Benchmarking Conformal BoR FDTD Algorithm for Efficient mm-Wave Design of Multiflare Antennas

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***Abstract*—This work is concerned with the assessment of accuracy and efficiency of FDTD algorithms for the design of millimetre-wave horn antennas. Specific interest is in smooth-walled multiflare horns, which at such frequencies appear as promising alternatives to corrugated horns, due to lower sensitivity to manufacturing tolerances and lower costs. Yet their modelling poses new challenges due to inclined or curved walls. We demonstrated that a conformal FDTD method in the Bodies-of-Revolution 2D formulation in cylindrical coordinates is specifically suitable for the task, retaining the geometrical flexibility of FDTD with the computational efficiency dedicated Method-of-Moment solvers.**

***Index Terms*—antennas, horns, electromagnetics, computational electromagnetics, MoM, FDTD, BoR.**

I. Introduction

Horn-type antennas have been studied in the technical literature for decades, and its theoretical analysis and design have received attention for many years, giving rise to a deep background in the topic [1]-[5]. As it happens with any electromagnetic device [6], modelling is a key aspect of advanced antenna design. Even when the full-wave modelling for horns has been already addressed by many techniques, its study allows to have a better understanding of electromagnetic problems, which is a must in antenna engineering research. Moreover, advances in this modelling also opens the possibility of making more sophisticated designs, especially when modern antenna feeders are now designed taking into account all the higher-order mode effects between multiplexers, polarizers and ortho-modes together with the horn [7]-[9]. Moreover, the availability of a theoretical framework to model the radiation produced by an aperture antenna also opens the possibility of using optimization strategies to adjust the field distribution at the aperture in order to synthesize a radiation pattern with certain desired features [10]. Thus, all these scenarios require analysis tools extremely fast, and assessment of different techniques for horns is the goal of this paper.

II. Theory

Horn antennas are, basically, a waveguide whose transverse section increases progressively along its longitudinal axis. Therefore, horns share the main advantages that waveguides present, like low power losses, great mechanical robustness and high-power handling capabilities. Additionally, they can achieve high directivity values and also present low return loss levels. All these characteristics make them especially suited for critical applications where high performance is required [10],[12],[13].

A. *Mode-matching modelling*

A horn-type antenna can be viewed as a two-port waveguide device, where one of the ports corresponds to the radiating aperture. The mode-matching technique [10],[11],[2] is a well-known approach to analyze a horn antenna, which is done in three steps. In the first step, the horn profile [14] is discretized in a high-number of very small two-port waveguide sections cascaded along the longitudinal axis. These partial problems are characterized by their Generalized Scattering Matrix (GSM) [6], which are cascaded retaining the high-order mode interaction between sections. Second, the electromagnetic field at the aperture is obtained after solving the resultant problem of the GSM cascading. Finally, in the third step, that computed field is inserted into the radiation integrals to obtain the far field as [1],[2] with the field equivalence principle. This approach is known to be very accurate for high directivity horns [15]. However, the main drawback of this modelling does not consider the radiation to the lateral/back of the antenna. Thus, as long as the antenna has very high directivity, this is not a problem. However, it still may have a significant impact on some parameters such as side lobes or return loss, as demonstrated in [16].

B. *Conformal FDTD modelling*

The theory and applications of the FDTD method are broadly described in [17]. The most popular variant is 3D FDTD in Cartesian coordinates, implemented in several commercial software packages including [18] tested in this work. As discussed in [18], for structures preserving the axial symmetry of boundary conditions another FDTD variant, namely the Bodies-of-Revolution (BoR) FDTD is advantageous. It incorporates the angular field dependence (angular mode number) analytically and restricts the spatial discretisation to half of the longitudinal long-section of the antenna. Specific co- and post-processing algorithms required by antenna problems have been proposed in [19] and an example implementation including locally conformal boudary models is available in [20]. It has been broadly used for corrugated horns, e.g. [21], and will be tested for the multiflare horn herein.

III. Benchmarking Example

Our benchmark example is based on [20]. In order to start the simulation for each method, the dimensions of the antenna design Fig.1 are required, which are listed in Table 1. The system is excited with a source of matching frequency equal 700 GHz that propagates electromagnetic waves with a circular TE11 mode. For the created source at the operating frequency of this antenna, the effective permittivity was calculated equal to 0.617803.

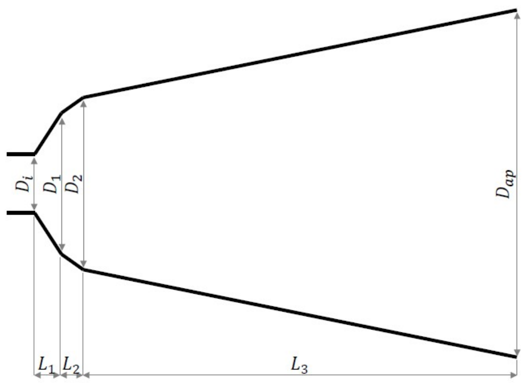

Fig. 1. Multiflare horn antenna after [22].

Tab. 1. Dimensions of the modeled antenna

	Diameters [mm]				***Lengths [mm]***		
Symbol	D_i	D_1	D_2	D_{ap}	L_1	L_2	L_3
Value	0.406	0.976	1.19	2.4	0.487	0.398	7.886

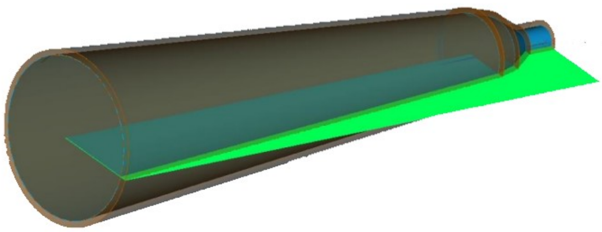

Fig. 2. 3D view of the considered multiflare antenna in NanoBat FreeCAD Modeller [23], which automatically generates 2D BoR mesh.

For axial symmetry of boundary conditions, also named Bodies of Revolution (BOR), which mesh is shown at Fig.2. This makes it's possible to drastically reduce the cost of memory and computing power needed to obtain convergent results of scatter matrix parameters. As a first step, tests were conducted to minimize simulation times to the required accuracy. The following Fig.3 shows two possibilities of conformal meshing used in FDTD calculations. A resolution of up to λ/30 meshes in all media was provided, while avoiding unnecessarily small cells.

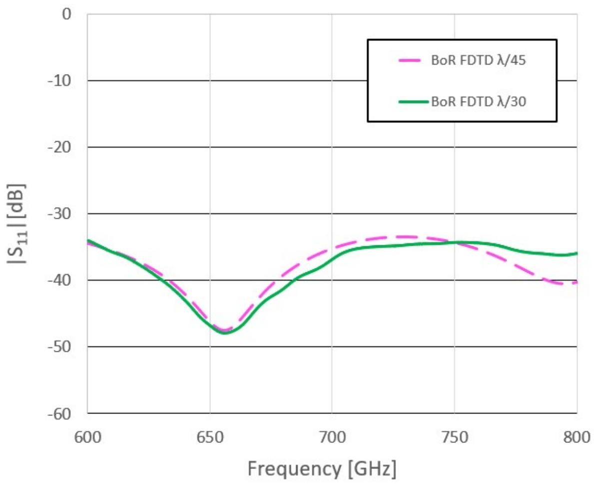

Fig. 3. Return loss.calculated by BoR FDTD at meshing of λ/30 (CPU time 3 seconds) and λ/45 (10 seconds).

This required the use of 31 MB of RAM memory with a created number of 327600 meshes with boundaries and get convergence values after 3 seconds. Increasing the resolution to λ/45 resulted in almost double the required resources. The accuracy of the calculation for this antenna at this resolution becomes comparable to the Mode-Matching method[14] and takes only 10 seconds.

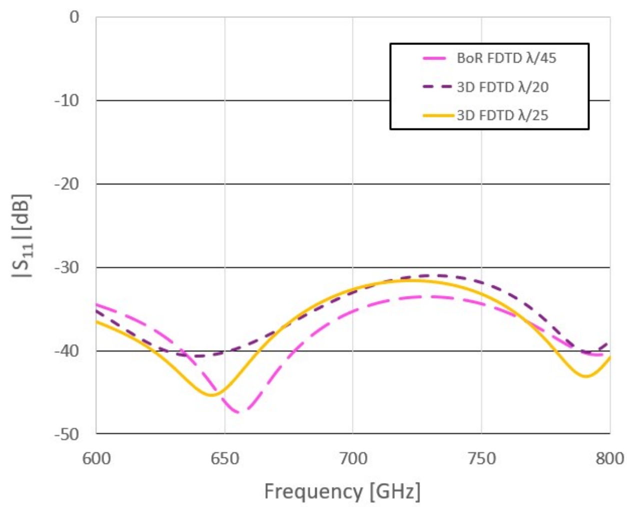

Fig. 4. Return loss calculated by 3D FDTD of meshing λ/20 (CPU 02:07:45) and λ/25 (2:48:17) compared with BoR FDTD of λ/45 (10 seconds).

However, when considering 3D FDTD calculations from tens of MB of RAM, as much as 4 GB should be allocated if λ /20 resolution is set, which is equivalent to 50789508 meshes. Increasing the resolution to λ/25 results in an increase in the order of an additional 4 GB of memory. However, it can be seen that as the resolution increases, the results of the S_{11} scattering matrix approach the BoR FDTD solution which is shown above on Fig.3. The increased amount of resources is associated with an increase in calculation time to 02:07:45 hours for λ/20 and 2:48:17 hours for λ/25. With higher resolution Both 3D FDTD and BoR FDTD methods were performed on a standard computer with parameters: i7-8700, 16 GB RAM and AMD Radeon Pro WX 3100. A change of computer workstation was required to get results for 3D FDTD with the λ/45 resolution. This was needed because the 3D mesh uses a huge amount of RAM equal to 45.856 GB. Calculation time tooks 11:59:41 hours. For the Mode-Matching method, 140 mods are considered for this type of antennas, where the number of modes at each discontinuity is assigned in terms of the surface ratio between such discontinuity and the aperture. With this method, the calculations were completed in 686.1 seconds on the computer i7-4790 CPU and 31.8 GB RAM. All methods were compared to the commercial CST [24] solution on figure below.

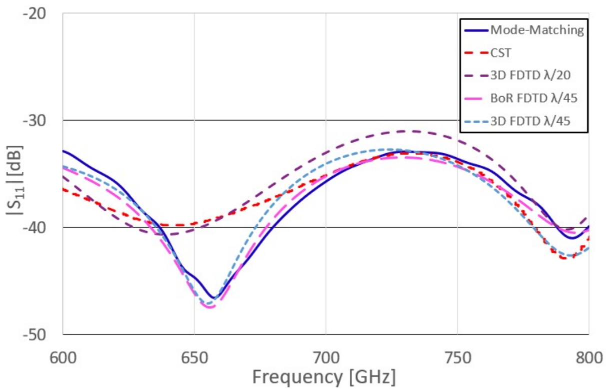

Fig. 5. Return loss calculated using different methods: Mode-Matching, 3D FDTD (CST[24] and in-house test code) and BoR FDTD [21] with conformal mesh generated by NanoBat Modeller [23].

IV. Conclusions and Ongoing Work

We have demonstrated that a conformal BoR FDTD algorithm combines the speed of dedicated mode-matching algorithms for horn antennas with the generality and geometrical flexibility of popular 3D FDTD solvers. This is because the BoR approach uses, in fact, the modal expansion in one (angular) space dimension, reducing the discretisation to 2D and thereby reducing memory and computing time by over 2-3 orders of magnitude, and making even large and complex structures tractable on a laptop or desk-top computer. The locally conformal approach additionally contributes to the accurate modelling of curved boundaries of multiflare antennas, while the time-domain approach makes simulation time practically independent of the number of calculated frequency points.

Our current work is concerned with running BoR FDTD within advanced optimisation regimes, such those of [19] and also based on artificial intelligence [25], of which results will be presented at the Conference.

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