Modeling of Microwave Ovens with Perforated Metal Walls

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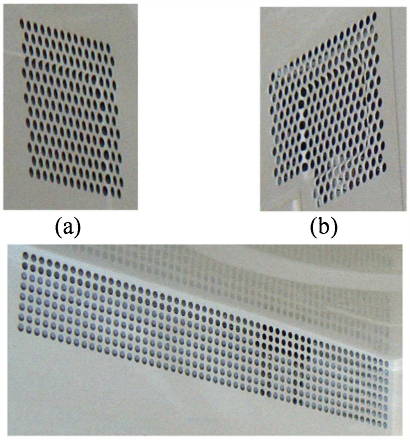
***Abstract* — An applied technique is proposed for resolution of issues arising in computational modeling of microwave ovens with perforated regions of metal walls. The technique relies on replacement of perforated segments by solid metal surfaces characterized by identical electric conductivity, which is calculated using *S*-parameters obtained by FDTD simulation of a perforated sheet in a waveguide. This approach is employed in FDTD modeling of a particular domestic microwave oven with two perforated wall segments with circular holes of diameter 3 and 3.6 mm. The resulting simulations show that perforated regions of metal walls make a negligible impact on the frequency characteristics of the reflection coefficient and so these regions can be safely replaced in the model by solid PEC sheets.**

***Index Terms* — Conductivity, impedance, microwave ovens, modeling.**

I. INTRODUCTION

While historically, technological progress in microwave power engineering has been associated with experiments, the increased use of computers and computational techniques has stimulated interest in modeling microwave heating. With the extensive literature on this subject (e.g., recently reviewed in [1]), the numerical algorithms and corresponding software have gradually become tools used in the design of components for microwave power applications. However, despite the demonstrated significant benefits such models could provide [1-2], accurate and adequate computer models of domestic microwave ovens – the most widespread microwave heating devices – have not yet been notably adopted by food engineers developing new microwaveable products. This can be explained by the particularly complex nature of the corresponding modeling work associated with multiphysics, sophisticated 3D geometry of both ovens and food, possible rotation of the turntable, etc. Modern state-of-the-art in electromagnetic (EM) and multiphysics modeling of loaded microwave ovens is given in [2] through consideration of the 750 W *MAX* Whirlpool oven.

One of the factors contributing to the complexity of models of microwave ovens is the presence of regions of oven walls which are, in fact, perforated to allow for for ventilation and lighting; typical examples are shown in Fig. 1. On the other side of these regions are closed cavities where the EM field, due to the typically large diameters of the holes, could leak. One may therefore expect that these wall regions could impact the frequency response of the oven's reflection coefficient $|S_{11}(f)|$ – one of the crucial characteristics responsible for energy efficiency of microwave ovens [1-2]. Direct representation of the perforated regions, along with introduction of the cavities hidden behind them, would require fine meshing and as a result, a remarkable increase of the size of the modeling project (and thus an increase of CPU time).


(a) (b)

(c)

Fig. 1. Perforated wall segments in two domestic microwave ovens – the 1.1 kW *Panasonic Inverter* (a), (b) and the 600 W *Sanyo Direct Access* (c) featuring equilateral triangle lattices (a), (b) and a square lattice (c) of circular holes.

Several approaches have been developed for modeling propagation through perforated shields (e.g., [3-4]), however, models of microwave ovens with perforated metal walls have never been reported in literature, so the goal of this paper is to present a simple practical step toward resolution of this issue. We suggest that in FDTD models of microwave ovens the perforated segments can be replaced by solid surfaces characterized by certain effective conductivity σ_{eff}, and we present a technique for determination of σ_{eff} for such sheets. Our approach may recall the technique of FDTD modeling of susceptors [5-6] whose thickness (usually less than 1 μm) cannot be accounted for with the use of conventional meshing. These thin susceptors are replaced in FDTD models by metallic layers of equivalent resistivity R_s with greater thickness (e.g., on the order of 1 mm), making the model more tractable. In place of pre-modeling measurement of R_s [5-6], in the present work, we determine the intrinsic impedance η of the perforated metal sheet with the help of an auxiliary FDTD model simulating the reflection and transmission coefficients of a waveguide structure containing the perforated sheet oriented perpendicularly to the direction of wave propagation. Once η is determined, we calculate the corresponding σ_{eff} to

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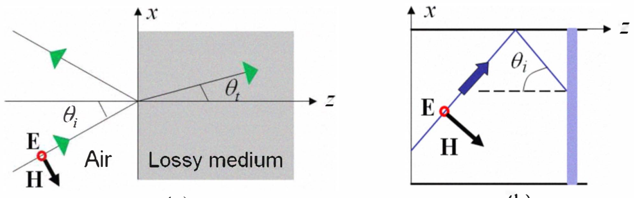

(a) (b)

Fig. 2. Plane wave of perpendicular polarization obliquely incident at the media interface (a) and an elementary TEM mode in a rectangular waveguide (b).

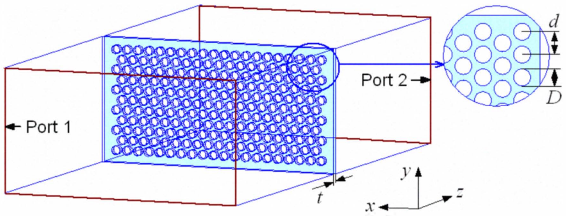

Fig. 3. The concept of an FDTD model simulating reflection and transmission through a perforated metal sheet.

be used in FDTD models as the characteristic input parameter of an equivalent solid surface representing the perforated wall segment.

A series of computational experiments performed with a model of the *Sanyo Direct Access* microwave oven shows that the frequency characteristics of $|S_{11}(f)|$ are not sensitive to a decrease in conductivity of the corresponding wall regions, even by up to 4-5 orders of magnitude. This indicates that, in practical microwave ovens, perforated wall segments may not make a considerable impact on performance, so in their models these regions could be safely represented by solid metal surfaces.

II. APPROACH

Electric conductivity σ of a lossy medium with permeability μ is known to be dependent on the intrinsic impedance η of the medium as follows:

$$\sigma = \left(\frac{1+j}{\eta}\right)^2 \frac{\omega\mu}{2}. \qquad (1)$$

We consider the reflection and transmission coefficients R and T for the obliquely incident plane wave hitting the interface between a lossy medium and free space [7]:

$$R = \frac{\eta\cos\theta_i - \eta_0\cos\theta_t}{\eta\cos\theta_i + \eta_0\cos\theta_t},\ T = \frac{2\eta\cos\theta_i}{\eta\cos\theta_i + \eta_0\cos\theta_t}, \qquad (2)$$

where θ_i and θ_t are the angles of the incident and transmitted waves, respectively (Fig. 3(a)). The angle θ_t in (2) can be expressed through θ_i with the use of Snell's law as follows:

$$\sin\theta_t = \frac{\eta}{\eta_0}\sin\theta_i, \qquad (3)$$

where η_0 is the impedance of free space. Combining (2) and (3), the intrinsic impedance of the lossy medium can be expressed for the field with perpendicular polarization as:

$$\eta = \eta_0 \frac{T\cos\theta_t}{T\cos\theta_i - 2R\cos\theta_i}. \qquad (4)$$

Applicability of this two-media (air-medium) model to the considered three-media (air-medium-air) scenario is assumed possible, as the typical thickness of the perforated wall segments of microwave ovens is much larger than the skin depth.

On the other hand, one can use an auxiliary FDTD model of a waveguide structure containing a perforated metal plate (Fig. 3) to compute the reflection and transmission coefficients of the system (S_{11} and S_{21} respectively). Assuming that they can be interpreted as R and T in (4), these modeled values can yield the effective electric conductivity σ_{eff} of a perforated metal sheet with D and d from (1).

Choosing geometry of the waveguide system with a single-mode regime, we consider decomposition of the dominant TE_{10} mode into the sum of two TEM waves propagating at angles φ with respect to the z-axis. Expressing the phase velocity in the direction of x (Fig. 2(b)) in terms of the waveguide's wide wall a and the wavelength λ, one can get that for the TE_{10} mode

$$\sin\theta_i = \frac{\lambda}{2a} \qquad (5)$$

Since orientation of the field components of the TEM modes (Fig. 4) is identical to that of the plane wave with perpendicular polarization (Fig. 2(a)), the angle of the incident wave θ_i in (4) can be considered equal to the angle θ_i associated with propagation of the TEM modes. Therefore, it follows from (3) and (5) that:

$$\cos\theta_i = \sqrt{1-\left(\frac{\lambda}{2a}\right)^2} \text{ and } \cos\theta_t = \sqrt{1-\left(\frac{\eta}{\eta_0}\right)^2\left(\frac{\lambda}{2a}\right)^2}. \qquad (6)$$

Substitution of (6) into (4) and rearrangement of terms leads to the formula:

$$\eta = \frac{\eta_0 S_{21}}{\sqrt{(S_{21}-2S_{11})^2 + S_{11}S_{21}\left(\frac{\lambda}{a}\right)^2 - (S_{11})^2\left(\frac{\lambda}{a}\right)^2}}, \qquad (7)$$

which explicitly expresses the intrinsic impedance of the perforated metal plate placed (as in Fig. 3) in a single-mode rectangular waveguide. The reflection and transmission coefficients (S_{11} and S_{21}) in (7) are determined from corresponding FDTD modeling.

Calculated by (7) and subsequently used in (1), η yields the effective conductivity σ_{eff} of the perforated metal plate that can be used as an input parameter of the corresponding wall segment in modeling the microwave oven.

For verification purposes, we employ an FDTD model of a rectangular waveguide of the same cross-section containing a solid plate with the effective electric conductivity σ_{eff} determined for the perforated wall. It is expected that the magnitude and phase of S_{11} in this model would be sufficiently close to the ones in (7).

III. COMPUTATIONAL RESOURCES

All FDTD simulations in this paper were performed using the full-wave 3D conformal FDTD simulator *QuickWave-3D* ver. 7.5 (*QW-3D*) [8].

Since both modeling projects in this paper are computationally expensive (the oven being electrically large and the waveguide system having multiple small holes in perforation), the computations were performed using an OMP version of the multithread implementation of the *QW-3D* simulator found particularly efficient in accelerating FDTD computations for the employed models. Simulations were run on a Dell T-4700 workstation (64-bit Windows XP) with 16 GB of RAM and two quad-core Intel Xeon 3.20 GHz processors. Computations were enforced by the Acceleware A30 card (NVIDIA Quadro FX 5600) implementing GPU technology in the form of integrated FDTD hardware accelerators.

IV. COMPUTATIONAL RESULTS

The procedure in Sec. II has been used to compute effective electric conductivity of the perforated plates. The modeled waveguide (86 x 43 mm) containing a PEC plate with an equilateral triangle lattice of circular holes is shown in Fig. 3. To ensure high accuracy of computation, the model was meshed with sufficiently small FDTD cells (chosen such that the number of cells is always not less than 20 cells per wavelength) and simulations were run until the energy in the system had dissipated to the level of 10^{-9}-10^{-10} [nJ].

Computational results were verified using a similar model in which the perforated sheet was replaced by a solid plate having the same computed σ_{eff} (Table I). The performed simulations have revealed the trends that *(a)* the smaller the thickness of the sheet, the smaller effective conductivity, and *(b)* the larger the hole diameter, the smaller the resulting σ_{eff}.

The developed technique has been applied to check for the effect of perforated walls on the frequency response of the reflection coefficient in the 600 W *Sanyo Direct Access*, a domestic microwave oven with two segments of perforated metal walls located in regions A and B as shown in Fig. 4. The considered device (with dimensions a = 290 mm, b = 300 mm, c = 185 mm) operates at 2.45 GHz and is excited by the waveguide ($g_a \times g_b$ = 86 × 43 mm) located at s = 35 mm and p = 152 mm from the cavity's edges. The oven contains a cylindrical 0.1 liter load (R = 25 mm, H = 51 mm) placed on the center of a turntable (a cylindrical disk of r = 136 mm and t = 5 mm) at a height l = 5 mm from the bottom.

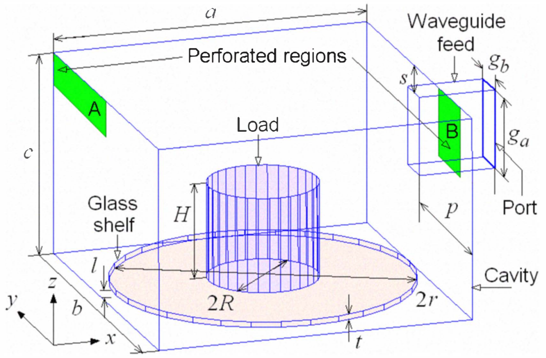

Fig. 4. Geometrical characterization of *Sanyo Direct Access* microwave oven segments A and B of perforation on the wall.

TABLE I.
VERIFICATION OF COMPUTED σ_{eff} *)

Waveguide model	D = 3.0 mm		D = 3.6 mm	
	$\lvert S_{11}\rvert$	$\sphericalangle S_{11}$	$\lvert S_{11}\rvert$	$\sphericalangle S_{11}$
Perforated sheet	0.9999	-94.57	0.9962	-95.31
Solid plate with σ_{eff}	0.9991	-94.26	0.9995	-94.24

*) 2.45 GHz, d = 4 mm, t = 1 mm.

TABLE II.
DIELECTRIC PROPERTIES OF THE LOAD (20 C, 2.45 GHz) [9]

Food product	**Dielectric constant ε'**	**Conductivity σ (S/m)**
Water	78.7	1.465
White bread	4.14	0.211
Corn oil	2.63	0.020

Simulation is performed for three food products (Table II) very different in their dielectric properties, and glass (ε' = 6.0, σ = 0) as the medium of the turntable. The oven possesses two perforated wall segments: A (220 × 35 mm) with D = 3.0 mm and d = 4.0 mm and B (60 × 80 mm) with D = 3.6 mm and d = 4.0 mm.

In the FDTD model, this system is discretized with a non-uniform mesh (the maximum cell sizes are 6 mm in air, 3.5 mm in glass, 4 mm in corn oil, 3.5 mm in white bread, and 1.2 mm in water) making approximately 365,000 to 1,072,000 cells (depending on the type of the load). FDTD simulation reaches steady state at about 120,000 (corn oil) to 230,000 (water) iterations, so a single computation takes from 22 min to 90 min.

Our simulations (Fig. 5) show that the characteristics before and after replacing PEC in segments A and B by solid segments with corresponding σ_{eff} of $1.2\cdot10^5$ S/m and $1.7\cdot10^5$ S/m, respectively, are indistinguishable. As seen from the curves in Fig. 8, a notable effect from perforation in segments A and B occurs only when σ_{eff} is decreased by 4-5 orders of

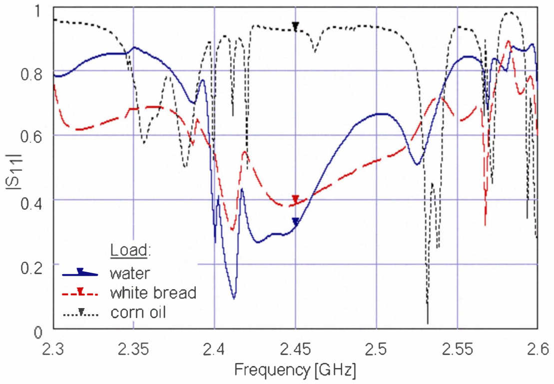

Fig. 5. Reflection coefficient in the microwave oven (Fig. 4) for the load represented by different food products; each curve represent two characteristics – segments A and B are PEC and solids with σ_{eff}.

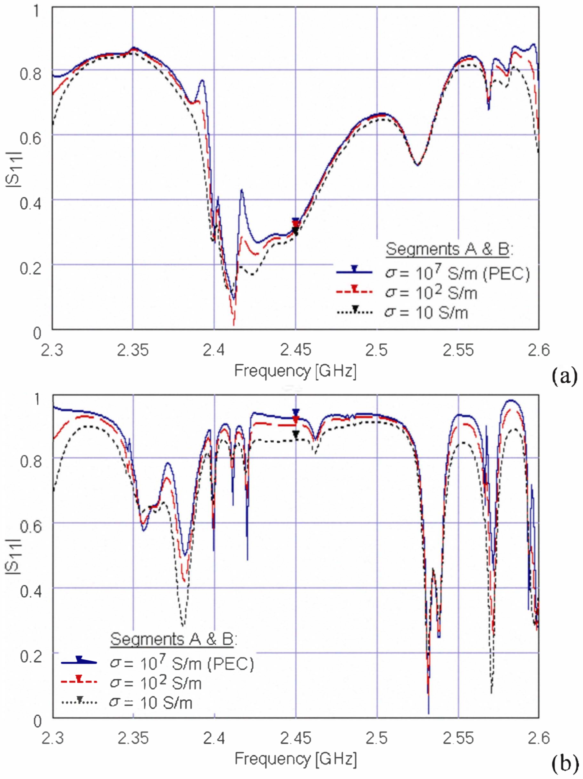

Fig. 6. Reflection coefficient in the microwave oven (Fig. 4) for different σ of Segments A and B; loads are water (a) and corn oil (b).

magnitude. These levels of effective electric conductivity appear unlikely to be reachable with any realistic parameters of perforation in metal walls of microwave ovens. It therefore may not be an exaggeration to state that when modeling microwave ovens, any perforated wall regions could be safely considered as solid PEC surfaces.

IV. CONCLUSION

We have proposed an applied approach to the problem of modeling perforated metal wall segments in microwave ovens. The potential impact of perforation on the frequency characteristic of the reflection coefficient may be checked through an FDTD-based determination of effective electric conductivity of the segment. An illustrative computation performed for a particular scenario has suggested that, when modeling practical microwave ovens, the presence of perforation could be likely ignored. The proposed technique is not exclusive to microwave ovens, and could also be used for characterization of perforated metal sheets or screens encountered in various problems of EM compatibility [10].

REFERENCES

[1] T.V. Koutchma and V.V. Yakovlev, Computer modeling of microwave heating processes for food preservation, In: *Mathematical Analysis of Food Processing*, M.M. Farid, Ed., CRC Press, 2010, pp. 625-657.

[2] M. Celuch and P. Kopyt, Modeling of microwave heating of foods, in: *Development of Packaging and Products for Use in Microwave Ovens*, M.W. Lorence and P.S. Pesheck, Eds., Oxford: Woodhead Publishing, 2009, pp. 305-348.

[3] C.-C. Chen, "Transmission of microwave through perforated flat plates of finite thickness," *IEEE Trans. Microwave Theory & Tech.*, vol. 21, no. 1, pp. 1-6, January 1973.

[4] _N. Doncov, A.J. Wlodarczyk, R. Scaramuzza, and V. Trenkic, "TLM modeling of perforated thin metal screens," *4th Intern. Conf. on Computation in Electromagnetics*, 2002.

[5] M. Celuch, W. Gwarek, and M. Soltysiak, "Effective modeling of microwave heating scenarios including susceptors," *2008 Recent Advances in Microwave Theory & Appl. (Microwave-2008)*, Jaipur, India, pp. 404-405, November 2008.

[6] W. Gwarek, M. Celuch, and J. Krupka, Modeling and measurements of susceptors for microwave heating applications," *2009 IEEE MTT-S Int. Microwave Symp. Workshop "Recent Advances in Microwave Power Applications & Techniques (RAMPAnT)*," June 2009.

[7] D.M. Pozar, *Microwave Engineering*, New York: J. Wiley & Sons, 2005.

[8] *QuickWave-3D*™, QWED Sp. z o.o., http://www.qwed.com.pl/.

[9] P.O. Risman, Microwave dielectric properties of foods and some other substances, in: *Development of Packaging and Products for Use in Microwave Ovens*, M.W. Lorence and P.S. Pesheck, Eds., Oxford: Woodhead Publishing, 2009, pp. 153-175.

[10] H.W. Ott, *Electromagnetic Compatibility Engineering*, New York: J. Wiley & Sons, 2009.