

Chapter 8 – Summary and Conclusions

8.1 Summary

A simulation framework for modeling electromagnetic wave propagation in a printed circuit board environment using Finite-Difference Time-Domain (FDTD) approach has been developed in this thesis. FDTD is chosen, as it is a time-domain method, which made it suitable for incorporating nonlinear components. Moreover being a time-domain method allows examination of the behaviors of the model during transient state. This is advantageous for studying the transient behavior for microwave oscillator circuits and circuits containing high-speed digital signals. High-speed digital signals are difficult to represent in frequency-domain, as the shape of the spectrum is complicated when the signal is pseudo-random (Mills 1993). Chapter Three and Chapter Four provide the algorithms to approximate a three-dimensional model using cubes, to include the presence of lumped components and all the update equations needed to find the E and H fields in the model as a function of time-step. Chapter Five introduces a convenient notation to describe a complex three-dimensional model cube-by-cube. This notation is very flexible and compact, with ample capacity to include new features in the future. In Chapter Five also, the algorithms presented in Chapter Three and Chapter Four are systematically converted into a computer program. Emphasis is placed on how to store the information describing the model, how to speed up the computation by performing pre-calculation and cross-referencing each field components with the appropriate update functions and coefficients. The architecture of the software is illustrated clearly in Chapter Five. Although it can be implemented in any programming languages supporting object-oriented technology, the software is coded using C++ programming language in this thesis as this language is widely supported at the moment. Conversion to other object-oriented languages such as JAVA can be easily done as both shares many similarities in the syntax. The architecture and data structures (or objects as it is called in object-oriented programming) of the software allows a lot of room for expansion in the future. Chapter Six lays the theoretical foundation for checking an important characteristic of the FDTD formulation, i.e. the

stability of the procedure. New stability theorems are derived based on energy consideration. The concept works by assuming the existence of a numerical energy. The field components are related to this numerical energy, if the numerical energy is bounded, so are the field components. The numerical energy will be bounded if it can be shown that all elements coinciding with the E field components diminish the numerical energy eventually. The theorems presented in Chapter Six are applicable to a general model with linear and nonlinear dielectric, discontinuous dielectric, linear and nonlinear lumped elements and boundary conditions. Verification of the effectiveness of the FDTD framework is performed in Chapter Seven, where four simulations are carried out. The simulations are compared with measurements or output from commercial SPICE based program.

The FDTD formulation does have its limitation at present. For circuits which emphasize on steady state sinusoidal response, the FDTD approach would be considerably slower than Method of Moments (MoM) or Finite Element Methods (FEM). This is a drawback of all time-domain approaches as the user has to wait for the system to achieve steady state from an initial stimulus. While frequency-domain approaches assume steady state has been reached and attempts to approximate the complex phasors of the field components directly. However as mentioned earlier frequency-domain methods do encounter serious obstacles when nonlinear elements are present. At present, to the best of the author's knowledge, frequency domain method which include non-linearity only works on circuit based simulators, such as the Harmonic Balance approach (Maas 1997). It is envisaged that the FDTD approach will not entirely replace other frequency-domain approaches, but will rather complement these methods.

8.2 Future Work

The followings are some remarks for future improvements:

1. Dispersive linear and nonlinear dielectrics could be included into the formulation as described in Sullivan (1996).

2. The stability theorems in Chapter Six are still not sufficient to guarantee that the FDTD solutions will converge to the actual solution as the discretization Δx , Δy , Δz and Δt approaches zero. The stability will only guarantee that the solution given by the FDTD method will not wander far from the actual solution. This is an important requirement if the approximate solution is to make physical sense. Effort could be carried out to find a corresponding Lax Equivalence Theorem for the general three-dimensional model with nonlinearity.
3. Support variable cell size and non-orthogonal cubes. This would enable the software to be more efficient in ‘filling up’ the three-dimensional space of the model. Non-orthogonal cubes, for example the triangular and tetra-hedral structures used in FEM (Itoh 1989) would allow better fitting for objects with curvature surface. The stability theorems in Chapter Six would require minor modification for variable cube size, but would require reformulation if non-rectangular shapes are used.
4. In Chapter Six, the stability conditions as embodied in Lemma 6.2 (equation (6.2.4b)) is more stringent compared to the CFL Stability Criterion. If an alternative grouping of the cells as in Appendix 3 can be found, a less stringent stability condition for the general three-dimensional model can be derived.
5. Lumped model for field effect transistor such as MOSFET and MESFET can be formulated according to the approach in Section 4.4. Notably for field effect transistors in the integrated circuit, the Berkeley Short-Channel IGFET Model (BSIM), (Massobrio and Antignetti, 1993) can be adapted to the FDTD framework.
6. In this thesis all conductors are assumed to be perfect electric conductor (PEC). As the density of the PCB increases, the width of conducting traces will decrease correspondingly. Current manufacturing precision can comfortably yield conducting trace with a width of 3.0mils and thickness of 1.0mils. Ohmic loss would be quite significant for a conducting trace with such cross-section. Furthermore for frequency beyond 10.0GHz, skin effect loss would also be considerable. Future effort could concentrate on embedding skin effect into the

electric field update equation. Such formulation would also be useful in modeling electromagnetic waves propagation within integrated circuit as the ohmic losses of the metallic and polysilicon layers are quite substantial.

7. Improve the speed of two-step simulation as mentioned in Chapter Seven. The d.c. solution can be solved by using other methods, such as artificially insert loss to hasten convergence, or use non-iterative method to find the d.c. solution, and then set the solution as a seed for transient simulation.

8.3 Conclusion

In recent years there is also another alternative formulation apart from Yee's original FDTD formulation. The new formulation is known as the Alternate-Direction Implicit (ADI) FDTD scheme as proposed by Namiki (1999 & 2000), and Zheng et.al (1999). However at present this method is not widely-accepted yet and it has not been applied to a general PCB model with dielectric discontinuity and lumped components. ADI method is originally developed for parabolic partial differential equations (Kreuzig 1988, Strikwerda 1989). It is applied to Maxwell's equations using the same space grid as in Figure 3.1. The key advantage of ADI-FDTD scheme is it is unconditionally stable for linear system, i.e. Δt is not subject to any limit. Thus it can be as large as required. However Δt is still limited by the numerical accuracy requirement as discussed in Section 3.5 (Zheng et.al 1999). Thus the benefit over conventional FDTD is only marginal for a model consisting of cubes with same size. However for a model with variable cube size, the benefit would be better (Namiki 2000). The computational requirement for ADI-FDTD scheme is higher in terms of memory requirement and the number of computations per iteration as it is an implicit scheme, i.e. simultaneous linear equations have to be solved. Nevertheless the matrix for the simultaneous linear equations is tridigonal (Kreuzig 1988), so it is easier to invert as compared to a full matrix. The larger computational steps per iteration and memory requirement are compensated by being able to increase Δt beyond the CFL Stability Criterion. Therefore if Δt is large, the number of time-steps needed to cover a particular

simulation period is smaller than conventional FDTD scheme (provided the slight decrease in accuracy can be tolerated).

The performance of ADI-FDTD schemes in nonlinear environment has not been verified. Moreover the von Neumann method used to verify the unconditionally stable nature of ADI-FDTD scheme (Namiki 1999) is not valid with the presence of nonlinear elements. Thus in this thesis, the formulation is not pursued. With the cause of instability phenomena explained in Chapter Six and Appendix 3-6, it is believed that there are still further improvements to the Yee's FDTD formulation yet to be discovered in terms of speed and accuracy.

With the continuation of future efforts, the FDTD framework could become a serious contender as an alternative tool for microwave and millimeter wave circuits simulation. Finally it should be cautioned that as with all computer simulations, the results are only as good as the models. This means that if the models are not accurate or do not reflect the actual physics of the components, then the result will not match well with measurements.