

# Accuracy of EM Simulation Tools in Modeling of Resonant Left-Handed Microstrip Lines

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**Abstract**—Split ring resonators and complementary split ring resonators are used in left-handed media to obtain negative values of permeability and permittivity, respectively. A typical resonant left-handed (LH) microstrip line, composed of complementary split ring resonators (CSSR) and capacitive gaps in the microstrip, exhibits a pass-band behavior. However, a significant shift between the measured and simulated values of the central frequency of the pass-band always occurs. In this paper, three widely used full-wave simulation tools: Ansoft's High Frequency Structure Simulator, EMSight in Microwave Office, and IE3D from Zeland Software Inc., are compared for the case of resonant LH transmission lines. The simulation results are compared with the measured data.

## I. INTRODUCTION

Recently, metamaterials came into focus of the research community, since they exhibit electromagnetic properties generally not found in nature. Metamaterials are artificial structures designed using sub-wavelength particles, whose size is typically smaller than one tenth of the propagating signal wavelength. Such a small size is a necessary condition for the synthesis of effective media. The structures obtained by using this approach can be considered as a continuous medium with effective parameters, namely effective dielectric permittivity and effective magnetic permeability. By a proper choice of the type and geometrical arrangement of constituent sub-wavelength particles, the effective parameters of metamaterials can be made arbitrarily small or large, or even negative. Among them, special attention has been paid to double-negative or left-handed (LH) metamaterials, that simultaneously exhibit negative values of permittivity and permeability in a certain frequency range.

The behavior of LH media was theoretically analyzed by Russian physics Victor Veselago in the late sixties, [1], who showed that only double-negative metamaterials can support propagating modes of the electromagnetic waves. Moreover, propagating constant in this case will be negative, and group and phase velocities will be antiparallel. Consequently, the electric field, magnetic field, and wavevector of an electromagnetic wave in a double-negative metamaterial will form a left-handed triad: while the energy would still travel away from the source, so as to satisfy causality, wave fronts will travel backward toward the source.

However, Veselago's ideas remained unexploited for almost thirty years. The first structure that exhibits negative permeability by decreasing the plasmon frequency into the microwave range was proposed in mid nineties, [2]. Three years later, the same group of authors proposed a particle called split-ring resonator (SRR), [3]. When illuminated by axial magnetic field, SRR provides negative permittivity at microwave range in a narrow frequency range above its quasi-static resonance. In the years to follow, SRR-based configurations attracted a lot of attention, [4], and [5].

In the microstrip technology, split-ring resonators can only be etched in the upper substrate side, next to the host transmission line. To enhance the coupling, the distance between the line and the rings should be as small as possible. A microstrip line loaded with split-ring resonators is a single-negative medium, and therefore exhibits a stop-band characteristic.

Using the Babinet principle, a new particle called complementary split-ring resonator (CSRR) was proposed in [6]. CSRRs are etched in the ground plane, beneath the microstrip, with their axes parallel to the vector of the electric field, thus contributing to the negative effective permittivity. In order to obtain left-handed behavior, particles that introduce negative effective permeability must be added to the structure. This is achieved by periodically etching capacitive gaps in the conductor strip. To achieve high magnetic coupling between the line and rings at resonance, CSRRs are etched in the ground layer underneath the gaps. This structure behaves as a band pass filter with a sharp transition in the lower band edge.

However, it has been noticed that simulation and measurement results for resonant LH transmission lines vary more than it is typical for microwave measurements. A shift between the measured and simulated values of the central frequency of the pass-band always occurs, that can not be explained by the discrepancy between the actual and the simulated values of the dielectric constant and substrate thickness.

In this paper, performances of three widely used full-wave simulation tools are compared with measurement results of a typical LH transmission line. Analyzed are the following solvers: Ansoft's High Frequency Structure Simulator (HFSS), EMSight - EM simulator in Microwave Office (MWO) from Applied Wave Research, and IE3D, EM solver from Zeland Software Inc.

## II. EM SOLVERS

The theoretical analysis of the behavior of circuits with distributed parameters presents a very complex task. That is why the circuits of this kind are simulated using specialized software packages. Generally, two types of simulation tools exist. The 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. However, these simulation tools do not perform full-wave electromagnetic (EM) analysis. Behavior of the predefined elements is modeled by approximate equations and the solution for the cascade of elements is calculated. Although the simulations of this kind are performed very rapidly, the results obtained have very narrow range of usage, defined by the range of validity of separate elements' models. If values outside the range of validity are used, simulation results will be extremely inaccurate and unreliable. Furthermore, *Schematic* simulation tools do not take into account mutual coupling between the elements. This can significantly influence the overall performances of the circuit. Therefore, such simulation tools can only be used for rapid prototyping.

The second type of simulation tools are full-wave EM solvers, based on various numerical methods for solving Maxwell's equations. A number of numerical methods exist, such as the Finite Element Method (FEM), and Method of Moments (MoM). Full-wave EM solvers, if used properly, provide accurate and reliable results that will confirm well to the measurement.

There is a great number of commercially available full-wave EM simulation tools today [7], [8]. The designer is left with the choice of many software packages and choosing the right one is not always straightforward. In this section, basic characteristics of three software tools used in comparison are given.

### A. Microwave Office (MWO)

The Design Environment from Applied Wave Research incorporates Microwave Office and Analog Office. It is a powerful fully-integrated design and analysis tool for RF, microwave, millimeterwave, analog, and RFIC design [9].

EMSight, a full-wave simulation tool 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 (3D) objects are allowed. Conductive layers can be connected by ideal vias.

A gridded, variable cell size mesh is automatically generated: smaller cells are used 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 reads from the cached version, resulting in a significant computational savings.

### B. High Frequency Structure Simulator (HFSS)

HFSS is an interactive software package for calculating EM behavior of a structure [10]. The software includes post-processing commands for analyzing this behavior in detail. In contrast to MWO, HFSS can be used to simulated 3D objects.

The simulation technique used to calculate the full 3D 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 the MWO that computes a separate solution for each frequency specified, HFSS performs a frequency sweep to generate a solution across a range of frequencies. Three sweep types exist: The fast sweep generates a unique full-field solution for each division within a frequency range and it is the 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. The discrete 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. The interpolating sweep estimates a solution for an entire frequency range produces the best results when the expected frequency response is smooth, or if the memory requirements of a fast sweep exceed available resources.

### C. IE3D from Zeland Software

IE3D is a full-wave, method-of-moments based electromagnetic simulator that solves the current distributions on 3D and multilayer structures of general shape. It is widely used in the design of MMICs, RFICs, LTCC circuits, microwave and millimeter-wave circuits, IC interconnects and packages, HTS circuits, patch antennas, wire antennas, and other RF or wireless antennas, [7], [11].

There is no limitation on the shape and orientation of the metallic structures analyzed by IE3D. IE3D can model real-life 3D structures such as conical vias, conical helix antennas, wire bonds and others.

Non-uniform mesh is automatically generated with rectangular or triangular cells. To ensure the highest efficiency, rectangular cells are used in the regular regions of the structure, since each rectangular cell is equivalent to at least two triangles. Triangular cells are used to accurately fit irregular boundaries. In IE3D, the efficiency of rectangular cells and flexibility of triangular cells are combined to yield the best result.

It is well known that current concentrates on the edges of metallic strips. Precise modelling of the high current concentration along the edges is critical to accurate simulation of printed circuits, especially coupled structures. Adding small cells along the edges usually can guarantee simulation accuracy. IE3D offers an option to create small edge cells automatically and to simultaneously minimize the number of cells in a simulation.

Most field solvers assume infinite ground planes in solving circuit and antenna problems. However, in many microwave and RF applications infinite ground plane assumption is not applicable. IE3D is able to model structures with finite ground planes.

Furthermore, IE3D can optionally allow users to model precisely the conductor thickness. Also, currents on all four sides of a metallic strip can be modelled exactly.

IE3D is specially formulated for modeling dielectric layers as thin as 0.1 microns. It provides accurate modelling of high dielectric constant materials and it's formulated with complex dielectric permittivity, permeability and conductivity. IE3D allows accurate modelling of lossy dielectric material.

IE3D can mix electromagnetic and nodal analysis. It has efficient matrix solvers for each type of structures. Full, symmetrical, partial, and iterative matrix solvers exist, that offer trade-off between solution time and RAM requirement.

### III. CONFIGURATION OF A RESONANT LH TRANSMISSION LINE

The design of metamaterials is based on the application of constitutive particles with sub-wavelength dimensions. The most commonly used sub-wavelength particle is SRR. When an SRR is exposed to the axial magnetic field, a current in the metallic ring is induced, while the split (gap) acts as capacitance, thus resulting in resonant nature of the structure. In order to increase the capacitance of the unit cell, two concentric rings are typically used. In this case, the capacitance of the unit cell is dominated by the capacitance between two concentric rings, rather than the capacitance of the splits.

Although initially circular SRRs have been proposed, square or rectangle geometries are often used, in order to enhance the coupling to the host microstrip line and/or ease the simulation and fabrication processes.

In this paper, square SRRs are used, shown in Fig. 1, where  $a$ ,  $b$ ,  $d$ ,  $w$  and  $g$  denote dimensions of its segments. To enhance the coupling and increase the inductance of the split-rings, separation between the concentric rings and dimensions of line are chosen to be the minimal achievable in standard PCB technology, i.e. equal to 100  $\mu\text{m}$ .

In order to compare various full-wave EM solvers, namely MWO, HFSS and IE3D, LH microstrip line is designed, that uses square CSRRs and gaps. CSRRs are designed as complementary to those shown in Fig 1, i.e. etched in the ground plane, underneath the conductor strip. Resonant LH line with three unit cells ( $M=3$ ) is shown in Fig. 2, where both top (dark grey) and bottom (light grey) conductive layers are shown.

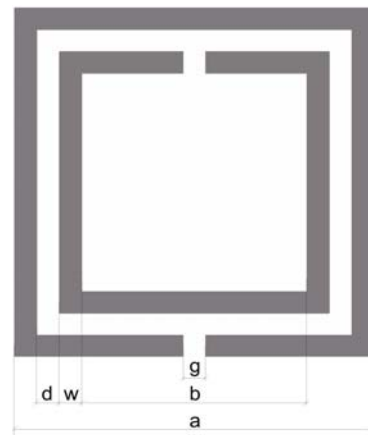


Fig. 1. SRR configuration.

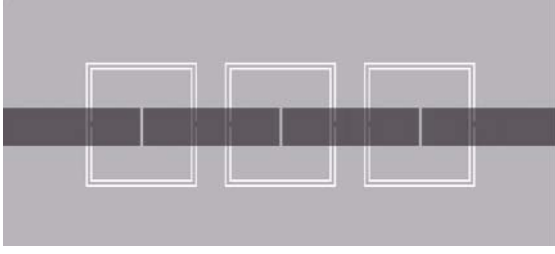


Fig. 2. Resonant LH microstrip line with three unit cells.

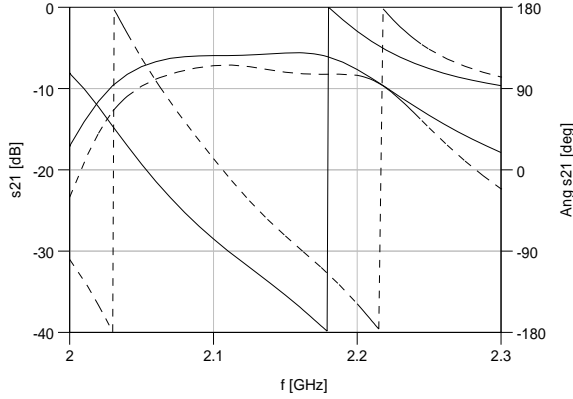


Fig. 3. Phase propagation for the proposed microstrip lines with  $M=4$  (dotted line) and  $M=3$  (full line) unit cells.

The overall dimensions of a single CSRR are equal to  $5 \times 5$  mm, i.e.  $\lambda/16 \times \lambda/16$  on a given substrate. The LH line is realized on a 1.27mm Taconic CER-10 substrate, having  $\epsilon_r=9.8$  and dielectric loss tangent equal to 0.0025. Conductor losses are modeled using bulk conductivity for copper.

Left-handedness of the proposed structure is evident from the comparison of phases of transmission coefficients obtained for a different number of unit cells  $M$ , Fig. 3. It can be seen that a phase advance exists in the passband, thus demonstrating backward propagation.

#### IV. SIMULATION AND EXPERIMENTAL RESULTS

Simulations were conducted for the same LH microstrip line separately in MWO, HFSS and IE3D. In HFSS, both fast and discrete frequency sweeps were used, and they produced very similar results.

In all simulation tools, conductors were modeled as real, characterized by the conductivity of copper (58.8MS/m) and having the thickness equal to  $17\mu\text{m}$ . Automatically obtained meshing was used in all cases, i.e. no additional refinements have been made. In MWO, the enclosure top was modeled as open, while the enclosure bottom was characterized by the conductivity of copper. Cell size was equal to  $100\mu\text{m}$  in both x- and y-directions. The criterion for convergence of the HFSS solution was maximal change of magnitude of  $S$  smaller than 0.02 (default). In IE3D, only the one half of the structure was simulated, while a perfect magnetic

conductor (PMC) boundary was set along the center of the host microstrip. The highest frequency was set to 7GHz, and 20 cells per wavelength were used. Automatic edge cells option was turned on, and edge cell width was equal to  $25\mu\text{m}$ . Meshing optimization was used.

In order to determine which simulator is more reliable, LH microstrip line was fabricated in standard PCB technology. Photographs of top and bottom layers of the fabricated structure are shown in Fig. 4.

The proposed LH transmission line can be characterized in terms of a band pass filter. All simulation and measurement results are compared in Fig. 5, and in Table 1, where  $f_{r1}$  and  $f_{r2}$  denote central frequencies of the first and second pass band,  $R$  is the ration between these two frequencies,  $B$  denotes 3dB bandwidth,  $s_{21,0}$  is insertion loss, and  $Q_L$  and  $Q_U$  are loaded and unloaded quality-factor, respectively. Results for the first and second harmonics are shown.

Significant differences between results obtained by different simulation tools are observable. None of the simulators correctly calculated the central frequency of the pass band. The best prediction was given by MWO, while HFSS simulation results differ from measurements for more then 15%. Measured insertion loss is 1-2 dB higher then the simulated one, which is acceptable, except in the case of HFSS, which predicted unrealistically high insertion loss (-7.45dB). However, it is interesting to note that HFSS gave the best prediction of the shape of the first pass band. IE3D inaccurately simulated the behavior in the stop band (especially around 3.5 GHz), and it also showed a significant downshift in the central frequency of the second pass band, equal to 10%.

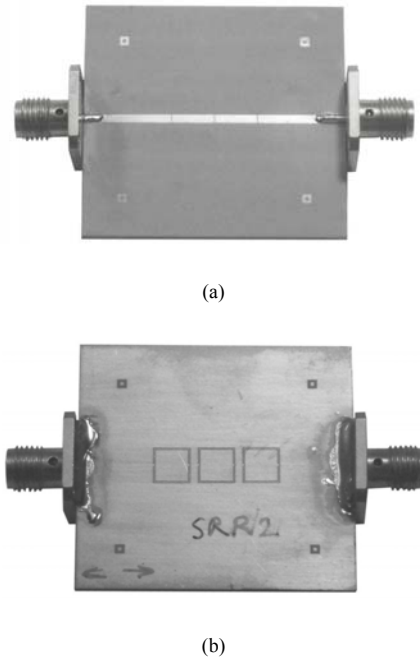
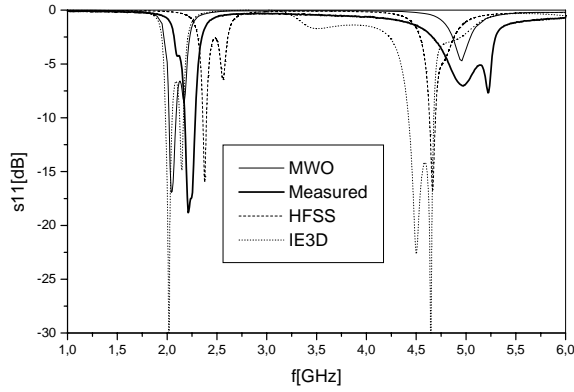
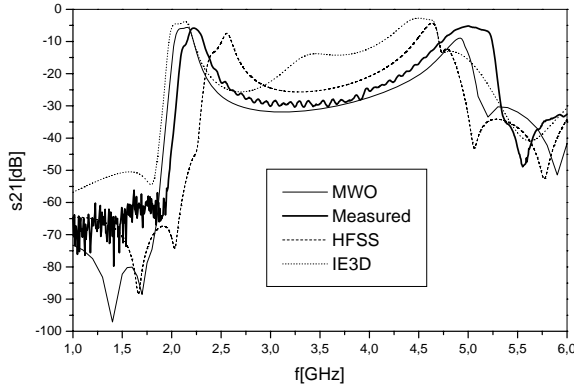


Fig. 4. Photographs of the fabricated resonant LH microstrip line: (a) top layer, (b) bottom layer.



(a)



(b)

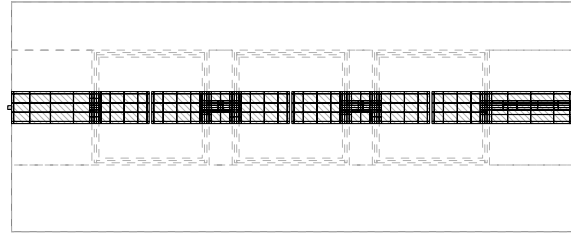
Fig. 5. Comparison of the measurement and simulation results of LH microstrip line: a) reflection coefficient, b) transmission coefficient.

TABLE I.  
COMPARISON OF SIMULATION RESULTS OBTAINED BY MWO, HFSS AND IE3D WITH THE MEASUREMENT DATA.

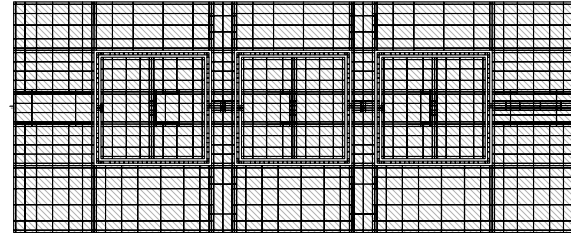
	MWO	HFSS	IE3D	Measured
$f_{r1}$ [GHz]	2.13	2.56	2.09	2.22
$f_{r2}$ [GHz]	4.92	4.62	4.5	5
R	2.31	1.8	2.15	2.25
B <sub>r</sub> [MHz]	193	115	186	158
$s_{21 \text{ } 0}$ [dB]	-4.96	-7.45	-3.767	-5.85
Att.Left [db]	-70.9	-64.59	-50	-60
Att.Right [db]	-29.8	-25.67	-26	-27
$Q_L$	10.72	22.17	11.47	14
$Q_U$	15.75	27.032	19.78	18.92

To explain the differences between analyzed simulation tools, meshing of both conductive layers is shown in Fig. 6.

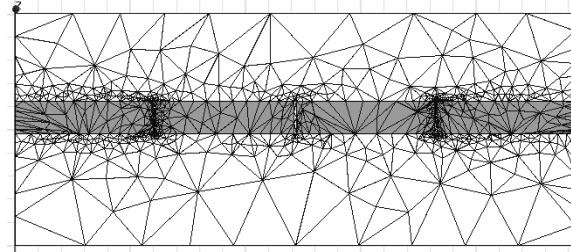
First, it can be seen that all simulation tools meshed the conductor in the bottom layer. It can be expected that better results would be obtained if magnetic currents were used instead, i.e. if the CSRRs were meshed instead of the ground plane. This option is available only in IE3D, and it could significantly improve its accuracy.



(a)



(b)



(c)

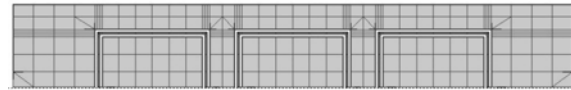
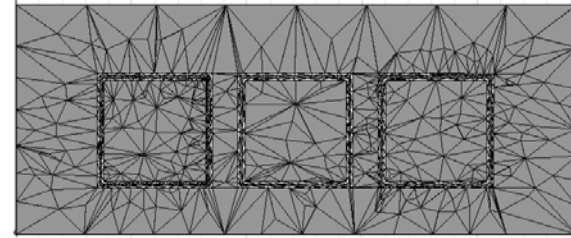


Fig. 6. Meshing of both conductive layers in the case of: a) MWO, b) HFSS, c) IE3D (only half of the structure is shown).

MWO produced the most accurate mesh. It is interesting to note that meshing of the bottom conductive layer is more refined in the centers of CSRRs, just underneath the gaps. Also, mesh in the bottom layer is refined at the positions where gaps exist in the upper conductive layer. MWO is the only simulation tool included in the comparison that exhibits such behavior:

meshing density in one conductive layer is influenced by the geometry of both the layer in question and the neighboring layer. This fact significantly contributes to the accuracy of MWO.

HFSS produced rather poor mesh, more dense near the ports then in the middle section of the circuit. This is especially visible when the upper conducting layer is analyzed: the first and the third gap in the microstrip are finely meshed, while the second one is not. The same observation holds for the bottom conducting layer. This un-uniform meshing density could be corrected by using virtual objects in the vicinity of the gaps. In this way, the meshing in the critical regions could be refined, and overall performances of HFSS could be improved.

IE3D produced rather coarse mesh. However, in this case 25 $\mu$ m cells exist at the edges of all metallic elements, not easily visible in Fig. 6c.

HFSS needed as much as 14 adaptive passes to reach convergence, while the simulations in MWO and IE3D were performed more rapidly. Table 2 shows convergence of solution results in HFSS. This illustrates that simulating a LH microstrip line was not a trivial task for HFSS: a mesh with more then 27000 tetrahedra was used.

TABLE II.  
CONVERGENCE OF THE SOLUTION IN HFSS

Pass No.	No. of Tetrahedra	Max. Mag. $\Delta S$
1	3942	N/A
2	4691	0.69345
3	5495	0.29129
4	6421	0.39283
5	7544	0.46807
6	8840	0.75054
7	10376	0.66809
8	12240	0.42823
9	14321	0.19937
10	16808	0.10865
11	16808	0.079075
12	19718	0.022136
13	23172	0.024069
14	27254	0.011479

## V. CONCLUSION

It has been observed that simulation results for LH structures based on the application of split-ring resonators significantly differ from the measured values, especially regarding the central frequency of the pass band. In this paper, performances of three widely used EM full-wave simulation tools are compared with measurement results of LH transmission lines.

None of the simulators correctly calculated the central frequency of the pass band. The best prediction was given by MWO, while HFSS simulation results differ from measurements for more then 15%. IE3D inaccurately simulated the behavior in the stop band (especially around 3.5 GHz), and it showed a significant downshift in the central frequency of the second pass band, equal to 10%.

Since HFSS is devoted to calculating full 3D EM field inside a structure, it shows superiority when simulating 3D structures, such as waveguides. When used for planar circuits, it is outperformed by MWO.

To explain the difference between performances of the simulation tools, meshing was analyzed in detail. Automatically obtained meshing was used in all simulators, i.e. no additional refinements have been made. HFSS produced rather poor mesh, more dense near the ports then in the middle section of the circuit. By using virtual objects in the critical regions, mesh could be refined, and overall performances of HFSS could be improved. Furthermore, all simulators were used for modeling of electric currents, i.e. meshing the conductors. If magnetic currents were used instead, i.e. if the CSRRs were meshed instead of the ground plane, significant improvements of performances could be expected. This will be analyzed in future investigations.

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