EM/Circuit Co-Simulation able to re-produce not only the same response curve but closely resemble the evaluation board’s IRL. IRL of the evaluation board is about -13.4 while the EM/Circuit Co-Simulation exhibits about -13.2dB at 2.5GHz.
A close similarity observed in Small Signal Gain (SSGain) of EM/Circuit Co-Simulation as compared to the evaluation board performance. This is evidently exemplifies in Fig. 6 where the SSGain of the evaluation board is about 12.8dB while for EM/Circuit Co-Simulation, a SSGain of 12.4dB is produced.

Graphed in Fig. 7, is the Reverse Isolation (ISO) performance comparison between EM/Circuit Co-Simulation and the evaluation board. A -19.6dB of the evaluation board’s isolation is able to be accurately predicted using EM/Circuit Co-Simulation which exhibits -20.0dB of ISO.

Although the response of the Output Return Loss (ORL) that exhibited from the EM/Circuit Co-Simulation are slightly swerved as compared to the evaluation board’s curve, the ORL at the intended 2.5GHz frequency is still comparable. This is obviously clarified by Fig. 8 where the evaluation board’s ORL is about -19.8dB as compared to -16dB for the EM/Circuit Co-Simulation. A 3.5dB difference in RL would not be a significant fig. since there will be only 0.15 of VSWR degradation when the RL is reduced by about 4dB.

Last but not least is the small signal stability or the Rollet Stability Factor (K-Factor) comparison. As revealed from Fig. 9, the K-Factor response of the EM/Circuit Co-Simulation is appear to be very similar and comparable to the actual evaluation board stability.

### Table I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured</th>
<th>Simulated</th>
<th>Δ</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Return Loss</td>
<td>-13.4</td>
<td>-13.2</td>
<td>0.2</td>
<td>dB</td>
</tr>
<tr>
<td>Small Signal Gain</td>
<td>12.6</td>
<td>12.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Reverse Isolation</td>
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<td>-20.0</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Output Return Loss</td>
<td>-19.8</td>
<td>-16.3</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Rollet Stability Factor</td>
<td>&gt; 1</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Tables I summarize the comparison between evaluation board performance and the EM/Circuit Co-Simulation results. With less than 0.5dB of data discrepancies which typically is negligible, EM/Circuit Co-Simulation apparently proven to be a highly reliable and alternative tools in modern microwave amplifier design.

### IV. CONCLUSION

A revolutionary and highly rigorous method in designing as well predicting small signal performances of microwave amplifier has been demonstrated. EM/Circuit Co-Simulation which integrates an FEM-based EM simulator with a typical SPICED-based microwave circuit simulator, able to produce a highly precise small signal parameters as compared to the measured performances. EM/Circuit Co-Simulation unarguably can be classified as first-time-right-designs methodology in modern microwave amplifier design. A careful cautious attention to the layout and simulation...
results accelerates the design process and provides a design cost savings by avoiding multiple PCB designs. It is observed that the entire evaluation board does not have to be analyzed in order to achieve accurate results. Simulating the entire PCB may improve the results with however it comes with the expense of significantly longer simulation time. All along, a brief review of various analysis techniques for electromagnetic problems has been re-visited. The work was demonstrated by the design of 2.5GHz PA that intended for IEEE 802.16e Mobile WiMAX application.

REFERENCES


Mohd Syuhaimi bin Kassim received B.Eng. (Electrical, Electronic and System Engineering) in 2001 from Universiti Kebangsaan, Malaysia and currently doing his M.Sc. in Communications Engineering in Universiti Malaysia Perlis (UnMAP).

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Prior to working in academia, Dr. Mohd Fareq bin Abd Malek has six years industry experience in the telecommunications industry where he worked with Siemens and Alcatel, Malaysia. Dr. Mohd Fareq bin Abd Malek currently serves as Senior Lecturer and Deputy Dean (Academic & Research) in Universiti Malaysia Perlis (UnMAP).
Below are the Fig. 2, Fig. 3 and Fig. 4 in original size and more visible form.

**Fig. 2.** Evaluation board layout generated with FEM-based simulator

**Fig. 3.** Selected section of the evaluation board layout
Fig. 4. EM/Circuit Co-simulation setup