MICROSTRIP AND PRINTED ANTENNAS

NEW TRENDS, TECHNIQUES AND APPLICATIONS

Editors

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Preface

Microstrip technology has been popular for microwave and millimeter wave applications since the 1970s and recently has taken off, with the tremendous growth in communications, wireless, as well as space-borne/airborne applications, although the concept dates back to 1952 [1]. The basic microstrip configuration is very similar to a printed circuit board (PCB) used for low frequency electronic circuits. It constitutes a low-loss thin substrate, both sides being coated with copper film. Printed transmission lines, patches, etc. are etched out on one side of the microstrip board and the other copper-clad surface is used as the ground plane. In between the ground plane and the microstrip structure, a quasi-TEM electromagnetic wave is launched and allowed to spread.

Such a structure offers some unique basic advantages such as low profile, low cost, light weight, ease of fabrication, suitability to conform on curved surface, etc. All these have made microstrip technology attractive since the early phase of its development.

Within a year of the pioneering article "Microstrip – a new transmission technology for the kilomegacycle range" appearing [1], Deschamps [2] had conceived of microstrip as "microwave antenna." But its practical application started nearly two decades later. Howell [3] and Munson [4] may be regarded as the pioneer architects of microstrip antenna engineering.

These early developments immediately attracted some potential research groups and the following studies were mainly concerned with theoretical analysis of different patch geometries and experimental verifications [5–12]. A parallel trend also developed very quickly and some researchers tried to implement conventional antennas such as dipole, wire, aperture, etc. in planar form [13–16]. They are commonly referred to as printed circuit antennas or simply *printed antennas*. Their operations and characteristics are completely different from those due to microstrip patches, although microstrip patch antennas, in many papers, are casually called printed circuit antennas. The topic *printed antenna* had acquired tremendous importance by the late 1970s and a three-day workshop held at New Mexico State University in Las Crises in October, 1979 was dedicated to *Printed Circuit Antenna Technology*.

The developments in microstrip antennas that occurred up to the late1970s were documented by Bahl and Bhartia in their famous book [17], published in 1980. The analysis and design aspects were addressed in another book by James, Hall and Wood [18], published in 1981. A contemporary article by Carver and Mink [19] discussed the fundamental aspects of microstrip antennas and this is still regarded as a good review paper for a beginner.

More activities in the area grew gradually and many applications were realized. The suitability of deploying such lightweight low profile antennas in airborne and space-borne systems initiated major developments in microstrip array technology. With the development of mobile and wireless communications, microstrip and other printed antennas attained a new focus to serve in different technology from the mobile handset to base station antennas. General information, gathered from journals, symposia and conference articles, reveals that about 50% of the whole antenna community has been active in microstrip or printed antenna practice for the past two or three decades.

The first handbook [20] was published in 1989, nearly a decade after the first book by Bahl and Bhartia [17]. Within another five years, microstrip antenna research had attained a level of maturity as is reflected in the title and topics of the microstrip antenna books published around the middle of 1990s [21–23]. The edited volume by Pozar and Shaubert [21] contains some published articles bearing the results of contemporary interests, such as bandwidth enhancement approaches, analysis and design techniques, aperture coupling and other feeding methods, active integrated antennas, conformal and phased arrays, etc. Narrow impedance bandwidth appears an inherent limitation of the microstrip element. The research and consequent developments in bandwidth enhancement were documented in [22]. Lee and Chen [23] covered some key areas of advances reported up to 1997.

The growing need and interest in microstrip antenna designs are reflected in three design handbooks [24–26] published at close interval from 2001 to 2004. Compacting, along with bandwidth widening of printed antennas, has attracted worldwide interest to support new wireless technology since the beginning of this century and its importance was reflected in titles [27–32] which appeared between 2002 and 2007.

The book edited by Lee and Chen [23] was a timely effort to incorporate major technological developments that had occurred up to1997, under the same cover. Since then, more than a decade has passed during which many new trends, techniques and applications in planar antenna technology have been developed. For example, RFID (Radio Frequency Identification) is an ideal example to showcase the need to this day. This application needs low cost antennas, printed on paper or very thin substrate. Another example is printed antenna using unconventional and new innovations, such as using metamaterials and defected ground structures (DGSs). Replacing a large parabolic dish with a flat microstrip array with a special feeding mechanism is also a new area of activity. The design of small ultrawideband (UWB) antennas with good performance is a challenging area. Antenna for the body area network is another interesting new topic.

From our long experience in teaching and mentoring doctoral and post-doctoral students and working with practicing engineers, we certainly feel there is a need for a book that is to address more recent topics of microstrip and printed antennas. We have chosen some topics that have recently been developed or have considerably advanced during the past decade and at the same time appear to be important to the new generation of researchers, developers and application engineers. We shared the ideas with some of our colleagues and friends who are the real technical experts and potential developers in those selected topics. They fully agreed with our views, gave valuable suggestions and delivered on their promise to contribute. Our collaborative efforts have finally culminated in the present title.

As indicated by the title, the focus is on the *New Trends, Techniques and Applications* of *Microstrip and Printed Antennas*. The chapters are organized as follows: Chapters 1–4 address advances in design, analysis, and optimization techniques, Chapters 5–10 focus on some important new techniques and applications, Chapters 11 and 12 deal with engineered materials applied to printed antenna designs, and finally Chapter 13 addresses advanced methods and designs of printed leaky wave antenna.

Chapter 1 deals with numerical techniques, which are essential in analyzing and designing planar antennas of any arbitrary geometry. A brief overview of the commonly used methods are discussed and the finite difference time domain (FDTD) technique is elaborated on, with special emphasis on the recent developments that occurred after 2003. Chapter 2 presents the advances in computer aided designs (CAD) of microstrip antennas reported during 2001 and onwards. The aim of this chapter is to provide accurate closed form expressions, which can be reliably used to compute essential design parameters such as operating frequency, input impedance and matched feed-location for a given antenna involving single or multiple dielectric layers. Chapter 3 embodies the Generalized Scattering Matrix (GSM) approach to analyzing the multilayer finite printed array structures. The methodology is demonstrated through examples. Chapter 4 deals with antenna optimization techniques. Optimization in terms of performance, size and cost is discussed and the basic concept of stochastic optimization techniques is demonstrated.

Chapter 5 describes microstrip reflectarray technology, its general principle, design, operation, and applications. Microstrip's inherent demerit of narrow bandwidth is dealt with in terms of spatial and frequency dispersions and some of the techniques to suppress these factors are presented. Chapter 6 deals with Reconfigurable Microstrip Antennas, which use switches, tunable materials, or control circuitry to give additional degrees of operational freedom or to make a single element operative in multiple frequencies. A wide variety of reconfigurability is discussed. The emerging trends and directions for future research have also been indicated.

Chapter 7 describes wearable antennas for body area networks. The properties of the human body in terms of electromagnetic radiations and the performance of multiple antenna systems in presence of the human body are described. Chapter 8 presents printed wireless antennas. These include three primary configurations: microstrip patch, slot, and monopole showing multiband, wideband, or ultra wideband performances. Significant developments reported since 2000 are addressed in this chapter. Chapter 9 deals with printed antennas for RFID tags. An RFID system may be one of the following types: active, passive, or in between of these two, based on the nature of the devices used and also any of LF, HF, or UHF type based on the frequency of operations. Passive tags operating at UHF place several specialized requirements on the associated antenna structures and these are described in this chapter. Chapter 10 deals with printed antennas for ultra-wideband (UWB) applications. This incorporates the innovative technologies to minimize ground plane effects on the performance of small printed antennas.

Chapter 11 presents applications of metamaterials to planar antenna and radiative system designs. Both leaky wave and resonant metamaterial antennas are discussed with special emphasis on their recent and somewhat exotic applications. Chapter 12 deals with defected ground structures (DGS) applied to microstrip antennas. This is a recently developed topic and all the major developments that have occurred after 2002 are discussed, indicating the future scope of development. This is probably addressed here as an exclusive book chapter for the first time. Chapter 13 concludes with printed leaky wave antennas. It includes both theory and some applications based on recent advances in technology.

Each chapter is designed to cover the range from fundamental concepts to the state-of-the-art developments. We have tried to satisfy a wide cross-section of readers. A student or a researcher may consider this a guide book to understanding the strength and weaknesses of the contemporary topics. To a practicing engineer, we hope that the book will be a ready reference to many new areas of applications. To an educator, the book appears as a comprehensive review and a source of up-to-date information.

Our sincere efforts and exercise will be successful if our readers appreciate and find it useful for their respective purposes.

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Yahia M. M. Antar

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1

Numerical Analysis Techniques

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1.1 Introduction

Microstrip and other printed antennas are constituted of, in general, patches, strips, slots, packaged semiconductor devices, radome, feed, etc. in a nonhomogeneous dielectric medium. Finite substrate and ground plane size are the norm. The dielectric used is very thin compared to the other dimensions of the antenna. The design of these antennas based on models such as transmission line model or cavity model is approximate. Besides, these designs fit regular-shaped geometries (rectangular, circular, etc.) only, whereas most of the useful antenna geometries are complex and do not conform to these restrictions [1]. The effect of surface waves, mutual coupling, finite ground plane size, anisotropic substrate, etc. is difficult to include in these types of design. The numerical techniques, on the other hand, can be used to analyze any complex antenna geometry including irregular shape, finite dielectric and ground plane size, anisotropic dielectric, radome, etc. The popular numerical techniques for antenna analysis include method of moments (MoM), finite element method (FEM), and finite difference time domain method (FDTD). MoM analysis technique, though efficient, is not versatile because of its dependence on Green's function. FEM and FDTD are the most suitable numerical analysis techniques for printed antennas. FDTD is found to be versatile because any embedded semiconductor device in the antenna can be included in the analysis at the device-field interaction level. This leads to an accurate analysis of active antennas. Maxwell's equations are solved as such in FDTD, without analytical pre-processing, unlike the other numerical techniques. Therefore, almost any antenna geometry can be analyzed. However, this technique is numerically intensive, and therefore require careful programming to reduce computation cost. We shall describe the advances in FDTD. Our reference in this respect is the classic book on FDTD by Taflove and Hagness [2].

A large number of FDTD algorithms have been developed. These can be classified as conditionally stable and unconditionally stable. The conditionally stable schemes include the original or Yee's FDTD also called FDTD (2,2), FDTD (2,4), sampling bi-orthogonal time-domain (SBTD) and their variants; and the unconditionally stable schemes include ADI

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(Alternate Direction Implicit), CN (Crank Nicolson), CNSS (Crank Nicolson Split Step), LOD (Local One-Dimensional) and their variants. The updating of fields in conditionally stable schemes does not require a solution of matrix equation as an intermediate step, and are therefore fully explicit. However, these schemes have a limit on the maximum value of the time step, which is governed by the minimum value of the space step through the Courant-Friedrich-Levy (CFL) condition.

$$c.\Delta t_{CFL} \leq \frac{1}{\sqrt{1/\Delta x^2 + 1/\Delta y^2 + 1/\Delta z^2}} \tag{1.1}$$

Due to the heterogeneous nature of the dielectric in the printed antennas, the wave velocity is less than c and may vary from cell to cell and from one frequency to another. We therefore introduce a safety margin and choose $\Delta t = (1/2)\Delta t_{CFL}$ uniformly to simplify coding and avoid instability. Defining the Courant number q as

$$q = \Delta t / \Delta t_{CFL} \tag{1.2}$$

implies that $q = 1/2$ and the wave takes $2\Delta t$ time to travel to the next node.

The value of Δt_{CFL} puts a severe computational constraint on the structures as they have fine geometrical features such as narrow strips or slots or thin dielectric sheets. Since the simulation time of an antenna is independent of space and time steps, the number of updates of fields increases linearly with the decrease in the time step. This results in an increase in processor time. The limitation on Δt_{CFL} is removed in some of the FDTD algorithms and these are therefore called unconditionally stable schemes. In these schemes one can use the same value of the time step over the whole geometry even if fine geometrical features exist without significantly affecting the accuracy of simulation results. Updating fields in unconditionally stable schemes is carried out in stages called time splitting and involves solving a set of simultaneous equations before going on to the next stage. These schemes therefore are more computationally intensive. However, their accuracy is similar to that of conditionally stable FDTD schemes.

The FDTD analysis of open region problems such as antennas necessitates the truncation of the domain to conserve computer resources. The truncation of the physical domain of the antenna is achieved through absorbing boundary conditions, either analytical ABC or material ABC. Material ABC in the form of PML can achieve a substantial truncation of domain with very low reflection. The design of PML should be compatible with the FDTD scheme employed for the rest of the antenna. A number of PML formulations are available. These are split-field and non split-field PML. Non split-field types are convenient for coding and are therefore preferred. Of the various PML formulations available now, uniaxial PML looks promising.

All the FDTD algorithms suffer from computational error, and the amount of error is related to the space and time step sizes employed. The error is quantified in the form of numerical dispersion. The goal of various FDTD schemes is to analyze multi-wavelength long complex geometries, efficiently and accurately. The complexity of the geometry may be in the form of fine geometrical dimensions, anisotropic dispersive medium, embedded packged semiconductor device, feed, mounting structure, etc. The efficient FDTD algorithms try to achieve this aim by increasing the permissible space step size without increasing dispersion, by an increase in the time step size compatible with fine geometrical features, the applicability of the algorithm to anisotropic and dispersive medium and reduced reflection from the PML medium. The presence of thin strips/slots makes uniform discretization an inefficient approach. New and efficient solutions are being tested in the form of a sub-cell approach, quasi-static approximation, etc. The treatment of PEC and PMC boundary conditions presented by irregular geometries is receiving due attention, while the interface conditions interior to the device are somewhat difficult to implement accurately. Modeling of fast variation of fields in metal, and analysis of curved geometries is being attempted. We shall now discuss the advances in FDTD analysis since 2003.

Yee's algorithm is outlined first in order to define the grid structure and the placement of electric and magnetic field components on the Yee cell. This grid will be used as a reference for other FDTD algorithms.

1.2 Standard (Yee's) FDTD Method

The FDTD method was first proposed by Yee in 1966 [3] and has been used by many investigators because of its host of advantages. However, computer memory and processing time for FDTD have to be huge to deal with the problems which can be analyzed using techniques based on the analytical pre-processing of Maxwell's equations such as MoM, mode matching, method of lines, FEM, etc. Therefore, the emphasis in the development of FDTD technique is to reduce the requirement for computer resources so that this technique can be used to analyze electrically large complex electromagnetic problems.

To determine time-varying electromagnetic fields in any linear, isotropic media with constants ε, μ, σ Maxwell's curl equations are sufficient; the curl equations are

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \tag{1.3a}$$

$$-\nabla \times \mathbf{E} = \mu \frac{\partial \mathbf{E}}{\partial t} \tag{1.3b}$$

The partial differential equations (1.3) are solved subject to the conditions that: (i) the fields are zero at all nodes in the device at $t = 0$ except at the plane of excitation; (ii) the tangential components of E and H on the boundary of the domain of the antenna must be given for all $t > 0$. For computer implementation of Equation (1.3), the partial derivatives are implemented as finite difference approximations, and are partly responsible for the inaccuracy of the solution. For better accuracy, the central difference approximation is used in FDTD and is defined as,

$$\left.\frac{\partial \mathrm{F}}{\partial \mathrm{u}}\right|_{\mathrm{u_o}} = \left.\frac{\mathrm{F}\left(\mathrm{u_o} + \frac{\Delta \mathrm{u}}{2}\right) - \mathrm{F}\left(\mathrm{u_o} - \frac{\Delta \mathrm{u}}{2}\right)}{\Delta \mathrm{u}}\right|_{\Delta \mathrm{u} \to 0} + \mathrm{O}(\Delta \mathrm{u})^2 \tag{1.4}$$

where $O(\cdot)$ stands for *the order of.* Use of Equation (1.4) converts Equation (1.3) into the following form:

$$E_x^{n+1}(i+\tfrac{1}{2},j,k) = \left(\frac{\varepsilon-\sigma\Delta t/2}{\varepsilon+\sigma\Delta t/2}\right)E_x^n(i+\tfrac{1}{2},j,k)$$
$$+\frac{\Delta t/\Delta y}{\varepsilon+\sigma\Delta t/2}\left(H_z^{n+1/2}(i+\tfrac{1}{2},j+\tfrac{1}{2},k)-H_z^{n+1/2}(i+\tfrac{1}{2},j-\tfrac{1}{2},k)\right)$$
$$-\frac{\Delta t/\Delta z}{\varepsilon+\sigma\Delta t/2}\left(H_y^{n+1/2}(i+\tfrac{1}{2},j,k+\tfrac{1}{2})-H_y^{n+1/2}(i+\tfrac{1}{2},j,k-\tfrac{1}{2})\right) \quad (1.5a)$$

$$E_y^{n+1}(i,j+\tfrac{1}{2},k) = \left(\frac{\varepsilon-\sigma\Delta t/2}{\varepsilon+\sigma\Delta t/2}\right)E_y^n(i,j+\tfrac{1}{2},k)$$
$$+\frac{\Delta t/\Delta z}{\varepsilon+\sigma\Delta t/2}\left(H_x^{n+1/2}(i,j+\tfrac{1}{2},k+\tfrac{1}{2})-H_x^{n+1/2}(i,j+\tfrac{1}{2},k-\tfrac{1}{2})\right)$$
$$-\frac{\Delta t/\Delta x}{\varepsilon+\sigma\Delta t/2}\left(H_z^{n+1/2}(i+\tfrac{1}{2},j+\tfrac{1}{2},k)-H_z^{n+1/2}(i-\tfrac{1}{2},j+\tfrac{1}{2},k)\right) \quad (1.5b)$$

$$E_z^{n+1}(i,j,k+\tfrac{1}{2}) = \left(\frac{\varepsilon-\sigma\Delta t/2}{\varepsilon+\sigma\Delta t/2}\right)E_z^n\left(i,j,k+\tfrac{1}{2}\right)$$
$$+\frac{\Delta t/\Delta x}{\varepsilon+\sigma\Delta t/2}\left(H_y^{n+1/2}(i+\tfrac{1}{2},j,k+\tfrac{1}{2})-H_y^{n+1/2}(i-\tfrac{1}{2},j,k+\tfrac{1}{2})\right)$$
$$-\frac{\Delta t/\Delta y}{\varepsilon+\sigma\Delta t/2}\left(H_x^{n+1/2}(i,j+\tfrac{1}{2},k+\tfrac{1}{2})-H_x^{n+1/2}(i,j-\tfrac{1}{2},k+\tfrac{1}{2})\right) \quad (1.5c)$$

$$H_x^{n+\frac{1}{2}}(i,j+\tfrac{1}{2},k+\tfrac{1}{2}) = H_x^{n-\frac{1}{2}}(i,j+\tfrac{1}{2},k+\tfrac{1}{2})-\frac{\Delta t}{\mu\Delta y}\left(E_z^n(i,j,k+\tfrac{1}{2})-E_z^n(i,j-1,k+\tfrac{1}{2})\right)$$
$$+\frac{\Delta t}{\mu\Delta z}\left(E_y^n(i,j+\tfrac{1}{2},k)-E_y^n(i,j+\tfrac{1}{2},k-1)\right) \quad (1.5d)$$

$$H_y^{n+\frac{1}{2}}(i+\tfrac{1}{2},j,k+\tfrac{1}{2}) = H_y^{n-\frac{1}{2}}(i+\tfrac{1}{2},j,k+\tfrac{1}{2})-\frac{\Delta t}{\mu\Delta z}\left(E_x^n(i+\tfrac{1}{2},j,k)-E_x^n(i+\tfrac{1}{2},j,k-1)\right)$$
$$+\frac{\Delta t}{\mu\Delta x}\left(E_z^n(i,j,k+\tfrac{1}{2})-E_z^n(i-1,j,k+\tfrac{1}{2})\right) \quad (1.5e)$$

$$H_z^{n+\frac{1}{2}}(i+\tfrac{1}{2},j+\tfrac{1}{2},k) = H_z^{n-\frac{1}{2}}(i+\tfrac{1}{2},j+\tfrac{1}{2},k)-\frac{\Delta t}{\mu\Delta x}\left(E_y^n(i,j+\tfrac{1}{2},k)-E_y^n(i-1,j+\tfrac{1}{2},k)\right)$$
$$+\frac{\Delta t}{\mu\Delta y}\left(E_x^n(i+\tfrac{1}{2},j,k)-E_x^n(i+\tfrac{1}{2},j-1,k)\right) \quad (1.5f)$$

The indices i,j, and k define the position of the field nodes, such that $x = i\Delta x,\ y = j\Delta y,\ z = k\Delta z$. The time instant is defined by $t = n\Delta t$. To implement the finite difference scheme in three dimensions, the antenna is divided into a number of cells, called Yee cells, of dimension $\Delta x\Delta y\Delta z$. One such cell is shown in Figure 1.1. Remarkably the positions of different components of E and H on the cell satisfy the differential and integral forms of Maxwell's equations. One may note from Figure 1.1 that the placements of the E and H nodes are offset in space by half a space step; it is called staggered grid. We note from Equation (1.5) that the time instants when the E and H field components are calculated are offset by half a time step, that is, components of E are calculated at $n\Delta t$ and components of H are calculated at $(n + 1/2)\Delta t$. The alternate update of E and H fields is called *leap frog* and saves computer processing time.

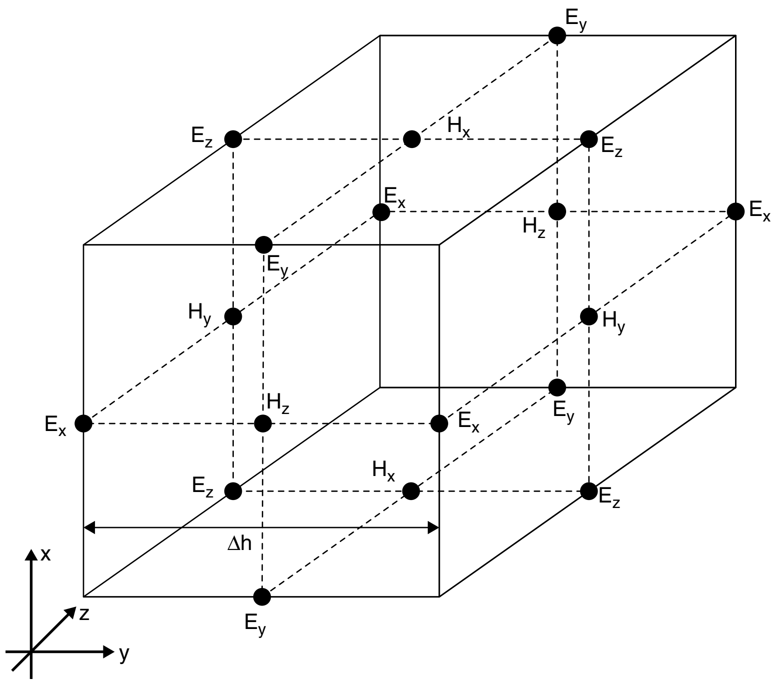

Figure 1.1 Geometry of Yee's cell used in FDTD analysis

1.3 Numerical Dispersion of FDTD and Hybrid Schemes

The finite difference form of derivative (1.4) has an error term $O(\Delta u)^2$. As a result, Equations (1.5 a–f) are second-order accurate, resulting in an approximate solution of the problem. The first sign of this approximation appears in the phase velocity v_{ph} for the numerical wave being different from that in the continuous case. This phenomenon is called numerical dispersion. The amount of dispersion depends on the wavelength, the direction of propagation in the grid, time step Δt and the discretization size Δu. The above algorithm is second-order accurate in space and time, and is therefore called FDTD(2,2). The numerical dispersion for plane wave propagation may be determined from the following expression

$$\left(\frac{\sin(\omega\Delta t/2)}{c\Delta t}\right)^2 = \left(\frac{\sin(\bar{k}\sin\theta\cos\varphi\Delta x/2)}{\Delta x}\right)^2 + \left(\frac{\sin(\bar{k}\sin\theta\sin\varphi\Delta y/2)}{\Delta y}\right)^2 + \left(\frac{\sin(\bar{k}\cos\theta\Delta z/2)}{\Delta z}\right)^2 \quad (1.6)$$

where $\bar{k}$ is the wave number for the numerical wave. The phase velocity $\bar{v} = \omega/\bar{k}$ is determined by solving Equation (1.6) as a function of discretizations $\Delta x, \Delta y, \Delta z, \Delta t$ and propagation angle θ, ϕ. The phase velocity is found to be maximum and close to the velocity of light for propagation along the diagonals and minimum for waves propagating along the axis.

1.3.1 Effect of Non-Cubic Cells on Numerical Dispersion

Devices with high aspect ratio may be analyzed by using uniform or non-uniform cell size. An alternative is to employ non-square or non-cubic cells. The influence of the aspect ratio of the unit cell on the numerical dispersion of FDTD(2,2) has been reported by Zhao [4]. It is found that the dispersion error $(c-\bar{v})/c$ increases with the increase in aspect ratio of the cell but reaches an upper limit for aspect ratios greater than 10. For N (number of cells per wavelength, $\lambda/\Delta) = 10$, the maximum dispersion error for non-cubic cells is 1.6% which decreases to 0.4% for N = 20, showing second-order accuracy. In general, the maximum error for non-cubic cells is about 1.5 times that of the corresponding error for cubic cells. For the non-square cells, this ratio is twice that of square cells [4]. For guidance, the minimum mesh resolution required to achieve a desired phase velocity error is plotted in Figure 1.2 for the cubic and non-cubic cells.

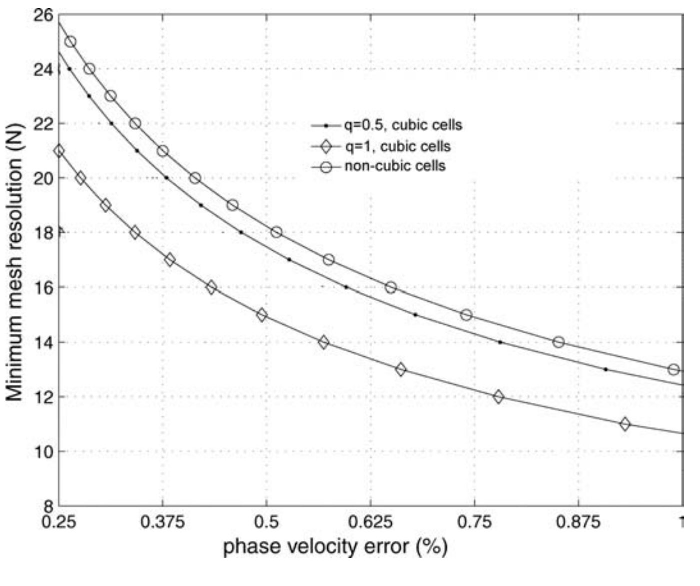

Figure 1.2 Comparison of minimum mesh resolution required for a given accuracy of phase velocity when non-cubic (with high aspect ratio) or cubic unit cells are employed. Reproduced by permission of ©2004 IEEE, Figure 8 of [4]