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Summary

The three-dimensional simulation code MAFIA was used to compute the cold-test parameters—frequency-phase dispersion, beam on-axis interaction impedance, and attenuation—for two types of traveling-wave tube (TWT) slow-wave circuits. The potential for this electromagnetic computer modeling code to reduce the time and cost of TWT development is demonstrated by the high degree of accuracy achieved in calculating these parameters. Generalized input files were developed for ferruled coupled-cavity and TunneLadder slow-wave circuits. These files make it easy to model circuits of arbitrary dimensions. The utility of these files was tested by applying each to a specific TWT slow-wave circuit and comparing the results with experimental data. Excellent agreement was obtained.

Introduction

MAFIA (solution of Maxwell's equations by the Finite Integration Algorithm), version 3.10, is a powerful, three-dimensional electromagnetic code written in FORTRAN 77. This code is used for the computer-aided design of fully three- and two-dimensional electromagnetic devices, such as magnets, radiofrequency (RF) cavities, waveguides, and antennas. The Finite Integration Technique algorithm in MAFIA produces a set of finite-difference matrix equations for the electric and magnetic field vectors in the structure under study. The solution of these equations yields static, frequency-domain or time-domain solutions of Maxwell's equations (refs. 1 and 2).

The code includes 10 multisection modules that have the interrelationships shown in figure 1. For this report, only four of MAFIA's modules were used to calculate the cold-test parameters: the M (mesh generator), R (matrix generator for E), E (eigenmode solver), and P (postprocessor) modules. The remaining modules are the S (static solver), T2 and T3 (two-dimensional and three-dimensional time-domain solvers, respectively), TS2 and TS3 (two-dimensional and three-dimensional particle-in-cell codes, respectively), and W3 (frequency-domain, eddy-current solver) modules.

Traditionally, hardware cold-testing procedures have been used to determine the RF phase shift (frequency-phase dispersion), interaction impedance, and attenuation of a cavity. In this report, the practicality and efficiency of four of the MAFIA modules described in the previous paragraph were demonstrated by using MAFIA instead of experimental cold testing to obtain these parameters for ferruled coupled-cavity and TunneLadder traveling-wave tube (TWT) slow-wave circuits. The MAFIA results were compared with experimental cold-test results with excellent agreement, indicating that time-consuming and costly hardware cold-test measurements can be avoided. Data from MAFIA simulations can be used as input for a coupled-cavity TWT RF-beam interaction computer model (ref. 3) that simulates the output RF power and beam characteristics of a TWT.

This report also demonstrates the utility of using generalized MAFIA input files for ferruled coupled-cavity or TunneLadder TWT circuits. By simply replacing the existing dimensions with the dimensions of the circuit of interest, one can readily determine dispersion curves, beam on-axis interaction impedance, and attenuation characteristics for any ferruled coupled-cavity or TunneLadder TWT circuit.

A symbols list is provided in appendix A to assist the reader.

Background

The first MAFIA simulation reported here models the ferruled coupled-cavity slow-wave circuit of Hughes Aircraft Company's 961HA TWT (which was developed under NASA Contract NAS3-25090, ref. 4). The 961HA is a 70-W, 59- to 64-GHz TWT for intersatellite communications. The design is a revision of an earlier model, the 961H (ref. 5), which had a slot mode oscillation problem caused by the interaction of the electron beam with the slot mode at the upper cutoff frequency.
Rousseau et al. solved this problem (ref. 5), by adjusting the dimensions of the coupling slot in the 961HA to shift the slot mode down in frequency.

The second simulation modeled the 29-GHz TunneLadder TWT slow-wave circuit (which was fabricated and tested by Varian Associates, Inc., under contract to NASA Lewis Research Center, NAS3–22466, ref 6). The TunneLadder is a millimeter-wave TWT with a fundamental forward-wave, slow-wave circuit derived from the Karp circuit (refs. 7 and 8). Operating with a fundamental forward wave allows a higher rate of gain with distance than with backward wave interaction. Karp (ref. 9) showed that this advantage can be further enhanced in the TunneLadder circuit by forming the ladder into a quasi-elliptical shape, thereby creating a tunnel through which the beam passes (fig. 3). This tunnel is supported by diamond dielectric chips in a double-ridge waveguide. The resulting TunneLadder circuit is a narrow bandwidth, high-efficiency, and mechanically sturdy millimeter wave amplifier. Its dimensions are listed in table II.

Two 29-GHz TunneLadder TWT’s, fabricated and tested by Varian Associates, Inc., successfully demonstrated the high gain per length and interaction efficiency attainable with this narrow bandwidth circuit. The length of the slow-wave circuit was only 2.86 cm, and the 10-kV, 215-mA electron beam was focused with a single permanent magnet. The first TWT (S/N 101) achieved a peak saturated RF output power of 365 W, a very high interaction efficiency of 17.0 percent, and a 3-dB bandwidth of 2.3 percent under pulsed operation. Because of an apparent vacuum leak, S/N 101 could not be operated under continuous wave conditions. The second TWT (S/N 102) was operational at continuous wave, with a peak saturated RF output power of 316 W, an interaction efficiency of 13.8 percent, and a bandwidth of 2.8 percent. The lower values of efficiency and power may have been due to a poor match in the
TABLE II.—DIMENSIONS OF VARIAN TUNNELADDER TWT CIRCUIT
[See fig. 3. All dimensions in millimeters.]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric height, a</td>
<td>0.2540</td>
</tr>
<tr>
<td>Dielectric width, b</td>
<td>0.3810</td>
</tr>
<tr>
<td>Dielectric length, f</td>
<td>0.2032</td>
</tr>
<tr>
<td>Ridge height, c</td>
<td>1.0160</td>
</tr>
<tr>
<td>Ridge width, d</td>
<td>1.9050</td>
</tr>
<tr>
<td>Waveguide gap, g</td>
<td>1.2446</td>
</tr>
<tr>
<td>Ladder length, h</td>
<td>0.1524</td>
</tr>
<tr>
<td>Ladder thickness, t</td>
<td>0.0635</td>
</tr>
<tr>
<td>Gap length, m</td>
<td>0.1651</td>
</tr>
<tr>
<td>Period, p</td>
<td>0.3175</td>
</tr>
<tr>
<td>Tunnel primary radius, r1</td>
<td>0.4300</td>
</tr>
<tr>
<td>Tunnel secondary radius, r2</td>
<td>0.3048</td>
</tr>
<tr>
<td>Side section height, s</td>
<td>3.2766</td>
</tr>
<tr>
<td>Side section width, w</td>
<td>0.8890</td>
</tr>
</tbody>
</table>

Despite these problems, the experimental results confirmed the high gain per length, high interaction efficiency, and narrow bandwidth characteristics predicted for the TunnelLadder circuit.

MAFIA Code

Input files from the four MAFIA modules used are given in appendixes B to I. The input files of appendixes B to E contain the full command terms, and the input files of appendixes F to I contain some abbreviated command terms that illustrate MAFIA's ability to recognize truncated commands. The interpretation of these abbreviations will be obvious to the user.

M, the Mesh Generator

The first step in simulating the dispersion, the beam on-axis interaction impedance, and the attenuation of a circuit is to model the structure using M, the mesh generator module of MAFIA. In this demonstration, a mesh was created for both circuits with the lines of the mesh as equally spaced as possible. The ratio of the largest to the smallest mesh size must not be too large because convergence problems may occur.

Both circuits were modeled with the grid boundaries matching the major geometrical features. Appendixes B and F show the generalized M module input files for the coupled-cavity and the TunnelLadder circuits, respectively. In the #general section, the scale command is used to scale the input dimensions to the actual size of the structure. The define command is used to assign the dimensions of the various circuit attributes to variable names that are used throughout the input files.

The circuits are modeled by using the various sections available in the M module of the MAFIA code: that is, #cylinder, #brick, #washer, and #ecylinder. Each material used is given a number. Later, the physical properties of these materials are defined in the R module.

To view a structure's geometries, the user can open a virtual graphics workstation within the M module and create a two- or
three-dimensional plot. Such plots allow the user to examine the structure at any cut or angle, verifying that it is properly modeled. The plots are created in the #2dplot, #3dplot, and #volumeplot sections of M. Before the mesh generator information is passed to the other modules of MAFIA, it must be stored in a mafia file. Along with all other file handling, this task is performed in the #file section.

In addition to the mafia file type, MAFIA recognizes log, command, and print files. The files listed in appendixes B to I are command files, which have a .com extension. These files pass input directly to MAFIA, providing an alternative to keyboard input. The two file types that are opened in the command files of appendixes B to I are the mafia and print types, which have .drc and .prn extensions, respectively. The mafia files are direct-access files where the calculations are stored, and the print files are optional files that can contain the output, making it possible for the user to examine the run simulation results, including any errors that have occurred. For example, the command at the head of appendix B,

```
#file name=fer2m action=open type=print status=unknown execute
```

opens a file named fer2m.prn that contains the output information from the mesh generator. (The equal signs are included here for clarity, but can be omitted in the input files.) The file section is opened again later in appendix B with

```
#file name=fer2 action=open type=magma status=unknown execute
```

This command opens fer2.drc, a mafia file that stores the data necessary for the other modules of MAFIA. Placing an end command at the end of an input file terminates the session and saves all important data to the allocated mafia file. This file is opened in each successive module and accumulatively stored with data.

R, the Matrix Generator for E

Module R is used to generate the matrix for calculating the eigenmodes in E. The R input files for each of the circuits are listed in appendixes C and G. Initially, the #file section must be used to open the mafia file that was written by M. If this mafia file is opened with the same name in all modules, intermediate results will accumulate within the file, saving time and space because the file will not have to be named and renamed in each module.

In the #material section, material properties are defined for each material number used in the M module. The numbers 0 and 1 are defined as a vacuum and a perfect conductor, respectively, in both of the R input files (appendixes C and G). Material 2 of the TunnelLadder geometry is defined as diamond with a dielectric constant of 5.5 (appendix G). This material is used for the dielectric chips that support the quasi-elliptical beam tunnel of the circuit.

The #boundary section is used to define the boundary conditions at the mesh boundaries. A boundary can be set as an electric or magnetic wall or as periodic. An electric wall is a boundary that simulates a perfect conductor with the electric field perpendicular to the wall. At a magnetic wall boundary, the tangential magnetic field is zero and the magnetic field is perpendicular to the wall.

Setting the boundary to be periodic activates the quasi-periodic boundary condition of MAFIA, which defines a fixed-phase advance for a uniform periodic structure. There are several benefits associated with the quasi-periodic boundary condition. First, the dispersion diagram can be generated from a model of a single axial period of the structure. Because only one period is modeled, the mesh can have a finer resolution. (Because of its alternating coupling slots, the ferruled coupled-cavity circuit has a period that is two cavities long.) In addition, many points can be calculated on the dispersion diagram, allowing for a high degree of accuracy in the frequency versus phase advance relationship and, consequently, in the group velocity.

After the materials and boundary conditions have been defined, the #matrix section of R is used to generate the system matrix of the eigenvalue problem.

E, the Eigenmode Solver

The #file section must be used again to open the mafia (.drc) file containing the M and R module data (appendixes D and H). It is also necessary to open a print (.prn) file to examine the results of E, because this is where the eigenmode information will be listed. Information is then entered in the #solver section. Here the number of modes desired can be specified, as well as the accuracy, frequency estimate, number of iterations, and other parameters. Once the execute command is given in this section, MAFIA begins to calculate the requested eigenmode information.

P, the Postprocessor

The postprocessor module of MAFIA, P, is interconnected with all the MAFIA modules (fig. 1). The #file section is used to open the mafia file that contains the results stored from the other modules (appendixes E and I). The postprocessor reads these results and can both display them graphically and perform secondary calculations. Secondary calculations include field energy and power loss, which are parameters used to calculate the beam on-axis impedance and attenuation.
Analysis

Dispersion Simulation

The frequency-phase dispersion characteristics of the slow-wave circuits were obtained by using the quasi-periodic boundary condition of MAFIA. This feature of the code allows the user to choose a fixed-phase advance per circuit cavity in the direction of periodicity. This parameter is defined in \( R \), the matrix generator for \( E \), as \( z_{\text{phase}} \) (see appendixes C and G), and the resonant frequencies for the given phase condition are calculated with \( E \), the eigenmode solver. Because the phase advance can be set to any value and the corresponding resonant frequencies for this phase shift per cavity will be calculated, an exceptionally accurate dispersion curve can be formed. This is critical in calculating the group velocity with dependable precision.

Experimentally, the frequency-phase dispersion characteristics are calculated by measuring the resonant frequencies in a truncated circuit section. The resonances correspond to standing waves, such that there are an integral number of half wavelengths (phase shifts of \( \pi \)) in the circuit length. No resonance is seen at 180° because the field pattern is shorted out by the shorting planes at the ends (ref. 10).

Impedance Simulation

The beam on-axis interaction impedance for the \( n \)th RF space harmonic (ref. 11) is defined as

\[
K_n = \frac{E_n^2}{2\beta_n^2 P_{RF}}
\]

where \( E_n \) is the beam on-axis electric field magnitude of the \( n \)th space harmonic, and \( \beta_n \) is the axial phase constant of the \( n \)th space harmonic defined by

\[
\beta_n = \frac{\phi + 2\pi n}{L}
\]

where \( \phi \) is the phase shift per cavity in radians of the fundamental space harmonic, \( n \) is the space harmonic order, and \( L \) is the length of one cavity. \( P_{RF} \) is the time-averaged RF power flow defined by

\[
P_{RF} = Wv_g
\]

where \( v_g \) is the group velocity and \( W \) is the time-averaged stored electromagnetic energy per unit length,

\[
W = \frac{W_T}{NL}
\]

with \( W_T \) the total energy in \( N \) cavities.

In the ferruled coupled-cavity TWT circuit, the beam is synchronous with only the first RF space harmonic. In the TunneLadder slow-wave circuit, the beam is synchronous with only the fundamental RF space harmonic. Thus in equation (1), we need to calculate only the first \((n = 1)\) and the fundamental \((n = 0)\) space harmonic terms for the ferruled coupled-cavity and TunneLadder circuits, respectively.

Calculating the beam on-axis interaction impedance with MAFIA is similar to experimental methods where frequency-phase dispersion characteristics are determined by measuring the resonant frequencies in a section of circuit that is shorted at both ends. Truncating the walls with either an electric or magnetic wall in MAFIA simulates standing waves in the length of the circuit. Table III lists the cavity configurations and boundary conditions required to obtain several resonant frequencies of the first forward RF space harmonic of the cavity mode (for the ferruled circuit) and of the fundamental RF space harmonic of the symmetric ladder mode (for the TunneLadder circuit). For each combination of cavity configuration and boundary conditions, the phase shifts per cavity for the resulting resonant frequencies are listed in the order of increasing frequency for the ferruled circuit, with the corresponding phase shifts for the TunneLadder circuit listed in the adjacent column.

### Table III — Boundary Conditions for Resonance at Various Phase Shifts per Cavity

<table>
<thead>
<tr>
<th>Cavities</th>
<th>Boundary conditions</th>
<th>Phase shift per cavity, ( \beta_L ), deg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ferruled circuit</td>
</tr>
<tr>
<td>2</td>
<td>magnetic electric</td>
<td>225, 315</td>
</tr>
<tr>
<td>3</td>
<td>magnetic electric</td>
<td>210, 270, 330</td>
</tr>
<tr>
<td>3</td>
<td>electric electric</td>
<td>240, 300</td>
</tr>
</tbody>
</table>
To determine the electric field space harmonic magnitude, \( E_1 \) or \( E_0 \), we perform a Fourier analysis (ref. 12) on the total on-axis axial electric field \( E_{\text{tot}} \). \( E_{\text{tot}} \) can be printed through the \#print section of the P module. The effective field as seen by the electron beam is the peak value of the particular space harmonic with which the beam is synchronous. For a traveling wave, this value \( E_n \) is half that calculated with MAFIA for a standing wave \( E_{nS} \) (ref. 13), so the value needed for equation (1) is

\[
E_n = \frac{1}{2} E_{nS}
\]  

(5)

To obtain \( W_T \) for equation (4), we use the \#energy section of the P module to calculate the total time-averaged electromagnetic field energy for a standing wave \( W_S \). The commands are listed in appendixes E and I. The total energy for a traveling wave is half that calculated for a standing wave (see appendix J), so the total energy of equation (4) is

\[
W_T = \frac{1}{2} W_S
\]  

(6)

Therefore, the total electromagnetic energy per unit length for a traveling wave \( W \) is

\[
W = \frac{1}{2} \frac{W_S}{NL}
\]  

(7)

and the total RF power flow can be defined as

\[
P_{RF} = \frac{1}{2} \frac{W_S}{NL} v_g
\]  

(8)

The group velocity of equation (3) is defined as

\[
v_g = \frac{\partial \omega}{\partial \beta_n}
\]  

(9)

and is extracted from the dispersion curve, which is plotted with frequency \( f \) (in hertz) versus phase shift per cavity \( \beta, L \) (in radians). Using these parameters yields \( v_g \) expressed as

\[
v_g = 2\pi L \frac{\partial f}{\partial (\beta_n L)}
\]  

(10)

Thus, the beam on-axis interaction impedance calculated with MAFIA can be expressed as

\[
K_n = \frac{E_{nS}^2 NL}{4\beta_n^2 W_S v_g}
\]  

(11)

**Attenuation Simulation**

The circuit attenuation is calculated by using the same truncation method used for the impedance simulations. Table III lists the values of phase shift per cavity for which this attenuation is calculated. The attenuation of a cavity is defined in decibels per unit length as (ref. 14)

\[
\alpha = 8.686 \frac{P_L}{2P_{RF}}
\]  

(12)

where \( P_L \) is the total power loss per unit length

\[
P_L = \frac{P_{LT}}{NL}
\]  

(13)

and \( P_{LT} \) is the total power loss for a traveling wave in \( N \) cavities. The postprocessor input files (appendixes E and I) contain the information needed to calculate the attenuation with MAFIA. The total time-averaged electromagnetic energy for a standing wave \( W_S \) is calculated as before in the \#energy section of P, and the total power loss for a standing wave \( P_{LS} \) is usually calculated in the \#losses section. The total power loss for a traveling wave is half that calculated for a standing wave (see appendix J):

\[
P_{LT} = \frac{1}{2} P_{LS}
\]  

(14)

Therefore, the attenuation in decibels per unit length can be expressed as

\[
\alpha = 4.343 \frac{P_{LS}}{W_S v_g}
\]  

(15)

and the attenuation in decibels per cavity can be expressed as

\[
\alpha = 4.343 \frac{P_{LS} L}{W_S v_g}
\]  

(16)
For the loss calculations, the conductivity must be supplied in the material section (see appendixes E and I). Also, for the case of a dielectric material (such as the diamond chips in the TunneLadder circuit), the loss tangent of the material must be defined in the material section and the power losses for this material will be calculated in the energy section.

Results

The ferruled coupled-cavity slow-wave circuit of the Hughes 961HA TWT and the TunneLadder slow-wave circuit of the Varian TWT were both modeled in the Cartesian coordinate system. The results from these simulations were then compared with experimental results.

Ferruled Coupled-Cavity Circuit

Dispersion simulations.—A MAFIA grid with a cell resolution of 43 by 43 in the transverse plane and of 17 cells per cavity in the longitudinal direction was generated for the ferruled coupled-cavity circuit. 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.

Compared with the experimental data provided by Hughes (A.L. Rousseau, 1988, Hughes Aircraft Co., Torrence, California, personal communication), the MAFIA results are consistently lower by an average of 1.11 percent for the cavity mode and of 0.90 percent for the slot mode. Increasing the resolution of the grid to 53 by 53 by 29 reduced the cavity mode frequency difference slightly, but again gave consistently lower values by an average of 0.86 percent for the cavity mode and of 0.92 percent for the slot mode. Figures 4(a) and (b), respectively, show the end and top views of the MAFIA high-resolution grid. The resonant frequencies obtained for the higher resolution grid are compared with fitted experimental data for the cavity and slot modes in tables IV and V, respectively, and in figure 5.

Impedance simulations.—The beam on-axis interaction impedance for the first forward space harmonic of the ferruled coupled-cavity circuit was calculated from equation (11). Figure 6 and table VI show that the impedance values match the experimental results very well with an average absolute difference of 3.77 percent for a phase shift per cavity \( \beta L \) between 210° and 315°. The large difference between the MAFIA results and the experiment for a phase shift of 330° per cavity is atypical of the rest of the impedance results (see table VI). This may be due to some error in determining the group velocity where the dispersion curve starts to flatten.

Figure 7 shows a three-dimensional cutaway of two cavities of the ferruled coupled-cavity circuit. The electric field is shown at a phase shift of 225° per cavity, with the size of the arrows proportional to the magnitude of the field.

Attenuation simulations.—The necessary input for the attenuation calculations includes a conductivity value for the conducting materials. Since actual losses in a circuit are consistently greater than the theoretically predicted values because of macroscopic surface roughness, work hardening due to machining, oxidation, and cavity-type surface irregularities (ref. 15), an effective conductivity value was used. This effective value of conductivity (1.9 \( \times 10^7 \) S/m (siemens per meter)) is that for which the MAFIA-simulated attenuation per cavity at 61.5 GHz matches the attenuation as estimated by Hughes (A.L. Rousseau, 1988, Hughes Aircraft Co., Torrence, California, personal communication), (0.036 dB/cavity) for the 961HA ferruled coupled-cavity TWT slow-wave circuit. The estimated attenuation was given for three frequencies: 59.0, 61.5, and 64.0 GHz. For this frequency band, figure 8 compares simulated results using the theoretical conductivity of copper, 5.8 \( \times 10^7 \) S/m, and using the effective value obtained with MAFIA, 1.9 \( \times 10^7 \) S/m, with the estimated results.

Figure 9 shows a three-dimensional cutout of the contour plot of the ferruled coupled-cavity circuit loss. The area of highest intensity is represented by the red shading, the lowest by blue. This plot indicates that most of the losses are concentrated at the slot.

TunneLadder Circuit

Dispersion simulations.—The TunneLadder TWT slow-wave circuit was modeled using MAFIA with a grid cell resolution of 55 by 59 in the transverse plane and of 15 cells per cavity in the longitudinal direction. Similar to the ferruled circuit, the lines of the mesh were matched with major geometrical features. Figures 10(a) and (b) show the end and top views, respectively, of the mesh generated by MAFIA.

The MAFIA results for the dispersion relationship are very close to experimental data with an absolute average frequency difference of 0.31 percent for the symmetric ladder mode (see fig. 11 and table VII). The MAFIA results proved to be better than those from a similar study that used a different three-dimensional electromagnetic computer code (ref. 16). Experimental data for other modes of the circuit were not available.

Impedance and attenuation simulations.—Experimental data for the beam on-axis interaction impedance and the circuit attenuation of the TunneLadder circuit of reference 6 were not available for comparison with the MAFIA-simulated results. However, the MAFIA results for the beam on-axis interaction impedance follow the same trend as the experimental impedance for a similar TunneLadder circuit (ref. 9). The impedance rises to a peak value around a phase shift per cavity of 60° and decreases with increasing phase shift (see fig. 12). Figure 13 shows a MAFIA three-dimensional electric field plot of the TunneLadder circuit at a phase shift of 45° per cavity. The field is large near the diamond dielectric chips (represented by navy blue). The placement of the dielectric chips contributes to the high axial electric field in the center of the beam hole and, thus, to the high impedance of the circuit.
Figure 4.—MAFIA grid for Hughes 961HA ferruled coupled-cavity TWT circuit (ref. 4). (a) End view. (b) Top view.
### TABLE IV. — CAVITY MODE RESONANT FREQUENCIES FOR FERRULED COUPLED-CAVITY TWT CIRCUIT

<table>
<thead>
<tr>
<th>Phase shift per cavity, $\beta_L$, deg</th>
<th>Fitted experimental frequency, $f_1$, GHz</th>
<th>MAFIA frequency, $f_1$, GHz</th>
<th>Frequency difference, $\Delta f_1$, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>----</td>
<td>52.87</td>
<td>----</td>
</tr>
<tr>
<td>210</td>
<td>54.34</td>
<td>53.83</td>
<td>-0.94</td>
</tr>
<tr>
<td>225</td>
<td>55.53</td>
<td>55.00</td>
<td>-0.95</td>
</tr>
<tr>
<td>240</td>
<td>57.13</td>
<td>56.59</td>
<td>-0.95</td>
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<tr>
<td>270</td>
<td>61.36</td>
<td>60.82</td>
<td>-0.88</td>
</tr>
<tr>
<td>300</td>
<td>66.6</td>
<td>66.07</td>
<td>-0.80</td>
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<tr>
<td>315</td>
<td>69.41</td>
<td>68.87</td>
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<tr>
<td>330</td>
<td>72.12</td>
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</tr>
<tr>
<td>360</td>
<td>75.47</td>
<td>74.86</td>
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</tr>
</tbody>
</table>

### TABLE V. — SLOT MODE RESONANT FREQUENCIES FOR FERRULED COUPLED-CAVITY TWT CIRCUIT

<table>
<thead>
<tr>
<th>Phase shift per cavity, $\beta_L$, deg</th>
<th>Fitted experimental frequency, $f_1$, GHz</th>
<th>MAFIA frequency, $f_1$, GHz</th>
<th>Frequency difference, $\Delta f_1$, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>----</td>
<td>113.12</td>
<td>----</td>
</tr>
<tr>
<td>210</td>
<td>112.69</td>
<td>111.60</td>
<td>-0.97</td>
</tr>
<tr>
<td>225</td>
<td>110.91</td>
<td>109.84</td>
<td>-0.96</td>
</tr>
<tr>
<td>240</td>
<td>108.64</td>
<td>107.57</td>
<td>-0.98</td>
</tr>
<tr>
<td>270</td>
<td>102.97</td>
<td>101.98</td>
<td>-0.96</td>
</tr>
<tr>
<td>300</td>
<td>96.47</td>
<td>95.66</td>
<td>-0.84</td>
</tr>
<tr>
<td>315</td>
<td>93.26</td>
<td>92.48</td>
<td>-0.84</td>
</tr>
<tr>
<td>330</td>
<td>90.31</td>
<td>89.49</td>
<td>-0.91</td>
</tr>
<tr>
<td>360</td>
<td>----</td>
<td>86.01</td>
<td>----</td>
</tr>
</tbody>
</table>

---

Figure 5.—Experimental data and MAFIA simulation of dispersion for cavity and slot modes of Hughes 961HA TWT.

Figure 6.—Experimental data and MAFIA simulations of beam on-axis interaction impedance for Hughes 961HA TWT.

### TABLE VI. — BEAM ON-AXIS INTERACTION IMPEDANCE FOR FERRULED COUPLED-CAVITY TWT CIRCUIT

<table>
<thead>
<tr>
<th>Phase shift per cavity, $\beta_L$, deg</th>
<th>Fitted experimental impedance, $K_1$, $\Omega$</th>
<th>MAFIA impedance, $K_1$, $\Omega$</th>
<th>Impedance difference, $\Delta K_1$, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>39.77</td>
<td>38.27</td>
<td>-3.77</td>
</tr>
<tr>
<td>225</td>
<td>23.27</td>
<td>21.59</td>
<td>-7.22</td>
</tr>
<tr>
<td>240</td>
<td>14.69</td>
<td>13.89</td>
<td>-5.45</td>
</tr>
<tr>
<td>270</td>
<td>7.08</td>
<td>6.94</td>
<td>-1.98</td>
</tr>
<tr>
<td>300</td>
<td>4.20</td>
<td>4.17</td>
<td>-0.71</td>
</tr>
<tr>
<td>315</td>
<td>3.46</td>
<td>3.58</td>
<td>3.47</td>
</tr>
<tr>
<td>330</td>
<td>2.96</td>
<td>3.50</td>
<td>18.24</td>
</tr>
</tbody>
</table>
Figure 7.—MAFIA three-dimensional electric field plot for Hughes 961HA ferruled coupled-cavity TWT circuit. Size of three-dimensional arrows is proportional to magnitude of the field. Phase shift per cavity, $\beta L$, 225°.

Figure 8.—Estimated data and MAFIA simulations of circuit attenuation for Hughes 961HA TWT.
Figure 9.—MAFIA three-dimensional contour plot of losses for Hughes 961HA ferruled coupled-cavity TWT circuit.
Figure 10.—MAFIA grid for Varian TunneLadder TWT circuit. (a) End view. (b) Top view.

Figure 11.—Experimental data and MAFIA simulation of dispersion for symmetric ladder mode of the Varian TunneLadder TWT.
TABLE VII. —SYMMETRIC LADDER MODE RESONANT FREQUENCIES FOR TUNNELADDER CIRCUIT

<table>
<thead>
<tr>
<th>Phase shift per cavity, $\beta L$, deg</th>
<th>Fitted experimental frequency, $f$, GHz</th>
<th>MAFIA frequency, $f$, GHz</th>
<th>Frequency difference, $\Delta f$, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-----</td>
<td>16.38</td>
<td>-----</td>
</tr>
<tr>
<td>30</td>
<td>24.15</td>
<td>24.14</td>
<td>-0.04</td>
</tr>
<tr>
<td>45</td>
<td>27.22</td>
<td>27.08</td>
<td>-0.51</td>
</tr>
<tr>
<td>60</td>
<td>28.93</td>
<td>28.81</td>
<td>-0.41</td>
</tr>
<tr>
<td>90</td>
<td>30.54</td>
<td>30.50</td>
<td>-0.13</td>
</tr>
<tr>
<td>120</td>
<td>31.16</td>
<td>31.21</td>
<td>0.16</td>
</tr>
<tr>
<td>135</td>
<td>31.30</td>
<td>31.41</td>
<td>0.35</td>
</tr>
<tr>
<td>150</td>
<td>31.37</td>
<td>31.54</td>
<td>0.54</td>
</tr>
<tr>
<td>180</td>
<td>-----</td>
<td>31.63</td>
<td>-----</td>
</tr>
</tbody>
</table>

Figure 12.—MAFIA simulations of beam on-axis interaction impedance and circuit attenuation for Varian Tunneladder TWT.
Figure 13.—MAFIA three-dimensional electric field plot for Varian TunneLadder TWT circuit. Size of three-dimensional arrows is proportional to magnitude of the field. Phase shift per cavity, $\beta L$, 45°.

The circuit attenuation for the TunneLadder circuit (also shown in fig. 12) was calculated by using the effective conductivity value ($1.9 \times 10^7$ S/m) obtained by matching the ferruled coupled-cavity simulated attenuation results with those estimated from the experiment. The MAFIA results indicate an increase of circuit attenuation with increasing phase shift. Figure 14 shows a MAFIA three-dimensional contour plot of the TunneLadder circuit loss. The losses are concentrated at the slots.
Conclusions

Generalized MAFIA input files were developed for coupled-cavity and TunneLadder traveling-wave tube (TWT) circuits. However, arbitrary circuit dimensions could be modeled by simply changing the dimensions in these files.

The generalized input files were used to simulate the cold-test parameters (i.e., frequency-phase dispersion, beam on-axis interaction impedance, and circuit attenuation) of two specific circuits: the Hughes 961HA ferruled coupled-cavity and the Varian TunneLadder TWT circuits. For the dispersion calculations, the agreement with experimental results is very good for the operating modes of both circuits, with an average frequency difference of 0.9 percent for the ferruled coupled-cavity circuit and of 0.3 percent for the TunneLadder circuit. The beam on-axis interaction impedance calculated for the ferruled circuit also shows good agreement, with a typical absolute average difference of about 4 percent. When an effective value for the conductivity of copper was used in the ferruled coupled-cavity attenuation calculations, the MAFIA results were very close to the estimated results. This effective conductivity, $1.9 \times 10^7$ S/m, was used to account for the actual losses in the circuit, which are consistently greater than the theoretically predicted values because of surface irregularities. These results demonstrate the reliability of MAFIA simulations and their ability to reduce expensive and time-consuming experimental procedures in the TWT design process.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 21, 1994
### Appendix A
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_n)</td>
<td>electric field amplitude of (n^{th}) space harmonic</td>
</tr>
<tr>
<td>(E_n)</td>
<td>on-axis axial electric field space harmonic magnitude of a traveling wave</td>
</tr>
<tr>
<td>(E_{nS})</td>
<td>on-axis axial electric field space harmonic magnitude of a standing wave</td>
</tr>
<tr>
<td>(E_{\text{tot}})</td>
<td>total on-axis axial electric field</td>
</tr>
<tr>
<td>(f)</td>
<td>frequency</td>
</tr>
<tr>
<td>(H_t)</td>
<td>magnetic field component tangential to the circuit walls</td>
</tr>
<tr>
<td>(K_n)</td>
<td>beam on-axis interaction impedance for (n^{th}) space harmonic</td>
</tr>
<tr>
<td>(L)</td>
<td>cavity length</td>
</tr>
<tr>
<td>(N)</td>
<td>number of cavities in simulation</td>
</tr>
<tr>
<td>(n)</td>
<td>space harmonic order</td>
</tr>
<tr>
<td>(P_L)</td>
<td>total RF power loss per unit length</td>
</tr>
<tr>
<td>(P_{LT})</td>
<td>total RF power loss of a traveling wave</td>
</tr>
<tr>
<td>(P_{LS})</td>
<td>total RF power loss of a standing wave</td>
</tr>
<tr>
<td>(P_{RF})</td>
<td>RF power flow</td>
</tr>
<tr>
<td>(p)</td>
<td>period</td>
</tr>
<tr>
<td>(v_g)</td>
<td>group velocity</td>
</tr>
<tr>
<td>(W)</td>
<td>electromagnetic energy of a traveling wave per unit length</td>
</tr>
<tr>
<td>(W_T)</td>
<td>total electromagnetic energy of a traveling wave</td>
</tr>
<tr>
<td>(W_S)</td>
<td>total electromagnetic energy of a standing wave</td>
</tr>
<tr>
<td>(z)</td>
<td>axial coordinate</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>attenuation of a cavity</td>
</tr>
<tr>
<td>(\beta_n)</td>
<td>axial phase constant for (n^{th}) space harmonic</td>
</tr>
<tr>
<td>(\delta)</td>
<td>skin depth</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>permittivity</td>
</tr>
<tr>
<td>(\eta)</td>
<td>intrinsic impedance of the media</td>
</tr>
<tr>
<td>(\theta)</td>
<td>slot arc</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>conductivity</td>
</tr>
<tr>
<td>(\phi)</td>
<td>phase shift per cavity for fundamental space harmonic (in radians)</td>
</tr>
<tr>
<td>(\omega)</td>
<td>angular frequency, (2\pi f)</td>
</tr>
</tbody>
</table>
Appendix B

MAFIA Mesh Generator File for Ferruled Circuit
(M Module Input File)

$**********************************************************************$
$ MAFIA mesh generator file for the ferruled circuit$
$**********************************************************************$

! rm -f fer2.drc
! rm -f fer2m.prn

$**********************************************************************$
$ Open an output file to view the results of m310$
$**********************************************************************$

#file name fer2m action open type print status unknown execute

#general text(1) ‘Ferruled 961ha cctwt circuit, 2 cav’
store noprintscreen nomenu

$ Define variable names and dimensions in 0.0001 m:
$**********************************************************************$
scale 0.0001

$Ferrule inner radius, rl
define rbeam = 2.794

$Ferrule outer radius, r2
define rfer = 4.318

$Slot inner radius, r3
define rpatc = 6.858

$Slot outer radius, r4
define rslot = 11.049

$Cavity radius, r5
define rcav = 11.049

$Cavity gap, h
define cavsp = 7.518

$Ferrule gap, g
define gap = 2.921

$Wall thickness, t
define wallth = 2.159

$Cavity length, L
define per = 9.6774

$Slot arc, theta, in degrees
define slota = 140.0

$ Define the mesh dimensions and spacings
$**********************************************************************$
define xreg1 16
define xreg2 5
define xreg3 5
define xreg4 8
$define yreg1 16
define yreg2 5
define yreg3 5
define yreg4 8
$define zreg1 6
define zreg2 6
define zreg3 10
define zreg4 6
define zreg5 3
$define xdim1 rbeam
define xdim2 rfer
define xdim3 rpatc
define xdim4 rcav
$define ydim1 rbeam
define ydim2 rfer
define ydim3 rpatc
define ydim4 rcav
$define zdim1 “wallth/2.0”
define zdim2 “(per - gap)/2.0”
define zdim3 “zdim2 + gap”
define zdim4 “per - zdim1”
define zmax per

#mesh xmesh “-ymax” s yreg4 “-ydim3” s yreg3 “-ydim2”
s yreg2 “-ydim1” s “yreg1/2” 0.0 s “yreg1/2”
ydim1 s yreg2 ydim2 s yreg3 ydim3 s yreg4 ymax
ymesh “-ymax” s yreg4 “-ydim3” s yreg3 “-ydim2”
s yreg2 “-ydim1” s “yreg1/2” 0.0 s “yreg1/2”
ydim1 s yreg2 ydim2 s yreg3 ydim3 s yreg4 ymax
z mesh “-zmax” s zreg5 “-zdim4” s zreg4 “-zdim3” s zreg3 “-zdim2”
s zreg2 “-zdim1” s zreg1 zdim1 s zreg2
zdms2 s zreg3 zdim3 s zreg4 zdim4 s zreg5 zmax
show
eexecute

$ Form the geometrical attributes of the ferruled circuit
$**********************************************************************$
#brick
material 1
volume “-xmax” xmax “-ymax” ymax “-zmax” zmax
eexecute
$ Hollow a cylinder the length of the period
#cylinder
material 0
part full
center 0.0 0.0
orientation z
radius rcav
range “-zmax” zmax
execute
$ Form slot1 and slot3 in the partition walls
material 1
range “-zmax” “-zdim4” execute
range “zdim4” zmax execute
part section point1 0.0 “ymax” angle “slota/2.0”
material 0
center 0.0 0.0
range “-zmax” “-zdim4”
excecut
range zdim4 zmax execute
center 0.0 0.0
part section point1 0.0 “ymax”
angle “-slota/2.0”
execute
range “-zmax” “-zdim4”
excecut
part section point1 0.0 “ymax”
angle “slota/2.0”
excecut
range “-zmax” “-zdim4”
excecut
$ Fill in the patches for slot1 and slot3
material 1
center 0.0 0.0
part section point1 0.0 ydim3
angle “-slota/2.0”
excecut
range zdim4 zmax execute
center 0.0 0.0
part section point1 0.0 ydim3
angle “slota/2.0”
excecut
range “-zmax” “-zdim4”
excecut
$ Form slot2 180 degrees from slot1 and slot3
define wedge “90 + (90 - slota/2.0)”
material 1
center 0.0 0.0
part section point1 0.0 ymax
angle wedge
range “-zdim1” “zdim1”
excecut
part section point1 0.0 ymax
angle “-wedge”
center 0.0 0.0
execute
$ Fill in the patch for slot2
material 1
center 0.0 0.0
part section point1 0.0 “-ydim3”
angle “-slota/2.0”
excecut
center 0.0 0.0
part section point1 0.0 “-ydim3”
angle “slota/2.0”
excecut
$ Form the ferrules
#washer
material 1
center 0.0 0.0
orientation z
inner rbeam
outer rfer
range “-zmax” “-zdim3”
part full
execute
range “-zdim2” zdim2
execute
range zdim3 zmax
execute
$ Hollow the beam hole
#cylinder
material 1
center 0.0 0.0
material 0
part full
orientation z
radius rbeam
range “-zmax” zmax
execute
$ Form the ferrules
#washer
material 1
center 0.0 0.0
orientation z
inner rbeam
outer rfer
range “-zmax” “-zdim3”
part full
execute
range “-zdim2” zdim2
execute
range zdim3 zmax
execute
$ Open the graphics station and view the geometry
$********************************************************************
open x
#2dplot
material all grid yes izcut 1
execute
swi
#3dplot
material 1 rotation 0 120 0 cells no ex
swi
close x
$********************************************************************
$ Open a mafia file and save the data from m310
$********************************************************************
#file name fer2 action open type mafia status unknown execute
end
Appendix C
MAFIA Matrix Generator File for Ferruled Circuit
(R Module Input File)

$ ********************************
$ MAFIA matrix generator file for the ferruled circuit
$ ********************************
noprintscreen

$ ********************************
$ Open the mafia file with stored results from m310
$ ********************************
#file name fer2 action open type mafia status unknown execute

$ ********************************
$ Define the boundary conditions
$ ********************************
define phase 225
#boundary
xboundary electric electric
yboundary electric electric
zboundary periodic

$ The desired phase is doubled for two modeled cavities
zphase "phase*2.0"

$ ********************************
$ Define the materials used in m310
$ ********************************
#material
material 1 type electric
material 0 type normal eps 1
show

$ ********************************
$ Start the matrix generation
$ ********************************
#matrix execute
end

Appendix D
MAFIA Eigenvalue Solver File for Ferruled Circuit
(E Module Input File)

$ ********************************
$ MAFIA eigenvalue solver file for the ferruled circuit
$ ********************************
noprintscreen

$ ********************************
$ Open the mafia file with stored results from m310 and r310
$ Open an output file to view the results
$ ********************************
#file name fer2 action open type mafia status unknown execute
name fer2e type print execute

$ ********************************
$ Enter the solver section setting desired parameters
$ ********************************
#solver
accuracy 0.0001
modes 10
iterations 3
execute
printscreen
echo 'zphase -->' @zphase
show
noprintscreen
end
Appendix E
MAFIA Postprocessor File for Ferruled Circuit
(P Module Input File)

$******************************************************************************$ $MAFIA postprocessor file for the ferruled circuit$ $******************************************************************************$
noprintscreen

$******************************************************************************$ $Open the mafia file with stored results from m310, r310, and e310$
$******************************************************************************$
#file name fer2 type mafia action open status unknown execute
name printz type print action open status unknown execute

define period 0.96774e-3
$set this to the period length in meters$
define cavnum 2
$^ number of cavities$
define evenodd 2
$^ odd/total/even synthesis corresponding to -1/0/1$
$^ This input is used for the Fourier analysis done on Eztot$
define vg 3.263998e+7
$group velocity in meters per second$
define phase "225"
$^ phase shift per cavity in degrees$
define zstart @zmin
$^ where the first longitudinal mesh point starts in meters$

$******************************************************************************$ $Define the location of symmetry planes$ $******************************************************************************$
#general
symmetry no no no no no no
$^ change symmetries accordingly$
define cnst 1.9e+7
$^ this value defines the conductivity in siemens per meter$

#material material 1 kappa cnst
conduct cnst cnst cnst cnst 0 0
$^ the conductivity is defined here$

printscreen

$******************************************************************************$ $The total energy is calculated$ $******************************************************************************$
#energy sym c/l density yes losses yes execute

$******************************************************************************$ $The power losses are calculated$ $******************************************************************************$
#losses sym b/l density yes execute
define powloss @metalpower
$^ the power loss is defined as the total losses$
$^ calculated at the boundaries and inner surfaces$
define atten "(8.686*powloss*period)/(2*@totalenergy*vg)"
$^ The circuit attenuation is defined in decibels per cavity$

printscreen
echo '%frequency' @frequency
echo '%period' period
echo '%energy' @totalenergy
echo '%powloss' powloss
echo '%atten' atten
echo '%phase' phase
echo '%cavnum' cavnum
echo '%evenodd' evenodd
echo '%vg' vg
echo '%zstart' zstart

$******************************************************************************$ $The axial electric field is printed$ $******************************************************************************$
#print
sym e/l
component z
normal x
yhigh @ddminy
$^ this value should be the second positive mesh point$
$^ in the y direction$
printscreen
execute
end
Appendix F
MAFIA Mesh Generator File for TunneLadder Circuit
(M Module Input File)

$ *******************************************************************
$ MAFIA mesh generator file for the TunneLadder circuit
$ *******************************************************************

rm -f tl.drc
rm -f tlm.prn

$ *******************************************************************
$ Open an output file to view the results of m310
$ *******************************************************************
#file name tlm type pr action open status unknown
ex
text(1) 'TunneLadder circuit'

$ *******************************************************************
$ Define variable names and dimensions in 0.0001 m:
$ *******************************************************************
define radpri 4.3
define radpri2 3.0

$ *******************************************************************
$ Define the mesh dimensions and spacings
$ *******************************************************************
define thick "thicW2.0"
define xreg1 6
define xreg2 2
define xreg3 4
define xreg4 2
define xreg5 6
define xreg6 10

$ *******************************************************************
define yreg1 4
define yreg2 8
define yreg3 2
define yreg4 8
define yreg5 14

$ *******************************************************************
define zreg1 6
define zreg2 1
define zreg3 3

$ *******************************************************************
define xdim1 "diWth/2.0"
define xdim2 radpri2
define xdim3 radpri
define xdim4 "xdim3 + thick"
define xdim5 "ridWth/2.0"
define xmax "xdim5 + sidWth"

$ define ydim1 thick
define ydim2 radsec

$Dielectric height, a
define diht 2.54

$Dielectric width, b
define dwth 3.81

$Ridge height, c
define ridht 10.16

$Ridge width, d
define ridwth 19.05

$Waveguide gap, g
define wgap 12.446

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175

$Tunnel primary radius, r1
$Tunnel secondary radius, r2

$Side section height, s
define sideht 32.766

$Ladder thickness, t
define thick 0.635

$Side section width, w
define sidwth 8.890

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175

$Dielectric height, a
define diht 2.54

$Dielectric width, b
define dwth 3.81

$Ridge height, c
define ridht 10.16

$Ridge width, d
define ridwth 19.05

$Waveguide gap, g
define wgap 12.446

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175

$Dielectric height, a
define diht 2.54

$Dielectric width, b
define dwth 3.81

$Ridge height, c
define ridht 10.16

$Ridge width, d
define ridwth 19.05

$Waveguide gap, g
define wgap 12.446

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175

$Dielectric height, a
define diht 2.54

$Dielectric width, b
define dwth 3.81

$Ridge height, c
define ridht 10.16

$Ridge width, d
define ridwth 19.05

$Waveguide gap, g
define wgap 12.446

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175

$Dielectric height, a
define diht 2.54

$Dielectric width, b
define dwth 3.81

$Ridge height, c
define ridht 10.16

$Ridge width, d
define ridwth 19.05

$Waveguide gap, g
define wgap 12.446

$Dielectric length, f
define dilgth 2.032

$Ladder length, h
define alad 1.524

$Gap length, m
define zgap 1.651

$Period, p
define period 3.175
define ydim3 "wgap/2.0 - diht"
define ydim4 "wgap/2.0"
define ymax "sideht/2.0"
$define zdimal "period/2.0 - dilght/2.0"
define zdimm2 "zgap/2.0"
define zmax "period/2.0"
#
mesh xmesh "-xmax" s xreg6 "-xdim5" s xreg5 "-xdim4" s xreg4 "-xdim3" s xreg3 "-xdim2" s xreg2 "-xdim1" s xreg1 xdim1 s xreg2 xdim2 s xreg3 xdim3 s xreg4 xdim4 s xreg5 xdim5 s xreg6 xmax
ymesh "-ymax" s yreg5 "-ydim4" s yreg4 "-ydim3" s yreg3 "-ydim2" s yreg2 "-ydim1" s yreg1 ydim1 s yreg2 ydim2 s yreg3 ydim3 s yreg4 ydim4 s yreg5 ymax
zmesh "-zmax" s zreg3 "-zdim2" s zreg2 "-zdim1" s zreg1 zdimal s zreg2 zdim2 s zreg3 zmax
ex
show
$*******************************************************************************
$ Form the geometrical attributes of the TunnelLadder circuit
$*******************************************************************************
$ Hollow out a space and form the ridge
#brick
material 0
vol "-xmax" xmax "-ymax" ymax "-zmax" zmax
ex
mat 1
vol "-xdim5" xdim5 "-ydim4" "-ydim3" "-zmax" zmax
ex
mat 1
vol "-xdim5" xdim5 ydim4 ymax "-zmax" zmax
ex
$ Form the ladder
mat 1
vol "-xmax" xmax "-ydim1" ydim1 "-zmax" zmax
ex
$ Form the dielectric chips
mat 2
vol "-xdim1" xdim1 "-ydim4" "-ydim3" "-zmax" "-zdim1"
ex
vol "-xdim1" xdim1 "ydim3" "ydim4" "-zmax" "-zdim1"
ex
vol "-xdim1" xdim1 ydim3 ydim4 "zdim1" zmax
ex
vol "-xdim1" xdim1 "-ydim4" "-ydim3" zdim1 "zmax"
ex
$ Form the beam tunnel

#ecylinder
material 1
center 0.0 0.0
semiaxes "radpri + thick2" "radsec + thick"
orientation z
range "-zmax" "zmax"
part full
ex
material 0
center 0.0 0.0
semiaxes radpri radsec
orienation z
range "-zmax" "zmax"
part full
ex
$ Form the slot in the tunnel
material 0
center 0.0 0.0
semiaxes "radpri + thick2" "radsec + thick"
orientation z
range "-zdim2" "zdim2"
part full
ex
$ Form the slots in the ladder
#brick
material 0
vol "-xmax" xmax "-ydim1" ydim1 "-zmax" zdimal
ex
$*******************************************************************************
$ Open the graphics station and view the geometry
$*******************************************************************************
open x
#2dplot
mat all grid y izcut 4
ex
swi
#3dplot
mat all rot 0 120 0 cells n ex
swi
close x
$*******************************************************************************
$ Open a mafia file and save the data from m310
$*******************************************************************************
#file name tl type mafia action open status unknown ex
end
Appendix G
MAFIA Matrix Generator File for TunneLadder Circuit
(R Module Input File)

$ ***********************
$ MAFIA matrix generator file for the TunneLadder circuit
$ ***********************
noprintscreen

$ ***********************
$ Open the mafia file with stored results from m310
$ ***********************
#file name tl action open type mafia status old ex

$ ***********************
$ Define the boundary conditions
$ ***********************
define phase 45.0
#boundary
  xboun elec elec
  yboun elec elec

zboun periodic
zphase phase

$ ***********************
$ Define the materials used in m310
$ ***********************
#material
  mat 1 type elec
  mat 0 type normal eps 1
  mat 2 type norm eps 5.5
show

$ ***********************
$ Start the matrix generation
$ ***********************
#matrix ex

end

Appendix H
MAFIA Eigenvalue Solver File for TunneLadder Circuit
(E Module Input File)

$ ***********************
$ MAFIA eigenvalue solver file for the TunneLadder circuit
$ ***********************
noprintscreen

$ ***********************
$ Open the mafia file with stored results from m310 and r310
$ ***********************
#file name tl action open type mafia status old ex
  name tle type print action open status unk ex

#solver
  accuracy 0.0001
  modes 8
  iter 3
  ex

printscreen
  echo 'zphase --->' @zphase
  show
  noprintscreen
end
Appendix I

MAFIA Postprocessor File for TunneLadder Circuit
(P Module Input File)

$ ****************************************************
$ MAFIA postprocessor file for the TunneLadder circuit
$ ****************************************************

noprintscreen
$ ****************************************************
$ Open the mafia file with stored results from m310, r310, and e310
$ Open an output file to view the results
$ ****************************************************

#file
name tl2 ty mafia act op stat unk ex

name printz ty print act op stat unk ex

def harmon 0
$ ^ set the harmonic of synchronization with the electron beam

def period 0.3175e-3
$ ^ set this to the period length in meters

def cavnum 2
$ ^ number of cavities

def evenodd 1
$ ^ odd/total/even synthesis corresponding to -1/0/1
$ This input is used for the Fourier analysis done on Eztot

def vg 1.7061 le+7
$ group velocity in meters per second

def phase "45"
$ total phase shift per cavity

def zstart @zmin
$ where the first longitudinal mesh point starts in meters

$ ****************************************************
$ Define the location of symmetry planes
$ ****************************************************
#general
sym no no no no no
$ change symmetries accordingly

define cnst 1.9e+7
$ this value defines the conductivity in siemens per meter

#material mat 1 kappa cnst
conduct cnst cnst cnst cnst 0 0
$ the conductivity is defined here
$ for each boundary
mat 2 taneps 3.0e-4

$ ****************************************************
$ The loss tangent for the dielectric material

printscreen
$ ****************************************************
$ The total energy is calculated
$ ****************************************************
#energy sym e/l density y losses y ex

$ ****************************************************
$ The power losses are calculated
$ ****************************************************
#losses sym b/l den yes ex

define powloss "@metalpower+@epspower"
$ @metalpower is the total loss from conducting material
$ @epspower is the total loss from the dielectric

define atten "(8.686*powloss*period)/(2*@totalenergy*vg)"
$ The circuit attenuation is defined in decibels per cavity

printscreen
echo '%harmon' harmon
echo '%frequency' @frequency
echo '%period' period
echo '%energy' @totalenergy
echo '%powloss' powloss
echo '%atten' atten
echo '%phase' phase
echo '%cavnum' cavnum
echo '%evenodd' evenodd
echo '%vg' vg
echo '%zstart' zstart

$ ****************************************************
$ The axial electric field is printed
$ ****************************************************
#print
sym e/l
comp z
norm x
ylow 0.0
yhigh @ddminy
$ this value should be the second positive mesh point in the y direction

printscreen
ex
end

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Appendix J
Determining the Energy and Power Loss Associated With a Traveling Wave

The electromagnetic energy in the structure per unit length can be expressed as

\[ W = \varepsilon \int_{\text{vol}} E^2 \, dv \]  

(17)

It follows that the total energy associated with a traveling wave can be expressed as

\[ W_T = \varepsilon \int_{\text{vol}} \sum_{n=-\infty}^{\infty} |A_n e^{-j\beta_n z}|^2 \, dv \]  

(18)

where \( A_n \) is the electric field amplitude of the \( n^{th} \) space harmonic. Thus,

\[ W_T = \varepsilon \int_{z=0}^{NL} \sum_{n=-\infty}^{\infty} F_n(A_n)^2 \, dz \]  

(19)

with

\[ F_n = \iint dx dy \]  

(20)

Integrating from \( z = 0 \) to \( z = NL \),

\[ W_T = NL \varepsilon \sum_{n=-\infty}^{\infty} F_n(A_n)^2 \]  

(21)

Proceeding in the same manner, we can express the total energy associated with a standing wave as

\[ W_S = \varepsilon \int_{\text{vol}} \sum_{n=-\infty}^{\infty} (2A_n \cos(\beta_n z))^2 \, dv \]  

(22)

Using the relationship,

\[ \int \cos^2(az) \, dz = \frac{z}{2} + \frac{\sin(2az)}{4a} \]  

(23)

we can evaluate the integral as

\[ W_S = 2NL \varepsilon \sum_{n=-\infty}^{\infty} F_n(A_n)^2 \]  

(24)

Therefore, it can be seen that the energy associated with a traveling wave is half that associated with a standing wave,

\[ W_T = \frac{W_S}{2} \]  

(25)

A similar argument can be used to prove that the total power loss associated with a traveling wave \( P_{LT} \) is half that associated with a standing wave \( P_{LS} \). The time-averaged power loss per unit length can be expressed as

\[ P_L = \frac{1}{2\sigma \delta} \int_{S} \mathbf{H}_t \cdot \mathbf{H}_t^* \, dS \]  

(26)

where \( \sigma \) is the conductivity in siemens per meter, \( \delta \) is the skin depth in meters, and \( \mathbf{H}_t \) is the magnetic field component tangential to the circuit walls. Because the magnetic fields are proportional to the electric fields by a factor \( \eta \), the intrinsic impedance of the media, it can be deduced that the magnetic fields associated with a traveling wave and a standing wave will have the same relationship as the electric fields associated with a traveling wave and a standing wave. (The value of the field for a traveling wave \( E_n \) is half that for a standing wave \( E_{ns} \). ref. 13.) It follows that the evaluation of equation (10) for the power loss associated with a traveling wave and a standing wave will also have the same relationship as the electromagnetic energy calculations just shown. Therefore, it can be determined that

\[ P_{LT} = \frac{P_{LS}}{2} \]  

(27)
References


The three-dimensional simulation code MAFIA was used to compute the cold-test parameters—frequency-phase dispersion, beam on-axis interaction impedance, and attenuation—for two types of traveling-wave tube (TWT) slow-wave circuits. The potential for this electromagnetic computer modeling code to reduce the time and cost of TWT development is demonstrated by the high degree of accuracy achieved in calculating these parameters. Generalized input files were developed for ferruled coupled-cavity and Tunneladder slow-wave circuits. These files make it easy to model circuits of arbitrary dimensions. The utility of these files was tested by applying each to a specific TWT slow-wave circuit and comparing the results with experimental data. Excellent agreement was obtained.

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