DESIGN TOOLS AND METHODOLOGY FOR HIGH-SPEED/HIGH-FREQUENCY CIRCUITS AND SYSTEMS

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SOS-96-4-R

March 1996

Design Tools and Methodology for High-Speed High-Frequency Circuits and Systems

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The essential and basic building blocks of an computer or communication system are electronics components or subsystems such as IC, chip packages, MCM, PCB, power/ground plans and backplanes (BP). As the signal speed and frequency increase, the dimensions of PCB and MCM become a significant fraction of the signal wavelength. The conventional electrical models of the components, interconnects and backplanes are not valid anymore. EM models become necessary. It becomes extremely important to develop design methodology that can incorporate several levels of modeling and analysis methods, from EM to circuits, and from simulation, to optimization, and to statistical design.

New techniques based on moment matching methods from circuit simulation area have been developed for the solutions of EM level equations [1,2]. The Maxwell's equations as well as its special case - Helmholtz equations are formulated into a set of ordinary differential equations based on spatial finite difference, or finite element method (FEM). The equations are solved by Complex Frequency Hopping (CFH) technique, which produces complete time/frequency responses using frequency domain simulation of the problem at only a few frequency points. Compared to conventional finite element approaches, our technique provides substantial computational speedup for comparable accuracy, as shown in Tables 1 and 2 for a waveguide example. These approaches will also provide a more consistent simulation environment for EM and circuit simulations .

Optimization-driven electromagnetic design has been advanced. EM coarse (EMC) model, in the absence of circuit-theoretic models, permits rapid exploration of different starting points, solution robustness, local minima, parameter sensitivities, and other design characteristics within a practical time frame [3,4]. Figure 1 shows an example of the solution of yield optimization based on Space Mapping technique for direct EM optimization. It demonstrates that space mapping optimization results in superior solution compared to a pure coarse model approach. A new aggressive Space Mapping strategy for electromagnetic optimization exploits every available EM analysis using the Broyden update, instead of performing upfront EM analyses around the starting point [5]. It dramatically speeds up the design optimization process by reducing the number of CPU intensive EM simulations. Device parameter extraction, statistical modelling and yield-driven design have been carried out within a mixed-domain, multi-simulator environment. The experiments included statistical modelling of a FET model, simulated by SPICE, combining frequency and time-domain specifications, and yield optimization where the active device SPICE simulations are combined with EM simulations of passive structures in a seamless and automated fashion.

A new fast multidimensional macro-modeling method for interconnects has been developed based on neural networks[6]. The model can be used for either device level or circuit level modeling. To predict delays with our models is hundreds of times faster than original simulators [7]. The use of this model facilitates the optimization level. Preliminary work incorporating neural network models into circuit optimization has also been pioneered. Figures 2 and 3 illustrates the structure of neural network/circuit simulation, and accuracy of the model for a 7 transmission line example.

References

[1]M. Li, Q.J. Zhang and M.S. Nakhla, "Solution of EM fields by asymptotic waveform techniques," *URSI Int. Symp. Signals, Systems and Electronics*, (San Francisco, CA), pp. 393-396, 1995.

[2]M.A. Kolbehdari, M.S. Nakhla and Q.J. Zhang, "Solution of EM problems using the finite element and complex frequency hopping techniques," *European Microwave Conf.* (Bologna, Italy), pp. 1079-1081, 1995.

[3] J.W. Bandler, R.M. Biernacki, S.H. Chen, D.G. Swanson, Jr., and S. Ye, "Microstrip filter design using direct EM field simulation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1353-1359, 1994.

[4] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2536-2544, 1994.

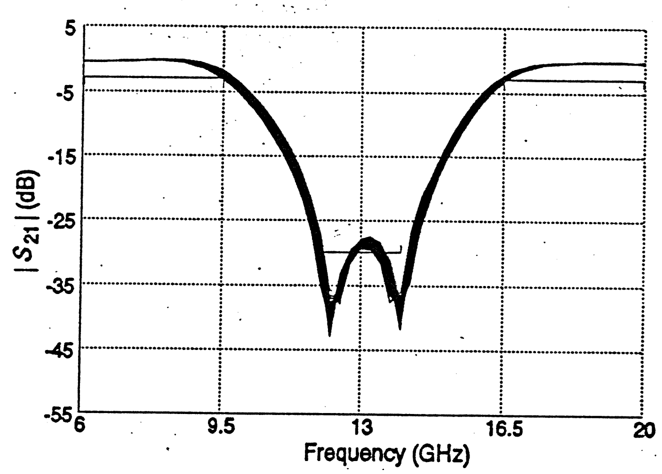
[5] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2874-2882, 1995.

[6] H. Zaabab, Q.J. Zhang and M.S. Nakhla, "A neural network modeling approach to circuit optimization and statistical design," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1349-1358, 1995.

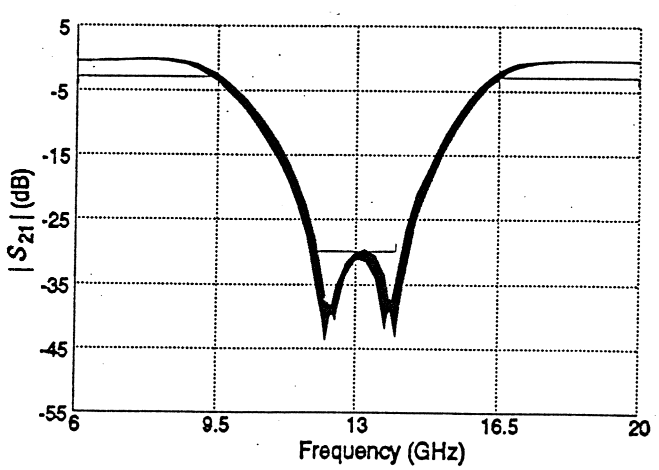
[7]A. Veluswami, Q.J. Zhang and M.S. Nakhla, "A neural network model for propagation delays in systems with high-speed VLSI interconnect networks," *IEEE Custom Integrated Circuits Conference*, (Santa, Clara, CA), pp. 387-390, 1995.

Table 1. Comparison of Resonant Frequencies from FEM/CFH Solution and Analytical Solution for a Rectangular Waveguide Example.

Mode	FEM/CFH (GHz)	Analytical (GHz)
TM_{11}	.18102	.180152
TM_{21}	.25158	.249827
TM_{31}	.33749	.335178
TM_{13}	.46328	.460658
TM_{23}	.49702	.492102



(a)



(b)

Figure 1. S parameter Monte Carlo sweep for a double folded stub filter after (a) coarse model and (b) space mapping yield optimization; both simulated using the fine model.

Table 2. CPU Comparison between FEM/CFH Technique and Conventional FEM for the Rectangular Waveguide Example

Matrix Size	FEM/ CFH	FEM	Speedup Ratio
25 x 25	0.3sec	5.8sec	19
289 x 289	18.66sec	753sec	41
1431 x 1431	8.3min	10.1 hr	72

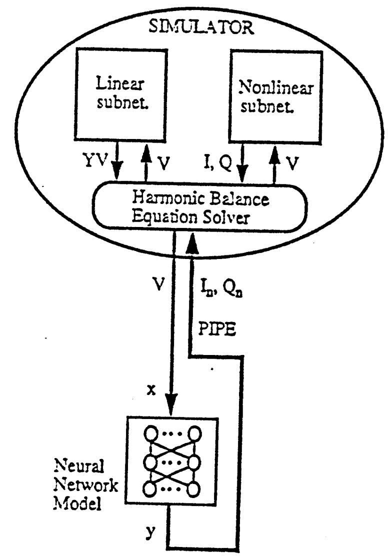


Figure 2. Connection of neural network models and harmonic balance simulator within OSA90/HOPE.

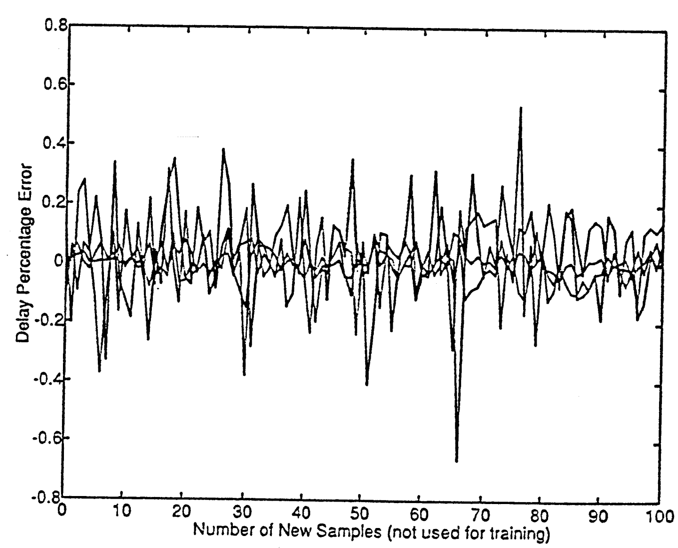


Figure 3. Percentage errors of signal propagation delay in a 7 transmission line network estimated by neural network model.

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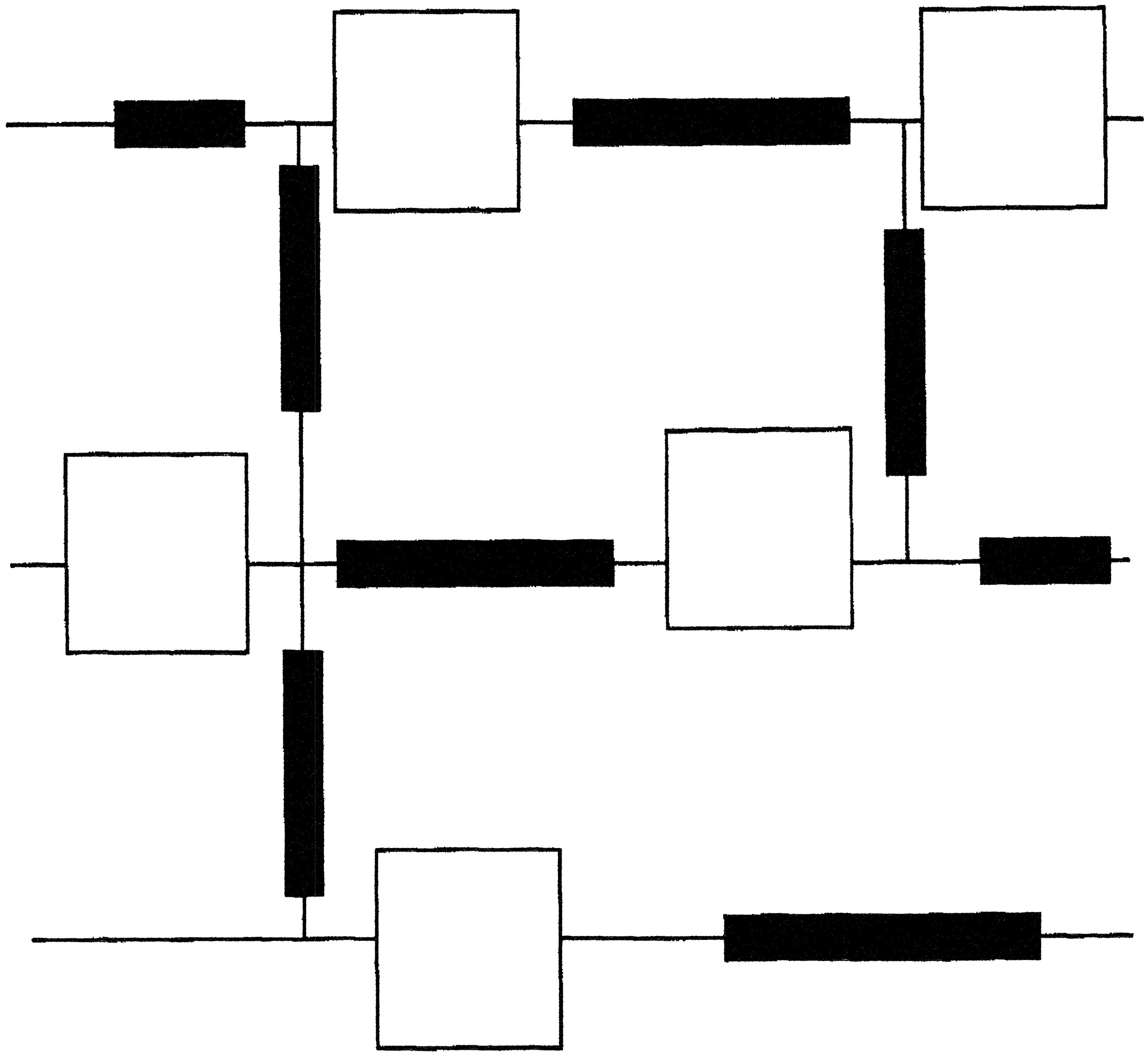
THE PROBLEM



EM Analysis by Complex Frequency Hopping

- Complex Frequency Hopping (CFH) and Asymptotic Waveform Evaluation (AWE) are recent techniques for solving large linear circuits

- EM equations are formulated into a set of ordinary differential equations by spatial discretization

- the resulting set of differential equations are solved by CFH

- the method is stable and computationally efficient

WAVE EQUATIONS

$$\nabla \times \nabla \times \begin{bmatrix} \mathbf{E} \\ \mathbf{H} \end{bmatrix} - \mu\epsilon \frac{\partial^2}{\partial t^2} \begin{bmatrix} \mathbf{E} \\ \mathbf{H} \end{bmatrix} = 0$$

$$\frac{\partial^2 \mathbf{E}_z(x, y, t)}{\partial t^2} = c^2 \left(\frac{\partial^2 \mathbf{E}_z(x, y, t)}{\partial x^2} + \frac{\partial^2 \mathbf{E}_z(x, y, t)}{\partial y^2} \right)$$

where c is the velocity of light

DISCRETIZATION

finite discretization in space

let $\mathbf{E}_z(i, j, t) = \mathbf{E}_z(x = i\Delta x, y = j\Delta y, t)$

let $\hat{\mathbf{E}}_z(i, j, s)$ be the Laplace transform of $\mathbf{E}_z(i, j, t)$

wave equation in the Laplace domain becomes

$$\frac{h^2}{c^2}s^2\hat{\mathbf{E}}_z(i, j, s) + 4\hat{\mathbf{E}}_z(i, j, s)$$
$$-\hat{\mathbf{E}}_z(i+1, j, s) - \hat{\mathbf{E}}_z(i-1, j, s)$$
$$-\hat{\mathbf{E}}_z(i, j+1, s) - \hat{\mathbf{E}}_z(i, j-1, s)$$
$$= \frac{h^2}{c^2}s\mathbf{E}_z(i, j, t)|_{t=0}$$

MATRIX FORM OF EQUATIONS

$$\left[s^2 \boldsymbol{A} + \boldsymbol{G}\right] \boldsymbol{X}(s) = \boldsymbol{B}(s)$$

where $\boldsymbol{A}$ and $\boldsymbol{G}$ are $N \times N$ real matrices containing constants (such as 1's, 0's, 4's, $\frac{h^2}{c^2}$), and

$$\boldsymbol{X}(s) \quad = \quad \begin{bmatrix} E(1,1,s) \\ E(1,2,s) \\ \vdots \\ E(n_x, n_y, s) \end{bmatrix}$$

COMPUTATION OF MOMENTS

when the expansion point is on the imaginary axis, $s_0 = jw_0$ moments can be solved from sets of real linear algebraic equations

for M_0:

$$\left[-w_0^2\boldsymbol{A} + \boldsymbol{G}\right]\boldsymbol{M}'_0 = w_0\hat{\boldsymbol{B}}$$

for M_1:

$$\left[-w_0^2\boldsymbol{A} + \boldsymbol{G}\right]\boldsymbol{M}'_1 = 2w_0\boldsymbol{A}\boldsymbol{M}'_0 + \hat{\boldsymbol{B}}$$

for $M_n, n = 2, 3, ..., 2q-1$:

$$\left[-w_0^2\boldsymbol{A} + \boldsymbol{G}\right]\boldsymbol{M}'_n = \boldsymbol{A}\left[(-1)^{n+1}2w_0\boldsymbol{M}'_{n-1} - \boldsymbol{M}'_{n-2}\right],$$

where $\boldsymbol{B}(s) = s\hat{\boldsymbol{B}}$; $\boldsymbol{M}_n = \boldsymbol{M}'_n$, if n is odd; and $\boldsymbol{M}_n = j\boldsymbol{M}'_n$, if n is even.

NETWORK TRANSFER FUNCTION

let scalar moments m_n represent the element of $\boldsymbol{M}_n$ corresponding to the grid location (i, j), i.e., the nth moments of $E(i, j, s)$

the moments m_n, $n = 0, 1, 2, ..., 2q - 1$ are matched to a lower order frequency domain transfer function

$$H(s) = \boldsymbol{X}_{[i,j]}(s) = \frac{a_0 + a_1 s + a_2 s^2 + ... + a_l s^l}{1 + b_1 s + b_2 s^s + ... + b_q s^q}$$

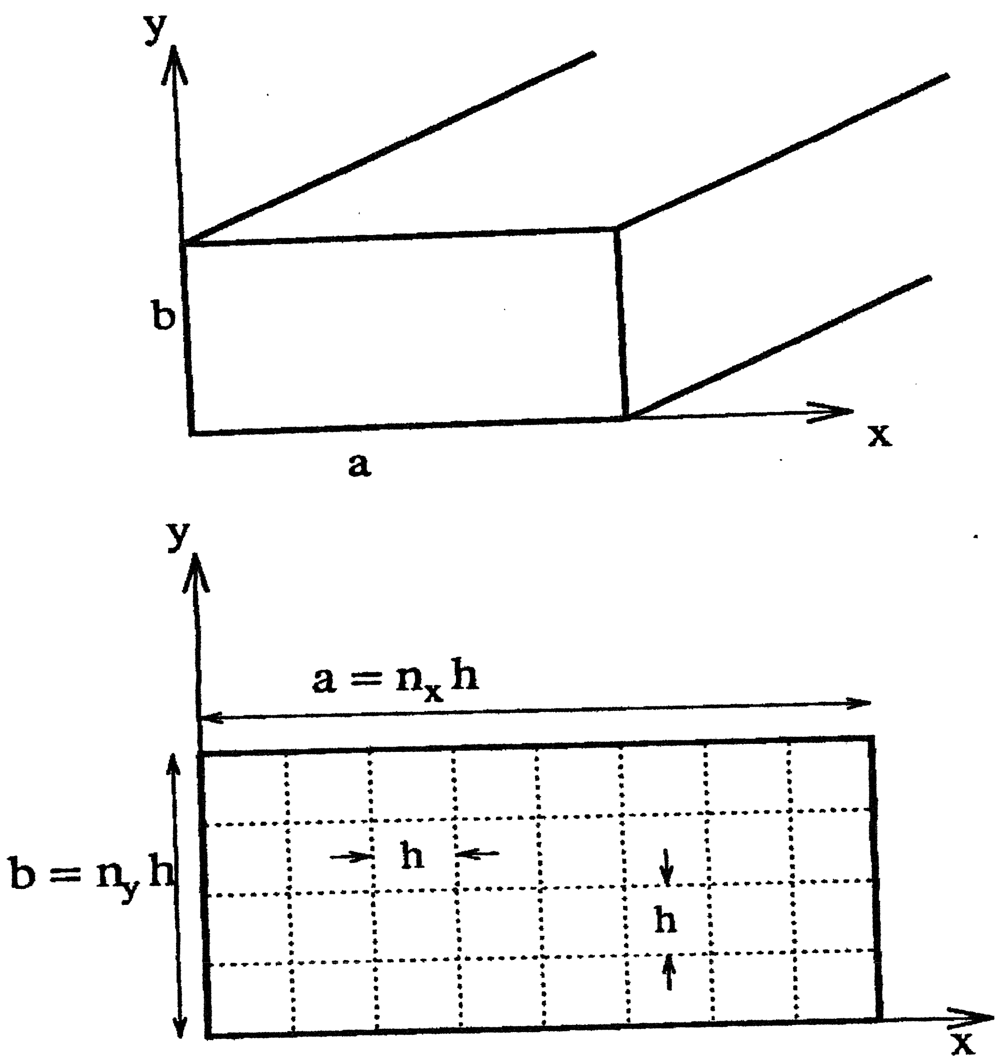
COMPUTATION OF TRANSFER FUNCTION COEFFICIENTS

For given l and q, the coefficients of the numerator and denominator are related to the moments by

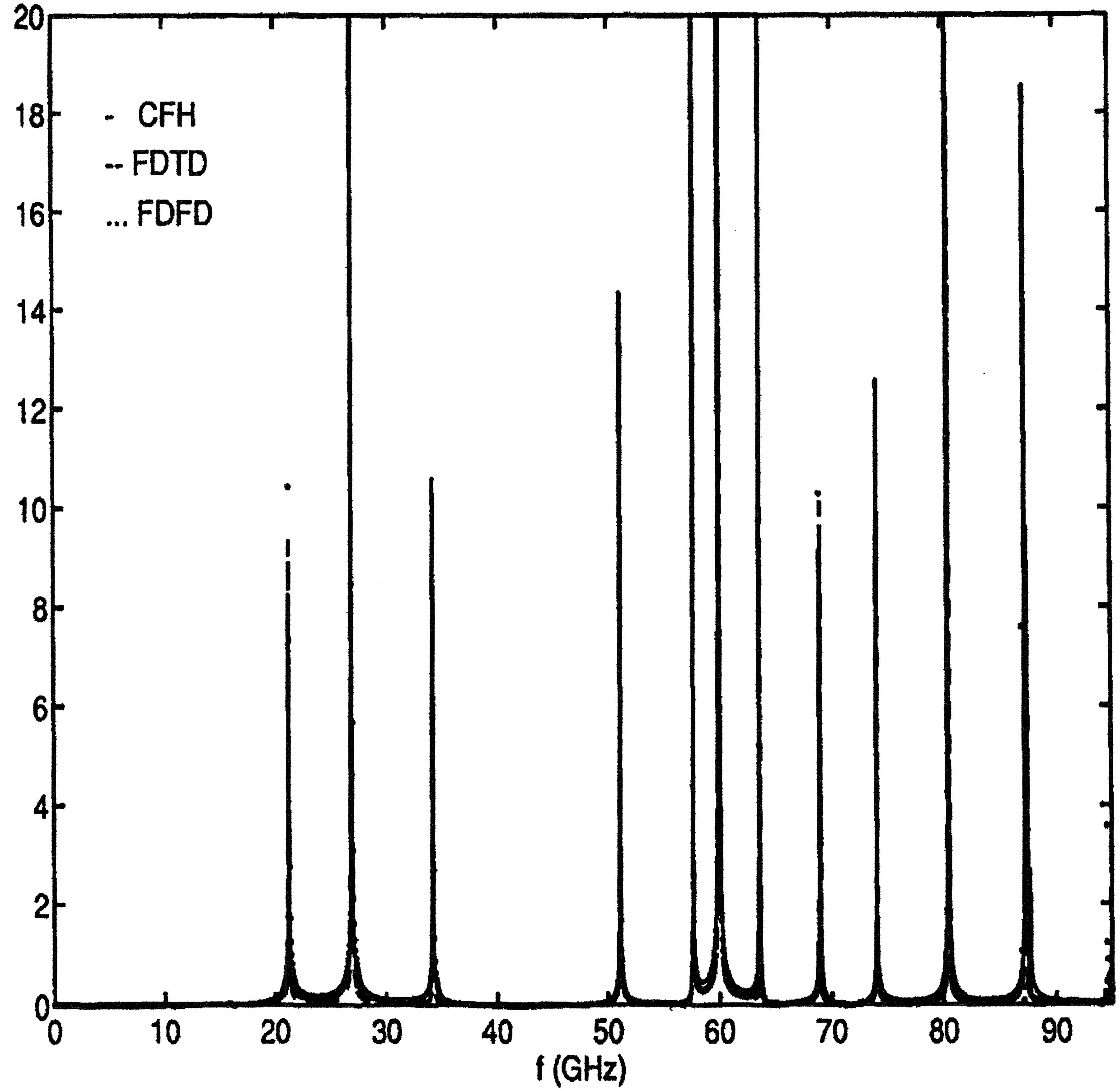
$$\begin{bmatrix} m_{l-q+1} & m_{l-q+2} & \cdots & m_l \\ m_{l-q+2} & m_{l-q+3} & \cdots & m_{l+1} \\ \vdots & \vdots & \vdots & \vdots \\ m_l & m_{l+1} & \cdots & m_{l+q-1} \end{bmatrix} \begin{bmatrix} b_q \\ b_{q-1} \\ \vdots \\ b_1 \end{bmatrix} = \begin{bmatrix} m_{l+1} \\ m_{l+2} \\ \vdots \\ m_{l+q} \end{bmatrix}$$

$$a_r = \sum_{j=0}^{r} m_{r-j} b_j \qquad r = 0, 1, \ldots, l \ .$$

where $m_j = 0$ if $j < 0$ and $l = q - 1$.



Rectangular Waveguide Example



Frequency Response

Cutoff Frequency

analytical fcut(GHz)	CFH	FDTD	FDFD
21.2281	21.2281	21.2217	21.2201
26.8526	26.8495	26.8494	26.8502
34.2310	34.2120	34.2231	34.2202
51.1253	51.1047	51.1094	51.1011
57.7478	57.7160	57.7080	57.7011
60.0444	59.9967	59.9887	59.9610
63.6859	63.6477	63.6477	63.6522
69.1162	69.0701	69.0542	68.9522
74.1487	74.1137	74.1153	73.9026
80.5579	80.5261	80.5340	80.4930
87.5289	87.4000	87.3506	87.2033
95.4118	95.3132	95.1715	95.0530
96.8188	96.7440	96.5816	96.1536
99.1185	98.9531	98.8973	98.8536