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EM/Circuit Co-Simulation: A Highly Accurate Method for Microwave Amplifier Design

Syuhaimi Kassim
School of Computer and Communication Engineering,
University Malaysia Perlis (UniMAP)
Perlis, Malaysia.
matmi78@gmail.com

Fareq Malek
School of Computer and Communication Engineering,
University Malaysia Perlis (UniMAP)
Perlis, Malaysia.
mfareq@unimap.edu.my

***Abstract* – This paper features a radical and highly accurate method of designing a microwave amplifier. A Full-wave Electromagnetic Simulator, which is based on the Method-of-Moments (MoM) numerical method, is used in parallel with the conventional microwave circuit simulator to demonstrate a superior performance outcome such as Stability, Return Loss and Small Signal Gain. This method known as EM/Circuit Co-Simulation guarantees a design that work with the first PCB and concurrently multiple PCB layouts are avoided, which saves design cost and development time respectively. The method is methodically demonstrated with the design of power amplifier (PA) based on E-pHEMT technology for IEEE 802.16e Mobile WiMAX applications.**

Keywords - Microwave Amplifier; IEEE 802.16e Mobile WiMAX; Method of Moments; Electromagnetic Simulator; EM/Circuit Co-Simulation

I. INTRODUCTION

Computer methods for analyzing Electromagnetics (EM) problems generally fall into one of three categories; Analytical Techniques, Numerical Techniques, and Expert Systems. Analytical techniques make simplifying assumptions about the geometry of a problem in order to apply a closed-form solution. Numerical techniques attempt to solve fundamental field equations directly, subject to the boundary constraints posed by the geometry whereas expert systems estimate values for the parameters of interest based on a rules database [14].

A. Analytical Techniques vs. Numerical Techniques

Analytical techniques can be a useful tool when the important EM interactions of the configuration can be anticipated. Expert systems approach a problem in much the same way as a quick-thinking where experienced Microwave or EMC engineer with a calculator would approach it. Numerical techniques generally require more computation than analytical techniques or 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 [8]. Numerical techniques, specifically, can be categorized into two groups; differential and integral.

B. Differential Methods

Finite Element Method (FEM) is one of the most widely used differential methods and applied computer simulation method in microwave engineering currently and closely integrated with CAD/CAM applications [10, 12, 16]. FEM is based on the idea of dividing a complicated object into small and manageable pieces. Typical procedures for microwave structural analysis, using FEM are as the following:

a) The structure was divided into smaller homogeneous elements with the corner of the elements called nodes.
b) The behavior of the physical quantities on each element was described.
c) Elements at the nodes were connected and assembled in order to form an approximate system of equations for the entire structure.
d) System of equations involving the unknown quantities at the nodes i.e. displacements were solved.
e) 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 of the field quantity is assumed. The goal of the FEM is to determine the field quantities at the nodes. Most FEM 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 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:

$$\mathrm{F} = \int_{\mathrm{V}} \frac{\mu|\mathbf{H}|^2}{2} + \frac{\varepsilon|\mathbf{E}|^2}{2} - \frac{\mathbf{J}\cdot\mathbf{E}}{2\,j\omega}\,dv \qquad (1)$$

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 **H** in terms of **E** and setting the derivative of this functional with respect to **E** equal to zero, an equation of the form $f(\boldsymbol{J},\boldsymbol{E}) = 0$ 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:

Corresponding Author: Syuhaimi Kassim, School of Computer and Communication Engineering, University Malaysia Perlis (UniMAP), Perlis, Malaysia.

$$\begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_n \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdots \\ y_{21} & y_{22} & \cdots \\ \vdots & \vdots & \\ \vdots & \vdots & y_{nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_n \end{bmatrix} \quad (2)$$

The values of **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 are not very effective for 3D electromagnetic radiation problems.

The major advantage of FEM 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.

C. Integral Methods

Integral methods such as Method of Moments or Moment Methods (MoM) on the other hand, only require discretization over "the structure in question" not free space as with "field methods. Boundary conditions do not have to be set and memory requirements scale proportional to the size of the geometry in question and the required solution frequency [1]. Method of Moment (MoM) usually employs time-harmonic Maxwell's equations or full wave solution of Maxwell's integral equations in the frequency domain. As a result, these methods are largely confined to linear systems [17].

MoM is a technique for solving complex integral equations by reducing them to a system of simpler linear equations. MoM employs a technique known as the "Method of Weighted Residuals". All weighted residual techniques begin by establishing a set of trial solution functions with one or more variable parameters.

The equation solved by MoM techniques is generally a form of the Electric Field Integral Equation (EFIE) or Magnetic Field Integral Equation (MFIE). Both equations can be derived from Maxwell's equations by considering the problem of a field scattered by a perfect conductor (or a lossless dielectric). These equations are of the form,

$$EFIE : \boldsymbol{E} = f_e\left(\boldsymbol{J}\right) \quad (3)$$

$$MFIE : \boldsymbol{H} = f_m\left(\boldsymbol{J}\right) \quad (4)$$

Where:

The terms on the left-hand side of these equations are incident field quantities and **J** is the induced current. The form of the integral equation used determines which types of problems a moment-method technique is best suited to solve [6, 15].

As for example one form of the EFIE may be particularly well suited for modeling thin-wire structures, while another form is better suited for analyzing a metal plates. Usually these equations are expressed in frequency domain however the MoM can also be applied in time domain [7]. The first step in MoM solution process is to expand ***J*** as a finite sum of basis (or expansion) functions,

$$\boldsymbol{J} = \sum_{i-1}^{M} J_i \boldsymbol{b}_i \quad (5)$$

Where:

$\boldsymbol{b}_i$ is the i[th] basis function and $\boldsymbol{J}_i$ is an unknown coefficient. Next, a set of M linearly independent weighting functions, *wj*, are defined. An inner product of each weighting function is formed with both sides of the equation being solved. In the case of the MFIE (Equation 4), this results in a set of M independent equations of the form,

$$< wj, \boldsymbol{H} >=< wj, f_m\left(\boldsymbol{J}\right) > \quad (6)$$

Where:

$$J = 1,2...,M$$

By expanding ***J*** using Equation (3), we obtain a set of M equations in M unknowns,

$$< wj, \boldsymbol{H} >= \sum_{i-1}^{M} < w_j, f_m\left(J_i, \boldsymbol{b}_i\right) > \quad (7)$$

Where:

$$J = 1,2...,M$$

This can be written in matrix form as:

$$\left[\boldsymbol{H}\right] = \left[Z\right]\left[\boldsymbol{J}\right] \quad (8)$$

Where:

$$Z_{ij} = < w_j, f_m(b_i >)$$

$$\boldsymbol{J}i = Ji$$

$$\boldsymbol{H}_j = < w_j, \boldsymbol{H}_{inc}$$

The vector **H** contains the known incident field quantities and the terms of the Z-matrix are functions of the geometry. The unknown coefficients of the induced current are the terms of the **J** vector. These values are obtained by solving the system of equations. Other parameters such as the scattered electric and magnetic fields can be calculated directly from the induced currents.

Depending on the form of the field integral equation used, moment methods can be applied to configurations of conductors' only, homogeneous dielectrics only, or very specific conductor-dielectric geometries. MoM techniques applied to integral equations are not very effective when applied to arbitrary configurations with complex geometries or inhomogeneous dielectrics. They also are not well-suited for analyzing the interior of the conductive enclosures or thin plates with wire attachments on both sides [5].

Nevertheless, MoM techniques do an excellent job of analyzing a wide variety of important three-dimensional electromagnetic radiation problems. General purpose MoM codes are very efficient in modeling wire antennas or wires attached to large conductive surfaces. They are widely used for antenna and electromagnetic scattering analysis. Several non-commercial general-purpose MoM computer programs are available [13].

The following sections of this paper intended to highlights the integration of MoM-based EM Simulator with a SPICE-based microwave circuit simulator in designing a 2.5GHz power amplifier for IEEE 802.16e Mobile WiMAX applications.

II. SIMULATION TOOLS, ENVIRONMENT AND METHODOLOGY

The EM/Circuit Co-Simulation feature in Agilent ADS software is manipulated in order to combine the EM analysis results with the SPICED-based circuit simulation. EM/circuit co-simulation technique carries out the EM and circuit simulation under a single simulation setup. Through the co-simulation method, it is important to place the layout component in the schematic with an exact idea and description of the pins on which various lumped elements need to be connected. In this case, layout look-alike components are much easier to use than traditional black-box representations, which are difficult to understand. Furthermore the set up require the user to remember the various pin details in order to connect the correct discrete components.

Layout look-alike components help with proper visualization of the layout and allow the designer to easily identify the location for the various discrete elements and perform the simulation while keeping potential errors to a minimum. Designers must take care when connecting discrete components to the physical layout during the simulation, so that parasitics resulting from unwanted coupling between the ports are taken into account.

With all port are assigned, the designer can start the simulation which will use the EM solver to simulate the distributed components and the circuit simulator to simulate the discrete parts as well to displays the composite results. Figure 2 shows how a layout look-alike component can help the designer to set up composite simulations and how the discrete components are connected to the layout. The red dots are the simulation ports inserted to the evaluation board layout to accommodate all possible components in actual evaluation board as exemplified in Figure 1. The major advantage obtained from this method is the setup is simple, and the designer can easily identify the sections of the layout for the appropriate discrete component connection.

In order to demonstrate the accuracy of the EM/Circuit Co-Simulation, a 2.5GHz E-pHEMT power amplifier was designed complete with a construction of an evaluation board. Biased with 4.8V voltage supply (Vdd) and 300mA of total current (Idd), the PA capable to deliver an Input and Output Return Loss (IRL & ORL) 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 real-life board space constraints taken into considerations. The evaluation board equipped with 0.031inch (31mils) of FR4 dielectric and 0603 small surface mount components. RF connections to the evaluation board were made via PCB edge-mounted microstrip to SMA coax transitions, J_1 and J_2.

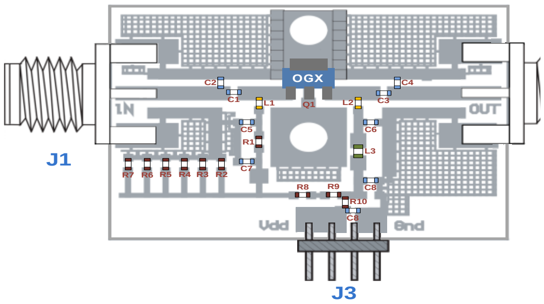

Figure 1: Evaluation Board for 2.5GHz Mobile WiMAX PA

LineCalc; passive structure analysis software from Agilent technologies were used to design the input and output 50Ω microstrip transmission lines.

Given;

Characteristic Impedance (Z_o) *= 50Ω*
Dielectric constant (ε_r) *of FR-4 = 4.6*
Operating Frequency = 2.5GHz
Conductor Thickness (T) = 0.7mils
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. Figure 2 shows the complete evaluation board layout that has been generated and using MoM-based EM simulator, Momentum from Agilent Technologies.

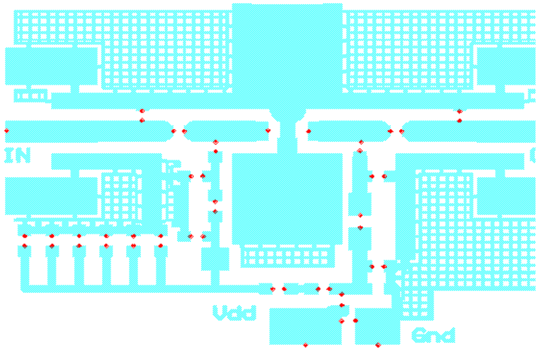

Figure 2: Complete evaluation board layout with simulation port inserted

The red dots in Figure 2 and Figure 3 are the simulation ports inserted to the evaluation board layout to accommodate all possible components in actual evaluation board as exemplify in Figure 1. The major advantage obtained from this method is the setup is simple, and the designer can easily identify the sections of the layout for the appropriate discrete component connection.

Ideally, in order to obtain a highly accurate simulation results, the entire evaluation board structure have to be modeled. However due to the time constraint and workstation capability, only a very critical layout section is selected to be analyzed as can be seen from Figure 3. The critical sections are such as 50Ω microstrip transmission line, DC feed traces including the bypass-decoupling traces that would have a great impact on low frequency stability.

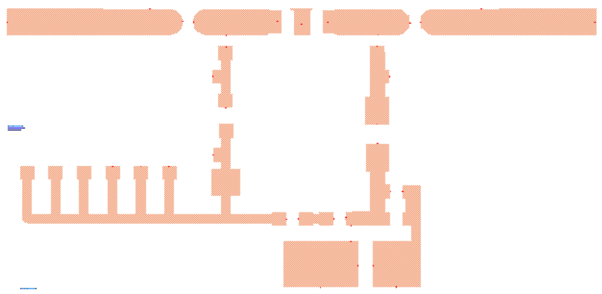

Figure 3: Selected section of the evaluation board layout

The evaluation board layout is then transferred to a schematic simulator and actual lumped component model is inserted to imitate the real evaluation board configuration as shown in Figure 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.

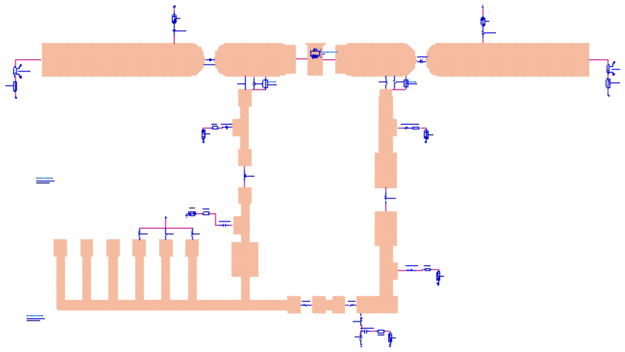

Figure 4: EM/Circuit Co-simulation setup

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 a successful method even if the model prediction does not exactly agree with measured performance, but the end amplifier performance still meets the design criteria and specifications.

III. Result and Discussions

A. Performance Comparisons

The evaluation board performance was measured under the following test conditions: V_{ds} 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.

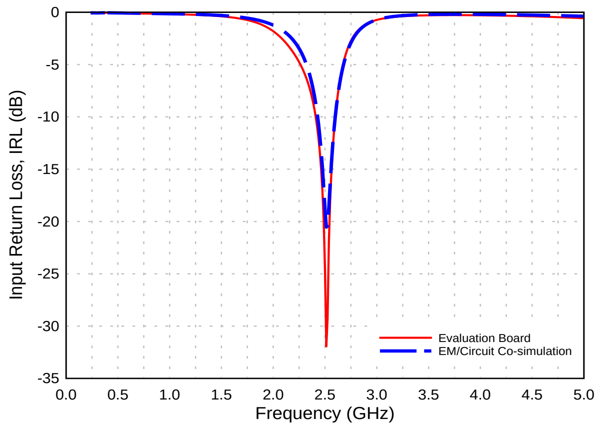

Figure 5: Input Return Loss (IRL) comparison

Figure 5 illustrates 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.

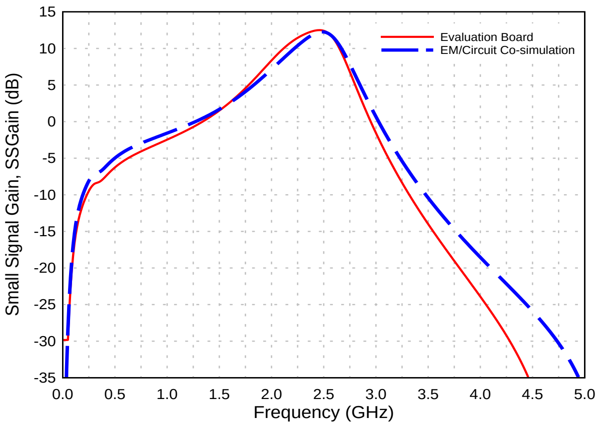

Figure 6: Small Signal Gain (SSGain) comparison

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 Figure 6 where the SSGain of the evaluation board is about 12.5dB while for EM/Circuit Co-Simulation, a SSGain of 12.2dB is produced.

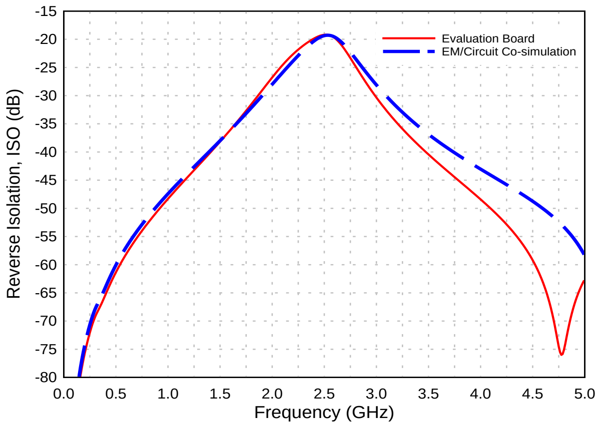

Figure 7: Reverse Isolation (ISO) comparison

Graphed in Figure 7, is the Reverse Isolation (ISO) performance comparison between EM/Circuit Co-Simulation and the evaluation board. A -19.4dB of the evaluation board's isolation is able to be accurately predicted using EM/Circuit Co-Simulation which exhibits -19.7dB of reverse isolation.

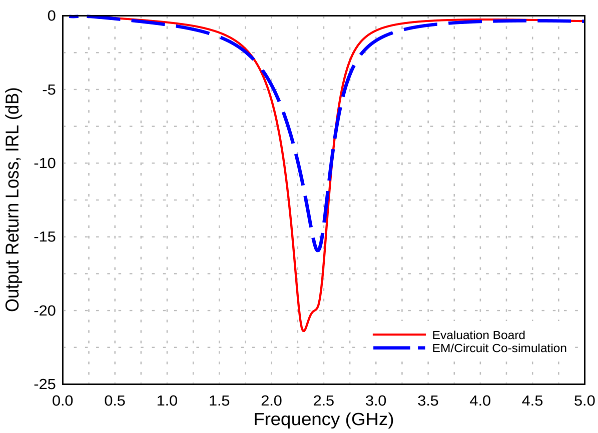

Figure 8: Output Return Loss (ORL) comparison

Although the response of the Output Return Loss (ORL) that exhibit from 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 Figure 8 where the evaluation board's ORL is about -19.6dB as compared to -16dB for the EM/Circuit Co-Simulation. 3.6dB difference in return loss would not be a significant figure since there will be only 0.15 of VSWR degradation when the return loss is reduced by about 4dB.

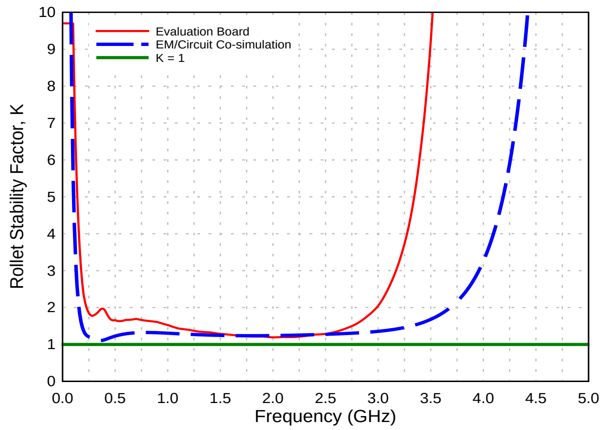

Figure 9: Rollet Stability Factor (K-Factor)

Last but not least is the small signal stability or the Rollet Stability Factor (K-Factor) comparison. As can be seen from Figure 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.

IV. Conclusion

A highly accurate method in predicting small signal performance and aiding the design of microwave amplifier has been addressed. EM/Circuit Co-Simulation which integrates a numerical-based EM simulator with currently market-available microwave circuit simulator, able to produce a highly precise small signal parameters as compared to the measured performance. EM/Circuit Co-Simulation undeniably can be classified as *first-time-right-designs* methodology in microwave amplifier design. All along, a brief review of various analysis techniques for electromagnetic problems hav been re-visited. The work was demonstrated by the design of 2.5GHz power amplifier intended for IEEE 802.16e Mobile WiMAX application.

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AUTHORS PROFILE

Mohd Syuhaimi Bin Kassim received B. Eng. (Electrical, Electronic and System Engineering) in 2001 from Universiti Kebangsaan Malaysia (UKM) and currently doing his M.Sc. in Communications Engineering in Universiti Malaysia Perlis (UniMAP). He is currently working as Application Engineer for RF and Microwave Products at Avago Technologies, Malaysia. He is responsible for various microwave products especially for Base Transceiver Station (BTS) transmitter line-up i.e. Gain Blocks, Driver and Power Amplifier (PA).

He had provided technical solutions globally for a numerous number of telecommunication giants such as Alcatel-Lucent, Huawei, Nortel, Zyxel, Nokia-Siemens, Ericsson, Andrew Wireless and others.

Mohd Syuhaimi bin Kassim's research interests are focusing on electromagnetic analysis for microwave circuits as well as microwave circuits and systems design especially on the linear Power Amplifier (PA) and transmitter technologies.

Dr Mohd Fareq bin Abd Malek received B.Eng (Hons) in Electronic and Communication Engineering from University of Birmingham, United Kingdom, M.Sc Eng (Distinction) in Microelectronic Systems and Telecommunications from University of Liverpool, United Kingdom and PhD in Electrical and Electronic Engineering from University of Liverpool, United Kingdom.

His research interests are in electromagnetic, antennas, microwave and wireless communication. He has so far published in 10 international journals, and in numerous conference proceedings. He has served as reviewers in international journals such as Progress in Electromagnetics Research (PIER) / Journal of Electromagnetic Waves and Applications (JEMWA) and International Journal of Computer Science and Security. He also has reviewed articles in various international conference proceedings such as International Conference on Antennas, Propagations and Systems (INAS2009), Industrial Symposium on Industrial Electronics and Applications (ISIEA2010 and ISIEA2009), Asia Pacific Symposium on Applied Electromagnetics and Mechanics (APSAEM2010), International Conference on Electronics Design and Systems Applications (ICEDSA2010), Defence and Security Technology Conference (DSTC2009), Vehicular Technology Conference (VTC2010-Spring). He has represented Malaysia in the Asia Pacific Telecommunity Conference (APT) for World Radio Communication (WRC2011) at Hangzhou, China in 2009. He is also the Editor in Chief of Journal of Engineering Research and Education.

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 (UniMAP).