Analysis of Radiation from X-band Slotted-waveguide Antenna Arrays Using the Parallel DDA-FE-BI-MLFMA

Xu-Min Sun, Ming-Lin Yang, and Xin-Qing Sheng
Center for Electromagnetic Simulation, School of Information Science and Technology
Beijing Institute of Technology, Beijing 100081, China

Abstract— The hybrid finite element-boundary integral-multilevel fast multipole algorithm (FE-BI-MLFMA) approach is adopted for fast and accurate computation of radiation from large slotted-waveguide antenna arrays. A simplified model is presented by using a thin current probe as the excitation and a layer of perfectly matched layer (PML) as the termination for slotted-waveguide antenna. Since each slotted-waveguide antenna can be generally considered as a single sub-domain, the domain decomposition algorithm (DDA) is applied in the FE-BI-MLFMA to reduce computation resource and achieve high efficiency. This DDA-FE-BI-MLMFA is parallelized to further strength its capability. To validate the presented approach for computing radiation from slotted-waveguide antenna arrays, a series of numerical experiments are performed. Good agreement between our calculated results and results from commercial software CST validates accuracy of the presented approach. To show capability of the proposed DDA-FE-BI-MLFMA, a large X-band slotted-waveguide antenna array containing eighteen waveguides is designed and its radiation characteristics are studied.

1. INTRODUCTION

The slotted-waveguide antenna arrays are widely used in real-life communication and radar system applications, because of their small size, light weight, compact structure, high efficiency, and low side lobe characteristics. The computation of radiation from slotted-waveguide antenna arrays is of growing interest due to its importance in practical applications. Various methods have been developed to compute the radiation from slotted-waveguide antennas, such as the variational approach in terms of equivalent network, the method of moments (MoM), the finite-difference time-domain (FDTD) method, the finite element method (FEM) and the hybrid finite element-boundary integral (FE-BI) method [1–10].

However, due to large number of slots and the mutual coupling between the slots through the waveguides and the exterior space, previous researches mainly focus on analysis of radiation by a single slot in a waveguide, 1-D slotted-waveguide arrays or small 2-D slotted-waveguide arrays in a planar surface. In real application, fast and accurate analysis of radiation from large slotted-waveguide antenna arrays containing tens of slotted-waveguides and comprising thousands slot elements cut in the wall of the waveguides still faces great challenges.

In this paper, an efficient approach is presented for fast and accurate analysis of radiation from large slotted-waveguide antenna arrays by using the FE-BI-MLFMA [11–13]. To simplify the calculation, for each single slotted-waveguide, a short and infinitesimally thin current probe is used as the front-end excitation. A perfectly matched layer (PML) is used to terminate end of the waveguide port and absorb the reflected wave from the antenna to make each slotted-waveguide antenna work in the travelling wave mode. Since each slotted-waveguide antenna can be considered as a single sub-domain, the domain decomposition algorithm (DDA) is applied to reduce computation resource and achieve high efficiency. To improve the convergence, the sparse approximate inverse (SAI) technique is applied to construct an efficient preconditioner [14, 15]. To further improve the capability, it is parallelized on a memory distributed computer system [13, 14]. The comparison between DDA-FE-BI-MLFMA computed results and the commercial software CST results for the radiation patterns of a slotted-waveguide array validates the accuracy of the presented approach. To show capability of the presented approach, a large X-band slotted-waveguide antenna array containing eighteen waveguides with Taylor amplitude and inverse phase excitation distribution is designed and its radiation characteristics are computed and analyzed.

2. COMPUTATIONAL ALGORITHM

Consider the radiation problem of a single slotted-waveguide antenna whose surface is denoted as S. A short current probe oriented in the z-direction and located at $(x_f,\, y_f)$ can be modeled as:

$$\mathbf{J}_{inp} = \hat{z} I_0 \delta\left(x - x_f, y - y_f\right) e^{-jk\varphi} \tag{1}$$

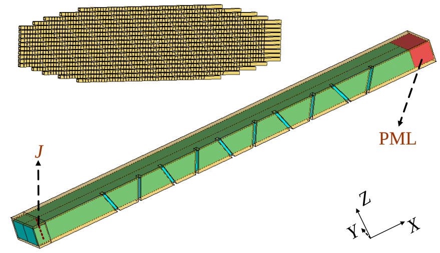

Figure 1: Simplified model for a slotted-waveguide antenna array.

where I_0 is the lumped current flowing into the antenna and φ is the phase. The location of the current is in the middle of the original waveguide excitation port. The front-end port of the waveguide is extended a small distance from the original feed location and terminated with an infinite thin PEC plate. At the end of the waveguide, it is filled with PML of thickness $0.3\lambda_g$, with λ_g being the waveguide wavelength. Then it is also terminated with infinite thin PEC plate.

According to the FE-BI-MLFMA presented in [11], the solution region is directly divided into the interior region and the exterior region by the surface S. The final FE-BI matrix equation system for a slotted-waveguide antenna array with N slotted waveguides can be written as:

$$\begin{bmatrix} \mathbf{K}^1 & 0 & 0 & \mathbf{B}^1\mathbf{T}_g^1 \\ 0 & \ddots & 0 & \vdots \\ 0 & 0 & \mathbf{K}^N & \mathbf{B}^N\mathbf{T}_g^N \\ \mathbf{P}^1\left(\mathbf{T}_g^1\right)^T & \dots & \mathbf{P}^N\left(\mathbf{T}_g^N\right)^T & \mathbf{Q} \end{bmatrix} \begin{bmatrix} E^1 \\ \vdots \\ E^N \\ \bar{H}_s \end{bmatrix} = \begin{bmatrix} b^1 \\ \vdots \\ b^N \\ 0 \end{bmatrix} \tag{2}$$

where $\bar{H}_s = Z_0 H_s$, with Z_0 being the free-space impedance. $\mathbf{P}$ and $\mathbf{Q}$ are the BI dense matrices, $\mathbf{K}$ and $\mathbf{B}$ are the sparse FEM matrices. $\mathbf{T}_g^i$ denotes the projection Boolean matrix between the global BI degrees of freedom (DOFs) and the FEM degrees of freedom (DOFs) of the ith slotted waveguide. E^i denotes the discretized unknowns of the electric fields for the ith waveguide, H_s denotes the discretized unknowns of the magnetic fields on the boundary of the whole antenna array.

In a slotted-waveguide antenna array, each slotted-waveguide antenna can be considered as a single sub-domain, and the domain decomposition algorithm (DDA) can be applied to the FE-BI-MLFMA to reduce the required computation resources and achieve high efficiency [12, 13]. After solving the sparse FEM matrices of each sub-domain, we can obtain:

$$E^i = \left(\mathbf{K}^i\right)^{-1}\left(b^i - \mathbf{B}^i\mathbf{T}_g^i\bar{H}_s\right) \tag{3}$$

Substituting Equation (3) into the BI equation, we can obtain the final equation system as:

$$\left[\tilde{\mathbf{P}} + \mathbf{Q}\right]\bar{H}_s = b \tag{4}$$

with

$$\tilde{\mathbf{P}} = -\sum_{i=1}^{N}\mathbf{P}^i\left(\mathbf{T}_g^i\right)^T\left(\mathbf{K}^i\right)^{-1}\mathbf{B}^i\mathbf{T}_g^i \tag{5}$$

$$b = -\sum_{i=1}^{N}\mathbf{P}^i\left(\mathbf{T}_g^i\right)^T\left(\mathbf{K}^i\right)^{-1}b^i \tag{6}$$

The equation system of (4) can be efficiently solved by using the iterative solvers such as the GMRES. The MLFMA is employed to speed up matrix-vector multiplications. This computational approach is also parallelized on a memory distributed computer system with an efficient preconditioner constructed by using the SAI technique [15].

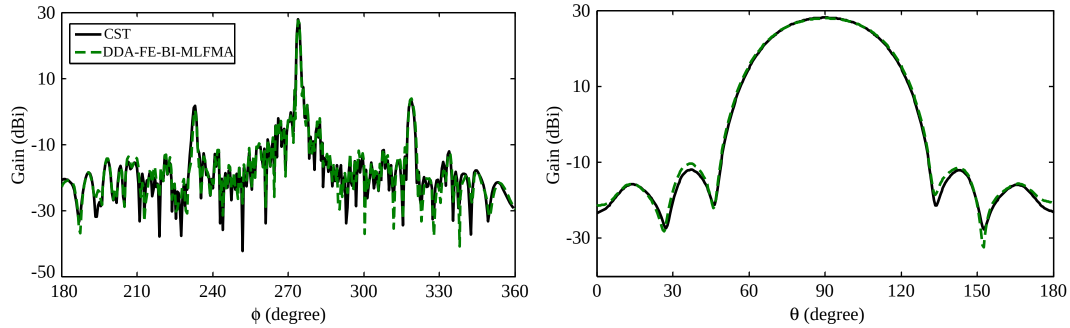

Figure 2: Radiation patterns for an antenna array containing two slotted-waveguides at 10 GHz. (a) *E*-plane. (b) *H*-plane.

Table 1: The radiation characteristics parameters of the slotted-waveguide antenna array.

Calculation method		DDA-FE-BI-MLFMA	CST
Gain (dBi)		27.9	28.1
3 dB beam width (°)	*E*-plane	1.0	1.0
	H-plane	33.1	34.4
Side lobe level (dB)	*E*-plane	−21.5	−21.4
	H-plane	−40.0	−39.4

3. NUMERICAL RESULTS

A series of numerical experiments are investigated in this section. All the computations are performed on the parallel computer platform *Liuhui*-II at the Center for Electromagnetic Simulation, Beijing Institute of Technology. It has 10 nodes, each node has 2 Intel X5650 2.66 GHz CPUs with 6 cores for each CPU, 96 GB memory.

As shown in Figure 1, a typical true 3D slotted-waveguide antenna array containing eighteen slotted waveguides is specially designed. For each slotted-waveguide antenna, we choose the BJ100 waveguide (22.86×10.16 mm), the main mode frequency of which ranges from 8.2 GHz to 12.5 GHz. We set the working frequency of the antenna as 10 GHz. The vertical spacing between every two neighbor waveguides is fixed as 5.2 mm. To achieve high gain and low side-lobe performance, the fed phase and inclination angle for each slot are strictly inversed to the adjacent ones, to the corresponding one in wall of the adjacent and the mirror symmetry waveguide.

We first validate the presented approach by comparing results with the CST results for the radiation patterns of the middle two slotted-waveguides. There are total 90 narrow-wall slot-radiating elements for each slotted-waveguide. The radiation characteristics parameters of the two slotted-waveguides antennas are listed in Table 1. Figure 2 shows the calculated radiation patterns in *E*-plane and *H*-plane respectively. Good agreement can be observed between the DDA-FE-BI-MLFMA and the CST results.

To demonstrate great capability of the presented approach for electrically large arrays, we compute radiation patterns of the whole large antenna array containing eighteen waveguides as shown in Figure 1. The radiation patterns for the array with equal-amplitude/Taylor-amplitude and inverse phase distribution feed in the *E*-plane and *H*-plane are shown in Figure 3. The computed radiation characteristics parameters are listed in Table 2. We can see from Figure 3, by using the Taylor-amplitude distribution feed, better side lobe can be achieved with wider main lobe and lower gain in the *H*-plane, but little influence on radiation patterns in the *E*-plane. Figure 4 shows the normalized orthogonal polarization radiation patterns for the large antenna array with Taylor-amplitude distribution feed in the *E*-plane and *H*-plane. We can see from these figures, suppression cross-polarization characteristics are obtained in *E*-plane (< -50.49 dB) and in *H*-plane (< -26.96 dB). In this calculation, the number of unknowns for the FEM part and the BI part is 5,306,784 and 2,291,742 respectively. It takes about 91 GB memory and 4 hours of CPU time with 16 MPI processes.

Table 2: The radiation characteristics parameters of the large slotted-waveguide antenna array.

Amplitude distribution		Taylor	Equal
Gain (dBi)		35.4	36.1
3 dB beam width (°)	E-plane	1.0	1.0
	H-plane	5.1	3.9
Side lobe level (dB)	E-plane	−18.7	−19.2
	H-plane	−32.5	−13.2

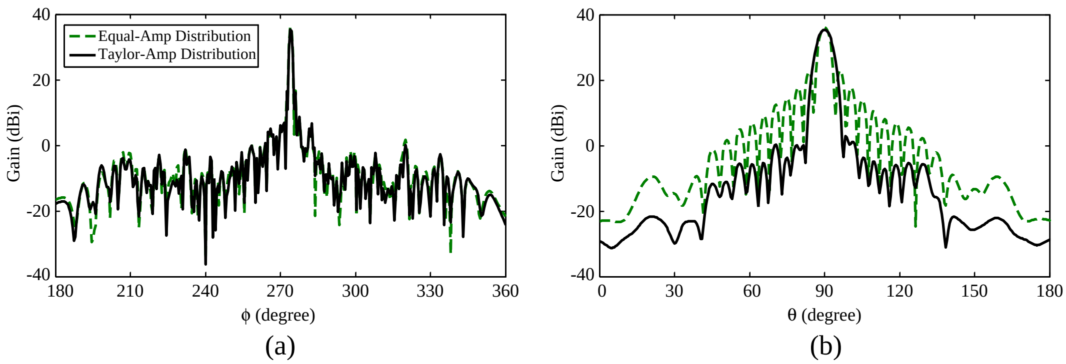

Figure 3: Radiation patterns for the large slotted-waveguide antenna array containing eighteen waveguides at 10 GHz. (a) E-plane. (b) H-plane.

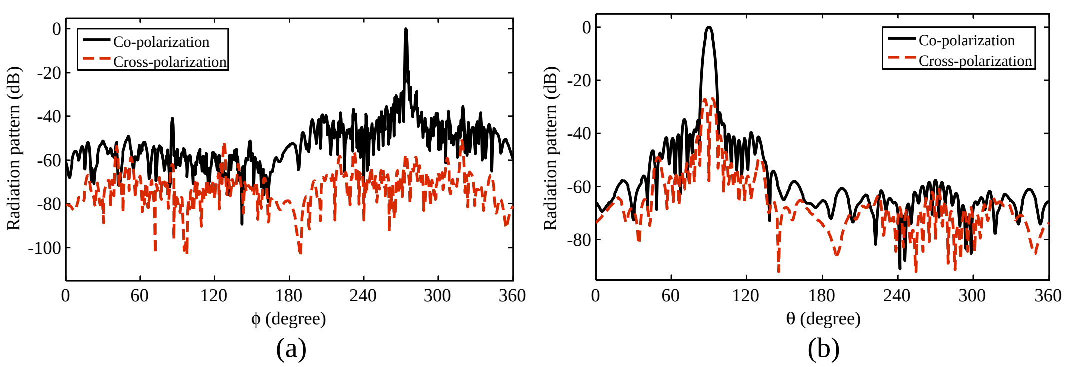

Figure 4: Normalized orthogonal polarization radiation patterns for the large slotted-waveguide antenna array at 10 GHz. (a) E-plane (b) H-plane.

4. CONCLUSION

An efficient computational approach using the FE-BI-MLFMA is presented for analysis of radiation from large slotted-waveguide antenna arrays. A simple but flexible and efficient model is presented to simplify the calculation. Comparisons between computed results and commercial software CST results validate the presented model for fast and accurate analysis of radiation from slotted-waveguide arrays. The radiation characteristics of a large carefully designed slotted-waveguide antenna arrays are computed to show the efficiency and capability of the presented approach.

ACKNOWLEDGMENT

This work is partially supported by the National Basic Research Program (973) under Grant No. 2012CB720702 and No. 61320602, the 111 Project of China under the grant B14010, and the NSFC under grant 61371002.

REFERENCES

1. Stevenson, A. F., "The theory of slots in rectangular waveguides," *J. Appl. Phys.*, Vol. 19, 24–38, Jan. 1948.

2. Oliner, A. A., "The impedance properties of narrow radiating slots in the broad face of rectangular waveguide," *IRE Trans. Antennas Propagat.*, Vol. 5, 4–20, Jan. 1957.
3. Jan, C. G., P. Hsu, and R. B. Wu, "Moment method analysis of sidewall inclined slots in rectangular waveguides," *IEEE Trans. Antennas Propagat.*, Vol. 39, 68–73, Jan. 1991.
4. Hirokawa, J. and P. S. Kildal, "Excitation of an untilted narrow-wall slot in a rectangular waveguide by using etched strips on a dielectric plate," *IEEE Trans. Antennas Propagat.*, Vol. 45, 1032–1037, Jun. 1997.
5. Prakash, V. V. S., S. Christopher, and N. Balakrishnan, "Method-of-moments analysis of the narrow-wall slot array in a rectangular waveguide," *IEE Proc., Microw. Antennas Propagat.*, Vol. 147, 242–246, Jun. 2000.
6. Krant, E. A., J. C. Olinier, and J. B. West, "FDTD solution of Maxwell's equations for an edge slot penetrating adjacent broadwalls of finite wall thickness waveguide," *IEEE Trans. Antennas Propagat.*, Vol. 42, 1646–1648, Dec. 1994.
7. Vouvakis, M. N., K. Z. Zhao, and J. F. Lee, "Finite-element analysis of infinite periodic structures with nonmatching triangulations," *IEEE Trans. Magn.*, Vol. 42, No. 4, 691–694, 2006.
8. Jin, J. M. and J. L. Volakis, "A hybrid finite element method for scattering and radiation by microstrip patch antennas and arrays residing in a cavity," *IEEE Trans. Antennas Propagat.*, Vol. 39, 1598–1604, Nov. 1991.
9. Stupfel, B., "A hybrid finite element and integral equation domain decomposition method for the solution of the 3-D scattering problem," *J. Comput. Phys.*, Vol. 172, 451–471, Sep. 2001.
10. Young, J. C., J. Hirokawa, and M. Ando, "Analysis of a rectangular waveguide, edge slot array with finite wall thickness," *IEEE Trans. Antennas Propagat.*, Vol. 55, 812–819, Mar. 2007.
11. Sheng, X. Q., J. M. Song, C. C. Lu, and W. C. Chew, "On the formulation of hybrid finite-element and boundary-integral method for 3D scattering," *IEEE Trans. Antennas Propagat.*, Vol. 46, 303–311, Mar. 1998.
12. Vouvakis, M. N., K. Zhao, S. M. Seo, and J. -F. Lee, "A domain decomposition approach for non-conformal couplings between finite and boundary elements for unbounded electromagnetic problems in R^3," *J. Comput. Phys.*, Vol. 225, No. 1, 975–994, Jul. 2007.
13. Yang, M. L., H. W. Gao, and X. Q. Sheng, "Parallel domain-decomposition-based algorithm of hybrid FE-BI-MLFMA method for 3-D scattering by large inhomogeneous objects," *IEEE Trans. Antennas Propagat.*, Vol. 50, No. 2, 4675–4684, Sep. 2013.
14. Pan, X. M. and X. Q. Sheng, "A sophisticated parallel MLFMA for scattering by extremely large targets," *IEEE Antennas Propagat. Mag.*, Vol. 50, 129–138, Jun. 2008.
15. Lee, J., J. Zhang, and C. C. Lu, "Sparse inverse preconditioning of multilevel fast multipole algorithm for hybrid integral equations in elecromagnetics," *IEEE Trans. Antennas Propagat.*, Vol. 52, 2277–2287, Sep. 2004.