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Three-Dimensional Simulation of Traveling-Wave Tube Cold-Test Characteristics Using CST MICROWAVE STUDIO

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Summary

The electromagnetic field simulation software package CST MICROWAVE STUDIO (MWS) was used to compute the cold-test parameters—frequency-phase dispersion, on-axis impedance, and attenuation—for a traveling-wave tube (TWT) slow-wave circuit. The results were compared to experimental data, as well as to results from MAFIA, another three-dimensional simulation code from CST currently used at the NASA Glenn Research Center (GRC). The strong agreement between cold-test parameters simulated with MWS and those measured experimentally demonstrates the potential of this code to reduce the time and cost of TWT development.

Introduction

CST MICROWAVE STUDIO (MWS) is electromagnetic field simulation software for the analysis and design of components such as antennas, filters, transmission lines, couplers, and resonators. To suit a variety of applications, the software contains four different simulation techniques: a Transient Solver, a Frequency Domain Solver, an Eigenmode Solver, and a Modal Analysis Solver. The simulations described in this report use the Eigenmode Solver. MWS has a user-friendly, Windows-based interface, making it simple to model three-dimensional (3D) structures. The code includes the option of user defined or automatic meshing and features a Perfect Boundary Approximation (PBA) method. This method allows mesh cells to be partially filled for a more accurate representation of shapes that do not conform to the Cartesian (x,y,z) or cylindrical (r,θ,z) coordinate systems, compared to MAFIA (solution of MAxwell's equations by the Finite Integration Algorithm) (refs. 1 and 2), which represents shapes with only rectangular or triangular mesh cells. MWS features optimizer and parameter sweep tools. In addition, procedures can be automated with Visual Basic for Applications (VBA) macros (ref. 3).

In this report, the accuracy and efficiency of MWS for simulating cold-test parameters is established for a ferruled coupled-cavity traveling-wave tube (TWT) circuit. In addition, compared to measured data, the MWS simulations are shown to be more accurate and more computationally efficient than previously calculated MAFIA results.

CST MICROWAVE STUDIO

A screenshot of the MWS Windows-based graphical user interface is shown in Figure 1. When first using MWS, the Quick Start Guide from the Help menu is useful. It lists the steps involved in using a particular solver.

Initialization

The first step for eigenmode analysis is to define units of length, frequency, and time in the Units window under the Solve menu. Note, a unit of length should be selected such that all critical parameters of the structure are greater than one. The background material must also be entered under the Solve menu. If the structure is entirely encased in metal, the background material can be set to *PEC* (Perfect Electrical Conductor). Next, the frequency range of interest must be defined. Lastly, variables for the structure dimensions can be entered in the Parameters box under the Edit menu. If a variable is assigned to each dimension and only the variables are used to define the structure, the circuit can be changed by simply editing the values of the variables in the Parameter List.

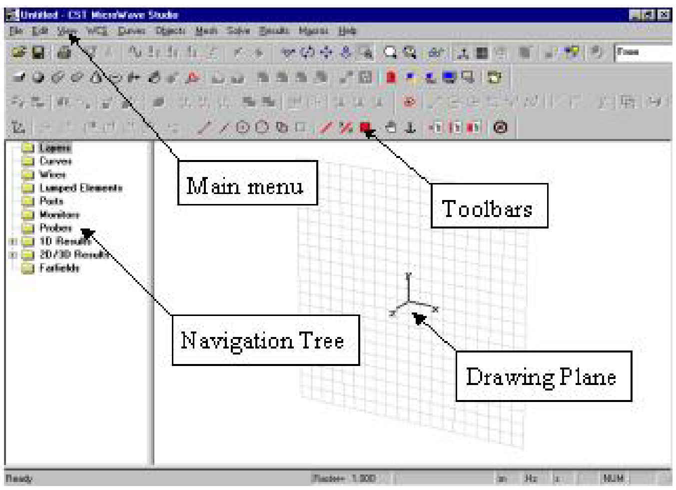

Figure 1.—MWS user interface.

Modeling the Structure

The first step in modeling a structure is to define the materials it consists of. Under the Objects → New Layer menu, the user can define the name, type, material properties, and color of new layers. The next step in defining the structure is to construct its geometry using the 3D shape tools under the Object menu. Some useful tools are the brick, cylinder, sphere, cone, and extrude. Coordinates can be entered graphically using the mouse or numerically using the Tab or Esc keys. Again, it is very useful to define the shapes in terms of parameters for easy editing.

Once an object has been defined, it can be transformed under the Objects → Transform Shape menu. The transform operations available are: translate, scale, rotate, and mirror. A very useful transformation is to check the *multiple objects* option while translating an object. This effectively copies and pastes the object, eliminating the need to define repetitive parts of the geometry.

In MWS, a complex shape can be created by combining simple shapes. If overlapping shapes are defined, MWS will prompt the user for a Boolean operation to combine them. The Boolean operations available for combining shapes are addition, subtraction, intersection, and insertion. The user may select *none*, but this is only recommended if one of the shapes is *PEC* or if the two shapes touch, but do not overlap (refs. 3 and 4).

While defining the structure, changing the view can be very helpful to check the model. The user may zoom in and out with the dynamic zoom or zoom in on a particular section with the box zoom. Pressing the space bar will return the view to the best fit of the structure. The structure can be turned with the free rotate and planar rotate tools. The user can also take advantage of the cutting plane tool to view a cutaway version of the model. Additionally, by selecting layers from the Navigation Tree, the structure can be viewed one layer at a time.

One of the most useful features of MWS is the History List, which is found under the Edit menu. This list shows all previous operations in chronological order. From the list, any operation can be added, hidden, deleted, or edited.

Mesher

MWS uses the Finite Integration Method with the Perfect Boundary Approximation for spatial discretization. The mesh is produced by an automatic mesh generator, which ensures a good compromise between accuracy and simulation time. Through the Mesh Properties dialog box, the user can enter values for the number of mesh lines per wavelength, the lower mesh limit, the ratio limit, and the adaptation limit. In addition, this dialog box lists the number of mesh lines in the x, y, and z directions and the total number of mesh cells. Note, the Parameter and History lists cannot be edited and macros cannot be run while in the Mesh View.

MWS also gives users the option to create a manual mesh. This is done by entering new fixpoints at all the boundaries of the structure. Intermediate fixpoints can then be inserted in between existing fixpoints. Once the user has defined a manual mesh, any changes made to the geometry of the structure will result in an error. Therefore, if the user intends to vary the parameters of a structure, automatic meshing should be used.

Eigenmode Solver

A major disadvantage of MWS, compared to MAFIA, is that the current version (3.4) does not have the ability to simulate periodic boundary conditions which allow the user to simulate a single circuit period and set an arbitrary phase advance in the longitudinal direction. Using MWS, the user must model several periods and truncate the longitudinal boundaries with electric (E) or magnetic (M) walls to force a discrete phase advance (ref. 5). An electric wall is a boundary that simulates a perfect conductor. This forces the electric field to be perpendicular to the wall. At a magnetic wall boundary the magnetic field is forced to be perpendicular to the wall. These boundary conditions can be input from the Solve menu.

Symmetry planes are another useful tool that can be activated from this dialog box. Symmetries can be set in the yz, xz, or xy planes and can either be magnetic or electric. For each symmetry plane used, the simulation time is reduced by a factor of two.

The Eigenmode Solver parameters can be set from the Solve menu. These parameters include the number of modes desired, accuracy, frequency estimate, and the number of iterations. Unlike MAFIA, setting a larger number of modes than desired does not increase precision in MWS. Changing the accuracy, frequency estimate, or the number of iterations may improve results, but at the cost of increased simulation time. Generally, these parameters can be left at their default settings. However, if improved accuracy is needed, ref. 3 suggests setting the frequency estimate to approximately 1.2 times the highest expected frequency. Once all the parameters are set, the solver can be started.

Post Processing

MWS allows the user to view the electric and magnetic fields of the calculated modes through the 2D/3D Results → Modes folder in the Navigation Tree. The cutting plane tool is very useful for getting a better view of the fields. The Plot Properties dialog box can be accessed under Results → Vector Plot or by right clicking with the mouse on the Drawing Plane. Here the plot type, phase, and number of objects plotted can be edited.

Under the Results menu, the user can access a simulation summary by selecting View Logfiles → Solver Logfile. This file contains units, a mesh summary, boundary conditions, modal frequency results, and the solver time associated with the simulation. The modal frequency results are used to create the dispersion curve, as will be discussed later. Another useful item located in the Results menu is the Loss and Q Calculation tool. Here the user can enter values for the conductivity and permeability of each layer that was set to PEC during the solver run (the conductivity or tangent delta for the dielectric layers have to be set before the solver run) and then calculate the power loss and Q factor of the circuit. The power loss is used to calculate the attenuation.

MWS contains a VBA editor and debugger; therefore, the majority of post-processing can be done very efficiently with user-defined macros. The user can take advantage of standard VBA language elements as well as the CST MWS language specific extensions. Particularly useful commands are GetFieldVector and GetTotalLoss, which are used for the automation of the impedance and attenuation calculations, respectively.

The ability to export data and images is included in MWS. To export bitmap images, select BMP under the File → Export menu; or for immediate use, select Edit → Copy View to Clipboard. To export the field data, there are several different methods available. The user can select the field of interest from the 2D/3D Results → Modes folder in the Navigation Tree and then export the data by selecting Plot Data (ASCII) under the File → Export menu. Note, the amount of data exported by this method is proportional to the number of arrows selected in the Plot Properties dialog box. If the user is only interested in analyzing the fields in one dimension of the circuit, the VBA code macro.910 – 1D Plot of 2D/3D Data Fields, can be executed to do this. Users can acquire this and several other useful macros from CST. Please note that these macros are supplied in addition to the standard MWS package; therefore technical support is limited.

Analysis

Following the dispersion simulation procedure described in ref. 5, the frequency-phase dispersion characteristics were obtained by modeling two- and three- cavity configurations of the structure. The different eigenmodes were forced by axially truncating the different cavity configurations with electric and magnetic boundaries, which corresponds to simulating standing waves with an integral number of half-wavelengths (phase shifts of π) in the length of the circuit. The cavity configurations and boundary conditions required to obtain several resonant frequencies are shown in Table 1. The on-axis interaction impedance for the n^{th} RF space harmonic and the attenuation per cavity were obtained using the procedures outlined in ref. 5.

TABLE 1.—BOUNDARY CONDITIONS FOR RESONANCE AT VARIOUS PHASE SHIFTS PER CAVITY

Cavities	Boundary conditions[a]	Phase shift per cavity[b], $\beta_1 L$, deg
2	M,E	225,315 (315,225)
3	M,E	210,270,330 (330,270,210)
3	E,E	240,300,360 (300,240)

[a]Electric wall, E; magnetic wall, M.
[b]Slot-mode phase shifts are in parentheses.

Results

Dispersion Simulations

The ferruled coupled-cavity circuit [ref. 6] has coupling slots which are rotated 180° at alternating cavity partition walls. Ferrules, hollow posts surrounding the beam hole, concentrate the RF electric field in the beam region to increase the on-axis interaction impedance of the cavity. The ferruled coupled-cavity circuit was created using cylinder and brick shapes. The structure is fully encased in metal, so the background material was set to *PEC*. The metal layer which includes the circuit elements was also set to *PEC* and the air layer was defined as *normal* with permittivity (ε) = 1 and permeability (μ) = 1. The primary motivation for simulating the ferruled coupled-cavity circuit was to compare MWS's performance to that of MAFIA. In doing so, the validity of MWS's model could be verified. Therefore, manual meshing was used in this circuit to create a grid with a cell resolution of 53 by 53 in the transverse (xy) plane and of 29 cells per cavity in the longitudinal (z) plane. This is the exact mesh used in the MAFIA simulations. The lines of the mesh were spaced as equally as possible with grid boundaries matching major geometrical features such as the beam hole and ferrules. The boundary conditions were set according to Table 1.

The resonant frequencies computed with MWS and MAFIA are compared with fitted experimental data (ref. 7) normalized to the center frequency of operation for the cavity and slot modes in Table 2 and in Figure 2. Compared with the experimental data, the MWS results are consistently lower by an average of 0.43 percent for the cavity mode and an average of 0.09 percent for the slot mode. In comparison, for the same grid resolution, the MAFIA results are consistently lower than the experimental results by an average of 0.86 percent for the cavity mode and of 0.92 percent for the slot mode. Therefore, the MWS simulations show better agreement with measured data, particularly at higher frequencies.

TABLE 2.—RESONANT FREQUENCY PERCENT ERROR FOR THE FERRULED COUPLED-CAVITY CIRCUIT

Phase shift per cavity, $\beta_1 L$, deg	MAFIA cavity mode frequency difference, $\|\Delta f\|$, percent	MWS cavity mode frequency difference, $\|\Delta f\|$, percent	MAFIA slot mode frequency difference, $\|\Delta f\|$, percent	MWS slot mode frequency difference, $\|\Delta f\|$, percent
210	0.94	0.41	0.97	0.11
225	0.95	0.42	0.96	0.12
240	0.95	0.43	0.98	0.16
270	0.88	0.37	0.96	0.13
300	0.80	0.35	0.84	0.03
315	0.78	0.38	0.84	0.06
330	0.73	0.40	0.91	0.05
360	0.81	0.65	-	-

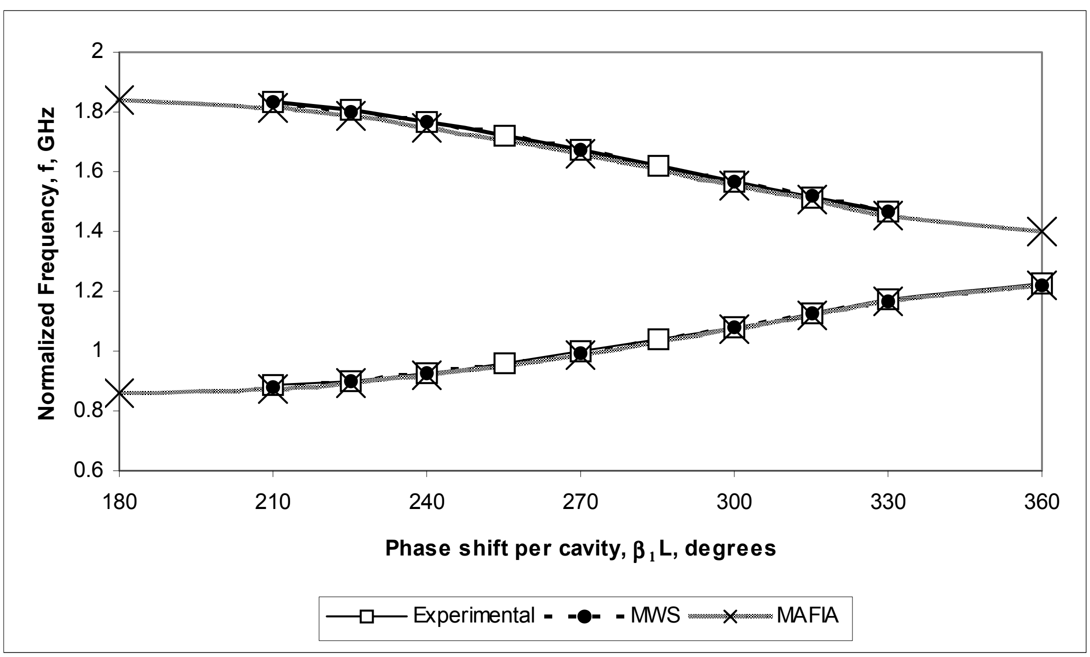

Figure 2.—Normalized experimental data, MWS and MAFIA simulations of dispersion for cavity and slot modes of the ferruled coupled-cavity circuit.

Impedance Simulations

Table 3 and Figure 3 compare the on-axis interaction impedances normalized to that at the operating frequency calculated with MWS and MAFIA with those measured experimentally (ref. 7). The MWS results match the experimental results well, having an average absolute difference of 3.39 percent between 210° and 315°. They show slightly better agreement than the MAFIA results, which have an average absolute difference from the experimental data of 3.77 percent between 210° and 315°. Note that both MWS and MAFIA had poor results for a phase shift of 330° per cavity. This may be due to some error in determining the group velocity where the dispersion curve starts to flatten or it may be due to experimental error.

TABLE 3.—ON-AXIS INTERACTION IMPEDANCE PERCENT ERROR FOR THE FERRULED COUPLED-CAVITY CIRCUIT

Phase shift per cavity, $\beta_1 L$, deg	MAFIA impedance difference, $\lvert\Delta K_1\rvert$, percent	MWS impedance difference, $\lvert\Delta K_1\rvert$, percent
210	3.77	0.50
225	7.22	5.77
240	5.45	5.87
270	1.98	2.93
300	0.71	0.38
315	3.47	4.86
330	18.24	17.69

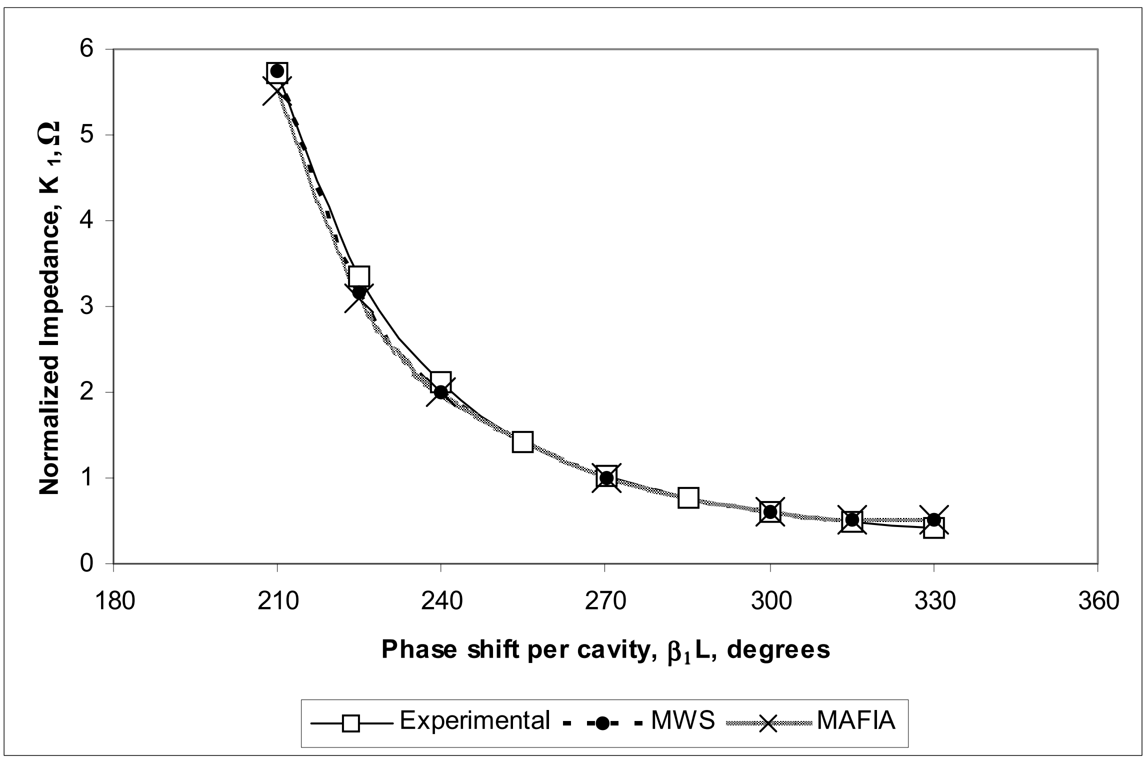

Figure 3.—Normalized experimental data, MWS and MAFIA simulations of on-axis interaction impedance for the ferruled coupled-cavity circuit.

Attenuation Calculations

The attenuation of the ferruled coupled-cavity circuit was calculated according to the procedure outlined in ref. 5. Note that the value of conductivity that matches the experimental data is lower than the theoretical conductivity since actual circuit losses are greater than theoretically predicted values due to machining, oxidation, and surface irregularities (ref. 8). Table 4 and Figure 4 compare MWS and MAFIA simulated results with the experimentally estimated results normalized to the value at the center frequency of operation.

TABLE 4.—ATTENUATION PERCENT ERROR FOR THE FERRULED COUPLED-CAVITY CIRCUIT OVER THE CIRCUIT BANDWIDTH

Normalized frequency, f, GHz	MAFIA attenuation difference, $\|\Delta\alpha\|$, percent	MWS attenuation difference, $\|\Delta\alpha\|$, percent
0.96 (lower band edge)	4.52	2.47
1.00 (center frequency)	0.59	1.77
1.04 (upper band edge)	6.01	5.58

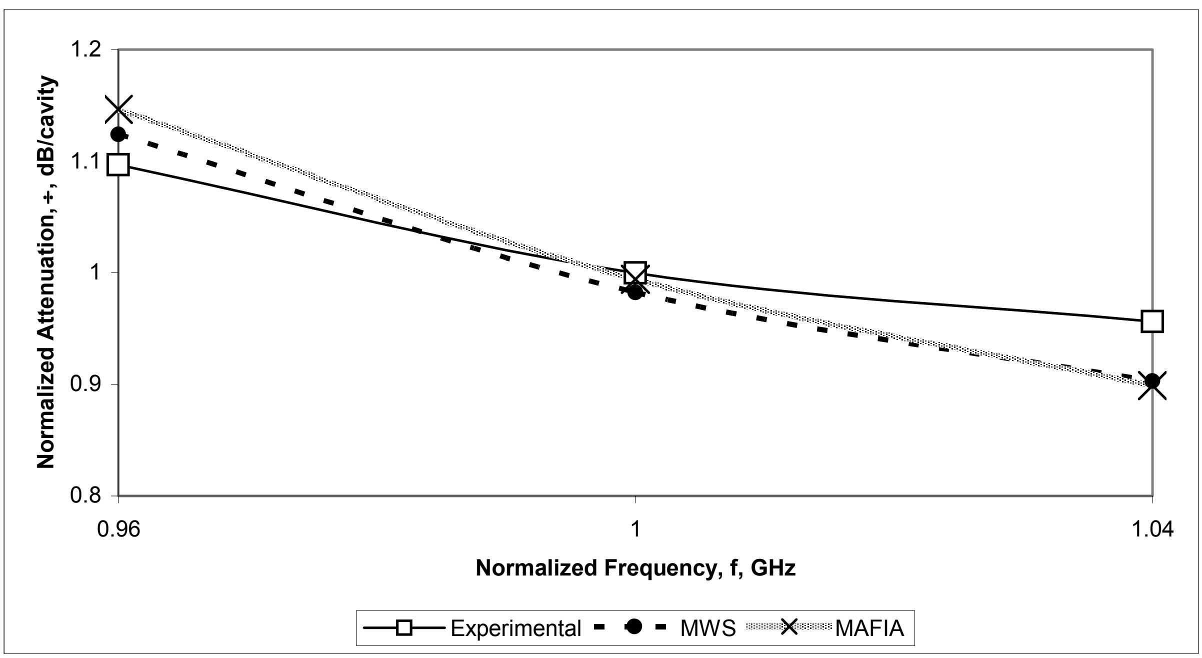

Figure 4. —Estimated experimental data and MWS and MAFIA simulations of attenuation for the ferruled coupled-cavity circuit over the bandwidth of operation.

Conclusions

A ferruled coupled-cavity TWT circuit was simulated in MWS. Methods for calculating frequency-phase dispersion, on-axis interaction impedance, and circuit attenuation in MWS were developed. The results of these methods proved to be more accurate and less time-consuming than MAFIA simulations. For the dispersion calculations, excellent agreement with experimental results was obtained; the ferruled coupled-cavity circuit model resulted in an average absolute frequency difference of 0.26 percent. Using MAFIA, an average absolute frequency difference of 0.89 percent was achieved. The on-axis interaction impedance and attenuation also showed good agreement. For the ferruled coupled-cavity circuit, MWS on-axis interaction impedance results had an average absolute difference of 3.39 percent between 210° and 315° while MAFIA had an average absolute difference of 3.77 percent. The MWS attenuation results had an average absolute difference of 3.27 percent while the MAFIA attenuation results had an average absolute difference of 3.71 percent. In general, the time required for MWS simulations on a 1.4 GHz dual processor PC was a factor of four times smaller than the time required for MAFIA simulations on a Sun Ultra 80 workstation. These results demonstrate the accuracy of MWS simulations and their capability to reduce expensive and time-consuming experimental cold-test procedures in the design process for TWT slow-wave circuits.

References

1 Weiland, T.: On the Numerical Solution of Maxwell's Equations and Applications in the Field of Accelerator Physics. Part Accel., vol. 15, 1984, pp. 245-292.

2 Weiland, T.: On the Unique Numerical Solution of Maxwellian Eigenvalue Problems in Three Dimensions. Part. Accel., vol. 17, 1985, pp. 227-242.

3 CST MICROWAVE STUDIO Version 3 Getting Started. CST Computer Simulation Technology, Darmstadt, Germany, Jan. 2001.

4 CST MICROWAVE STUDIO Version 3 Tutorials. CST Computer Simulation Technology, Darmstadt, Germany, Jan. 2001.

5 Maruschek, J.W.; Kory, C.L.; and Wilson, J.D.: Generalized Three-Dimensional Simulation of Ferruled Coupled-Cavity Traveling-Wave Tube Dispersion and Impedance Characteristics. NASA TP-3389, 1993.

6 Gilmour, Jr., A.S.: Principles of Traveling Wave Tubes. Artech House, Boston, 1994, p. 375.

7 A.L. Rousseau, 1988, Hughes Aircraft Co., Torrence, California, personal communication.

8 Tischer, F.J.: Experimental Attenuation of Rectangular Waveguides at Millimeter Wavelengths. IEEE Trans., vol. MTT-27, no. 1, Jan. 1979, pp. 31-37.

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