Fusion of Technology in Analysis, Design and Comparison of Numerical Techniques for Rectangular Microstrip Patch Antenna

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Abstract:- In today's scenario higher integration and smaller layout size are the two major trends in RF and Microwave industry, lead to more prominent role in electromagnetic high order effects. Recent years the important in the development of numerical techniques has been the versatility of the method. In this paper, we have present the various numerical techniques to compute such effects in Microwave Integrated Circuit based designs, highlighting their specific features with comparison of numerical techniques for design of rectangular Microstrip Patch Antenna. Here we are compared few numerical techniques, in this Finite Element Method is a more powerful and versatile, more storage requirement, less CPU time. Numerical characterizations and modelings of guided wave passive components have been an important research topic in the recent years. This is due to increased research and development in millimeter-wave integrated circuits and monolithic integrated circuits. Another aspect important in the development of numerical techniques has been the versatility of the method. Higher integration and smaller layout size, two major trends in today's RF/microwave industry, lead to more prominent electromagnetic high order effects. In this paper, the authors present a survey of existing Numerical techniques to compute such effects in microwave integrated circuits, highlighting their specific advantages/disadvantages and comparison for a circuit designers and simulation results also compared.

Index Terms:- Microwave Integrated Circuits, Numerical Techniques, Artificial Neural Networks.

1. Introduction

Since their introduction in the 1950s, Microwave Integrated Circuits (MICs) have played an important role in advancing the RF/microwave technologies. This progress would not have been possible without the advances of solid-state devices and planar Transmission Lines (TLs). These structures are the backbone of MICs, and represent an important research topic for many engineers. Along with the advances of MICs and planar TLs, numerous Electromagnetic Methods (EM) for RF/Microwave passive structures have been developed for accurate MIC analysis and design. It is no longer efficient or even feasible, to tune a circuit once fabricated. Therefore, accurate characterization methods that can include high frequency EM effects are needed to design the structures. These methods have in turn helped further investigation and development of new planar lines. Not only have planar lines fulfilled their most fundamental objective of delivering signals, but they can also be exploited to create various RF/Microwave devices, such as wideband hybrid junctions, by appropriately combining them. Furthermore, any EM numerical techniques needs to be as efficient as possible in terms of both CPU time and storage requirements, although recent advances in computers impose less severe restrictions on the method. Therefore, numerical techniques are chosen on the basis of trade-off's between accuracy, speed, storage requirement and versatility and are often structure-dependent. In this paper, the authors present a brief overview of existing EM numerical methods used in MIC modeling and design, highlighting their specificities for circuit designers.

2. Numerical Techniques for Microwave Integrated Circuits

Numerical solution of EM problems started in the mid-1960s with the availability of modern high speed computers. Since then, considerable effort has been expended on solving complex EM-related problems for which closed form analytical solutions are either intractable or do not exist. Based on Maxwell's equations, each numerical method has its own unique advantages and disadvantages for specific needs. These methods, in fact, provide a foundation for the derivation of current and future analysis methods. They not only represent some of the most useful and commonly used techniques for analyzing planar lines, but also serve as means to present the fundamentals of applying EM theory to the analysis of boundary-value problems. There are two approaches in analyzing a TL: quasi-static and full-wave. The first produces line parameters for the TEM mode only. On the other hand, the dynamic approach can produce the line parameters not only for the TEM but also for the hybrid modes, whose parameters are frequency dependent. TEM mode parameters obtained by the static approach are theoretically only valid at dc. However, a number of millimeter-wave circuits up to W-band have successfully been designed using only static results. Nevertheless, at microwave and millimeter-wave frequencies, a dynamic approach remains the most appropriate for more accurate determination of the line parameters.

2.1 Variational Method (VM)

In EM problems, solutions are usually obtained by directly solving appropriate differential or integral equations while Variational Methods operate by seeking a functional that gives the max-imum/minimum of a desired quantity [1- 4]. Its main advantage is that it produces stationary formulas, which yield results insensitive to the first-order errors. There are three kinds of variational methods, depending on the technique used to obtain approximate solutions expressed in a variational form: the direct method based on the classical Rayleigh-Ritz or simply Ritz procedure, the indirect method such as Galerkin and least squares, and the semi-direct method based on separation of variables. Applications of Variational methods include analysis of TLs to obtain characteristic impedances, effective dielectric constants, and losses, analysis of discontinuities, determination of resonant frequencies of resonators, and determination of impedances of antennas and obstacles in waveguides.

2.2 Spectral Domain Analysis (SDA)

The spectral-domain analysis (SDA) is extensively used in analyzing planar transmission lines, resonators, and scattering problems [5–7]. It is basically a Fourier transformed version of the integral equation method; but compared to the conventional space-domain integral equation method, the SDA has several advantages: (i) its formulation results in a system of coupled algebraic equations instead of coupled integral equations, (ii) closed-form expressions can easily be obtained for the Green's functions, (iii) incorporation of physical conditions of analyzed structures via the so-called basis functions is achieved with stationary solutions. These features make the SDA numerically simpler and more efficient than the conventional integral equation method.

SDA is applicable to the following structures:
(i) Most planar transmission lines such as Microstrips, Finelines, and CPWs in multilayer configurations. (ii) Both open and enclosed structures. (iii) Slow-wave lines with lossy dielectric materials. (iv) Resonators of planar configurations. Two formulation methods are: (i) General approach: It provides a better understanding of SDA and its formulation. (ii) Immittance approach: It is much simpler for derivation of the formulations.

2.3 Mode Matching Method (MMM)

The Mode-Matching Method is a useful technique for structures consisting of two or more separate regions [8, 9]. Based on matching the EM field at the boundaries of the different regions, it lends itself naturally to boundary-value problems. It has widely been used for scattering and transmission problems, as well as TL analysis. Scattering problems include discontinuities in waveguides and transmission lines, and obstacles in a medium. Transmission problems include analysis of filters, impedance transformers, and power dividers. TL analyses include determination of the line propagation constant and characteristic impedance, such as those of microstrip lines and coplanar strips. Coplanar strips with finite strip metallization thickness have been analyzed.

2.4 Finite Difference Time Domain (FDTD)

The Finite Difference Method has been applied to solve many EM-related problems such as TL problems and Waveguides [10]–[12]. Finite difference solution basically involves three steps: (i) dividing the solution region into a grid of nodes (ii) approximating the given differential equation by finite difference equivalent that relates the dependent variable at a point in the solution region to its values at the neighboring points (iii) solving the difference equations subject to the prescribed boundary conditions and/or initial conditions. This method is well known to be the least analytical. The mathematical preprocessing is minimal, and the method can be applied to a wide range of structures including those with odd shapes. A price one has to pay is numerical efficiency. Certain precautions have to be taken into account when the method is used for an open-region problem in which the region is truncated to a finite size. Also, the method requires that mesh points lie on the boundary.

2.5 Method of Moments (MoM)

The use of MoM [13],[14] has been successfully applied to a wide variety of EM problems of practical interest such as radiation due to thin-wire elements and arrays, scattering problems, microstrip and lossy structures, propagation over an inhomogeneous earth, and antenna beam pattern, to mention a few. The literature on MoM is already so large as to prohibit a comprehensive bibliography. A partial bibliography is provided by Adams [15]. The procedure for applying MoM usually involves four steps: (i) derivation of the appropriate integral equation (IE), (ii) conversion (discretization) of the IE into a matrix equation using basis (or expansions) functions and weighting (or testing) functions, (iii) evaluation of the matrix elements, and (iv) solving the matrix equation and obtaining the output parameters.

2.6 Finite Element Method (FEM)

Although the FDM and the MoM are conceptually simpler and easier to program than the Finite Element Method (FEM), FEM is a more powerful and versatile numerical technique for handling problems involving complex geometries and inhomogeneous media. The systematic generality of the method makes it possible to construct general-purpose computer programs for solving a wide range of problems in different fields and with little modifications [16]. The finite element analysis involves basically four steps [17],[18]: (i) discretizing the solution region into a finite number of subregions or elements, (ii) deriving governing equations for a typical element, (iii) assembling all elements in the solution region and, (iv) solving the obtained system of equations.

Recently, the boundary element method has been proposed [19],[20]. This is a combination of the boundary integral equation and a discretization technique similar to the finite element algorithm as applied to the boundary. Essentially, the wave equation for the volume is converted to the surface integral equation by way of Green’s identity. The surface integrals are discretized into N segments (elements), and their evolution in each element is performed after the field quantities are approximated by polynomials. One of the advantages of this method lies in the reduction in number of storage locations and CPU time resulting from the reduction in the number of dimensions.

2.7 Transmission Line Matrix Method (TLM)

The TLM is a numerical technique for solving field problems using equivalent circuit representation. It is based on the equivalence between Maxwell’s equations and voltages/currents equations on a mesh of continuous two-wire transmission lines [21], [22]. A major advantage of the TLM as compared with other numerical techniques is the ease with which even the most complicated structures can be analyzed. Its exibility and versatility reside in the fact that the mesh incorporates the EM field properties and their interaction with the boundaries and material media. Hence, the EM problem need not be formulated for every new structure. Another advantage of using the TLM is that there are no problems with convergence, stability or spurious solutions. The method is limited only by the amount of memory storage required by the mesh. Also, being an explicit numerical solution, the TLM method is suitable for nonlinear or inhomogeneous problems since any variation of material properties may be updated at each time step. Note that the TLM method is a physical discretization approach, compared to the FDM and FEM which are mathematical discretization approaches.

In the TLM, a field discretization involves replacing a continuous system by an array of lumped elements and dividing the solution region into a rectangular mesh of transmission lines. Junctions are formed where the lines cross forming impedance discontinuities. A comparison between the TL and Maxwell’s equations allows equivalences to be drawn between voltages/currents on the TL and EM fields in the solution region. Thus, the TLM involves two basic steps [23]: (i) replacing the field problem by the equivalent network and deriving analogy between the field and network quantities. (ii) Solving the equivalent network by iterative methods.

2.8 Method of Lines (MoL)

The method of lines was introduced into the EM community in the 1980s [24],[25]. It is regarded as a special FDM but more effective with respect to accuracy and computational time than the regular DFM. Originally, MoL was developed for problems with closed solution domain, but absorbing boundary conditions appropriate for MoL have been investigated [26], [27]. The MoL is a differential-difference approach of solving elliptic, parabolic, and hyperbolic partial diff erential equations and thus, involves discretizing a given differential equation in one or two dimensions while using analytical solution in the remaining direction. The MoL has the merits of both the FDM and the analytical method; it does not yield spurious modes nor does it have the problem of “relative convergence.” Besides, the MoL has the following properties that justify its use: (i) Computational efficiency: the semi analytical character of the formulation leads to a simple and compact algorithm that yields accurate results with less computational effort than other techniques. (ii) Numerical stability: by separating discretization of space and time, it is easy to establish stability and convergence. (iii) Reduced programming effort: by making use of the state-of-the-art well documented and reliable ordinary differential equations solvers, programming effort can be substantially reduced. (iv) Reduced computational time: since only a small amount of discretization lines are necessary in the computation, there is no need to solve a large system of equations. To apply MoL usually involves the following five steps: (i) partitioning the solution region (ii) discretization of the differential equation, (iii) transformation to obtain decoupled ordinary differential equations, (iv) inverse transformation and introduction of the boundary conditions, (v) solution of the equations into layers.

2.9 Artificial Neural Networks (ANN)

The recent exploitation of iteratively refined surrogates of fine, accurate or high-fidelity models and the implementation of Space Mapping (SM) methodologies address this issue of neural-based approaches for solving EM-related problems [28]. ANN modeling is one of the most recent trends in microwave CAD. Fast, accurate and reliable Neural Network models can be trained from measured or simulated data. Once developed, these neural models can be used in place of CPU-intensive EM models of devices to speed up microwave design. A full review of ANN applications in RF/microwave modeling and design is found in [29]–[31].

3. Comparison Between Numerical Techniques

As mentioned earlier, there are two groups of numerical methods, namely, differential and integral methods. The major advantage of the differential methods is their adaptability to various complex structures [41]–[43]. However, larger is the complexity of these structures, dense should be the grid. On the other hand, integral methods are well adapted to the programming on microcomputers. Each numerical method has advantages and disadvantages. Various aspects of numerical methods are qualitatively compared in Table 1, but in practice, there is no clear-cut boundary assigned between such aspects, since an experienced designer can often improve a numerical processing. Model intended to characterize planar microwave structures must satisfy the schedule of the analyzed structure and obey to certain severe constraints whose effectiveness depends on these models. Among these constraints: short CPU time, compactness memory and a good precision. The choice of an optimal method must carry out a good compromise between these requirements [32].

Table 1: Comparison of the main numerical techniques of millimeter-wave structures

Numerical Methods	Storage Requirement	CPU Time	Versatility	Preprocessing
Finite Difference Time Domain (FDTD)	L	L	E	-
Finite Element Method (FEM)	L	M/L	E	S
Transmission line Matrix (TLM)	M/L	M/L	E	S
Method of Moments (MoM)	S/M	S/M	G	M
Transverse Resonance Method	S/M	S/M	Ma	M
Method of Lines (MoL)	M	S	G	M/L
Spectral Domain Approach (SDA)	S	S	Ma	L
Artificial Neural networks (ANN)	S	S	M	L

E- Excellent, G-Good, L- Large, Ma- Marginal, M- Moderate, S - Small

4. Simulation Results and Discussion

A Microstrip Patch antenna shown in fig.1 is simulated using IE3D for MOM, FIDELITY for FDTD and ANSOFT- HFSS for FEM. The results obtained in all these three numerical techniques are shown in figure 2. Parameters like CPU time, Storage requirement, Versatility and Pre-processing of all these three numerical techniques are presented in table 2.

This article describes the design of Microstrip patch antennas operating at 2.4 GHz. Design considerations are given for two Microstrip antennas, a single element probe-fed square patch and an electromagnetically coupled square patch, both operating at a frequency of 2.4 GHz. Measurements of input VSWR and frequency are presented. Particular attention is paid to the radiation properties of the antennas the radiation pattern and polarization purity. A Microstrip patch antenna consists of a very thin metallic patch placed a small fraction of a wavelength above a conducting ground-plane. The patch and ground-plane are separated by a dielectric. The patch conductor is normally copper and can assume any shape, but simple geometries generally are used, and this simplifies the analysis and performance prediction. The patches are usually photo etched on the dielectric substrate. The substrate is usually non-magnetic. The relative permittivity of the substrate is normally in the region between 1 and 4, which enhances the fringing fields that account for radiation, but higher values may be used in special circumstances. Due to its simple geometry, the half wave rectangular patch is the most commonly used Microstrip antenna. It is characterized by its length L, width w and thickness h, as shown in Figure 1.

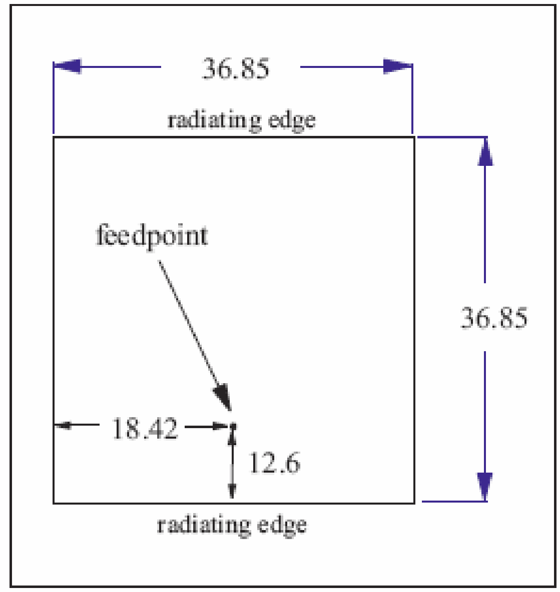

Fig.1 Structure of Microstrip Patch Antenna

The simplest method of feeding the patch is by a coplanar Microstrip line, also photo etched on the substrate. Coaxial feeds are also widely used. The inner conductor of the coaxial-line (sometimes referred to as a *probe*) is connected to the radiating patch, while the outer conductor is connected to the ground-plane, as shown in Figure 2.

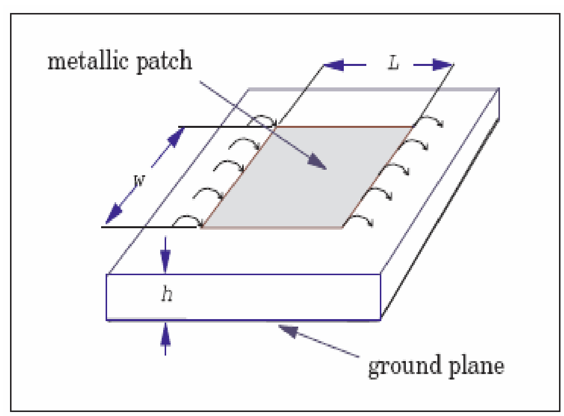

Fig 2. A square Microstrip patch antenna showing fringing fields that account for radiation.

The following calculations are based on the transmission-line model of Derneryd [6]. The width *w* of the radiating edge, which is not critical, is chosen first. In this case, a square geometry was chosen because it can be arranged to produce circularly polarized waves. The length *L* is slightly less than a half wavelength in the dielectric. The calculation of the precise value of the dimension *L* of the square patch is carried out by an iteration procedure. To obtain an initial value of L,

$$L = \frac{c}{2 f_0 \sqrt{\varepsilon_r}} \tag{1}$$

For f_0 = 2.4 GHz and ε_r = 2.33, this yields the value L = 40.1 mm. We then compute [7] a value for the effective relative permittivity ε_{eff} for Microstrip lines, with w/h , by means of equation (2) for the square antenna:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12h/L}}\right) \tag{2}$$

It is found that ε_{eff} = 2.141. With this value of ε_{eff}, now calculate the fringe factor ΔL [36], given by equation (3),

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0.300)}{(\varepsilon_{eff} - 0.258)} \frac{(w/h + 0.262)}{(w/h + 0.813)} \tag{3}$$

The value of ΔL turns out to be 1.63 mm, and by means of Equation (4),

$$L = \frac{c}{2 f_0 \sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{4}$$

Obtained the improved value of L of 36.84 mm. The foregoing procedure may be repeated with a result that L becomes 36.85 mm, compared with the initial value of 40.1 mm. Further iterations would only produce minor improvements, and the design was based on L = 36.85 mm. The accuracy of this model in predicting resonant frequency is better than 2 percent for thin substrates.

A rectangular Microstrip Patch antenna is simulated using IE3D for MOM, FIDELITY for FDTD and ANSOFT- HFSS for FEM. The results obtained in all these three numerical techniques are shown in figure 3, 4,5 and 6 VSWR vs. frequency are plotted.

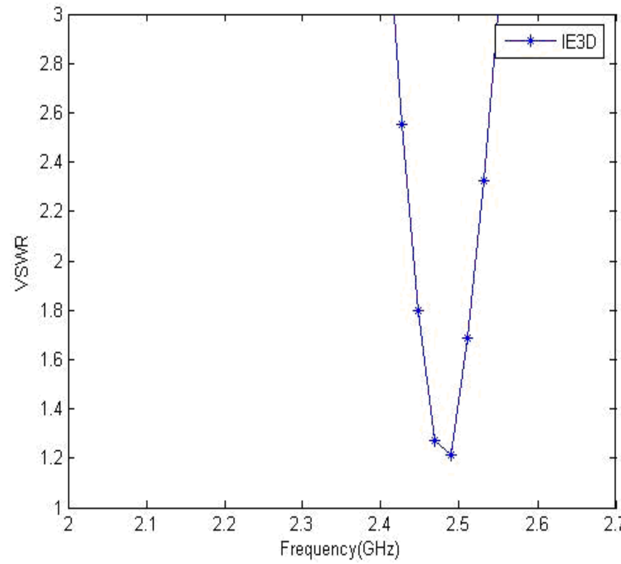

Fig.3 Simulated results for Method of Moments Using IE3D

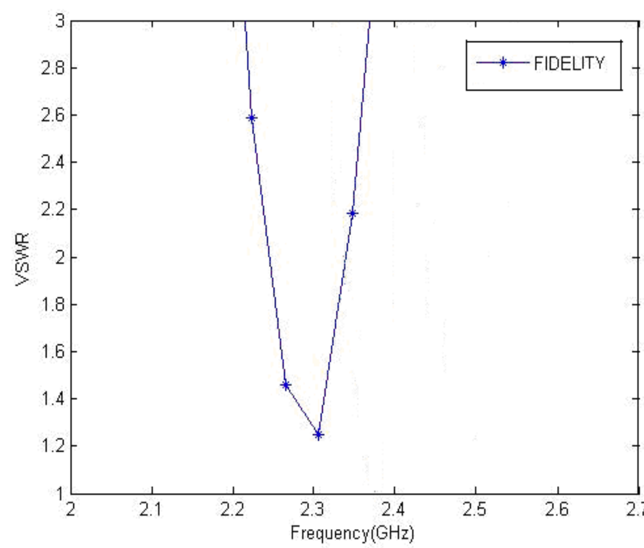

Fig.4 Simulated results for Finite Difference Time Domain Method Using FIDELITY

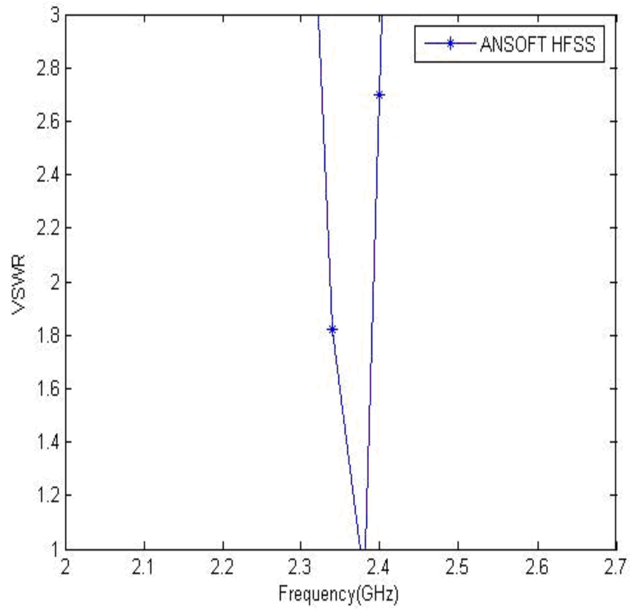

Fig. 5 Simulated results for Finite Element Method Using HFSS

Parameters like CPU time, Storage requirement, Versatility and Pre-processing of all these three numerical techniques are presented in table 2.

Table 2: Simulation results of few numerical techniques of millimeter-wave structures

Numerical Methods	Storage Requirement	CPU Time	Versatility	Preprocessing
Method of Moments (MoM)	26.780625kb	47.304×10^{-36} sec	G	M
Finite Difference Time Domain (FDTD)	5.175kb	3.651577×10^{-12} sec	E	L
Finite Element Method (FEM)	138.595 kb	12.96×10^{-24} sec	E	S

According to structure of antenna the resonating frequency must be at 2.4GHz. The plot indicates that the FEM- HFSS technique has resonating frequency around at 2.4GHz and also we can see from plot that FDTD-Fidelity and MOM-IE3D results have deviated from actual frequency. Even return losses are less for FEM when compare to both MOM and FDTD. Here VSWR vs. frequency plot is presented and it shows that FEM has better VSWR.

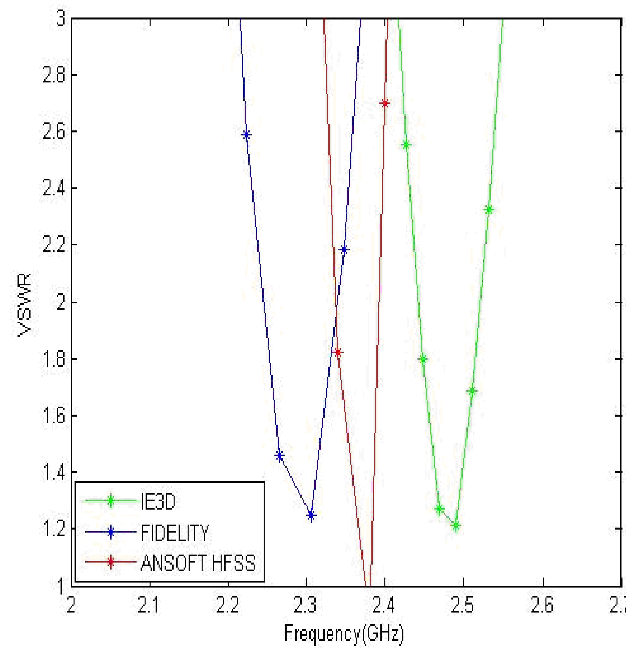

Fig.6 Simulation results of comparison of few Numerical Techniques For IE3D (MOM), FIDELITY(FDTD), Ansoft HFSS(FEM)

According to the structure of antenna the resonating frequency must be at 2.4 GHz. The plot indicates that the FEM- HFSS technique has resonating frequency around at 2.4GHz and also we can see from plot that FDTD-Fidelity and MOM-IE3D results have deviated from actual frequency. Even return losses are less for FEM when compare to both MOM and FDTD. Here VSWR vs. frequency plot is shown in figure 6 presented and it shows that FEM has better VSWR compare to other numerical techniques.

5. Conclusion

This paper provides brief descriptions for numerical techniques useful for Microwave and Millimeter-wave structures. As illustrated each method has it's own merits and demerits. For instance but the Finite Element Method requires considerable computation time and memory locations, it's a versatile technique. The authors presented the Numerical techniques to compute such effects in Microwave Integrated Circuits, highlighting their specific merit/demerit and compared few numerical techniques for rectangular Microstrip Patch Antenna and simulated results also compared. Finally, the steady improvement of personal computers affords an additional opportunity for numerical analysis tasks.

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