Analysis of Waveguide Aperture Coupling Using the Finite-Difference Time-Domain Method

P. Alinikula and K. S. Kunz

Abstract—**The finite-difference time-domain method has been applied to a variety of scattering and coupling electromagnetic problems. It has not until now been applied to an interior propagation and coupling problem, given here in the form of aperture coupled waveguides. This problem demonstrates the method's ability to model a rather complex problem where energy not only propagates in a waveguide but couples to and then propagates within a second waveguide. The coupling consists of a single and a double aperture. The first case establishes modeling requirements and the second case is compared to experiment. Agreement is typically within experimental error thereby validating the method for this application.**

I. Introduction

WAVEGUIDE coupling through an aperture is a fundamental electromagnetic problem. It has been approximated reasonably well with Bethe small hole theory [1], and with some more recent modifications of it [2]. However, these analytic solutions do not apply to arbitrary shaped complex waveguide coupling structures. Instead, numerical methods have to be used.

Finite-difference time-domain (FDTD) method has proven to be a very promising technique for time-domain analysis of passive microwave and millimeter wave structures. FDTD's strength is in its capability to model any volumetric structure with rectangular cells. No requirements for symmetry or smooth surfaces are needed. Better modeling is of course achieved by using more cells. Additionally, the FDTD code can handle complex materials; lossy and anisotropic dielectrics as well as ferromagnetic materials are currently included in the code and some feasibility studies have been conducted with nonlinear dielectrics and chiral materials.

Recently, FDTD has been used in modeling microstrip structures [3], [4] and in predicting aperture coupling for a shielded wire [5]. These results suggest that FDTD could be successfully applied to waveguide coupling problems.

The objective of this letter is to model coupled waveguides using FDTD. The forward and backward couplings are predicted for two geometries: a single circular aperture and a dual circular aperture. The single aperture coupler simulations are performed using different mesh dimensions and different simulation durations to observe the model's sensitivity and by that means determine the setup for FDTD waveguide simulations. The dual aperture geometry, however, is selected to be the same as in [2] in order to be able to compare the calculated results with measurements.

Manuscript received February 11, 1991; revised March 27, 1991.
The authors are with the Department of Electrical and Computer Engineering, Pennsylvania State University, University Park, PA 16802.
IEEE Log Number 9101742.

II. FDTD Description

The FDTD field formalism is by now well known ([6], [7]), and will not be presented here. Only the introduction of the field into the waveguide requires discussion. The electric wall approach is used for wave launching. An incident transverse electric field is allowed to appear spatially only at a transverse plate in the other end of the lower waveguide. The amplitude of the field has a half wavelength sinusoidal distribution across the plate in the x direction and is uniform in the y direction. Thus, the launched wave approximates the TE_{10} mode. The incident field has a spatial variation in the z direction given by a Gaussian envelope imposed on a sinusoidally varying carrier. The sinusoidally varying portion of the waveform reduces dc signal markedly while shifting the frequency content of the pulse upward. However, a truncated pulse has always an infinite frequency band and therefore some energy is forced inside the waveguide at frequencies below cutoff. This energy is kept to a minimum by using a relatively long Gaussian envelope.

III. Model of Coupled Waveguides

The problem space, shown in Fig. 1 consists of 4 sides that are defined to be perfectly conducting, i.e., the tangential electric field components on these planes are forced to be zero. The remaining two sides, the ends of the waveguides, are open. Electric fields on these sides fulfill Mur's first-order approximate absorption condition [8]. This condition produces some reflection for waves that are not normal to the boundary. Although the group velocity is less than the velocity of light, the phase velocity of the wave decomposed into two intersecting waves is still c_0. The angle of each component becomes larger the closer one gets to the cut-off frequency of the waveguide and simultaneously Mur's absorption boundary conditions get worse. A simulation was conducted with a long waveguide in order to separate the reflected wave. At the operating frequency range 8–13 GHz the reflection was 35–50 dB down from the incident wave, and therefore the wave is close enough to normal that the first-order Mur condition was deemed adequate for this investigation.

1051-8207/91/0800-0189$01.00

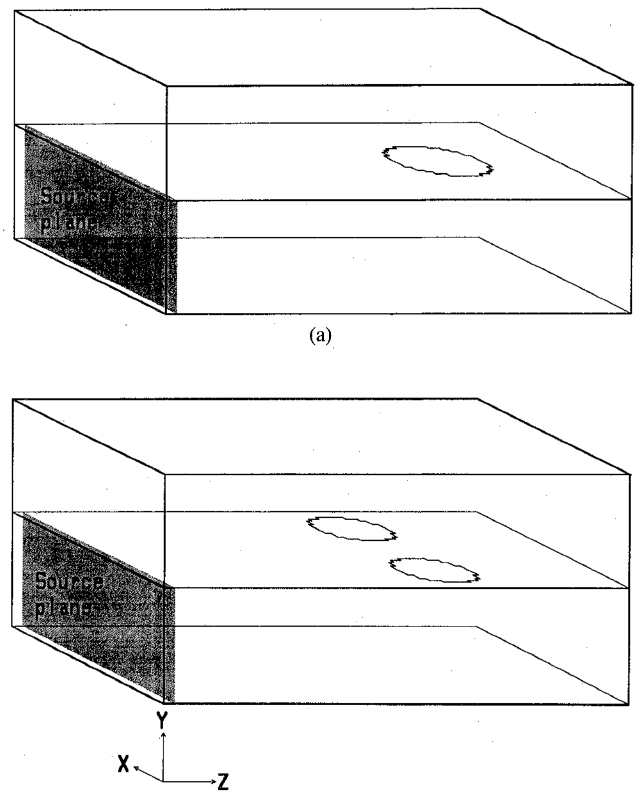

Fig. 1. Two aperture geometries. (a) single-centered coupling. (b) Two parallel circular coupling.

The metal plate between the two waveguides is defined to be infinitely thin, but effectively it has an approximate thickness of half the cell. Circular apertures are approximated with square cells. Several different diameters 8, 12, 13, and 16 were used. Naturally, the actual shape is modeled more accurately when more cells are used. The distance of the aperture from the source launcher was selected so that the whole pulse can fit inside the guide before the aperture is encountered. The test locations of the electric field components in the backward and forward propagation directions were selected to be 1/4 of the aperture diameter away from the edges of the aperture. Transversely the test locations are in the middle of the upper waveguide. The coupling coefficient was calculated as the ratio of electric field at the test location inside the upper waveguide and the electric field inside an undisturbed single waveguide.

Two aperture geometries that were analyzed are shown in Fig. 1. The first one (Fig. 1(a)) consists of a single-centered coupling aperture with circular shape and relatively large size. The diameter of the aperture is 0.375a, where $a = 22.86$ mm is the broad-side dimension of all the waveguides. Moreover, all the waveguides have a 2:1 ratio between the sides. Three different mesh dimensions were used: $22 \times 16 \times 55$, $32 \times 16 \times 80$, and $43 \times 16 \times 108$ in x, y, and z directions respectively. The corresponding diameters of the apertures were 8, 12, and 16 cells. The second structure (Fig. 1(b)) has two parallel circular coupling apertures that are slightly smaller in size. Mesh dimensions are $42 \times 26 \times 108$ in x, y, and z directions. The diameter of the apertures is 13 cells, which corresponds to 7.08 mm. This geometry was constructed to be identical to one in [2, Fig. 6] in order to be able to compare the results.

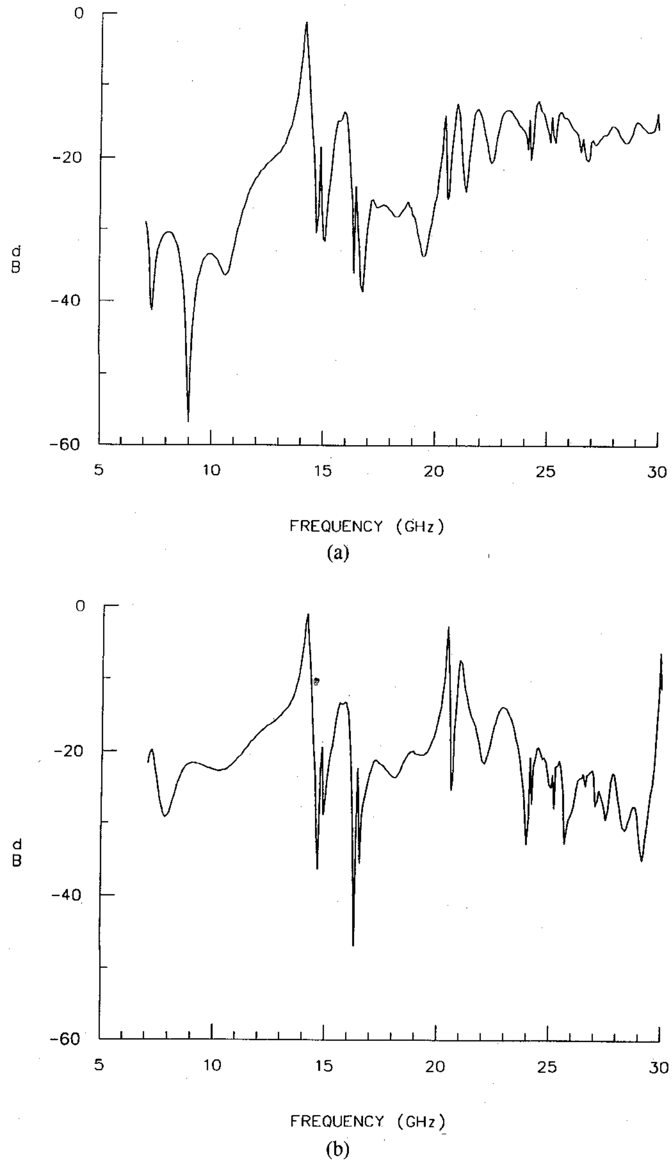

Fig. 2. (a) Forward coupling 16×80 cells, holes 12 cells. (b) Backward coupling, $32 \times 16 \times 80$ cells, holes 10 cells.

IV. Results

Single-aperture coupler simulations showed that after 8192 timesteps the remaining energy in propagating waves was so small that the truncation had negligible effect on the fast Fourier transformed response. The forward and backward coupling coefficients for $32 \times 16 \times 80$-cell geometry with 12 cell hole diameter are shown in Figs. 2(a) and (b).

The model's sensitivity for mesh dimensions was examined by comparing responses of the single-aperture geometry with three different mesh dimensions. The forward and backward coupling coefficient comparisons at a narrower frequency band are shown in Figs. 3(a) and (b). The results show significant difference between the $22 \times 16 \times 55$, and $32 \times 16 \times 80$-cell geometries, whereas the responses for $43 \times 16 \times 108$ and $32 \times 16 \times 80$-cell geometries are very close.

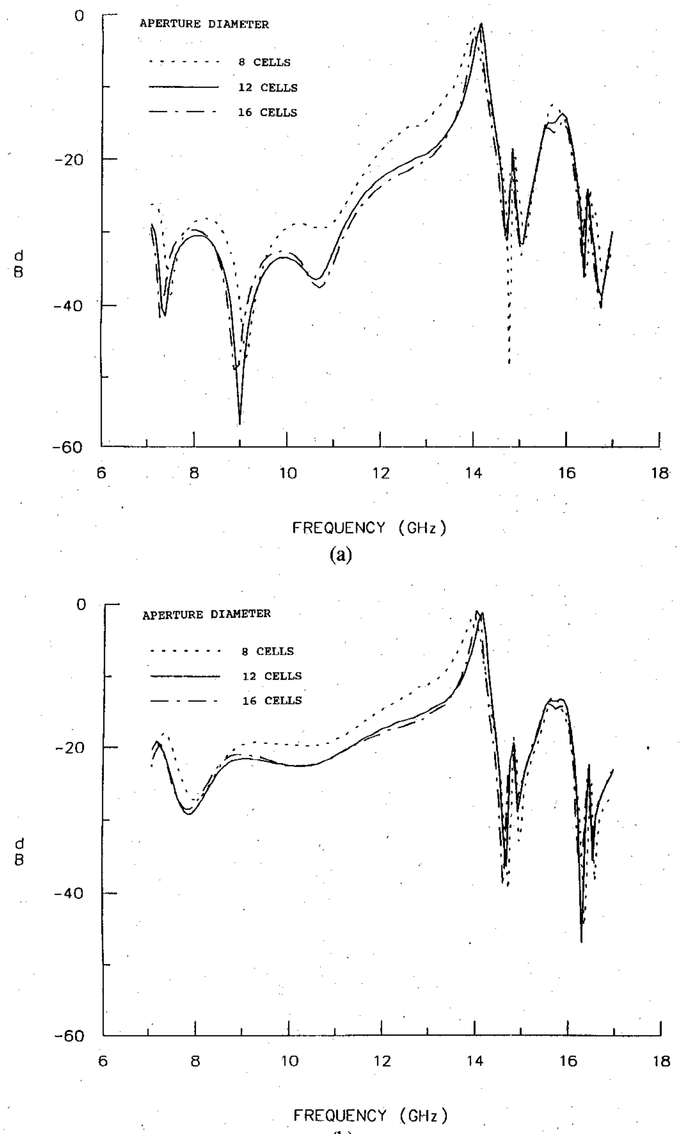

Fig. 3. (a) Forward coupling. 8, 12, 16 cell holes comparison. (b) Backward coupling. 8, 12, 16 cell holes comparison.

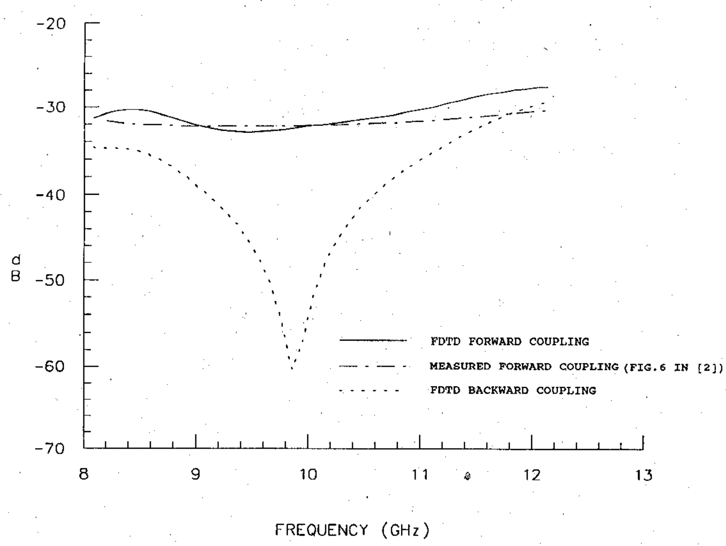

Fig. 4. 2-hole coupler: FDTD results and measurements.

The results indicate that 32 cells is sufficient for modeling the broad side of the waveguide and 12 cells for the aperture diameter respectively.

The forward and backward coupling coefficients for a coupler with two apertures are shown in Fig. 4. The experimental forward coupling results from [2] for the same structure are also shown. The forward coupling coefficient is a very close match to the experiment. Except for the band edges, the simulation results fall inside the measurement accuracy range. Moreover, in [2] it was observed that the directivity (forward/backward coupling) was larger than 3 dB. Simulations support this with a minimum of approximately 2-dB directivity.

V. Conclusion

Simple waveguide coupling problems were successfully analyzed using the FDTD method. A sufficient setup for waveguide modeling was determined. Results, that showed little sensitivity to either mesh dimensions or simulation duration, were achieved using 32 cells for the broad side of the waveguide, 12 cells for the aperture diameter, and 8,192 timesteps. With a well modeled geometry an accuracy inside measurement error range was achieved. Although these simple problems can be approximated reasonably well with analytical expressions, the results show FDTD method's potential in solving more complicated waveguide problems. Combinations of dielectric and metal screws and slabs as well as waveguide junctions can be analyzed in the same manner and with the same resources.

References

[1] H. A. Bethe, "Theory of diffraction by small holes," *Phys. Rev.*, vol. 66, pp. 163–182, Oct. 1944.

[2] R. Levy, "Improved single and multiaperture waveguide coupling theory, including explanation of mutual interactions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 331–338, Apr. 1980.

[3] D. M. Sheen, S. M. Ali, M. D. Abouzahra, and J. A. Kong, "Application of the three-dimensional finite-difference time-domain method to the analysis of planar microstrip circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 7, pp. 849–857, July 1990.

[4] J. Moore and H. Ling, "Characterization of a 90° microstrip bend with arbitrary miter via time-domain finite difference method," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 4, pp. 405–410, Apr. 1990.

[5] K. Kunz, D. Steich, and R. J. Luebbers, "Low frequency shielding characteristics of cylindrical shell with a varying size aperture," submitted to *IEEE Trans. Electromagn. Compat.*

[6] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 302–307, May 1966.

[7] K. S. Kunz and K. M. Lee, "A three-dimensional finite-difference solution of the external response of an aircraft to a complex transient EM environment: Part I—The method and its implementation," *IEEE Trans. Electromagn. Compat.*, vol. EMC-20, pp. 328–333, May 1978.

[8] G. Mur, "Absorbing boundary conditions for the finite-difference approximation of the time-domain electromagnetic-field equations," *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, pp. 377–382, May 1981.