Computer Modeling in the Development of Mechanisms of Control over Microwave Heating in Solid-State Energy Systems

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It is now commonly acknowledged that the rapidly growing technology of generation of microwave energy by solid-state semiconductor chains may make a revolutionizing impact on the entire field of microwave power engineering[1]. The chief reason for this is the potential capability of this technology to maintain electronic control over the key electromagnetic (EM) characteristics of microwave heating systems. The possibility of manipulating frequency, magnitude, and phase of the signal is expected to essentially improve controllability of microwave thermal processing (in comparison with traditional magnetrons) in terms of both of its key characteristics: energy efficiency and distribution of heating patterns[1,2].

The decisive factor in the increasing adoption of solid-state power sources is the recent progress in design of highly efficient, low-cost solid-state amplifiers, made possible by vital improvements in LDMOS and GaN technology. The RF Energy Alliance (RFEA), a non-profit technical association comprised of companies dedicated to realizing solid-state energy's potential as a clean, efficient, controllable source of power and heat[3], has recently set up the short-term goal of developing sources with an output power of 300 W with better than 70 % efficiency[1]. In May 2016, MACOM announced the release of a GaN on Si transistor with these characteristics[4]. The RFEA anticipates impending achievement of the level of $12 per module for sources of this type[1]. This fast development has prompted such major manufacturers of domestic microwave ovens as Miele, Panasonic and Whirlpool to recently join the RFEA in breaking down barriers to wide-market adoption by collaborating on methods that reduce costs and complexities of solid-state energy ovens.

In the meantime, while in commercial publications there is no shortage of general common-sense-based assertions about the potential benefits of solid-state energy sources, specific mechanisms of control over the heating process still have to be developed. In such development, the role played by computer modeling may be crucial. Indeed, in the absence of critical uncertainties caused by a magnetron's chaotic irradiation spectra depending on many parameters of the process, in solid-state systems, EM characteristics may be well predictable if simulated with the use of adequate and accurate computer models. In other words, appropriately conducted virtual experimentation may be a notable part of the development of particular microwave heating processes[5], and of the design of practical applicators[2,6].

The main characteristics which can be routinely modeled with the use of advanced EM modeling tools (based on finite element or FDTD methods) are the scattering matrix parameters (i.e., the reflection and transmission coefficients) and distributions of the EM field in the cavity, and of dissipated power within the processed material. Consider a typical two-port rectangular cavity[1] containing a tray and a load, as shown in Fig. 1. The tray is made of a low loss dielectric (e.g., FR4). The rectangular load (with rounded corners, made of a certain lossy material) is centered on the tray. This scenario mimics a two-feed solid-state microwave oven. The illustrative computation showing essential characteristics of this system was conducted with an FDTD model[7] and validated against analytical results, as presented elsewhere[2]. Simulation of frequency responses of the reflection coefficients in both ports connected with the empty system indicates that the horizontal and vertical feeds excite different resonant frequencies f_{ri} in the ISM band around 2.45 GHz; there are eight (i = 1, …, 8) of them, and they are listed in the first row of Table 1. Similarly to the reported results[2], simulation of EM fields at those resonances shows the electric field distributions displayed in Fig. 2. The resulted field distributions in this case resemble those of the eigen modes in the corresponding rectangular resonator.

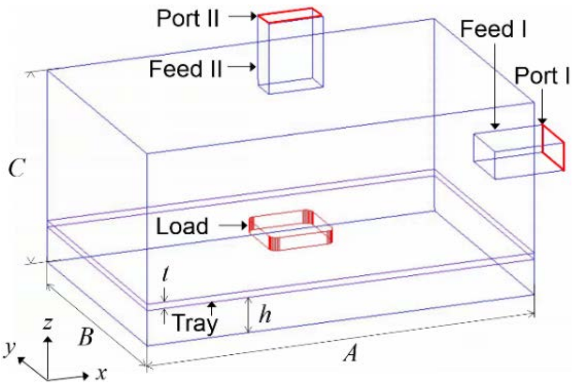


Figure 1. A 3D view of the loaded rectangular cavity

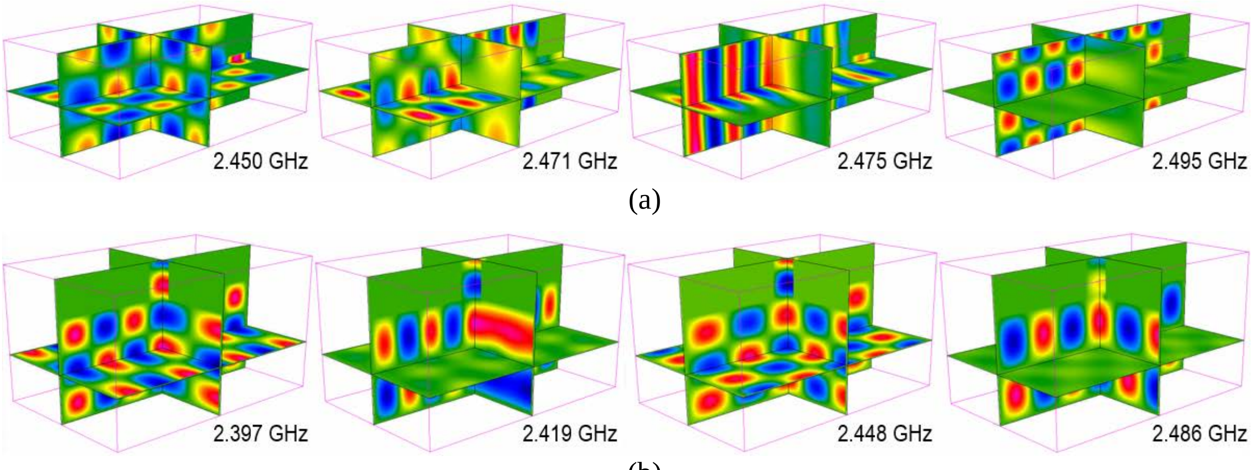
Table 1. Resonant Frequencies in the System in Fig. 1: Empty and Loaded Cavity*)

Load (complex permittivity)	Port	Resonant frequencies (GHz)
None	I	2.450, 2.471, 2.475, 2.495
	II	2.397, 2.419, 2.448, 2.486
Alumina	I	2.442, 2.470, 2.479, 2.486
(ε = 1.52 - *j*0.0004)	II	2.421, 2.447, 2.455, 2.492
Zirconia	I	2.407, 2.439, 2.451, 2.470, 2.476, 2.484, 2.493
(ε = 6.69 - *j*0.190)	II	2.404, 2.411, 2.434, 2.448, 2.481
Apple	I	2.431, 2.437, 2.468, 2.478, 2.490
(ε = 18.4 - *j*7.8)	II	2.415, 2.432, 2.445, 2.474, 2.486
Beef	I	2.435, 2.468, 2.478, 2.493
(ε = 48.2 - *j*16.2)	II	2.414, 2.433, 2.446, 2.473, 2.486

*) A = 612 mm, B = 400 mm, C = 300 mm, t = 10 mm, h = 55 mm; Load: 50 x 50 x 20 mm, ports I & II: WR430, centered on facets

Insertion of a lossy load in the cavity dramatically changes the frequency characteristics of the reflection coefficients. For loads of relatively small size and lower loss factor, resonances shift and become wider (and their number may increase, as in the cases of zirconia and apple loads (see Table 1), but for larger loads and higher loss factors, the curve may even lose its resonant profile (for examples of such characteristics, see Fig. 3 in Ref.[2]). The level of energy coupling that is invoked by that insertion is therefore conditioned by the resulting value of the reflection coefficient, rather than by the location of the load with respect to the maxima or minima of the electric field at some particular frequency.

Accordingly, profiles of dissipated power P_d induced in the load are different at different f_r. Simulated distributions of P_d for four resonant frequencies (at which the loads have substantially better energy coupling) associated with each feed are shown in Fig. 3. The patterns are highly non-uniform, and some of them dominate over others (e.g., for alumina, the value of P_{dmax} in the pattern generated by Port I at 2.470 GHz dominates it counterpart from Port II at 2.447 GHz by 7.6 times). This is explained by the depths of corresponding resonance: the deeper the resonance, the higher the energy coupling and the values of dissipated power in the pattern.



(a)

(b)

Figure 2. Patterns of instantaneous electric field visualized in the coordinate planes at the resonant frequencies in the empty system in Fig. 1 excited by Ports I (a) and II (b) in the ISM frequency range.

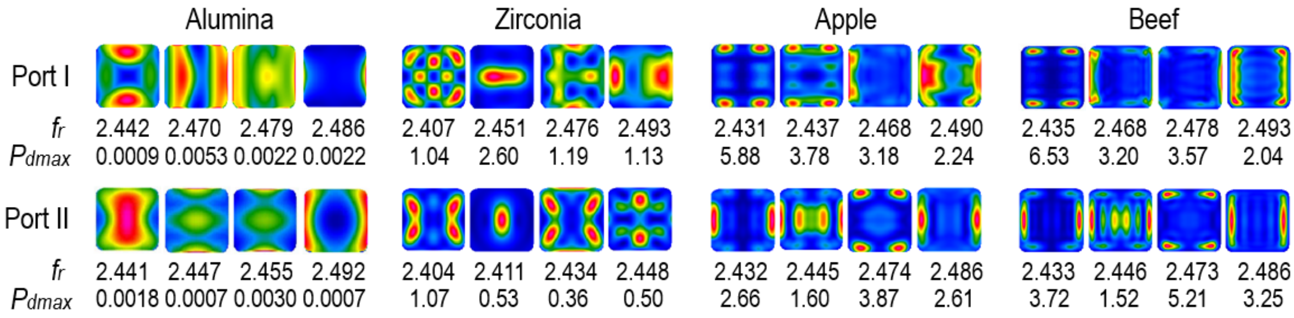


Figure 3. Relative patterns of densities of dissipated power in the central horizontal plane through the loads (50×50×10 mm) in the system in Fig. 1; each pattern is given along with the value of its resonant frequency f_r (GHz) and the maximum value of dissipated power P_{dmax} ($\times 10^{-3}$) (W/mm^3) in that pattern.

The sensitivity of power density distributions to small changes in frequency is a well-known effect; it was explicitly demonstrated, e.g. for a dielectric block in a microwave oven[8]. However, that study was carried out in order to characterize a particular (measured) radiation spectrum of a particular magnetron. Here, the solid-state microwave system places the effect of frequency variation of patterns of dissipated power in an essentially dissimilar context. With full control over frequency of generation, one can think of regimes of thermal processing based on frequency alterations that mix up heating patterns of different profiles and effectively smooth out the temperature hotspots in the load.

Computation of patterns of dissipated power is a crucial and informative step in CAD of processes and systems powered by solid-state generation. Simulation of temperature fields may add complications to the modeling project as it requires computational tools for more advanced multiphysics modeling in which an EM solver is coupled with a thermal one through the temperature-dependent characteristics of complex permittivity and thermal parameters of the processed material (fully defined in the operational temperature range). Another issue is the thermal boundary conditions whose choice may be not obvious for a particular scenario and whose implementation in the thermal solver may be not readily available in many applicable multiphysics simulators. However, for most practical materials (characterized by not very high thermal conductivity), the patterns of dissipated power and temperature (at the initial stage of heating) are very similar.

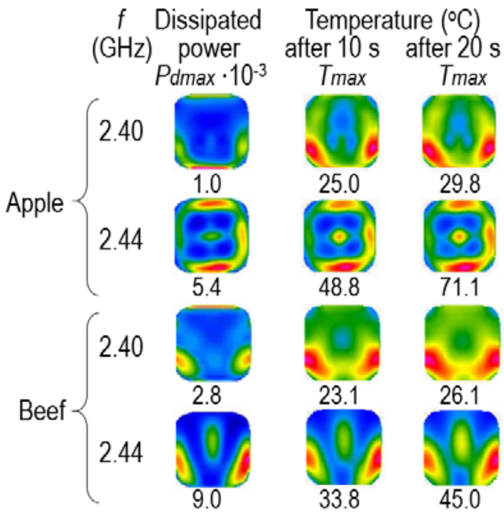


Figure 4. Relative patterns of densities of dissipated power and temperature in the central horizontal plane through the loads (50×50×10 mm) in the system in Fig. 1; for the given frequencies f, each P_d pattern is presented with the maximum value of dissipated power P_{dmax} (W/mm^3), and each T pattern is presented with the maximum value of temperature in that pattern; initial temperature of the process is 20°C.

This observation is illustrated by Fig. 4 where the P_d patterns, the output of EM modeling, are compared with T patterns resulted from the solution of the coupled EM-thermal problem for two types of loads in the considered system (Fig. 1). It is seen that the hot- and cold-spot distributions, corresponding to lower values of P_{dmax}, become gradually more spread in the temperature profiles due to low coupling with microwave energy, and the impact of thermal conductivity. On the other hand, distributions corresponding to higher P_{dmax} remain almost unchanged, since coupling with microwaves prevails over thermal conductivity and the loads are heated in accordance with the dissipated power profiles. This means that one can interpret patterns of dissipated power as the worst (in terms of the level of non-uniformity) temperature distribution which, in the course of heating, can either stay the same, or become more relaxed due to heat diffusion.

The considered computational results illustrate why solid-state energy systems are seen as a very promising technology in microwave power engineering. Electronic control over the frequency and magnitude of the signal, in combination with multiple feeds providing excitation of diverse modes in the ISM frequency range, indeed seem to open the horizon for practical techniques resolving the issue of intrinsic non-uniformity of microwave heating and making the process energy efficient. It is also evident that computer modeling is going to play a decisive role in the development of specific mechanisms of applicable control.

For further reading:

1. K. Werner, “RF energy systems: realizing new applications,” *Microwave Journal*, Vol. 58, No 12, pp. 22-34, December 2015.
2. V.V. Yakovlev, “Frequency control over the heating patterns in a solid-state dual-source microwave oven,” *IEEE MTT-S Int’l Microwave Symp. Dig. (Phoenix, AZ, May 2015)*, 978-1-4799-8275-2/15.
3. http://rfenergy.org/.
4. http://enewspro.penton.com/preview/microwavesrf/MWRF-07/20160526_MWRF-07_808/display?elqTrack=true/.
5. E.M. Moon, C. Yang, V.V. Yakovlev, “Microwave-induced temperature fields in cylindrical samples of graphite powder – experimental and modeling studies,” *Int’l J. Heat & Mass Transfer*, Vol. 87, No 8, pp. 359-368, 2015.
6. E. M. Moon, C. Yang, M. Patel, H. He, V. V. Yakovlev, “Microwave-induced temperature fields in graphite powder heated in a waveguide reactor,” *IEEE MTT-S Int’l Microwave Symp. Dig. (Tampa, FL, June 2014)*, 978-1-4799-3869-8/14.
7. *QuickWave* 2015, QWED Sp. z o.o. http://www.qwed.com.pl/.
8. D.C. Dibben, A.C. Metaxas, “Time-domain finite-element analysis of multimode microwave applicators,” *IEEE Trans. Magn.*, Vol. 32, No 3, pp. 942-945, 1996.

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