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A new FDTD model of microwave susceptors on curved surfaces

Adam Raniszewski, Mateusz Krysicki,
Andrzej Wieckowski
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska 15/19, 00-665 Warsaw, Poland
e-mail: ap.raniszewski@gmail.com

Malgorzata Celuch
QWED Sp. z o. o.
Krzywickiego 12 lok. 1, 02-078 Warsaw, Poland
e-mail: mceluch@qwed.eu

Vadim V. Yakovlev
Worcester Polytechnic Institute
100 Institute Rd., Worcester, MA 01609, US
vadim@wpi.edu

Abstract— **Susceptors are thin lossy metal layers used to control local dissipation of power during microwave heating processes. While they may have a dominant effect on final temperature patterns, their electromagnetic modeling has been a long recognized challenge, due to small transverse dimensions, microwave semi-transparency, and complicated shapes. This work addresses effective representation of susceptors deposited upon or buried within microwaveable food packages of non-Cartesian geometries. It focuses on packages shaped as cylinders or truncated cones, which are non-trivial to be described on a Cartesian mesh, but more easy to define in a cylindrical system. Borrowing from previous experience with soft and hard antenna surfaces, an idea of simplifying the susceptor structure is proposed. Two specific models are implemented in the FDTD environment and validated. Computational examples prove a significant reduction in RAM and CPU requirements, within a permissible accuracy margin. Conclusions apply to potential use of the new models for microwave heating simulations, but also emphasis synergy effects between various microwave technologies.**

I. INTRODUCTION

The finite-difference time-domain (FDTD) method has become a "must-to-have" tool for most microwave engineers, as virtual prototyping allows their companies to save a lot on traditional cut-and-try designs. Yet there remains one recognized problem limiting FDTD application to various scenios of practical importance, namely, representation of so-called sub-cell features [1]. Since FDTD is based on space meshing (typically cuboidal in the Cartesian space), approximating multiple media within one cell, curved metal boundaries, or field singularitities at metal edges are challenging tasks. Many software packages ignore such challenges and resort to the classical stair-case approximation [1]. More advanced approaches require introducing inhomogeneous cells and their effective parameters [2][3][4][5], additional equations for calculating E-field componenents perpendicular to metal surfaces [2][3], or even coupling of equations that serve to update several field nodes [5]. Those additional feature improve the accuracy to computer resources ratio, at the expense of more complicated programming. Not only the essential FDTD code has to be refined, but also a proper geometry definition in 3D CAD environment so that they can be mapped onto the modified conformal FDTD onto the modified conformal FDTD mesh.

As a previous demonstration of the problem, one may quote soft and hard surfaces in antenna design [7]. They are anisotropic boundary conditions that behave like metal (PEC) in one or two directions and like dielectric in the other two or one direction. While being natural boundary conditions in acoustics, soft and hard surfaces as such do not physically exists in electromagnetic. They are artificially created as dielectric-filled metal corrugations [7]. Hence their direct FDTD implementation is feasible [8], but requires extra computer resources due to small corrugation dimensions to be discredited. A way around has been implemented in QuickWave (QW-3D and QW-V2D) software modeling soft and hard surfaces as wire grids [9].

More recently, a similar problem has struck manufacturers of industrial microwave power installations or microwaveable food packages. Here, one often deals with susceptors, which are metal layers buried within a dielectric for local control of dissipated power. The metal is high-conductivity but thin, and therefore semi-transparent. This excludes direct application of earlier FDTD models for lossy metal boundaries such as in [1]. An solution based on replacing the thin metal by a thicker lower-conductivity dielectric has been successfully developed [10]. It has been shown accurate and effective for plain (spatially continuous) susceptors parallel to one of the coordinate planes. Patterned but still flat susceptors have been considered in [12].

In this work, we move to more demanding cases, when the susceptor covers a surface of a non-Cartesian food package or vessel. This includes cylindrical or conical cups filled with soup or desserts, or microwave popcorn whose paper bag uncontrollably expands under temperature changes/

We shall propose two methods of defining such complex geometries within the graphical interface and converting them

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into effective and previously validated FDTD sub-cell models. Both approaches borrow from the previous work on anisotropic boundary conditions for antenna design [7][8] and essentially convert the susceptor into a wire grid conformal with the pre-defined FDTD mesh. An important feature is, that any *a posteriori* changes of meshing cause both models to automatically adapt to the new mesh, without any further user interaction.

We shall compare the two new models against each other to check their consistency. Then, we shall also demonstrate their accuracy, by comparison with a direct FDTD approach to thin metal layers. The latter approach requires much finer meshing to properly capture the thickness and shape of the susceptor. Hence, our new models will also be shown noteworthy for computational effectiveness.

II. NEW CONCEPT OF SUSCEPTOR MODELS

Any engineer's dream is to achieve accurate results for any structure and as fast as possible. In any programme that uses the FDTD method, such as [9], it is theoretically possible to approximate any shape, but at the expense of more computing power. Every programme has certain permissible cell types. Due to mesh generating properties, cells like in Fig.1a may be difficult to capture. If we cannot manipulate the object placement, can we try and adjust the mesh? A cell like in Fig.1b is a standard for any FDTD code. However, since we now increase the number of cells three times, we need 27 times more of RAM and 81 times more in computing time. The third approach, used in [9] and by us herein, is shown in Fig.3c. It is a compromise between accuracy and requirements for memory and time, but requires conforming an FDTD mesh to the edge of the structure, and in practical cases, this has to be done by the software automatically.

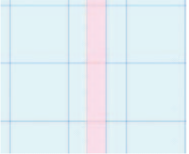

Fig.1. Example of approximation(1)

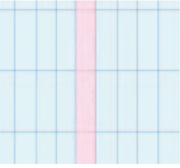

Fig.2. Example of approximation(2)

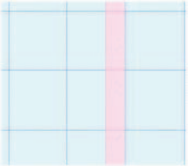

Fig.3. Example of approximation(3)

It should be noted that by using the third method we can implement all possible geometrical figures, even those naturally described in non-Cartesian systems. A simple illustration is a ring. Income CAD packages, analytical approximations of many typical figures are implemented. Yet in a majority of FDTD codes, we approximate the circle by a polygon. We first set a pre-defined number of points along the circle, and then connect them with straight lines. In classical FDTD, based on a stair-case mesh, all those lines must coincide with the mesh lines (Fig.4). In more advanced approaches, such as [9], the lines may be oblique.

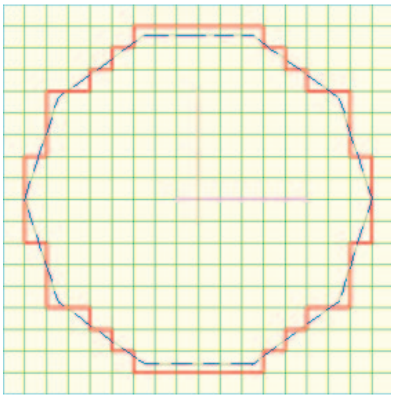

Fig.4. A circle drawn traditional and its polygonal approximation in a stair-case FDTD.

A more interesting example is a ring of small width. Traditionally, we decompose it into two circles. However, the width is too small, we end up with cells like in Fig.1a. We prevent that by the polygon approach described above and generate a figure as in Fig.5b.

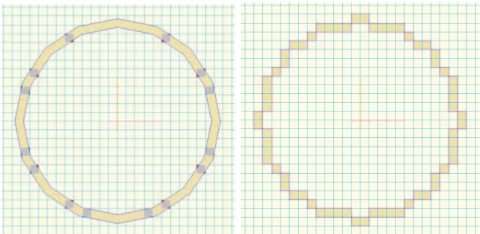

Fig.5.Ring approximation by traditional method and our method.

In real-life electromagnetic simulations we are mostly interested in three-dimensional objects. Consider a tube structure with thin walls. Following the methodology leading to Fig.5b, we only need to specify the height to have a ready model.

The most difficult example will be a truncated cone, such as a package of yoghurt (Fig.6). We now need many rings connected by side-lines that reflect the slope of the sidewall. Our idea is to divide the figure into thin slices, estimate each by a ring, and connect the rings appropriately (Fig.6). Typical FDTD will approximates the side-walls in a stair-case manner (Fig.6c). Our target is to come as close to Fig.6b as possible.

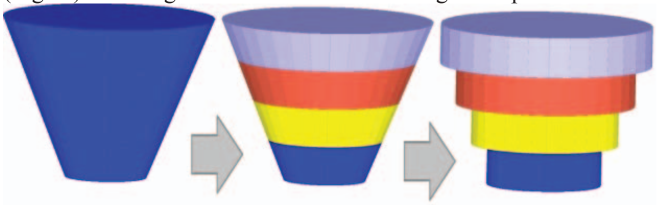

Fig.6. A simple approximation scheme for a truncated cone.

Each new element located on the previous is responsible for the widening or narrowing of the body, and the use of adequate amount layers improves the linearity (or curvature) of the side walls. To ensure integrity and continuity of the structure each two successive elements should fit together, i.e., the upper ring of the lower element should coincide with the lower ring of the upper one. Several layers can be merged into a single FDTD cell by the mesh generator [9]. Fig.7 demonstrates this for vertical section of a tube.

III. NEW MODELS

Using the principles and examples of approximation described above, can solve the problem for a structure with a thin susceptor shown in Fig 6. The approximated figure is composed of many smaller elements as in Fig.7. Two models will be proposed.

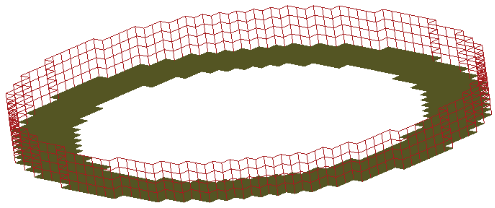

Fig.7. Approximated element.

In the first model, each ring is created as described above. The side walls are connected by wires lying on the FDTD grid lines (red lines in Fig 7). Wires lying on the ring are not shown, as they do not change the electromagnetic fields.

The other model relies on the use of cuboids to build the foil. The side walls are built as above. We then enforce a medium inside and create a thin coating using cuboids snapped to the mesh lines (Fig.8). Those cuboids must of a final thickness, according to the functions and limitations of a particular FDTD code. In [QW], the foil thickness must be at least 1% of the FDTD cell size. The final implementation of this type of a structure is shown in the following figures. Fig.9 shows fulfilling the task of connecting ring between the two elements in the *XY* plane. Fig.10 shows two elements imposed on themselves the *XZ* plane.

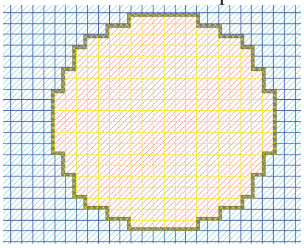

Fig.8.Approximated circle. Plane *XY*

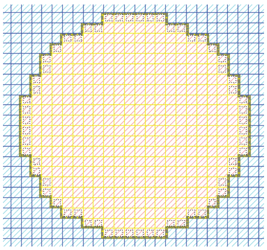

Fig.9.Approximated circle with metal ring. Plane *XY*

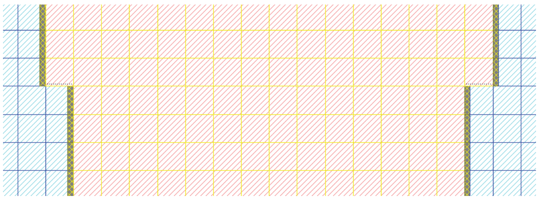

Fig.10. Two approximated elements imposed on themselves. Plane *XZ*

IV. SIMULATIONS AND COMPARISON OF MODELS

In order to compare the classical and our models, the reflection coefficient (S11) curve is calculated for a microwave oven. The "traditional" models is built with standard QW library objects [9]. Each object consists of a metal bottom, metal foil-covered walls, uncover top, and the whole vessel is filled with cheese (Fig.10). Our new models are built as explained above.

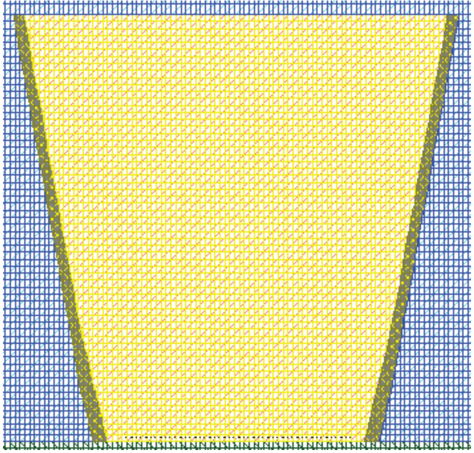

Fig.11. *XZ*- section of a conical vessel with cheese.

The results of Fig.12 confirm that:

- our two new models are mutually consistent and provide indistinguishable results for the oven discredited with 2 million cells,
- the results of our models agree very well with those of the model constructed with library elements; however, the latter one requires 4 million cells to achieve such a comparable accuracy.

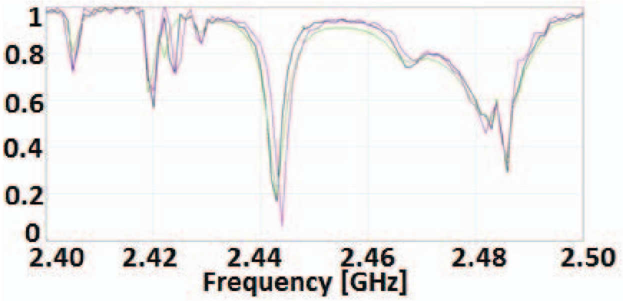

Fig.12. S11 curves for two new models(pink line – first model 2Mcellswith wires , blue line- second model 2Mcells) and model with standard QW elements technique 4 Mcells(red line).

V. CONCLUSIONS

Two new methods of approximating microwave susceptors on non-Cartesian surfaces have been proposed and validated. They are based on earlier work on anisotropic boundary conditions for antenna design and borrow from the "wire grid" concept, being an FDTD replica of the classical Faraday cage. Both models have been shown to greatly improve the accuracy to computer resources ratio of FDTD algorithms. Moreover, they now allow microwave engineers to approach many practical problems, previously unsolvable with the typically available computing resources.

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