Comparison of Commercially Available Full-Wave EM Simulation Tools for Microwave Passive Devices

Vasa Radonić, Vesna Crnojević-Bengin, Ljiljana Živanov

Abstract — **A great number of software packages specialized for CAD and EM simulation of microwave components is commercially available today. However, choosing optimal package for an application is not trivial. This paper presents comparison of two widely used full-wave EM simulation tools: Ansoft's High Frequency Structure Simulator and EMSight - EM simulator in Microwave Office from Applied Wave Research (AWR).**

***Keywords* — CAD, Design Automation, Simulation Software, Microstrip Resonators.**

I. Introduction

The explosive growth in commercial interest in RF, microwave and millimeter wave systems, especially in wireless communications and mobile and satellite communication systems, has provided a significant challenge to conventional microwave circuits and their design methodologies. Due to the high operating frequencies, circuit dimensions are of the same order of magnitude as the operating wave-length, therefore requiring distributed parameter approach.

Because of the large number of mutual couplings, influence of housing, other adjacent components on the same substrate, etc, theoretical analysis of the behavior of circuits with distributed parameters is very complex. Therefore, circuits of this kind are simulated using specialized software packages.

There are two types of simulation tools. First type, often called *Schematic*, offers a number of predefined elements such as microstrip lines, gaps, bands, junctions, etc. User can create his own circuit by choosing elements from the libraries and connecting them in a desired manner. Simulations of this kind are typically performed very fast. However, these simulation tools do not perform full-wave electromagnetic (EM) analysis. Behavior of the predefined elements is modeled by approximate equations that often have very narrow range of usage. For example, model for the element *gap* is valid only in the following range:

$$\begin{gathered} 0.5<w/H<2.5, \\ 0.1<s/H<1, \\ 1<\varepsilon r<16, \end{gathered} \tag{1}$$

V. Radonić is with the Technical School "9. maj", Bačka Palanka, Serbia & Montenegro; (phone: 381-63-518335; fax: 381-21-758232; e-mail: vasaradonic@eunet.yu).

V. Crnojević-Bengin and Lj. Živanov are with the Department of Electronics, Faculty of Technical Sciences, University of Novi Sad, Serbia & Montenegro; (e-mail: bengin@uns.ns.ac.yu, lilaziv@uns.ns.ac.yu).

where s denotes the gap, w is the width of the microstrip, H is the substrate thickness, and εr is dielectric constant of the substrate.

By examining (1), it can be seen that, in the case of 1.575mm thick substrate, gaps smaller than 160µm could not be simulated, although this value is well within the possibilities of conventional Printed Circuit Board (PCB) technology. Also, using substrates with high dielectric constant, very attractive technique for miniaturization of passive microwave components, is not feasible using *Schematic*. If values outside the range of validity are used, simulation results will be extremely inaccurate and unreliable.

Schematic simulation tools can therefore be used only for rapid prototyping, i.e., for determining approximate behavior of the circuit.

Second type of simulation tools are full-wave EM solvers, based on various numerical techniques that basically use Maxwell's equations, such as Finite Element Method (FEM), Method of Moments (MoM) or numerical Green's method. Full-wave EM solvers, if used properly, provide accurate and reliable results that will conform well to the measurement.

There is a great number of commercially available full-wave EM simulation tools today [1], [2]. The designer is left with the choice of many software packages and choosing the right one is not always straightforward.

In this paper, we compare two widely used full-wave EM simulation tools: Ansoft's High Frequency Structure Simulator (HFSS) and EMSight - EM simulator in Microwave Office (MWO) from Applied Wave Research Inc. (AWR). Their performances are compared in solving *s*-parameters for two resonant structures. First is a conventional λ/2 microstrip resonator, and the second is recently proposed 2-D Hilbert resonator [3]. The second structure was chosen because it consists of a fractal line comprised of a great number of short straight line segments at right angles. These segments are coupled to each other and theoretical analysis of the entire structure would present a very complex task.

II. Full-Wave EM Solvers

A. Microwave Office

The AWR Design Environment incorporating Microwave Office and Analog Office is a powerful fully-integrated design and analysis tool for RF, microwave, millimeterwave, analog, and RFIC design [4].

EMSight from Microwave Office allows users to simulate arbitrary multi-layered EM structures. EMSight is a full-wave EM solver based on a modified spectral-domain method of moments applied to three-dimensional circuits in a rectangular enclosure filled with a planar, piece-wise constant stratified media. This method is used to accurately determine the multi-port scattering parameters for predominantly planar structures.

EMSight can analyze circuits with an unlimited number of layers and an unlimited number of ports. However, circuits need to be planar in nature, so no three-dimensional (3-D) objects are allowed. Conductive layers can be connected by vias.

A gridded, variable cell size mesh is automatically generated which places smaller cells in areas that have high variations in current densities, and larger cells in areas with more uniform current variations. The user can control the mesh by changing the meshing density of specific polygons. The generated mesh can be viewed while the geometry is being edited so the effect of changing the meshing density is seen instantly. The discontinuities that arise from the excitations at the ports can be automatically removed by EMSight's de-embedding algorithm. In addition, arbitrary reference planes can be used for the de-embedding.

The EM Sight solver computes a separate solution for each frequency specified in the frequency range.

An FFT-based matrix filling algorithm is employed to speed the matrix filling process. Unique about EMSight's approach is that the FFT tables that are used to fill the matrix are transparently cached on the hard drive. When user needs to solve a circuit that uses the same size enclosure and the same dielectric stackup, the FFT table information is read from the cached version, resulting in a significant computational savings.

B. High Frequency Structure Simulator

HFSS is an interactive software package for calculating EM behavior of a structure [5]. The software includes post-processing commands for analyzing this behavior in detail. In contrast to MWO, HFSS can be used to simulated 3-D objects.

The simulation technique used to calculate the full 3-D EM field inside a structure is based on the Finite Element Method (FEM). In general, FEM divides the full problem space into thousands of smaller regions and represents the field in each sub-region (element) with a local function.

In HFSS, the geometric model is automatically divided into a large number of tetrahedra, where a single tetrahedron is a four-sided pyramid. This collection of tetrahedra is referred to as the finite element mesh. There is a trade-off among the size of the mesh, the desired level of accuracy, and the amount of available computing resources. It is desirable to use a mesh fine enough to obtain an accurate field solution but not so fine that it overwhelms the available computer memory and processing power.

To produce the optimal mesh, HFSS uses an iterative process, called adaptive analysis, in which the mesh is automatically refined in critical regions. First, it generates a solution based on a coarse initial mesh. Then, it refines the mesh in areas of high error density and generates a new solution. When selected parameters converge to within a desired limit, HFSS breaks out of the loop.

In contrast to MWO that computes a separate solution for each frequency specified, HFSS performs a frequency sweep to generate a solution across a range of frequencies. There are three sweep types. Fast sweep generates a unique full-field solution for each division within a frequency range and is best for models that will abruptly resonate or change operation in the frequency band, as it will obtain an accurate representation of the behaviour near the resonance. Discreete sweep generates field solutions at specific frequency points in a frequency range and should be used when only a few frequency points are necessary to accurately represent the results in a frequency range. Interpolating sweep estimates a solution for an entire frequency range and produces best results when the expected frequency response is smooth, or if the memory requirements of a fast sweep exceed available resources.

III. Resonator Configurations

In order to compare presented full-wave EM solvers, namely MWO and HFSS, two configurations are analyzed. First one is a conventional end-coupled $\lambda/2$ microstrip resonator, shown in Fig.1.

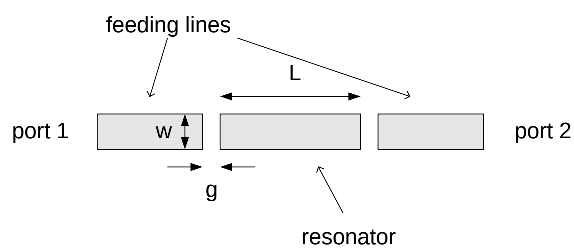
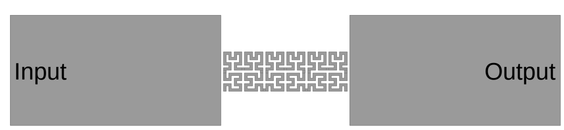
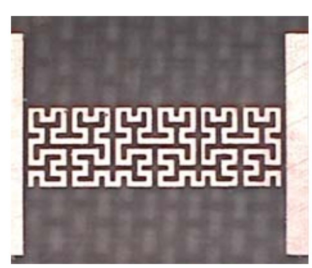


Fig. 1 Conventional end-coupled microstrip resonator.



(a)



(b)

Fig. 2 2-D Hilbert resonator: (a) layout of the entire structure, (b) enlarged detail of the fabricated prototype.

Second configuration used for comparison is recently proposed 2-D Hilbert resonator, depicted in Fig.2. It uses *N*=3 electrically connected Hilbert fractal curves of the third order to foster PBG effect and achieve smaller length of the resonator, while preserving its performances.

Both resonators are constructed on 1.575 mm thick PCB substrate having relative dielectric constant εr=2.17 and dielectric loss tangent equal to 0.0009. Feeding lines are 10mm long, gaps equal to 125µm, while the length of the resonators is 18mm for the conventional, and 5.875mm for 2-D Hilbert resonator. Conductor losses were modeled using bulk conductivity for copper.

IV. Simulation Results

Simulations were conducted for conventional and 2-D Hilbert resonator separately in MWO and in HFSS, using same parameters. Fast frequency sweep was used in HFSS.

In Fig. 3 simulation results obtained by MWO for both resonators are shown, while Fig. 4 and 5. show HFSS results for conventional and 2-D Hilbert, respectively.

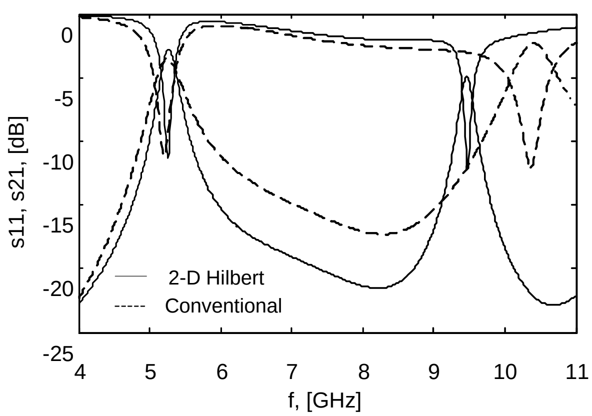


Fig. 3. Simulation results for conventional and 2-D Hilbert resonator obtained from MWO.

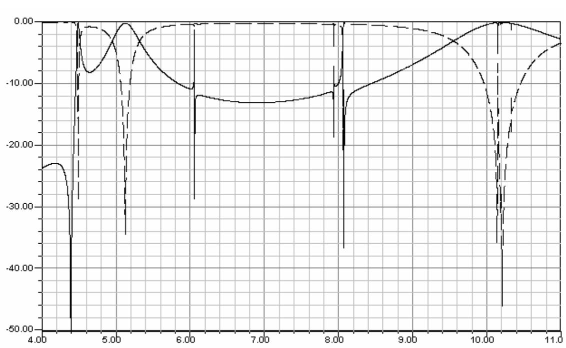


Fig. 4. Simulation results for conventional resonator obtained from HFSS (full line s_{21}, dotted s_{11}).

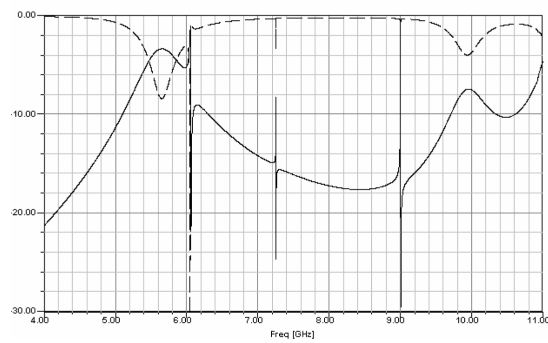


Fig. 5. Simulation results for 2-D Hilbert resonator obtained from HFSS (full line s_{21}, dotted s_{11}).

The criterion for convergence of the HFSS solution was maximal change of magnitude of *S* smaller then 0.02 (default). HFSS needed as much as 13 adaptive passes to reach convergence, while MWO simulations were performed more rapidly. Table 1 shows convergence of solution results in HFSS. It can be seen that simulating simple structure such as a conventional resonator, was an antiviral task for HFSS.

Table 1 Convergence of the solution in HFSS for conventional $\lambda/2$ resonator.

Pass no.	No. of tetrahedra	Max mag. ΔS
1	1228	n/a
2	1480	0.25303
3	1778	0.14142
4	2137	0.082466
5	2566	0.30632
6	3082	0.20612
7	3708	0.3192
8	4454	0.17015
9	5346	0.10421
10	6421	0.055976
11	7705	0.031153
12	9247	0.02931
13	11097	0.015945

Table 2 compares simulation results for conventional resonator obtained from MWO and HFSS, where f_r is resonant frequency, *B* denotes 3dB bandwidth, s_{21_0} is insertion loss, and Q_L and Q_U are loaded and unloaded quality-factor, respectively.

Table 2 Comparison of MWO and HFSS simulation results for conventional resonator.

	HFFS	MWO
$f_{r,}$ [GHz]	5.12	5.27
B, [MHz]	380	405
s_{21_0}, [dB]	-0.2	-3.11
Q_L	13.5	13
Q_U	300	25

Apart from the resonant peak at 5.12GHz, HFSS also produced very narrow peak at 4.5GHz, not existing in the reality, Fig. 4. Although conductivity for copper was used for all microstrip lines, HFSS produced surprisingly small insertion loss, Table 2.

Table 3 shows convergence of HFSS solution results in the case of 2-D Hilbert resonator. It is worth noting that convergence was achieved after only 6 passes, and with smaller number of tetrahedra, although the structure simulated was far more complex than in the previous case.

Table 3 Convergence of the solution in HFSS for 2-D Hilbert resonator.

Pass no.	No. of tetrahedra	Max mag. ΔS
1	3215	n/a
2	3871	0.21573
3	4659	0.11018
4	5596	0.3661
5	6726	0.060671
6	8073	0.011681

In order to determine which simulator is more reliable, measurement results, shown in Fig. 6, were used for comparison. Table 4 compares MWO, HFSS and measurement results for 2-D Hilbert resonator.

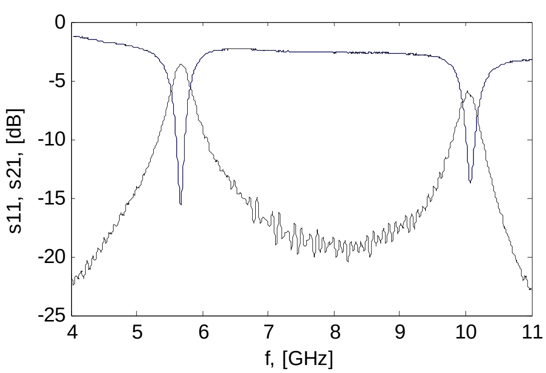


Fig. 6. Measured *s*-parameters for 2-D Hilbert resonator.

Table 4 Comparison of MWO and HFSS simulation results with the measured values for 2-D Hilbert resonator.

	HFFS	MWO	Measured
$f_{r,}$ [GHz]	5.65	5.25	5.67
B, [MHz]	800	270	385
s_{21_0}, [dB]	-3.35 dB	-2.79	-3.32
Q_L	7	19	14.7
Q_U	13	40	27.5

By comparing Fig. 3 and Fig. 5 with Fig. 6, a good agreement can be noted between MWO and the measurement. Resonant frequency is shifted from 5.27 GHz (MWO simulation) to 5.67 GHz (measurement). Since manufacturer specifications for substrate material allow εr variations in the range +/- 0.02 as well as variations of substrate thickness, this can be explained by the discrepancy between actual and simulated values of the dielectric constant and substrate thickness. Insertion loss equal to -3.32 dB was measured at the resonant frequency, in contrast to -2.79 obtained through simulations. This can be explained as the influence of SMA connectors used for measurement.

Again, HFSS produced a non-existing resonant peak at 6.05GHz, Fig. 5. In this case, simulated resonant frequency and insertion loss show very good agreement with the measurements. However, *s21* characteristic is less steep, resulting in lowered Q_L. Insertion loss in the stopband is higher then in reality. Second resonant peak is correctly positioned at 9.95GHz, but its simulated insertion loss is much higher then measured.

V. Conclusion

In this paper simulation results obtained by HFSS and MWO were compared for two resonant structures: a conventional end-coupled resonator and novel 2-D Hilbert resonator comprised of great number of short straight line segments positioned at right angles. Both structures were fully planar in nature. Simulation results for 2-D Hilbert were also compared to the measured ones.

Although generally regarded as better, HFSS produced poorer results. It needed 13 adaptive steps to reach convergence in the case of a simple structure such as conventional λ/2 resonator. Furthermore, although microstrip lines were modeled as having finite conductivity, HFSS did not estimate insertion losses well. MWO, on the other hand, produced results that agreed well with the measurement.

In the case of more complex geometry, such as 2-D Hilbert resonator, HFSS performed much better: it needed only 6 adaptive passes and simulated resonant frequency and the insertion loss correctly. However, it showed too wide passband with lower insertion loss in the stopband.

Poor performances of HFSS in this comparison emerge from the fact that it was used for simulation of planar circuits – something that HFSS is not primarily designed to do. HFSS calculates the full 3-D EM field inside a structure and shows its superiority when simulating 3-D structures, such as waveguides. When used for planar circuits, it is outperformed by, generally weaker, MWO.

To conclude, a great attention should be paid when choosing an EM simulator. It should be compatible with the geometry of the analyzed circuit and rapidly give reliable solutions.

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