Efficient Electromagnetic Simulation of Shielding Mechanisms in Microwave Ovens

The door to a microwave oven forms part of the heating cavity, allowing access to the oven interior. The seal around the door is never perfect, so electromagnetic fields will leak out of the oven, potentially interfering with other electrical equipment or exceeding safety limits for power levels in human operators. Oven designs have to meet legal requirements for the amount of power which can leak beyond a certain distance from the oven (due to human exposure concerns), and also have to meet electromagnetic compatibility (EMC) requirements. This article discusses how electromagnetic simulation can be used to design effective shielding mechanisms in order to adhere to these standards.

Microwave heating is caused by the interaction of a high-frequency electromagnetic field with a dielectric. Common uses of microwave heating include cooking, drying and sterilization – all effects that can be dangerous or destructive outside the controlled environment of the heating cavity. To prevent injury to operators, microwave ovens need to be well-shielded to prevent leakage of RF fields.

Different regulatory bodies set different exposure limits and specify different experimental set-ups. A few examples are given in Table 1:

Body	Power density at 5 cm from the oven
British Standards Institution (UK) and IEC (International)	5 mW/cm² [1]
FDA (USA)	1 mW/cm² prior to purchase, 5 mW/cm² afterwards [2]
Ministry of Economy, Trade and Industry (Japan)	1 mW/cm² when the door is shut, 5 mW/cm² when the door is ajar to the maximum extent before triggering the cut-off [3]
Radiation Protection Bureau (Canada)	1 mW/cm² with a test load, 5 mW/cm² without [4]

Table 1 Microwave oven exposure limits.

Another reason to improve microwave oven shielding is electromagnetic compatibility (EMC). Electromagnetic fields produced by the oven can couple into other electronic devices, causing spurious signals and potentially damaging the device. To complicate matters, most domestic microwave ovens operate on the industrial, scientific and medical (ISM) band at around 2.45 GHz. Because this band is unregulated, it has become widely used for short range wireless communication systems such as Wi-Fi and Bluetooth. Noise from microwave ovens can cause significant interference to networks using these technologies.

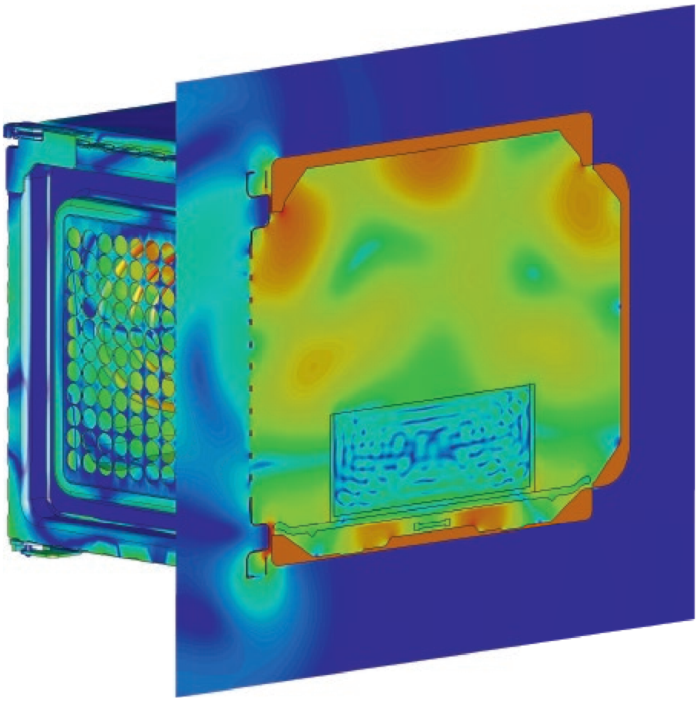

Figure 1 Leakage from a poorly shielded oven.

If a microwave oven consisted solely of a sealed heating cavity, shielding it would be trivial. However, practical considerations mean that a real microwave oven includes several potential leakage points. Because objects need to be loaded into and removed from the oven, there needs to be a door. This introduces a seam along the edge of the cavity through which electromagnetic fields can escape.

Another potential source of major leakage is the window. While the window is necessary to allow the cooking process to be monitored, it needs to be carefully designed to make sure that EM radiation in the visible portion of spectrum can pass through, but radiation in the microwave spectrum cannot. The effect of both the door seam and the window can be seen in Figure 1.

Identifying Shielding Problems

Before deciding which part of the shielding to improve, it's important to understand where the most leakage occurs. Because exposure limits are typically based on the maximum value at any point, rather than an averaged value, redesigning an already-effective shield will not usually bring a failing oven into compliance.

Simulation offers several techniques for analyzing the properties of a design. To quickly identify the directions in which the oven leaks the most energy, a farfield monitor can be used. The farfield pattern of the oven may be used as an indication of which components are leaking (Figure 2). For example, if the majority of the radiation leaks from the side of the oven, this could be an indication that the seals and seams need to be improved; if the radiation peaks are to the front, then the door may be a greater problem.

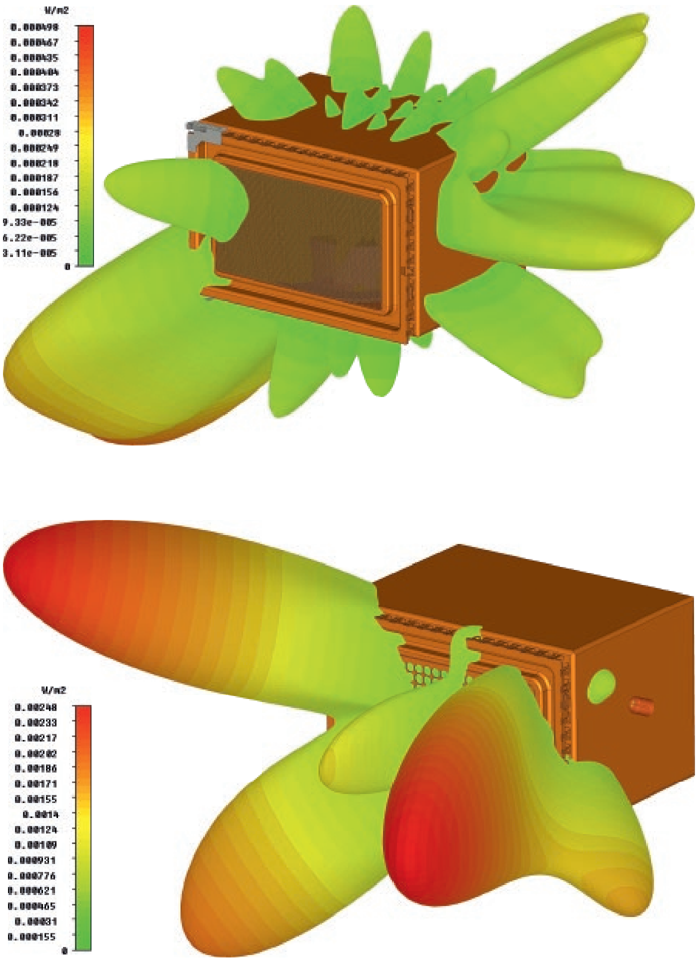

Figure 2 Farfield patterns for ovens with a door mesh consisting of holes of 1 mm diameter (left), and 6 mm diameter (right). The radiation is clearly higher when larger holes are used.

Once the primary source of leakage has been identified, the nearfield and the power density distribution of the oven can be used to find the exact mechanism of failure. The power density monitor can be defined to cover a cuboid 5 cm from the surface of the oven, allowing simulation to mimic the regulatory compliance test and showing hotspots where problematic power densities are likely to occur. In Figure 3 the power densities at the rear of the oven are close to zero, as would be expected for a solid metal cavity, but there are several hotspots at the front which approach the 5 mW/cm^2 (or 50 W/m^2) limit, suggesting the door should be the focus of further investigation.

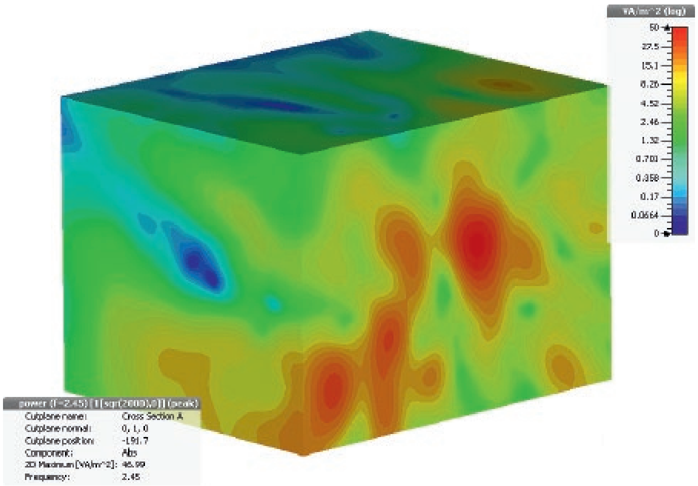

Figure 3 Power density distribution at 5 cm from an oven.

Finally, the oven can be simulated in a real world exposure situation. The effect of the electromagnetic fields on the human body can be hard to predict, as structures within the body reflect and focus energy in complicated ways. Including body models in simulation – either homogeneous phantom models or heterogeneous voxel models – means that the specific absorption rate (SAR) can also be calculated. SAR is a measure of the power absorbed by the body, with recommended limits depending on the type of tissue affected. In typical operation, a microwave oven obeying the 5 mW/cm^2 limit poses no SAR problems at 5 cm, but body parts extremely close to the oven (i.e. within 1 mm) may, in the worst case scenario, exceed the SAR threshold[5].

CST MICROWAVE STUDIO® includes a toolbox for various types of SAR calculation, including point values, volume averages and averages over an entire organ. These can be used to ensure that SAR limits are not exceeded in normal use – by moving and posing the body model, different scenarios can be assessed. Thermal simulation with CST MPHYSICS® STUDIO can be used to verify the heating of the body, taking into account bio-heat effects.

Shielding Mechanisms

Once the source of the leakage has been identified, the design of the shielding mechanisms can be modified to improve shielding. This paper will demonstrate the investigation and redesign of two shielding mechanisms – the door fins and the window mesh – using simulation.

Door Fins

Because a perfect metal-on-metal seal between the door and the casing is difficult to achieve, microwave ovens include a quarter-wavelength choke structure constructed from fins arranged around the edge of the door (Figure 5). These fins act as a short circuit, effectively blocking microwaves from passing through. However, because they need to be resonant at the frequency of the fields, they need to be carefully designed for optimal shielding.

Various parameters describe the shape of the fins, such as their size, spacing, and the gap between the door and the oven. The parameters which have been considered in this study are shown in Figure 6. A parameter sweep over these four variables was then carried out in order to investigate the effect of changing the fin design. Parameter sweeps not only illustrate the relationship between different elements of a device and its behavior, but also offer a good starting point for a more detailed analysis.

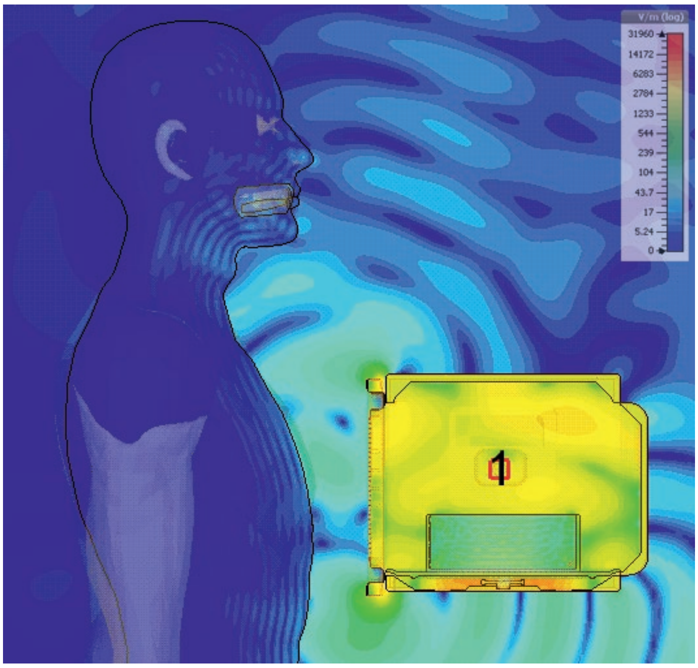

Figure 4 A field simulation using a homogeneous body model.

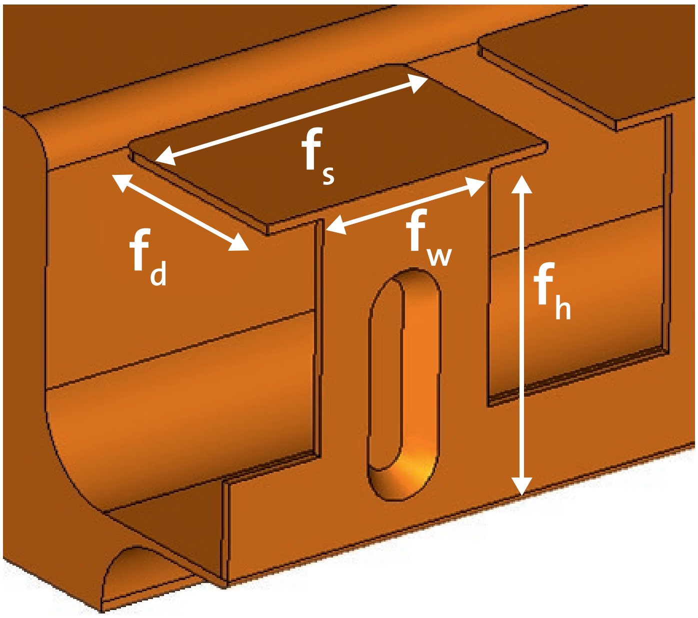

Figure 6 Parameters of the fin design.

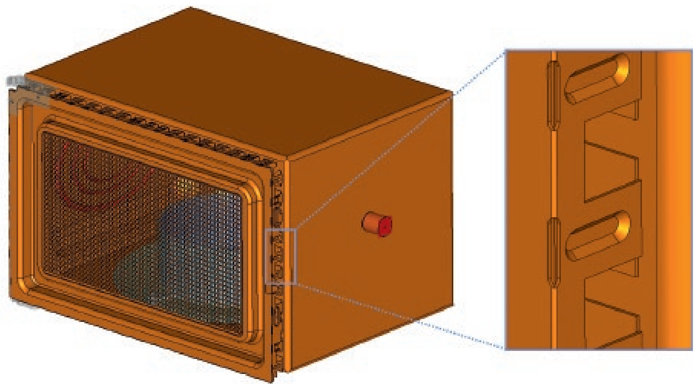

Figure 5 Door fins (highlighted) in a microwave oven.

To find the design that offers the best shielding, the fins can be optimized using full-wave 3D simulation. The fins can be isolated from the rest of the model – there is no need to simulate the entire heating cavity – and simulated in a section of rectangular waveguide with ports on either side of the shielding structure. These ports calculate power transmission through the fins using S-parameters, with a low S_{21} value corresponding to good shielding. Using periodic boundary conditions reduces the simulation complexity even further.

As shown in Figure 7, changing the dimensions of the fins had a major effect on the effectiveness of the fins, pushing their resonant frequency out of the ISM band. A few runs are highlighted – these all fall within the ISM band, but they have different combinations of dimensions. This allows the designer some freedom in choosing a suitable geometry.

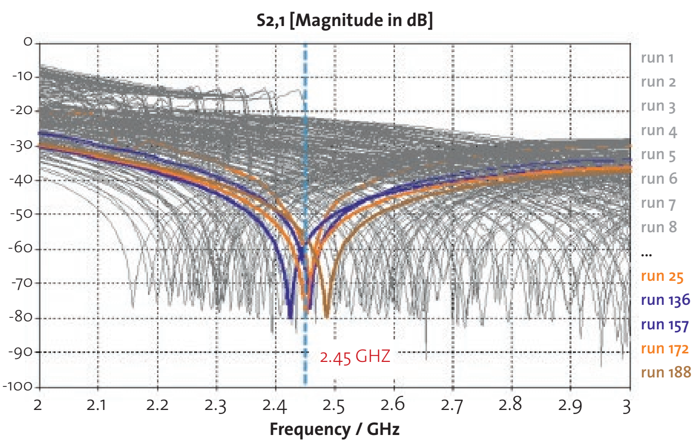

Figure 7 Parameter sweep results. Some close fits are highlighted.

Optimization is another parametric approach which is well suited to shielding problems. While a parameter sweep searches the entire parameter space equally, optimization attempts to "home in" on the optimal value more efficiently. Optimizers can be local or global – local optimizers search for the minimum in the region of a defined starting point, while global optimizers scatter points across the parameter space before converging to the minimum.

The optimal value to be searched for is defined using goals. Depending on the requirements of the problem, this can be searching for a maximum or minimum value, or for the parameters that generate results nearest to a set target. These goals can be defined either at a single point, or across a range. The goal in this case is to minimize S_{21} at 2.45 GHz, the central frequency of the oven.

The results from the parameter sweep suggest that a local optimization will be useful – the highlighted runs are all close to the optimal value, and their parameter values are reasonably similar. By selecting a suitable starting value (in this case, run 172), optimization can be used to fine-tune the properties of a design.

The optimizer used in this case was the Trust Region Framework algorithm. This is a versatile local optimizer suitable for a variety of problem types. The Trust Region Framework algorithm can take advantage of sensitivity information – the derivative of the S-parameters with respect to the parameters – to speed up the optimization process.

For problems where the starting value is less clear or the parameter space is more complex, the Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) is a good alternative. CMA-ES is a global optimizer, so its results are less dependent on the initial value, and like the Trust Region Framework, it is a very versatile algorithm.

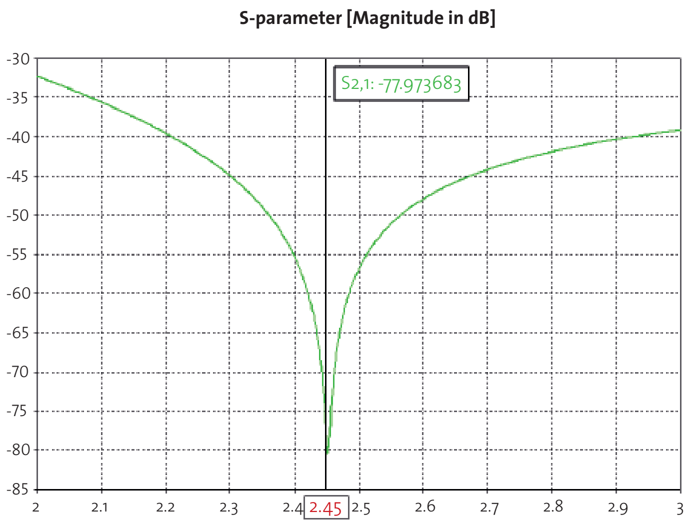

Figure 8 S-parameters of the optimized door fins.

The results of the optimization are shown in Figure 8, with the redesigned fins giving a best-case 80 dB transmission, and at least 55 dB transmission across the 2.4–2.5 GHz ISM band. When these fins were implemented in the full model, they produced in a 6% reduction in the maximum value of the power density at 5 cm, relative to the original design.

Window Mesh

To prevent radiation from leaking through the window, microwave ovens include a metal mesh in the door. This mesh has to allow visible light through while stopping microwave radiation. In effect, this mesh is a high-pass frequency selective surface (FSS).

The mesh works as a shield because the diameter of the holes is much smaller than the wavelength of the microwave radiation. This means that the mesh approximates a solid sheet of metal at these frequencies. The mesh is thicker than the skin depth at microwave frequencies, and so it is an effective shield. Optical frequencies, by contrast, have far shorter wavelengths, and so they pass through the holes unimpeded.

Designing an effective mesh means selecting the right size and arrangement for the holes. Smaller holes will produce a more effective shield, but this effect needs to be balanced against the additional manufacturing difficulties of producing a very fine mesh and the visibility restrictions caused by the small holes. Simulation can be used to investigate different mesh designs, to help the engineer find the design that balances safety, visibility and manufacturing constraints.

The mesh can be simulated by modeling a single hole with periodic boundary conditions. By parameterizing the size of the hole (or its depth – not shown here) and performing a parameter sweep, a design curve can be created showing how the shielding effect varies with frequency. As can be seen in Figure 9, transmission drops off steeply as the holes become smaller.

The same approach can be used to assess the effectiveness of different mesh designs. Unit cells can be staggered to represent alternative arrangements of holes, and the individual elements can be remodeled to simulate the effect of different hole shapes, such as the alternating rows of large and small holes shown in Figure 10.

As with the door fins, the redesigned mesh can then be implemented in the full model. As expected, smaller hole sizes corresponded to reduced maximum power density values. For holes with a radius of 2.4 mm, the maximum power density 5 cm from the front of the oven was 4.7 mW / cm²; when the radius was reduced to one 1 mm, the maximum power density was reduced to 1.9 mW / cm².

Combining the two meshes as shown in Figure 10 to produce a hybrid mesh, with r = 2.4 mm and r ≈ 1 mm alternately, gave slightly degraded performance – the maximum power density increased to 5.6 mW / cm².

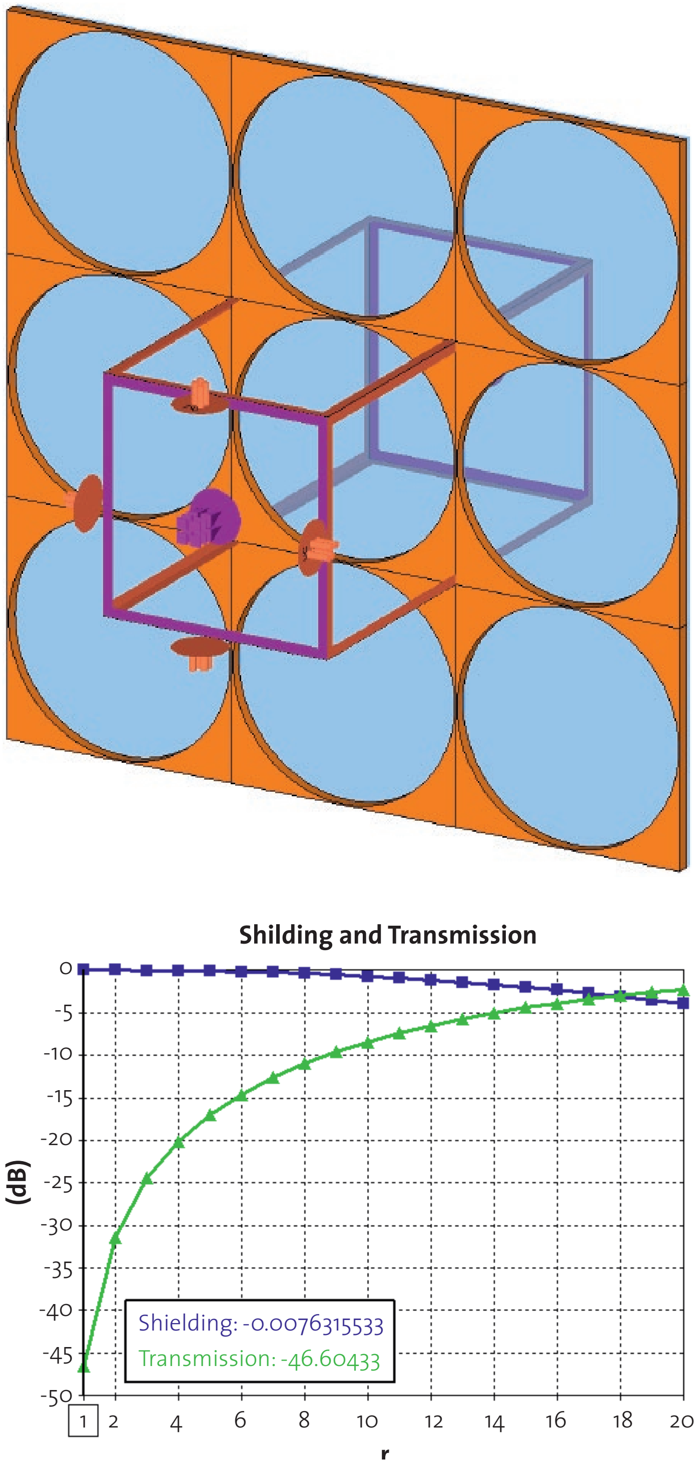

Figure 9 (top) A small section of mesh, with a single unit cell highlighted. (bottom) Shielding effect versus hole radius (in millimeters), with the values at r = 1 mm shown in the inset.

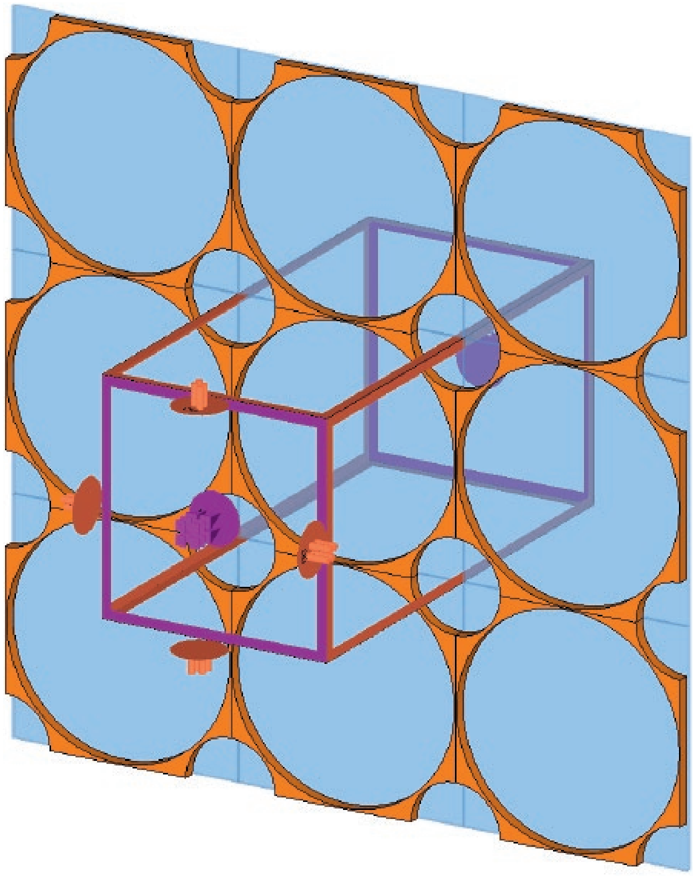

Figure 10 An alternative mesh design, offering greater visibility.

Conclusion

To bring a microwave oven to market, the designer needs to make that it complies with leakage limits. Electromagnetic simulation can support the development of the shielding mechanisms, making it easier to compare different possible designs and select the best for the situation. With parameter sweeps and optimization, the best dimensions for the design can be found, and an informed decision can be made when balancing two opposing design considerations.

This article has covered the design of shielding mechanisms for microwave ovens. CST whitepapers on the modeling and design of microwave oven magnetrons and microwave heating cavities are also available from www.cst.com.

[1] IEC 60335-2-25, "Household and similar electrical appliances. Safety - Part 2–25: Particular requirements for microwave ovens, including combination microwave ovens".

[2] 21CFR1030.10 "Performance standards for microwave and radio frequency emitting devices – Microwave ovens", U.S. Food and Drug Administration.
http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?FR=1030.10

[3] "Ordinance Concerning Technical Requirements for Electrical Appliances and Materials (Electrical Appliance and Material Safety Law)", Section 95, Ministry of Economy, Trade and Industry (Japan).

[4] "Radiation Emitting Devices Regulations (C.R.C., c. 1370)", Schedule II, part III, Department of Justice (Canada). *http://laws-lois.justice.gc.ca/eng/regulations/C.R.C.,_c._1370/page-4.html*

[5] "Microwave ovens", EMF Fact Sheet, Federal Office of Public Health (Switzerland).
http://www.bag.admin.ch/themen/strahlung/00053/00673/03752/index.html?lang=en

Authors
Marc Rütschlin, *CST AG – Sales/Support*

CST AG
Bad Nauheimer Str. 19
64289 Darmstadt
Germany

info@cst.com
http://www.cst.com