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Exciting a waveguide to drive microwave devices

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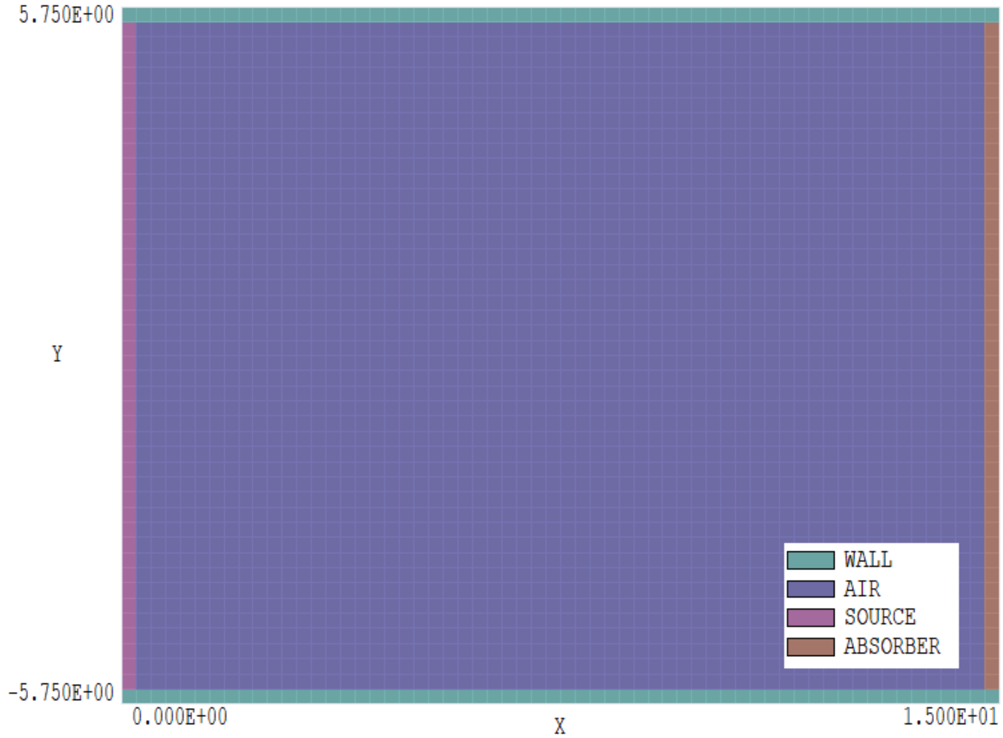

Figure 1: Waveguide geometry viewed from above (z direction). Dimensions in centimeters.

Aether is a versatile computer package to simulate electromagnetic equipment in both the time and frequency domains. This tutorial illustrates code techniques to generate a rectangular waveguide mode to drive devices like microwave ovens. In preparation for a subsequent oven calculation, we will take the frequency as $f = 2.45$ GHz and approximate the geometry of a WG8 (WR430, R22) waveguide[1]: width $a = 11.0$ cm and height $b = 5.5$ cm. Figure 1 shows the mesh geometry. The **MetaMesh** input file to define the system, WG8.MIN, is listed at the end of this report. The `GLOBAL` section has two features specific to **Aether** calculations:

- A regular (rather than conformal) mesh is required. The command `Smooth 0` instructs the code not to alter the shapes of the box elements.
- A uniform element size of 0.25 cm is applied in all directions to create cubic elements. There is little advantage to rectangular elements or variations in element size because the time step for numerical stability is determined from the smallest element dimension.

The calculation represents a waveguide section of length 15.0 cm along the propagation direction (x). A source layer one element in thickness fills the input and an absorbing layer fills the exit. The solution volume has length 15.0 cm, width 11.5 cm and height 6.0 cm to accommodate a the guide metal wall in the transverse directions one element in thickness. The mesh generation procedure is

[1]https://www.everythingrf.com/tech-resources/waveguides-sizes

to fill the entire solution volume with elements that have the property of metal then to carve out a box representing the air space. Finally, layers are defined at the entrance and exit to represent the source and absorber.

The **Aether** calculation is controlled by the file WG8.AIN, with the content:

```
* ---- CONTROL ----
Mode = RF
Mesh = WG8
DUnit =   100.0
Freq =   2.45E+09
NPeriod =  10
* ---- 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
* AbsLayer(3) = 0.25
Sigma(3) =   0.882
* Jz(3,1) > 1.0*cos(0.2856*$x)
Jz(3,1) > 2.278E4*cos(0.2856*$x)
Epsi(4) =   1.00000E+00
Mu(4) =   1.00000E+00
* AbsLayer(4) = 0.25
Sigma(4) =   0.882
* ---- DIAGNOSTICS ----
History =  2.50  0.00  0.00
History =  14.00  0.00  0.00
Probe =  14.00  0.00  0.00  Ez
EndFile
```

It was prepared interactively with the setup dialog in **Aether** and modified with a text editor. The parameter *NPeriod* in the Control section sets the duration of the time-domain calculation before conversion to a complex-number frequency-domain solution. It must be long enough to ensure that the solution relaxes to a steady state. In this heavily-damped example, the duration of 10 periods is more than sufficient. In the RF mode, the command

```
SMod(1) = 0.000
```

sets the phase of the sinusoidal drive function for Source 1 to 0.0^o.

The goal is to generate a TE_{10} wave carrying 900 W of power. The vacuum wavelength is $\lambda = c/f = 12.24$ cm. In the coordinate system of Fig. 1, the electric field variation is

$$E_z = E_0 \cos\left(\frac{\pi y}{a}\right). \tag{1}$$

The magnetic field component normal to the propagation direction is

$$H_y = -\left(\frac{E_0}{Z_m}\right) \cos\left(\frac{\pi y}{a}\right). \tag{2}$$

The mode impedance is

$$Z_m = \frac{\eta}{\sqrt{1-(\lambda/2a)^2}}. \tag{3}$$

where $\eta = 377.3\ \Omega$ for air. The wave group velocity is

$$v_g = c\,\sqrt{1-(\lambda/2a)^2}. \tag{4}$$

Substituting values for this calculation, we find $Z_m = 453.3\ \Omega$ and $v_g/c = 0.831$. Finally, Eq. 2 implies that the current in the source layer should vary as

$$j_z = j_0 \cos(\pi y/a). \tag{5}$$

to excite the TE_{10} mode preferentially.

We can now discuss the values for the region properties in the **Aether** input file. Elements that comprise the wall (region 1) are set to the `Metal` property (ideal field excluder). The internal volume (region 2) has the parameters of air or vacuum, $\epsilon_r = 1.0$, $\mu_r = 1.0$ and $\sigma = 0.0$ S/m. Note that there are commented commands in the definition of the source (region 3) and downstream absorber (region 4). We will make multiple runs, using the code to determine some required numerical values. The commands for the absorbing layer are

```
Epsi(4) =   1.00000E+00
Mu(4) =   1.00000E+00
* AbsLayer(4) = 0.25
Sigma(4) =   0.882
```

In an initial calculation, the command

```
AbsLayer(4) = 0.25
```

instructs **Aether** to find the conductivity of an ideal absorbing layer of thickness 0.25 cm. The listing file (`ALS`) for the run reports a value $\sigma = 1.0618$ S/m. As described in the **Aether Reference Manual**, the value applies when a wave is incident at 90°. The effective thickness of the layer increases when the incidence angle θ is less than 90.0/dg. In this case, the conductivity should be multiplied by $\sin\theta$. The $TE_1 0$ mode of a waveguide can be viewed as a superposition of two waves that propagate at an angle with respect to the propagation axis given by

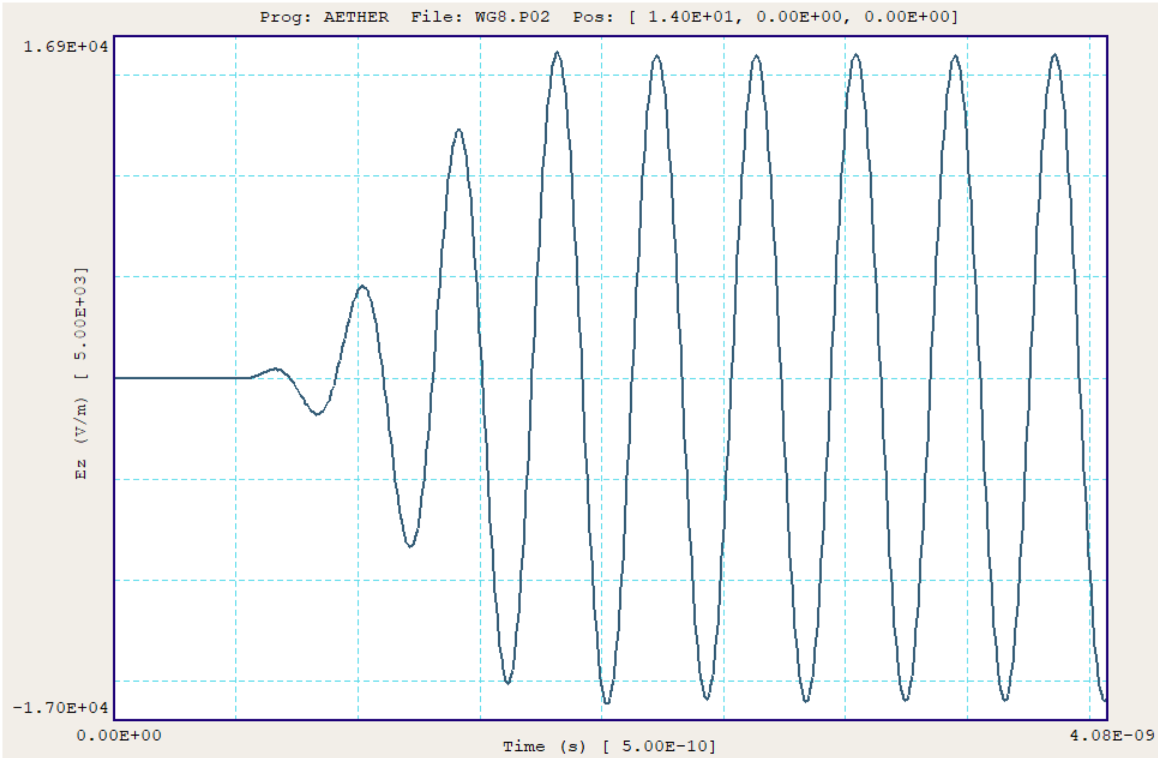

Figure 2: Vertical electric field $E_z(t)$ at the waveguide center near the absorbing layer, time domain solution.

$$\sin\theta = \frac{v_g}{c}. \tag{6}$$

Equation 6 implies that the best layer conductivity is $\sigma = 1.0618 \times 0.831 = 0.882$ S/m, the value used in subsequent calculations. The source layer is also defined as a absorber to capture reflected wave components. In addition, it is assigned a drive current density following Eq. 5. In an initial calculation, the current density amplitude is set to an arbitrary value, $j_0 = 1.0$ A/m^2. The `ALS` file shows the power deposited in the absorber is 1.734×10^{-6} W. To a achieve transmitted power of 900.0 W, the current density amplitude is changed to

$$j_0 = \sqrt{\frac{900.0}{1.734 \times 10^{-6}}} = 2.278 \times 10^4 \ \ \mathrm{A/cm}^2. \tag{7}$$

The calculation run time is about one second. We conclude by inspecting the results and checking how they compare to theoretical predictions. Figure 2 shows a plot of the vertical electric field $E_z(t)$ during the initial time domain solution measured at the center of the waveguide near the absorber. The highly-damped solution has clearly settled into equilibrium, confirming the validity of the frequency-domain conversion. Figure 3 shows plots of the vertical electric field in the plane $z = 0.0$ cm. The measured distance between the peaks of 7.4 cm equals half the guide wavelength. The wavelength is λ_g14.8 cm. The theoretical prediction is

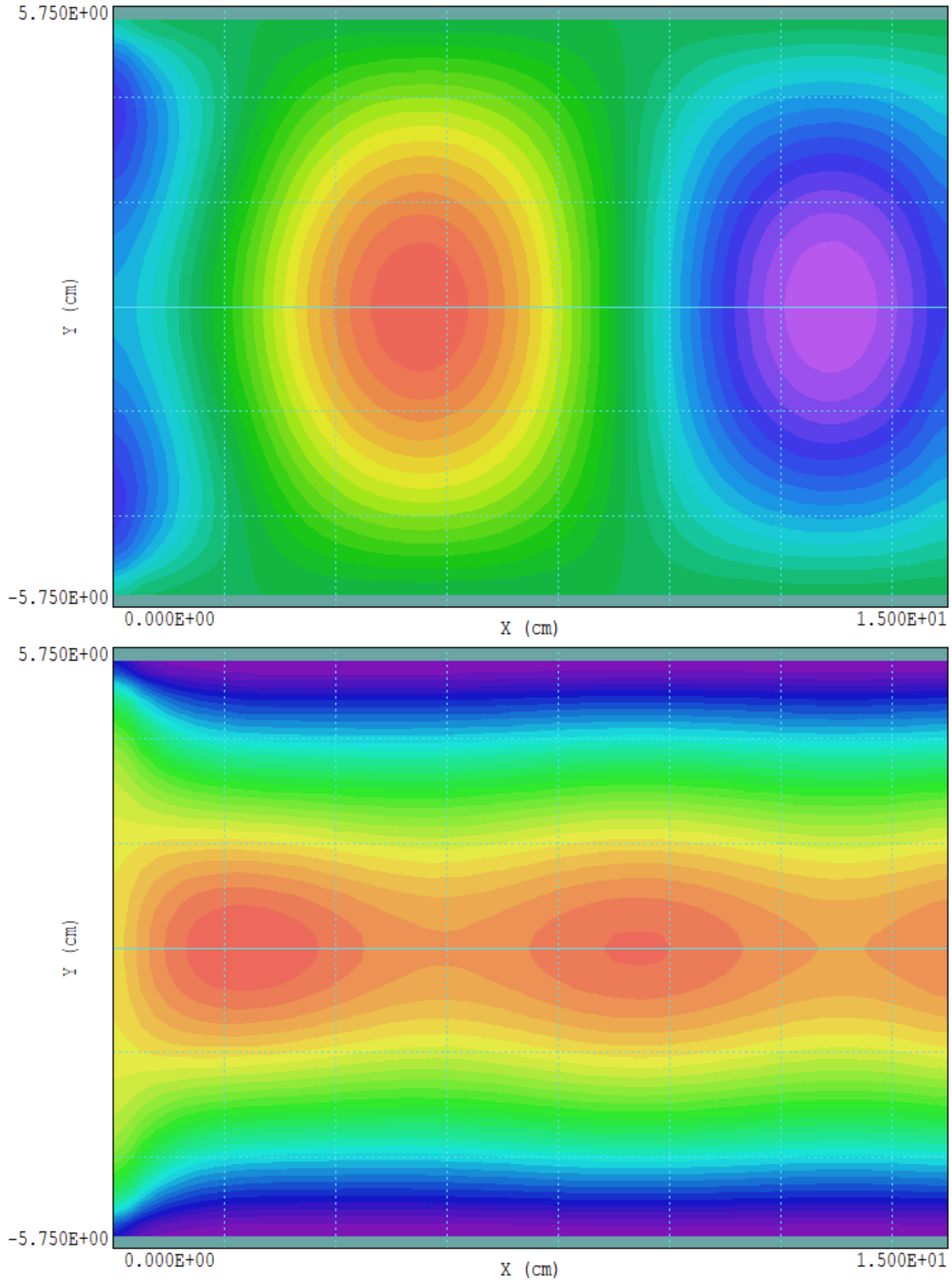

Figure 3: Vertical electric field in the plane $z = 0.0$ cm. Upper: E_z at a relative phase of 45° with contour limits ±170.6 V/m. Lower: $|E_z|$ with contour limits 0.0 to 170.6 V/m.

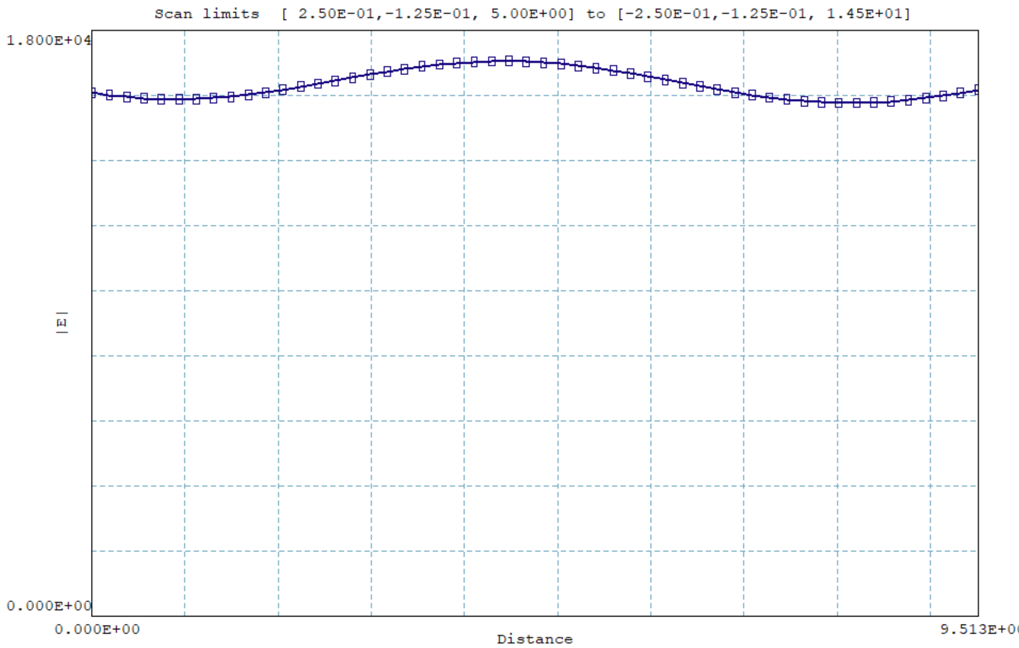

Figure 4: Scan of $|E_z(x)|$ along the waveguide centerline.

$$\lambda_g = \lambda \frac{c}{v_g} = 14.7 \ \ \text{cm}. \tag{8}$$

A scan in x along the center of the lower figure gives a maximum value $|E_z| = 170.6$ V/m and a minimum value 158.9 V/cm for an average value of 164.8 V/cm. A similar scan of $|H_y|$ gives an average value 0.362 A/cm. The predicted guide impedance is

$$Z_g = \frac{|E_z|}{|H_y|} = 455.1 \ \ \Omega, \tag{9}$$

within 0.4% of the theoretical value. Finally, note that the field magnitude in the lower plot of Fig. 3 has a variation that does not occur for a perfect traveling wave. This feature indicates that there is a wave component reflected from the absorbing layer that interferes with the forward wave. The voltage standing wave ratio is $V_{SWR} = 170.6/158.9 = 1.074$. The ratio of the reflected wave electric field amplitude to that of the forward wave is given by:

$$\frac{V_{SWR} - 1}{V_{SWR} + 1} \tag{10}$$

The implication is that the reflected wave amplitude is only 3.4% of the incident field amplitude. Therefore, the downstream termination layer absorbs 99.9% of the incident radiation.

File: WG8.MIN

```
GLOBAL
  XMesh
      0.000  15.000  0.250
  End
  YMesh
     -5.750   5.750  0.250
  End
  ZMesh
     -3.000   3.000  0.250
  End
  RegName(1): Wall
  RegName(2): Air
  RegName(3): Source
  RegName(4): Absorber
  Smooth 0
END
PART
  Region: Wall
  Name: MetalWall
  Type: Box
  Fab:  15.000  11.500  6.000
  Shift: 7.500   0.000  0.000
END
PART
  Region: Air
  Name: Air
  Type: Box
  Fab:  15.000  11.000  5.500
  Shift: 7.500   0.000  0.000
END
PART
  Region: Source
  Name: Source
  Type: Box
  Fab:  0.250  11.000  5.500
  Shift: 0.125   0.000  0.000
END
PART
  Region: Absorber
  Name: Absorber
  Type: Box
  Fab:     0.250  11.000  5.500
  Shift: 14.875  0.000  0.000
END
ENDFILE
```