

## SIMULATION OF COMPONENTS OF MICROWAVE HEATING APPLICATORS BY *FEMLAB*, *MICROWAVELAB*, AND *QUICKWAVE-3D*

V.V. KOMAROV\* AND V.V. YAKOVLEV\*\*

\*Department of Radio Engineering, Saratov State Technical University, Saratov 410054, Russia

\*\*Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, MA 01609

**Abstract:** *FEMLAB* and *MicroWaveLab*, two finite element solvers, are evaluated in the context of needs of microwave power engineering. Limitations of the codes are identified by simulation of characteristics of applicators based on circular and rectangular waveguides as well as coaxial-to-ridged- and coaxial-to-double-ridged waveguide transitions. Results are verified by *QuickWave-3D*.

### INTRODUCTION

Because of the recent remarkable increase in the quality of modeling and the certain decrease in the costs of software and hardware, engineers working with microwave non-communication applications have become more interested in computer simulations. However, for most of them, this arena remains new and unexplored. A recent review [1] made an informational contribution to the field and introduced a database of contemporary electromagnetic (EM) software applicable to the typical industrial problems of microwave power engineering. Pursuing the same informational objectives, in the present paper, we provide supplementary material associated with two pieces of software not included in the database in [1] and consider examples of their use.

In accordance with [1], among the computer programs related to the EM processes in the microwave power systems, there are so-called “mathematical” codes for numerical solutions of corresponding boundary value problems (BVP) derived from Maxwell’s equations. Those codes were not included in the list of the computational tools, which appear to be suitable for engineers designing industrial equipment for microwave thermal processing. The “mathematical” codes require certain familiarity with the partial differential equations, BVP, and issues in numerical techniques; they are not oriented solely on the electromagnetic problems, but usually also on mechanics, heat conduction theory, acoustics, etc. In the illustration below, we consider an example of the use of the finite element solver *FEMLAB*<sup>1</sup> for characterization of a cylindrical traveling wave applicator with the axial processed material and address the limitations of this use.

In contrast to the “math” codes, general-purpose EM simulators are specifically developed for a variety of problems associated with radar and telecommunication devices, EMC and other systems. The 16 full-wave 3D codes available in the market have passed the selection criteria to be included in the database in [1]; the level of adjustment of some of those codes to the needs of the microwave power industry is examined in [2]. In the present paper, we address the EM solver *MicroWaveLab*. This product, originally developed by MacNeal-Schwendler Corp. (presently, MSC Software Corp.<sup>2</sup>) and later purchased by Ansoft Corp.<sup>3</sup>, seems to be able to help engineers and practitioners analyze and design systems of microwave thermal processing. The main reason why this product is not present in the mentioned software database is the fact that about 2 years ago it was withdrawn from the market. However, it is still in active use in a number of universities and industrial companies worldwide. Here we illustrate some capabilities of *MicroWaveLab* analyzing two problems: a rectangular applicator with the thin centered processed material and two supplementary dielectric wedges and transitions from coaxial line to the ridged and double-ridged waveguides.

Considering examples of modeling of the microwave components by *FEMLAB* and *MicroWaveLab* we verify the obtained results by (partially) solving the same problems with the use of *QuickWave-3D*, the universal EM solver based on the conformal FDTD method. *QuickWave-3D* has proven to be an effective and reliable tool for EM analysis [3], and the software has been successfully used for modeling systems of microwave power engineering [4-6].

### *FEMLAB*

Solver *FEMLAB* has been developed for numerical solution of 2D elliptical, parabolic and hyperbolic nonlinear differential equations using the finite element method (FEM). A number of *MATLAB* procedures have been implemented in *FEMLAB*, which actually operates on the *MATLAB* v.5.3 platform [7]. Formulation of a generalized differential equation in the so-called “coefficient form” is the main peculiarity of this program. Selecting appropriate coefficients, the user obtains the necessary equation, for example, the Helmholtz’s equation, or time dependent heat conduction equation describing physical processes in microwave heating systems. The known technique based on the Galerkin’s principle for nodal finite elements (first-order approximation) is implemented in *FEMLAB* for transformation of differential equations to equivalent systems of algebraic equations.

<sup>1</sup> <http://www.comsol.se>

<sup>2</sup> <http://www.macsch.com>

<sup>3</sup> <http://www.ansoft.com>

The solver has been tested in computations of eigenmodes of several inhomogeneous waveguide structures. A good agreement between *FEMLAB*'s results and analytical data in [8] has been demonstrated only in the domain of the so-called "fast waves" for  $\beta/k < 1$ , where  $\beta$  is the phase constant and  $k$  is the free space wavenumber. This drawback is explained by the fact that the BVP solved in *FEMLAB* does not include the interface boundary conditions for  $\beta \neq 0$ . This in fact implies that it would not be feasible to expect highly accurate data from the *FEMLAB* analysis of the microwave heating problems where partial filling of a cavity is a principal point.

Some parameters of 2D components can nevertheless be determined by *FEMLAB* with sufficient accuracy. The code may be useful in microwave heating practice when it is required to find out the number and types of modes propagating in the waveguide system, including in the presence of dielectric materials. For instance, cutoff frequencies  $f_{ci}$  of  $p$  modes ( $i = 1, \dots, p$ ) could be of particular interest. For *FEMLAB*, the problems of that type appear to be natural: finding cutoff frequencies and the fields of the corresponding modes means determining eigenvalues and corresponding eigenfunctions of a matrix eigenvalue problem. The solution is explicit, quick, and convenient. At the same time, if the dielectric constant (DC) of the material is quite high, the mode for which the field is computed and visualized is hardly identified because the user has no implications on the originating modes. Consequently, no specific recommendations as of how the modes could be excited are generated.

Table 1 contains the cutoff frequencies obtained by *FEMLAB* for the construction shown in Fig. 1. The DC was intentionally set up quite high to imitate the value typical for some food products. The Table also includes  $f_{ci}$  computed by *QuickWave-3D* (300,000 cells; cell size in the cross-section is  $2 \times 2$  mm). The agreement between the values is reasonable. Because of the nature of the FDTD technique, computation of  $f_{ci}$  by *QuickWave-3D* is more complicated, but at the same time beneficial practice-wise: the full-wave comprehensive solution implemented in the software generates the cutoff frequencies of the modes along with information on the type of their excitation. This information allows the user to easily track the field structures from the originating modes through the DC ranging from 1 to 45 and identify the modes as shown in Table 1.

The possibility of using *FEMLAB* for modeling of temperature patterns is another feature of the software, making it a notable option for some R&D-type microwave projects. Another advantage is associated with the low price of the software: it costs 10 to 20 times less than the full-wave EM simulators.

## MICROWAVELAB

This computational tool based on 3D FEM in time domain was designed for comprehensive simulations of EM processes. The solver allows one to obtain parameters of scattering matrix ( $S$ -parameters), dispersion, wave impedance, and the field structure in the frequency range for microwave components partially loaded with lossless and lossy dielectric materials. *MicroWaveLab* seems to be satisfying all the selection criteria suggested in [1] except one: computation of the power dissipated in the material absorbing the EM field has not been implemented.

After a little practical work with the software, the user can notice that *MicroWaveLab* is very sensitive to the size and curving of mesh elements. In order to generate an appropriate finite element model it is necessary to satisfy two major conditions. The first one is connected with maximum size of triangle  $L_{\max}$  and the wavelength of the signal  $\lambda$  in the network:

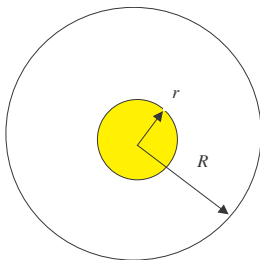


Fig. 1. Geometry of a cylindrical applicator with axially symmetric processed material

$$L_{\max} \leq 0.1\lambda 2^{p-1} \quad (1)$$

where  $p$  is the finite element order ( $p = 1, 2$ ). The second condition is that the user is required to evaluate a computational error in a local sub-domain where maximum gradients of the EM field are obtained [9].

Calculation of  $S$ -parameters may be useful in a variety of situations, for instance, to define matching characteristics of the microwave heating applicator to other components of the circuit. For example, the voltage standing wave ratio (VSWR)  $\rho$  can be expressed as [10]:

Table 1. Cutoff Frequencies in WC451 ( $R = 57.3$  mm) with Axial Dielectric Rod (Relative DC = 45).

| $r/R$ | Result                           | Mode and cutoff frequency (in GHz) in the range 0.5-4 GHz |                  |                  |                  |                  |                  |       |      |       |      |                  |
|-------|----------------------------------|---|------------------|------------------|------------------|------------------|------------------|-------|------|-------|------|------------------|
|       |                                  | TE <sub>11</sub>  | TM <sub>01</sub> | TE <sub>21</sub> | TM <sub>11</sub> | TE <sub>01</sub> | TE <sub>31</sub> |       |      |       |      |                  |
| 0     | Analytical                       | 1.543   |                  | 2.014            |                  | 2.555            |                  | 3.209 |      | 3.209 |      | 3.509            |
| 0.15  | <i>QuickWave-3D</i>              | 0.78  | 1.49             | 1.96             | 2.03             | 2.58             | 2.76             | 3.12  | 3.17 | 3.42  | 3.51 | 3.56             |
|       | Mode: quasi-...<br><i>FEMLAB</i> | TM <sub>01</sub>  | TE <sub>11</sub> | TM <sub>11</sub> | TE <sub>01</sub> | TE <sub>21</sub> | TM <sub>02</sub> | -     | -    | -     | -    | TE <sub>31</sub> |
|       |                                  | -   | 1.44             | -                | -                | -                | 2.78             | -     | -    | -     | -    | 3.66             |

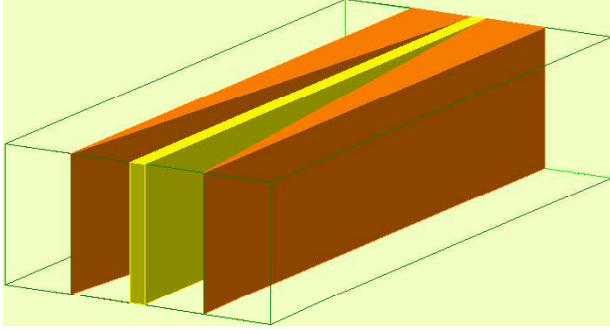


Fig. 2. Traveling wave applicator with centred heated layer and two symmetric dielectric wedges visualized by *QuickWave-3D*.

the phase coefficient and the reflection coefficient  $|S_{11}|$  have been computed by *QuickWave-3D*.

Simulations have been made for a piece of rectangular waveguide with the cross-sectional sizes  $a = 90$  mm (wide wall) and  $b = 45$  mm (narrow wall) and the length  $L = 200$  mm; the width of the centred processed material is  $s = 5$  mm. The wedges are considered to be lossless. In the input of the structure, their edges are located in the midpoints of the lateral spaces between the sample and the waveguide walls; the wedge's width is linearly increased along the waveguide (Fig. 2). This construction resembles the one suggested in [12] for making the electric field in a rectangular applicator more uniform along the direction of wave propagation.

The computed normalized propagation constant is given in Table 2, where  $\alpha$  is the attenuation coefficient. In *MicroWaveLab*, the finite element mesh with approximately 9,000 prismatic elements was used for the symmetrical one-quarter of the 3D structure with corresponding boundary conditions on the planes of symmetry. In *QuickWave-3D*, the construction was discretized into approximately 274,000 cells with a cell size of 1.5 mm for the entire construction. An agreement between the two computations seems to be reasonable. It turned out that reflections in this applicator depend on the dielectric constant of the (lossless) wedges in a hardly predictable manner. The dispersion characteristics of  $|S_{11}|$  possess resonances with different positions of the minima (Fig. 3); for example, at  $f = 2.45$  GHz, the level of reflections increases non-linearly by 15 dB with an increase of  $\epsilon_2$  from 2.1 to 9.0.

### Second example

*MicroWaveLab* has also been used for designing and modeling of the components for excitation of the dominant mode in the standard ridged waveguide (RW) and double-ridged waveguide (DRW) by a coaxial line. The use of the RW and DRW as the basic elements of microwave heating systems was reported, for example, in [13].

The modeled transitions consists of a short section of the standard RW or DRW (100 mm length) and the coaxial lines with various  $D/d$ , where  $D$  and  $d$  are the diameters of the external and the internal conductors respectively. The internal conductor is connected with the metal septum at  $l = 42$  mm from the short-circuit end wall (Fig. 4).

Simulations of the transitions have been carried out using the finite element mesh with about 19,000 tetrahedrals (*MicroWaveLab*) and with about 177,000 rectangular cells of the finite difference mesh (*QuickWave-3D*). Fig. 5 shows the reflection coefficient of the transitions in the frequency range surrounding 2.45 GHz. Both codes have revealed the resonant character of the graphs. Certain differences in the values of  $|S_{11}|$  can be justified by the nature of the computational approaches (*MicroWaveLab* is a circuit-solver whereas *QuickWave-3D* is a field-solver) and distinctions in modeling of the internal conductor, which turns out to be a critical parameter with respect to the reflection coefficient.

Table 2. Propagation Constant of the Dominant Mode in the Wedge Applicator for  $\epsilon_1 = 3.8 - i0.38$  ( $f = 2.45$  GHz)

| $\epsilon_2$ | Code                | $(\beta/k)_{11}$ | $(\alpha/k)_{11}$ | $(\beta/k)_{21}$ | $(\alpha/k)_{21}$ |
|--------------|---------------------|------------------|-------------------|------------------|-------------------|
| 2.1          | <i>MicroWaveLab</i> | 0.956            | 0.057             | 1.302            | 0.043             |
|              | <i>QuickWave-3D</i> | 0.959            | -                 | 1.284            | -                 |
| 3.8          | <i>MicroWaveLab</i> | 0.976            | 0.054             | 1.724            | 0.032             |
|              | <i>QuickWave-3D</i> | 0.976            | -                 | 1.691            | -                 |
| 9.0          | <i>MicroWaveLab</i> | 1.030            | 0.048             | 2.666            | 0.018             |
|              | <i>QuickWave-3D</i> | 1.036            | -                 | 2.612            | -                 |

$$\rho = (10^{0.05S_{11}} + 1)/(10^{0.05S_{11}} - 1) \quad (2)$$

where  $S_{11}$  (the reflection coefficient) is in dB, and the power of losses in a heated sample ( $W$ ) is [11]:

$$W = (1 - 10^{-0.1S_{11}} - 10^{-0.1S_{21}})^{0.5} \quad (3)$$

where  $S_{21}$  (the transmission coefficient) is also in dB.

### First example

Phase and attenuation coefficients of the rectangular applicator with the thin slab of the lossy material (complex relative DC is  $\epsilon_1 = 3.8 - i0.38$ ) and two auxiliary dielectric wedges ( $\epsilon_2$ ) have been determined with the aid of *MicroWaveLab*. The

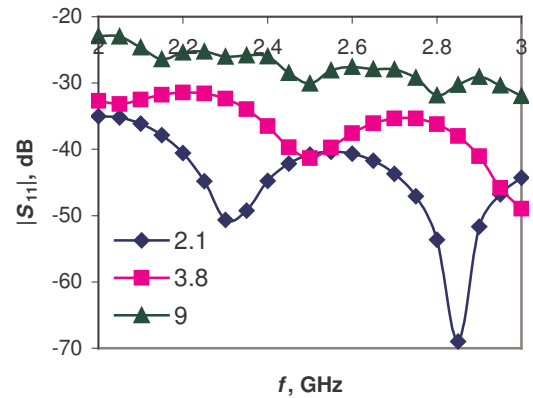


Fig. 3. Reflections in the wedge applicator for different DC of the wedges; computed by *QuickWave-3D*.

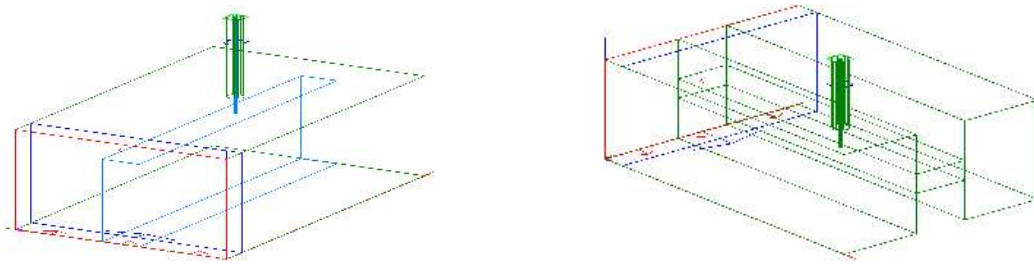


Fig. 4. Coax-to-RW (left) and coax-to-DRW (right) transitions visualized by *QuickWave-3D*'.

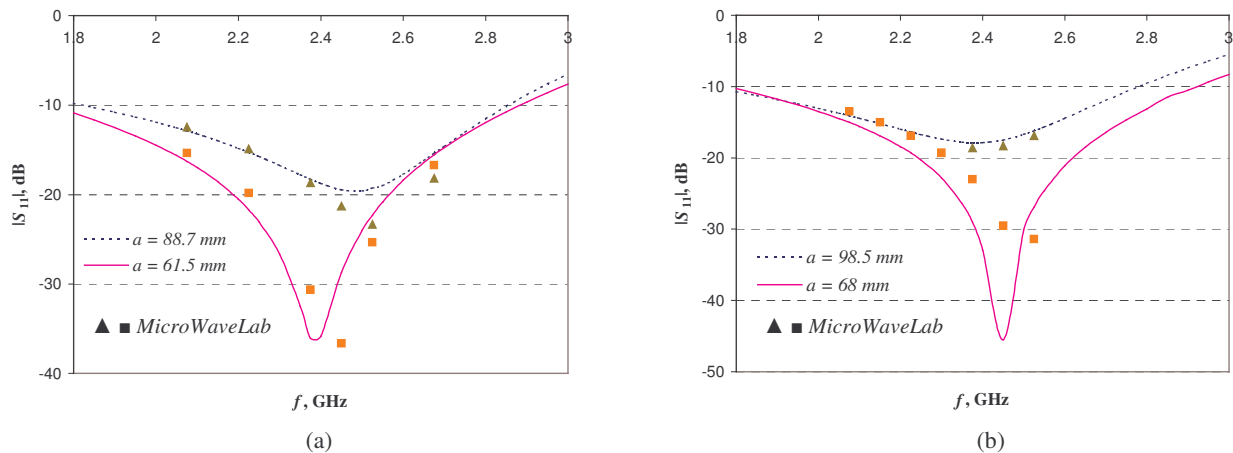


Fig. 5. Reflections in the transitions to the RW ( $D/d = 4.8$  for  $a = 61.5$  mm and  $D/d = 4.4$  for  $a = 88.7$  mm) (a) and the DRW ( $D/d = 4.72$  for  $a = 98.5$  mm and  $D/d = 5.3$  for  $a = 68$  mm) (b);  $d = 1$  mm: computed by *MicroWaveLab* and *QuickWave-3D*.

## CONCLUSION

Both considered finite element codes, *FEMLAB* and *MicroWaveLab*, have demonstrated rather limited options in the design of industrial systems of microwave power engineering. *FEMLAB* does not allow one to go beyond finding the cutoff frequencies of 2D structures with materials of relatively high DC. Although *S*-parameters determined by *MicroWaveLab* seem to be accurate, impossibility to compute and visualize patterns of the dissipated power appears to be a serious disadvantage in modeling microwave heating. *QuickWave-3D*, used for verification of the results, has confirmed its powerful capabilities beneficial for comprehensive analysis of microwave components and design of industrial systems.

## REFERENCES

1. V.V. Yakovlev, Commercial EM codes suitable for modeling of microwave heating – a comparative review, In: *Lecture Notes in Computational Sciences and Engineering*, Springer Verlag, 2001(to be published).
2. V.A. Mechenova and V.V. Yakovlev, Examining of contemporary electromagnetic software capable to model problems of microwave heating, *Submitted to the 8<sup>th</sup> AMPERE Conference in Microwave and HF Heating, Bayreuth, Germany, Sept. 2001*.
3. M. Mirotznik, Conformal EM analysis, *IEEE Spectrum*, vol. 25, No 4, pp. 84-85, April 1998.
4. P.O. Risman, A microwave oven model: examples of microwave heating computations, *Microwave World*, vol. 19, No 1, pp. 20-23, 1998.
5. M. Celuch-Marcysiak and W.K. Gwarek, Advanced features of FDTD modeling for microwave power applications, *Presented at the 35<sup>th</sup> Microwave Power Symposium, July 2000, Montreal, Canada*.
6. H. Marshall, V.A. Mechenova, and V.V. Yakovlev, Computer characterization of microwave high-power load, *Present Proceedings*.
7. M.S. Mirotznik, Finite element analysis marries Matlab, *IEEE Spectrum*, vol. 27, No 8, pp. 19-20, August 2000.
8. N. Marcuvitz, *Waveguide Handbook*, Peter Peregrinus Ltd., 1993
9. *MicroWaveLab*, User's Guide, Ansoft Corp., 1997.
10. B.C. Wadell, *Transmission line design handbook*, Artech House, 1991.
11. Ye.A. Vorob'ev, *Shielding of microwave constructions*, Moscow, Radio i Svyaz Publishing, 1979 (In Russian.)
12. L. Outifa, M. Delmotte, and H. Jullien, Dielectric and geometric dependence of electric field and power distribution in a waveguide heterogeneously filled with lossy dielectrics, *IEEE Trans. Microwave Theory Techn.*, vol. MTT-45, No 8, Pt. 1, pp. 1154-1161, August 1997.
13. V.A. Kolomeytssev, V.V. Komarov, and V.V. Yakovlev, Double-ridged traveling wave applicator for efficient microwave duplicating of fabric, *Proc. 31<sup>st</sup> Microwave Power Symposium, July 1996, Boston, MA*, pp. 159-160.