Modeling a microwave oven with Aether

Field Precision LLC
E mail: techinfo@fieldp.com
Internet: https://www.fieldp.com

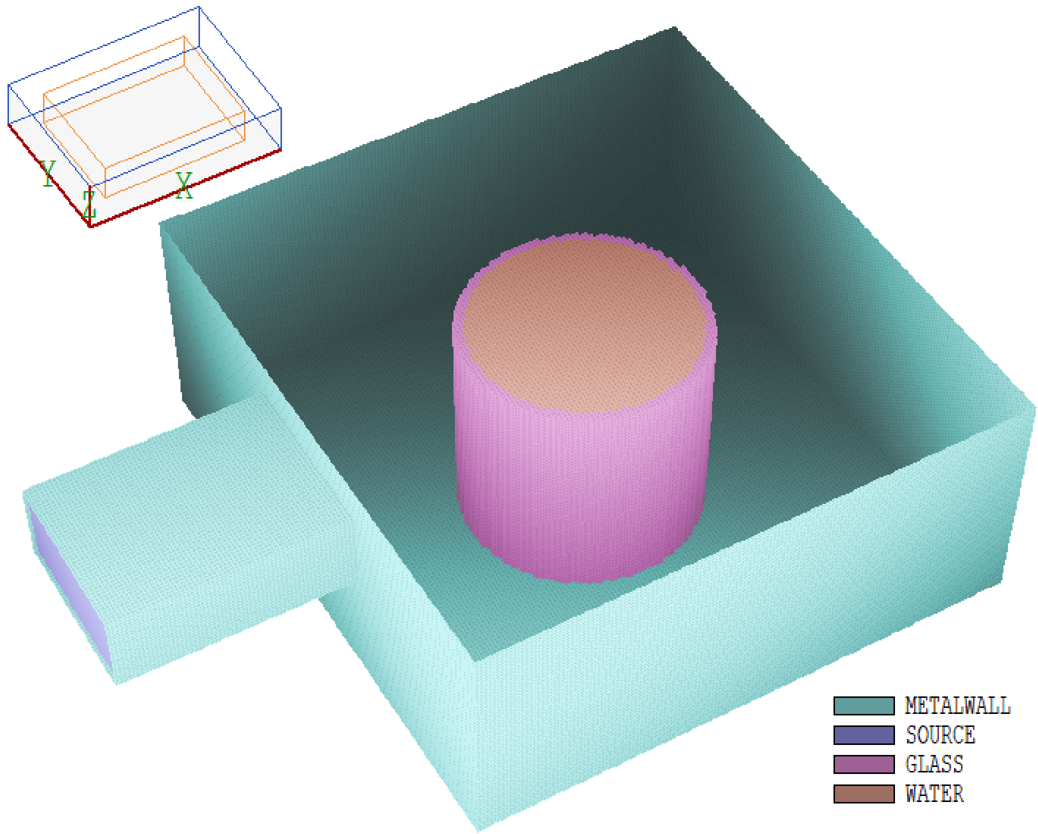

Figure 1: Cutaway view of the mesh showing the oven chamber and waveguide with a large pitcher of water. A WG8 waveguide carrying power in the TE_{10} mode enters from the left. Element size: 0.25 cm.

We had a recent inquiry about applying **Aether** to model a microwave drying system. As a demonstration, we made a calculation of radiation patterns and power transfer in a microwave oven. Figure 1 shows a cutaway view of the system, a Sharp Carousel oven chamber with power input from a WG8 (WR430) waveguide carrying a TE_{10} mode entering through the side wall. The chamber dimensions are 36.0 cm width along the front and back walls, 38.0 cm depth and 22.0 cm height. The waveguide dimensions are 11.0 cm width, 5.5 cm height and 15.0 cm length. The waveguide has a source layer at the entrance that generates the desired mode and absorbs reflected energy. The load is a water-filled glass pitcher with outer radius 7.5 cm, inner radius 7.0 cm and height 15.0 cm. The water depth is 14.5 cm. The frequency in all calculations is 2.45 GHz. As shown in Fig. 1, the x axis corresponds to position along the width and the direction of propagation, the y axis to position front to back and the z axis with height.

A preliminary calculation for the waveguide is described in the tutorial *Exciting a waveguide to drive microwave devices*[1]. The report has detailed information on the physical basis of the present

[1]https://www.fieldp.com/tutorials/WaveguideDrive.pdf

calculation, including the choice of source parameters and element size. The source generates 900 W when matched to an ideal load. The complete input file to define the mesh for this study, `MicrowaveOven.MIN`, is listed at the end of the report. In response, **MetaMesh** creates a regular mesh of cubic elements with side length 0.25 cm. With the exception of the source layer, the chamber and waveguide are surrounded by metal walls one element in thickness. A feature of interest in the file is the use of script directives to perform block operations. For example, the directives

```
#SHIFT 0.000   0.000   0.000
  ...
#ENDSHIFT
```

bracket the part sections that define the waveguide. The entrance position of the waveguide to the chamber can be varied by changing the y and z values in the `#SHIFT` command. A second `#SHIFT` section is included to move the water-filled pitcher to different positions in the chamber. In the listing, the pitcher is centered in the chamber with the bottom 1.0 cm above the floor.

An initial run was performed with the pitcher and water removed to illustrate the electromagnetic mode of an empty chamber. In this case, damping of the solution was provided solely by absorption in the waveguide source layer. An extended run length was required for the lightly-damped system to ensure the time-domain solution settled to an equilibrium before conversion to a frequency-domain form. The **Aether** input file `MicrowaveOvenEmpty.AIN` had the content:

```
* ---- CONTROL ----
Mode = RF
Mesh = MicrowaveOvenEmpty
DUnit =   100.0
Freq =   2.45E+09
NPeriod = 60
Parallel 4
* ---- CURRENT SOURCES ----
SMod(1) =        0.000
* ---- REGION PROPERTIES ----
Metal(1)
Epsi(2) =   1.00000E+00
Mu(2) =   1.00000E+00
Sigma(2) =   0.00000E+00
Epsi(3) =   1.00000E+00
Mu(3) =   1.00000E+00
Sigma(3) =   0.882
Jz(3,1) > 2.278E4*cos(0.2856*\$y)
* ---- DIAGNOSTICS ----
History =  23.000  0.00  11.00
Probe =    23.000  0.00  11.00  Ez
EndFile
```

The functions of most of the input commands were discussed in the waveguide tutorial. We will concentrate on features related to the control and monitoring of the solution convergence. Because of the light damping, the empty-chamber solution was set to run for 60 RF cycles. With 3 million elements and four-core parallel processing, the solution time was a little over 10 minutes. Two methods were employed to monitor convergence:

- The `History` command instructed the code to record temporal records of all field quantities at a specified point. The data were recorded in a file that could be analyzed with the **Probe** program included with **Aether**.
- The `Probe` command made a formatted record in the **Aether** listing file (`ALS`) of a specified field quantity at a given location. The record showed the time variation of the quantity and the relative change each quarter period

The spatial location in both commands is a point of maximum E_z in the empty chamber. Figure 2 shows the probe signals. The upper plot indicates that a steady state with small oscillations is attained. The lower signal confirms that the field value changes by less than 1% per quarter period at the run conclusion. The frequency-domain solution derived at the end of the run is illustrated in Fig. 3. The waveguide chamber supported a resonant mode with 36 regions of maximum electric field magnitude. The standing wave pattern in the waveguide indicates that all energy entering the oven chamber is reflected.

We now consider the solution with the water load in the chamber. The properties of the Pyrex glass are straightforward: $\mu_r = 1.0, \epsilon_r = 4.7$. Water properties are more complex. The material has two features that present challenges in numerical simulations:

- The high relative dielectric constant ($\epsilon_r \cong 80$) excludes electric fields and slows the propagation of electromagnetic radiation by a factor of about nine. Additionally, modes exhibit small scale features because the vacuum wavelength is reduced by the same factor.
- The dielectric properties are temperature dependent.

Figure 4 shows the real and imaginary parts of relative dielectric constant of liquid water as a function of temperature. For the initial time-domain **Aether** solution, the effect of the imaginary component ϵ_r'' is represented by a conductivity,

$$\sigma = 2\pi f \epsilon_0 \epsilon_r'' \ \ \text{S/m}. \tag{1}$$

At 2.45 GHz, the relationship is $\sigma = 0.1362\epsilon_r''$ S/m. At room temperature (20° C), Fig. 4 and Eq. 1 imply that $\epsilon_r \cong 79.0$ and $\sigma \cong 1.4$ S/m.

Although the solution with the load has higher damping, convergence is slowed by the reduced rate of radiation penetration into the water volume. Again, the run time is taken as 60 RF periods. A probe at the center of the water volume shows a stable solution with small oscillations at the end. Figure 5 is a plot of $|\mathbf{E}|$ in the vertical midplane. The field distribution is quite different from that of the unloaded chamber (Fig. 3). The distribution in the waveguide indicates that it carries

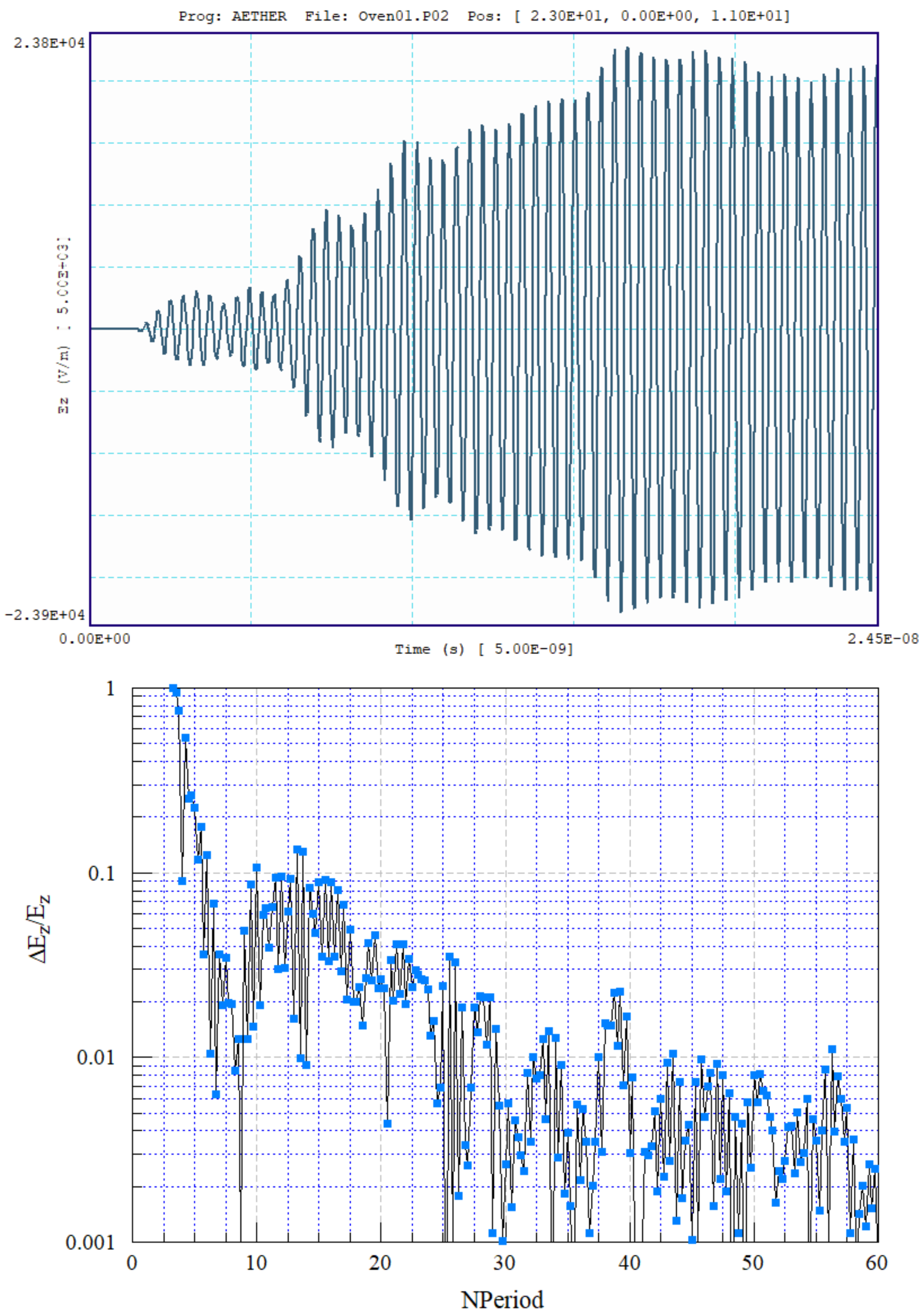

Figure 2: Solution convergence for an empty chamber. Probe position: $x = 23.0$ cm, $y = 0.0$ cm and $z = 11.0$ cm. Upper: $E_z(t)$. Lower: $\Delta E_z/E_z$ as a function of elapsed RF periods.

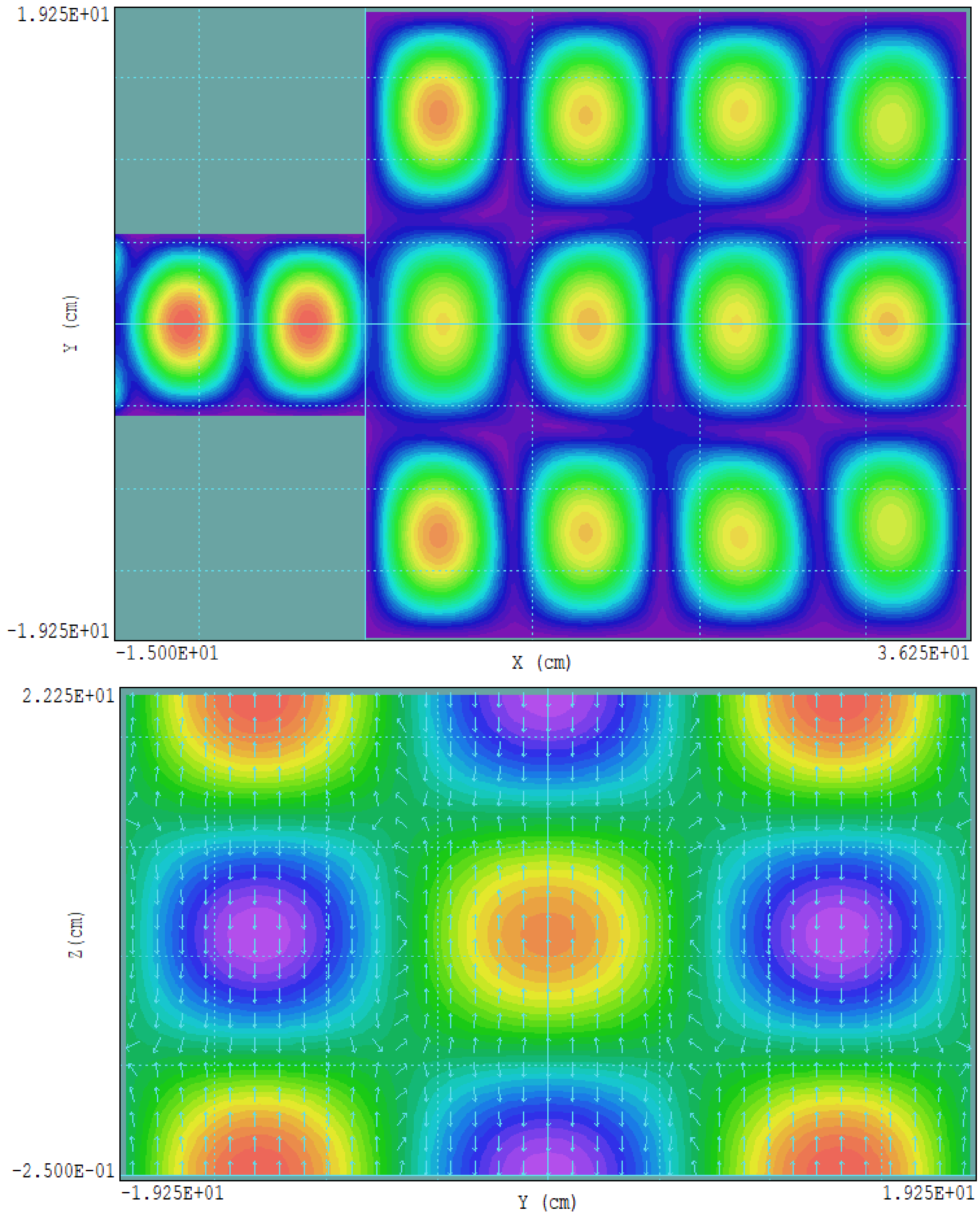

Figure 3: Field variation in the unloaded microwave oven. The maximum field amplitude is about 250.0 V/m. Upper: View from above, $|\mathbf{E}|$ in the plane $z = 0.0$ cm. Lower: View along propagation direction, E_z at phase 90.0^o in the plane $x = 23.0$ cm with field direction arrows.

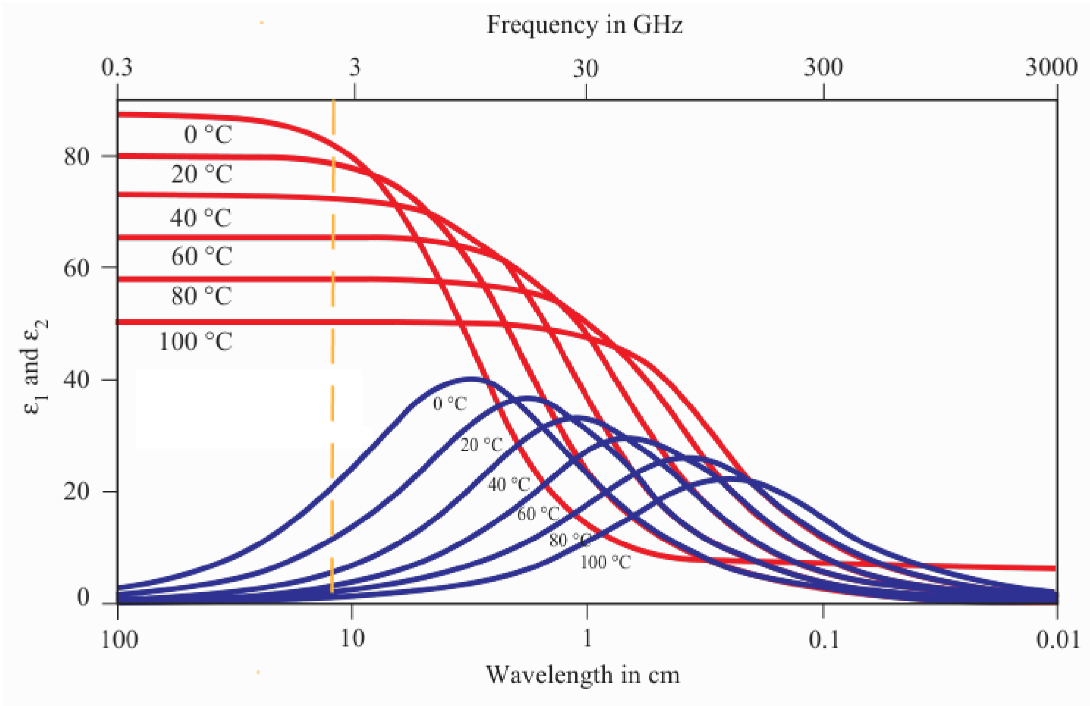

Figure 4: Real and imaginary parts of the relative dielectric constant for water. Dashed line at 2.45 GHz.

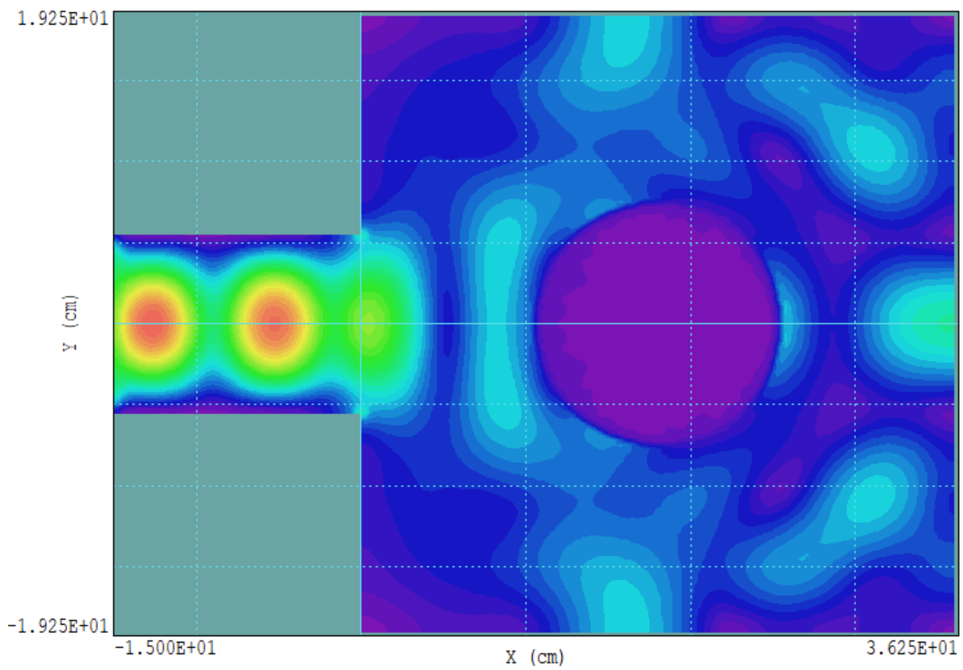

Figure 5: Microwave oven chamber with a pitcher of water at 20°C. Plot of the amplitude of $|\mathbf{E}|$ in the plane $z = 0.0$ cm .

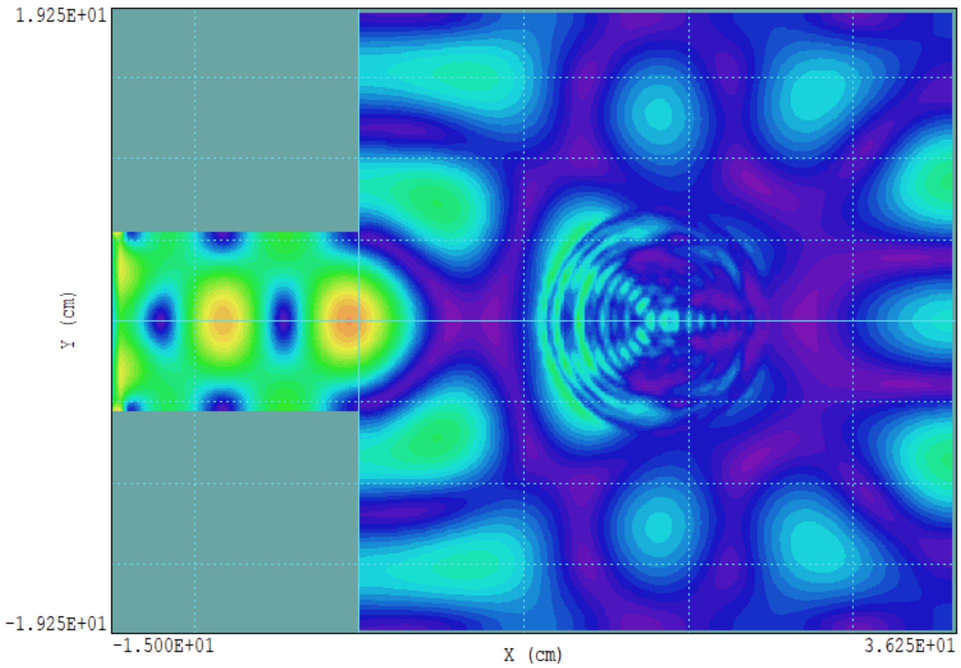

Figure 6: Plot of $|\mathbf{H}|$ at 0.0° phase offset and 20.0°C in the plane $z = 0.0$ cm.

predominantly a traveling wave from the source to the water load. Integrals in the **Aether** listing file show that the total power absorbed in the water is 767.4 W. A scan of $Ez(x)$ along the center of the waveguide gives maximum and minimum values of 215.2 V/cm and 107.3 V/cm, giving a standing wave ratio of $V_{SWR} = 2.0$. In turn, this value implies that the reflected wave amplitude is about 33% of the incident wave and the reflected power is 85.2 W. At 60 °C, the water dielectric properties are $\epsilon_r = 65.0$ and $\sigma = 0.55$ S/m. With these parameters, the solution gives an absorbed power of 653.1 W. The field distributions in the water volume are complex. Figure 6 shows a plot of $|\mathbf{H}|$ at 0.0° phase offset and 20.0°C in the plane $z = 0.0$ cm. For comparison, the free-space wavelength in water at that temperature is $\lambda = 1.38$ cm.

File: MicrowaveOven.MIN

```
GLOBAL
  XMesh
    -15.000  36.250  0.250
  End
  YMesh
     -19.250 19.250  0.250
  End
  ZMesh
      -0.250 22.250  0.250
  End
  RegName(1): MetalWall
  RegName(2): Air
  RegName(3): Source
  RegName(4): Glass
  RegName(5): Water
  Smooth 0
END
PART
  Region: MetalWall
  Name: MetalWall
  Type: Box
  Fab:  51.250  38.500  22.500
  Shift: 10.625  0.000  11.000
END
PART
  Region: Air
  Name: OverChamber
  Type: Box
  Fab:  36.000  38.000  22.000
  Shift: 18.000  0.000  11.000
END
* Move the waveguide
#SHIFT 0.000   0.000   0.000
PART
  Region: Air
  Name: Waveguide
  Type: Box
  Fab: 15.000  11.000  5.500
  Shift: -7.500  0.000  11.000
END
PART
  Region: Source
  Name: Source
  Type: Box
  Fab: 0.250  11.000  5.500
  Shift: -14.875  0.000  11.00
END
#ENDSHIFT
* Move the water-filled pitcher
#SHIFT 0.000   0.000   1.000
PART
  Region: Glass
  Name: Glass
  Type: Cylinder
  Fab: 7.500 15.000
  Shift: 18.000  0.000  7.500
END
PART
  Region: Water
  Name: Water
  Type: Cylinder
  Fab: 7.000 14.500
  Shift: 18.000  0.000  7.750
END
#ENDSHIFT
ENDFILE
```