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Application of the FD-TD Method to the Electromagnetic Modeling of Patch Antenna Arrays

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Abstract

The FD-TD method and the Berenger Perfectly Matched Layer (PML) absorbing condition are applied to the modeling of a 32-element patch array. Numerical results for the return loss at the array feed are presented and compared to measured results for the purpose of model validation.

1 Introduction

The Finite Difference Time Domain (FDTD) algorithm developed by Yee [1] has found widespread use in electromagnetic analysis. The ability of FDTD to provide in a single run the broadband response of a structure is attractive for microwave/millimeter-wave component analysis, antenna design, and the prediction of radiated emissions from packaged electronic components and systems. The nature of the algorithm makes it ideally suited for implementation on massively parallel computers, facilitating analysis at the system rather than component level. With recent advances in desktop computing, the method has gained popularity for problems traditionally analyzed using frequency domain techniques [2].

However, the method is not without its limitations. One of the fundamental complications in using the method, which is of relevance to this paper, has been the proper truncation of the grid for outgoing waves. One of the more popular techniques used to address this problem has been one-way wave equations (or annihilators), such as the first and second order Mur [3] algorithms. Unfortunately, this approach tends to be narrow band and directional. Another approach has been to introduce absorbing media to cause the decay of the fields. However, reflections from the absorbing material have limited the use of this approach. Recently Berenger proposed the Perfectly Matched Layer (PML) [4] which overcomes this problem by matching the phase velocity and impedance of the absorber to the physical medium.

In this paper we apply the FDTD method with the PML absorbing boundary condition to a 32-element patch antenna array. While integral equations techniques are well-suited for the analysis of such radiators, recent advances in portable electronics call for novel antenna designs which can benefit from the modeling versatility of the FDTD method. More specifically, active antennas are recently being considered for use in smart id cards, miniature GPS receivers, personnel sensors, and highway automation applications. The increased effective length, increased bandwidth, improved noise factor, and reduced mutual coupling in array applications are some of the attributes of active antennas that explain the interest in their use in small form factor transceiver designs [5]. The presence of non-linear devices within the antenna structure necessitates the use of a non-linear electromagnetic solver for the modeling of electromagnetic radiation from the antenna. FDTD has been demonstrated as the method of choice for such modeling [6].

In the next section we discuss the issues relating to the excitation and characterization of the patch antenna array with respect to the FDTD algorithm. Also, we will provide a brief overview of the PML. In Section 3, we provide numerical results for the return loss of the array.

2 Theory

2.1 FDTD

Because the Finite-Difference Time-Domain method is well known [1], [7], we will focus our discussion on the issues specific to the structure under consideration.

2.1.1 Excitation and Characterization Techniques

The feed for the patch array consists of a short section of coaxial line, modeled with a stair step approximation, representing the coaxial feed. The inner conductor of the coaxial line extends to the microstrip line connected to the feed network of the patch array. A port plane is then defined at some chosen reference plane. In the port plane we solve Laplace's equation to find the quasi-TEM transverse electric field distribution. This field is imposed on the boundary as an incident field. Assuming TEM propagation, with an appropriately averaged cell velocity, the incident and reflected fields are separated. A Mur type one-way wave equation is then applied to the reflected field at the port plane.

To compute the return loss for the coaxial line-driven patch antennas, a separate simulation of the uniform section of the coaxial line, defined in the port plane, is performed to determine the incident field waveform (voltage, current, or Poynting flux) in the reference plane and to characterize the coaxial line. The incident waveform from the port simulation is then used to determine the reflected waveform in the simulation of the patch antenna. An FFT of the ratio of the incident and reflected waveforms provides the return loss as a function of frequency. To reduce the computation time, the late time response can be computed efficiently using either Prony's Method [8] or the Matrix Pencil Method [9].

2.2 Berenger PML

The Berenger PML [4] splits the field into sub-components and introduces electric and magnetic conductivities to cause the decay of propagating fields. The values of the PML conductivities are assigned directly at the corresponding field locations on the grid. The conductivities are chosen to satisfy the matching condition

$$\frac{\sigma_i}{\epsilon} = \frac{\sigma_i^*}{\mu} \tag{1}$$

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where i indicates the direction (x, y, or z) and σ^* represents magnetic losses, which enforces the continuity of the wave impedance and phase velocity independent of frequency. Alternatively, the PML can be interpreted in terms of stretched coordinates [10]. To reduce the numerical reflections from the PML interface, a gradual spatial variation of the conductivities is used

$$\sigma_i(x_i) = \sigma_{i,max}\left(\frac{x_i}{L}\right)^2 \tag{2}$$

where L is the length of the PML and $\sigma_{i,max}$ is the maximum conductivity value. The PML region is terminated with a PEC. The apparent reflectivity from the PML region is given by [4]

$$R = e^{\frac{-2\langle\sigma_i\rangle L}{\epsilon_0 c}} \tag{3}$$

where $\langle\sigma_i\rangle$ denotes the spatially integrated conductivity value. For the aforementioned parabolic profile it is $\langle\sigma_i\rangle = \sigma_{i,max}/3$.

We have implemented the PML in a code [11] which supports multiple blocks (conformal regions of space with separate meshes) as a new type of block using the PML field update equations. The PML and standard blocks are connected by forcing the losses to be zero over the cells in the connection plane of the PML block, thereby allowing the total field to be decomposed into the partial field components. This configuration reduces the total overhead in the problem by incurring the overhead of the PML only where needed. It should be noted that because of conductor masking [11] the PML absorbing boundary condition results in additional field solve regions which avoid the issues associated with implementing boundary conditions on massively parallel architectures.

3 Numerical Results

In Figure 1 the geometry of a section of a coaxial transmission line-fed microstrip patch array is shown. The entire array consists of 192 patches and is formed by six of the sub-sections shown in Figure 1 aligned side by side and driven in phase. The grounded dielectric substrate is 0.031 inches thick with a dielectric constant of 2.2.

Exploiting the symmetry in Figure 1, we simulated only the lower 16 patches and the associated feed network. A small ten element long stair-step approximation to the coaxial transmission line was used to drive the antenna. A nearly uniform grid with 148 by 103 cells in the plane of the antenna and 10 cells in the transverse direction (4 cells in the substrate) was used. This grid resulted in a coarse discretization of the geometry. The inset-fed patch feed lines and gaps were each modeled as being one cell wide. The serpentine line used to feed clusters of eight patches was separated by only 1-2 cells from itself and adjacent patches in some locations.

PML blocks were located at 3 cells from the edge of feed line on the right side and 5 cells from the edge of the patches on the left side with $\sigma_{i,max} = 10.7$ S. On the lower side a PML block was also placed 5 cells from the edge of the patches with $\sigma_{i,max} = 10.5$ S. A PML block with $\sigma_{i,max} = 20.2$ S was placed 6 cells above the plane of the patches. The PML parameters were based on $m = 2$ and $q \approx 4$. The PML blocks were chosen to be 8 cells thick. Of the 423236 cells in the simulation 55% of them were located in PML blocks.

The total CPU time required on an HP 9000/735 workstation was approximately 11 hours for 17700 time steps. In Figure 2 we show the computed and measured return loss. The measured return loss curve was derived from a VSWR measurement of the first array sub-section with the other five sections left open (no difference was noted from the case of match terminating the other five sections).

The array was designed to work at 17 ± 0.3 GHz with a thin dielectric coating, however the measurements were made without the coating present. The poor agreement is most likely due to the inadequate resolution of the power splitting network. At the time this paper was written further studies were under way to comprehend the reasons for these discrepancies.

4 Acknowledgments

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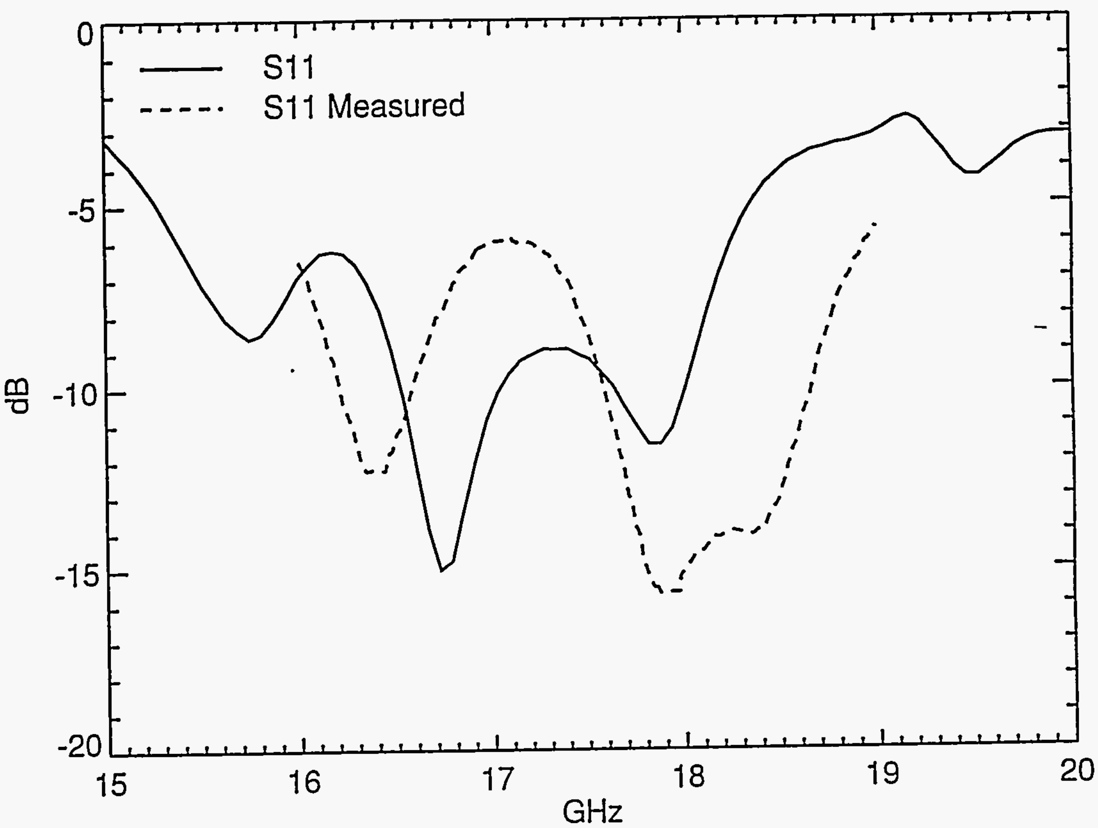

Figure 2: Computed and measured return loss for a subsection of a patch array antenna.

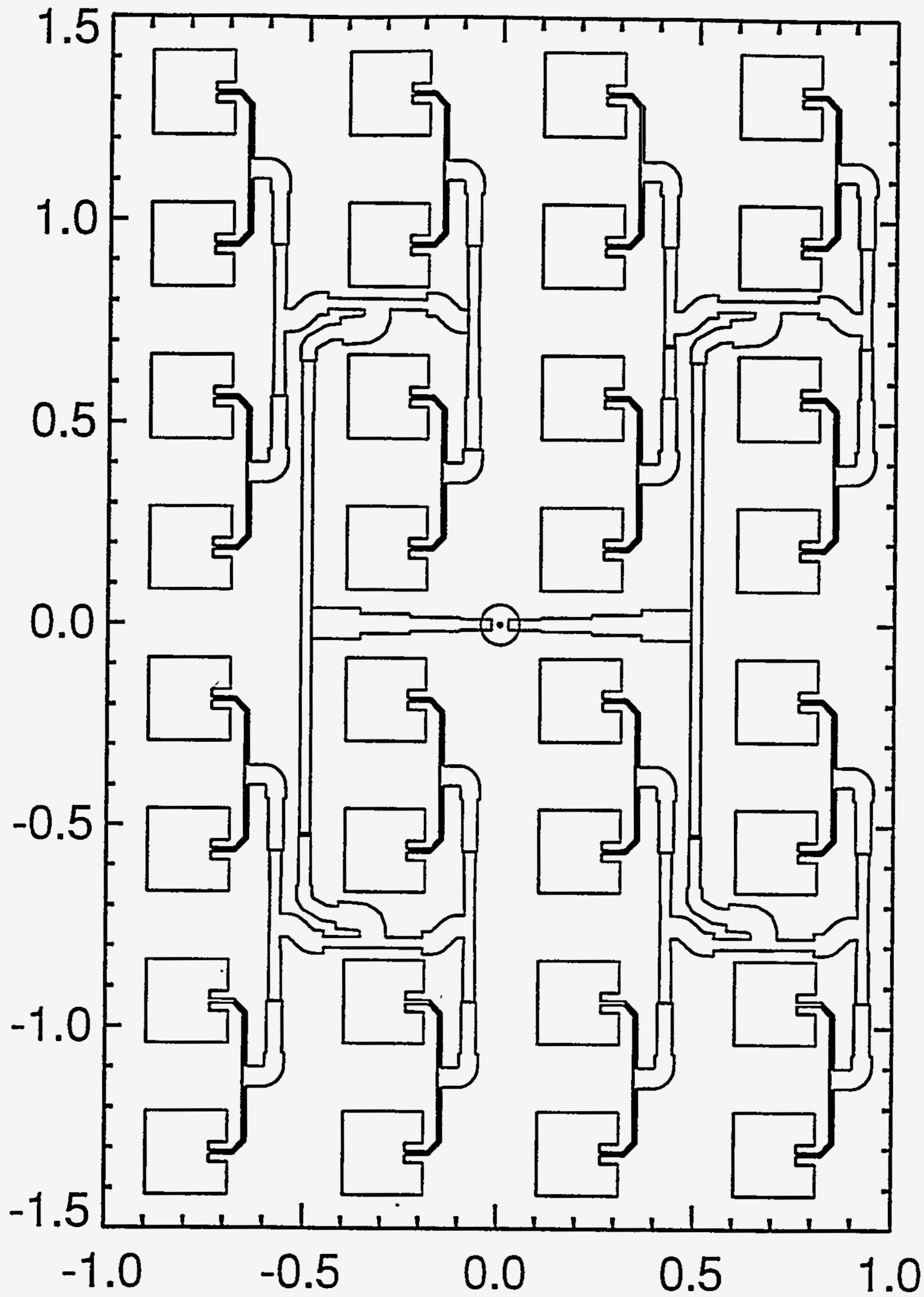

Figure 1: A subsection of a microstrip patch array antenna (in units of inches).