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SUMMARY

RF input/output coupler characteristics for the TunneLadder traveling-wave tube have been calculated using the three-dimensional computer code, MAFIA and compared to experimental data with good agreement. Theory behind coupling of the TunneLadder interaction circuit to input and output waveguides is presented and VSWR data is calculated for variations on principal coupler dimensions to provide insight into manufacturing tolerances necessary for acceptable performance. Accuracy of results using MAFIA demonstrates how experimental hardware testing of three-dimensional coupler designs can be reduced.

INTRODUCTION

Development of RF input and output couplers for traveling-wave tube (TWT) slow-wave circuits is a critically important step in the design process for TWTs. Efficient coupling of power into and out of the interaction circuit is of great importance to TWT efficiency. Typically, coupler designs are determined experimentally by cold-test results using designs that have been successful in the past as a starting point and iteratively altering them until good performance is achieved. Because slow-wave circuits and couplers are extremely difficult to fabricate, this trial-and-error method can be very costly and time-consuming, restricting freedom and creativity in the design process. This makes the need for computational methods crucial as they lower cost, reduce tube development time and allow freedom to introduce novel methods.

A 10X scaled model of the RF input/output coupler and slow-wave structure of the Varian 29 GHz TunneLadder TWT has been simulated with the three-dimensional electromagnetic computer code, MAFIA. The TunneLadder TWT is a 400 W, ladder-based traveling-wave amplifier that has been proposed as a low-cost alternative to coupled-cavity TWTs for millimeter wavelength, high power, narrow-band space communication applications (ref. 1). The circuit has a small hot bandwidth of approximately 2.3 percent and high interaction impedance which contributes to its high gain per unit length of about 52 dB/in. It was chosen as a model for this study since experimental data were available for comparison, however this method is applicable to a wide variety of devices including coupled-cavity and helix TWTs. The slow-wave circuit design of the TunneLadder, based on the forward-wave Karp structure (ref. 2), has a periodic ladder shaped into a quasi-elliptical beam tunnel supported by diamond dielectric chips in a double ridge waveguide. Figures 1(a) and (b) show cross-sectional and top views, respectively, of several cavities of the TunneLadder slow-wave circuit. The input and output couplers each have a reduced height waveguide short which is tapered from standard waveguide height. An inductive iris and capacitive post are placed at the point of transition to the circuit, having the beam axis as the axis about which they are symmetrical. Schematics of the coupler design are shown for cross-sectional and top views in figures 2(a) and (b), respectively.

RF input/output coupler characteristics were calculated using MAFIA (Solution of MAxwell's equations by the Finite-Integration-Algorithm), a powerful, three-dimensional, electrodynamic code written in FORTRAN 77 that is used for the computer-aided design of two dimensional and fully three dimensional electromagnetic devices such as magnets, RF cavities, waveguides, antennas, etc. The Finite Integration Technique (FIT) algorithm produces a matrix of finite-difference equations for 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. 3 and 4).

COUPLING THEORY

One way of making a good broadband transition between two waveguides is to slowly taper the geometry of one so that it gradually turns into the other, but such transitions have the disadvantage of requiring a longer length. Applying this gradual transition method at the slow-wave structure to waveguide transition would significantly increase the space along the electron beam, thus increasing the size, weight and power consumption of the electron beam confining magnet. It is obviously preferable to have a short length of slow-wave structure along the electron beam, but this requires an abrupt geometry change in the coupler and thus an abrupt change in impedance and field configuration, causing reflection. This sudden change can be canceled out by a shunt susceptance of suitable magnitude placed appropriately in the feed waveguide. A subsequent reduction in matched bandwidth will also occur, but is acceptable with a narrow bandwidth device such as the TunneLadder TWT.

In addition to ensuring a good impedance match over the desired bandwidth of the wanted propagation mode, prevention of coupling to undesired modes must also be taken into account. The dispersion relationship as calculated with MAFIA (ref. 5) of the two lowest order modes of the TunneLadder slow-wave structure, the symmetric and antisymmetric ladder modes, are plotted in figure 3. The MAFIA electric field plots for each mode at about 2.9 GHz are shown for transverse and axial planes of the slow-wave circuit in figures 4 and 5, respectively. Figure 4(a) shows that for the wanted symmetric ladder mode, each ridge and ladder has the same RF potential as its opposite member in the transverse plane. The axial electric field is nonzero along the beam axis (fig. 5(a)). For the antisymmetric ladder mode, figure 4(b) shows that this mode does not posses the same symmetry, with transverse E-field lines crossing the midplane (x, z plane at y = 0). The z component of E is zero on the axis and everywhere on the midplane (fig. 5(b)). The TunneLadder coupler design accounts for these differences in field configuration so as to provide a good match to the symmetric ladder mode over the desired bandwidth, without exciting the antisymmetric ladder mode.

SIMULATION

The slow-wave circuit and input/output assembly was modeled as a symmetrical structure at the input and output waveguide to imitate the experimental configuration. We see from figure 3 that at the operating frequency of 2.9 GHz (29 GHz for the full size model), the phase shift per cavity is approximately 60°. The experimental cold-test model (ref. 1) consists of 32 slow-wave cavities, but to conserve computational time, only three cavities are included in the MAFIA model so as to retain electric field properties of the 32 cavity model at 2.9 GHz. To further increase computational efficiency, the tapered waveguide was not included in the simulation, reflections and attenuation along this gradual taper assumed to be minimal, and only half of the structure was modeled taking advantage of symmetry in the y direction. The MAFIA geometry is shown in figure 6 (the conducting boundaries of the model are not included in the plot).

After modeling the three-dimensional mesh with the MAFIA mesh generator, two-dimensional meshes of input and output ports of the rectangular waveguide are modeled and the MAFIA eigenmode solver is used to calculate modes at each port. The waveguide is considered infinitely long at the ports. The MAFIA three-dimensional time domain solver is then used to feed power continuously at the input port at a particular frequency. The input power couples with the TunneLadder slow-wave circuit symmetric ladder mode via the coupling components, propagates through the slow-wave structure and exits at the output port. The simulation continues until steady state is reached at which time the ingoing and outgoing mode amplitudes at both ports are recorded. The MAFIA post-processor is then used to calculate reflection and transmission coefficients. VSWR data are calculated as

$$VSWR = \frac{1+|S_{11}|}{1-|S_{11}|} \tag{1}$$

RF losses were calculated for the slow-wave circuit using the method outlined in reference 5. The necessary MAFIA input includes an effective conductivity value and appropriate dielectric loss tangent. The loss tangent for diamond was taken to be 0.0001. The effective conductivity value was approximated by a study by Gilmour et al. (ref. 6) where theoretical and experimental TWT helix loss was determined from about 2 to 16 GHz for a copper plated helix. Gilmour et al. found excellent agreement between calculated and measured loss when helix surface roughness was assumed to cause the resistivity to increase by a factor of approximately 2. The attenuation in dB/cavity as calculated with MAFIA was multiplied by 32 for comparison with the experimental cold-test model. The input/output waveguide attenuation was assumed negligible.

COUPLER GEOMETRY VARIATIONS

Various coupler dimensions were varied including thickness t and aperture size a of the inductive irises, and outer diameter D and gap size g of the capacitive post (see fig. 2), to demonstrate the sensitivity of VSWR to manufacturing tolerances. This series of alterations is useful as it may be necessary to hold tighter tolerances on certain dimensions for required operating performance. Each dimension was varied in increments of ±0.01 in. (±0.001 in. at 29 GHz).

RESULTS AND DISCUSSION

The VSWR data is compared to experiment in figure 7. Results calculated using MAFIA compared to measured data are slightly higher with an average VSWR difference of 0.12 over the 5 percent bandwidth. The lower experimental VSWR data imply that the actual losses are higher than those approximated in the MAFIA model. This is not surprising considering the complex fabrication process for the TunneLadder (ref. 1). The ladder element of the circuit and the metallization of the diamond chips uses Amzirc, copper doped with zirconium, which is necessary for active-diffusion brazing of the diamond supports to the ridge in the waveguide block, and the ladder to both the diamonds and the waveguide block. A total of four gold-diffusion brazing cycles were performed at 800 °C. Thus the loss levels will be higher than theoretical conductivity values because of its decreased conductivity due to both the zirconium content and the absorption of gold as a result of the brazing cycles (ref. 7). This increased loss increases the attenuation of the reflected wave, therefore lowering VSWR.

Figure 8 shows effects of varying iris thickness t, iris aperture size a, outer capacitive post diameter D, and capacitive post gap g, on VSWR. The post gap appears to be the most sensitive dimension, while the most promising simulated variation for lowering VSWR is to adjust the iris gap –0.04 in. It is apparent that the tolerance should be held most tightly for the post gap as a small change significantly affects VSWR. The iris width, iris gap and post diameter, on the other hand, can be fabricated with less care given to holding a tight tolerance, and therefore cut down on cost.

The CPU time for one frequency point with an IBM RISC/6000 Model 590 Workstation is about 6 hours.

CONCLUSIONS AND FUTURE WORK

Good agreement achieved between measured and computer-derived VSWR for the highly complex TunneLadder slow-wave circuit to waveguide transition show the accuracy and dependability of the MAFIA code. This success indicates that hardware cold-testing can be greatly reduced by computational efforts. Expensive and time-consuming trial-and-error coupler design can be avoided by incorporating simulation into the design process.

With the success of the three-dimensional modeling of helix TWT slow-wave circuits (ref. 8), future work will involve modeling input/output couplers for helix TWTs. The reflection coefficients calculated with MAFIA can also be used as input for the NASA coupled-cavity TWT code (ref. 9) to obtain gain ripple results.

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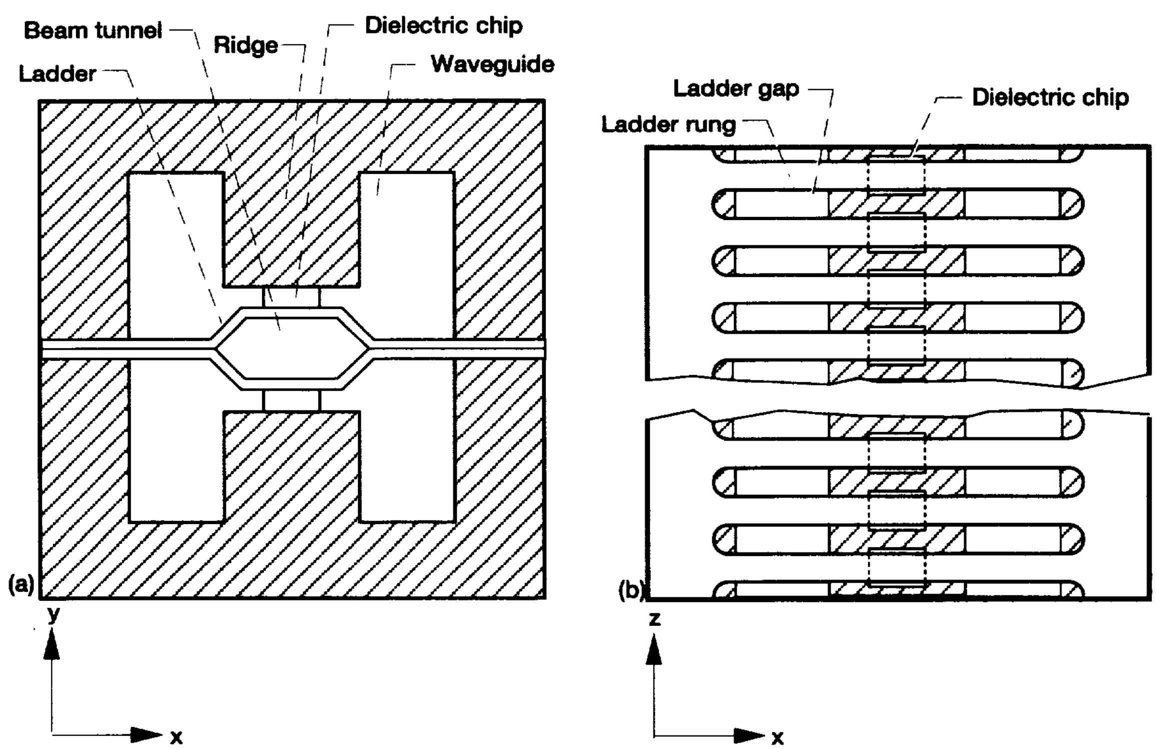

Figure 1.—TunneLadder slow-wave circuit schematic. (a) Cross-sectional view. (b) Top view.

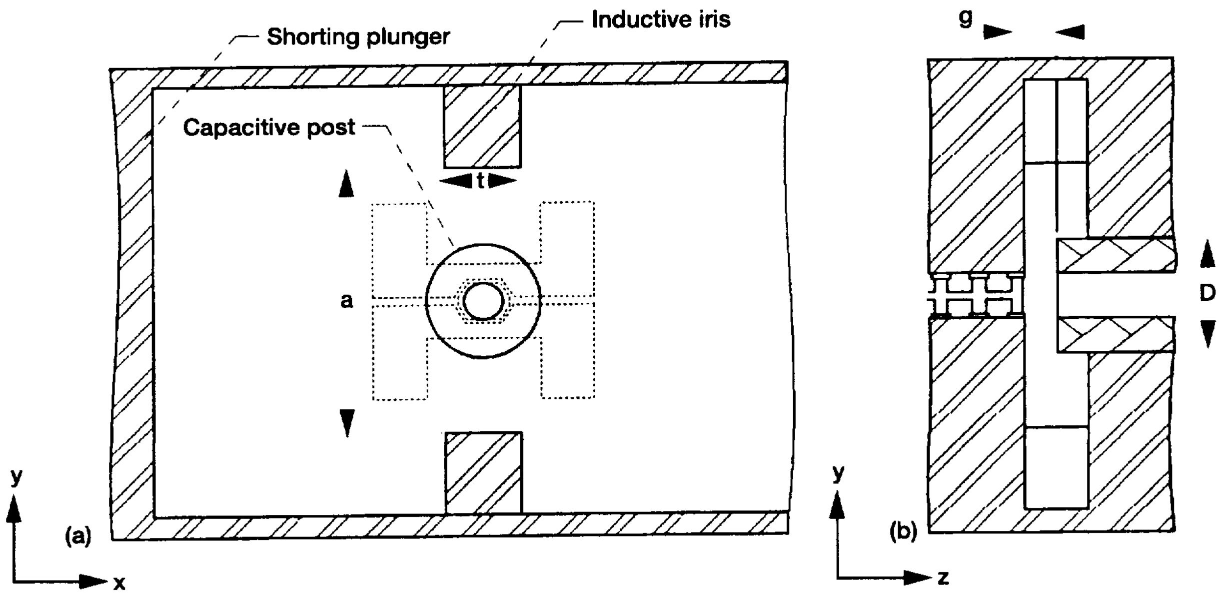

Figure 2.—TunneLadder coupler design. (a) Cross-sectional view. (b) Top view.

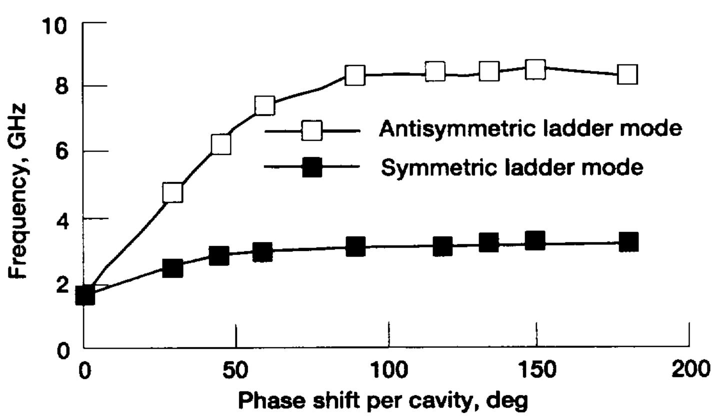

Figure 3.—Dispersion characteristics for TunneLadder symmetric ladder and antisymmetric ladder modes calculated using MAFIA.

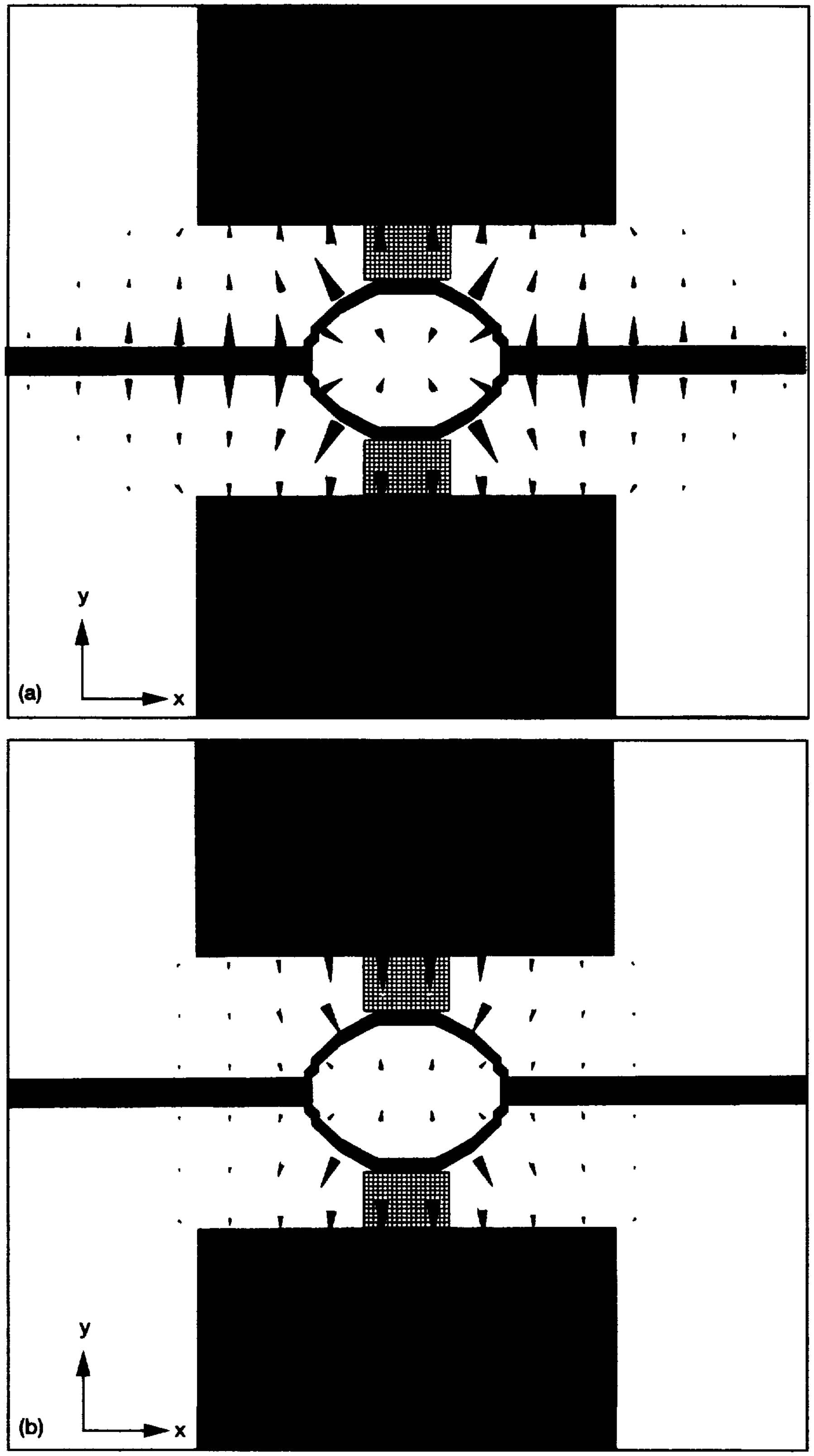

Figure 4.—MAFIA electric field plot at the slow-wave circuit/coupler interface at about 2.9 GHz. (a) Symmetric ladder mode. (b) Antisymmetric ladder mode.

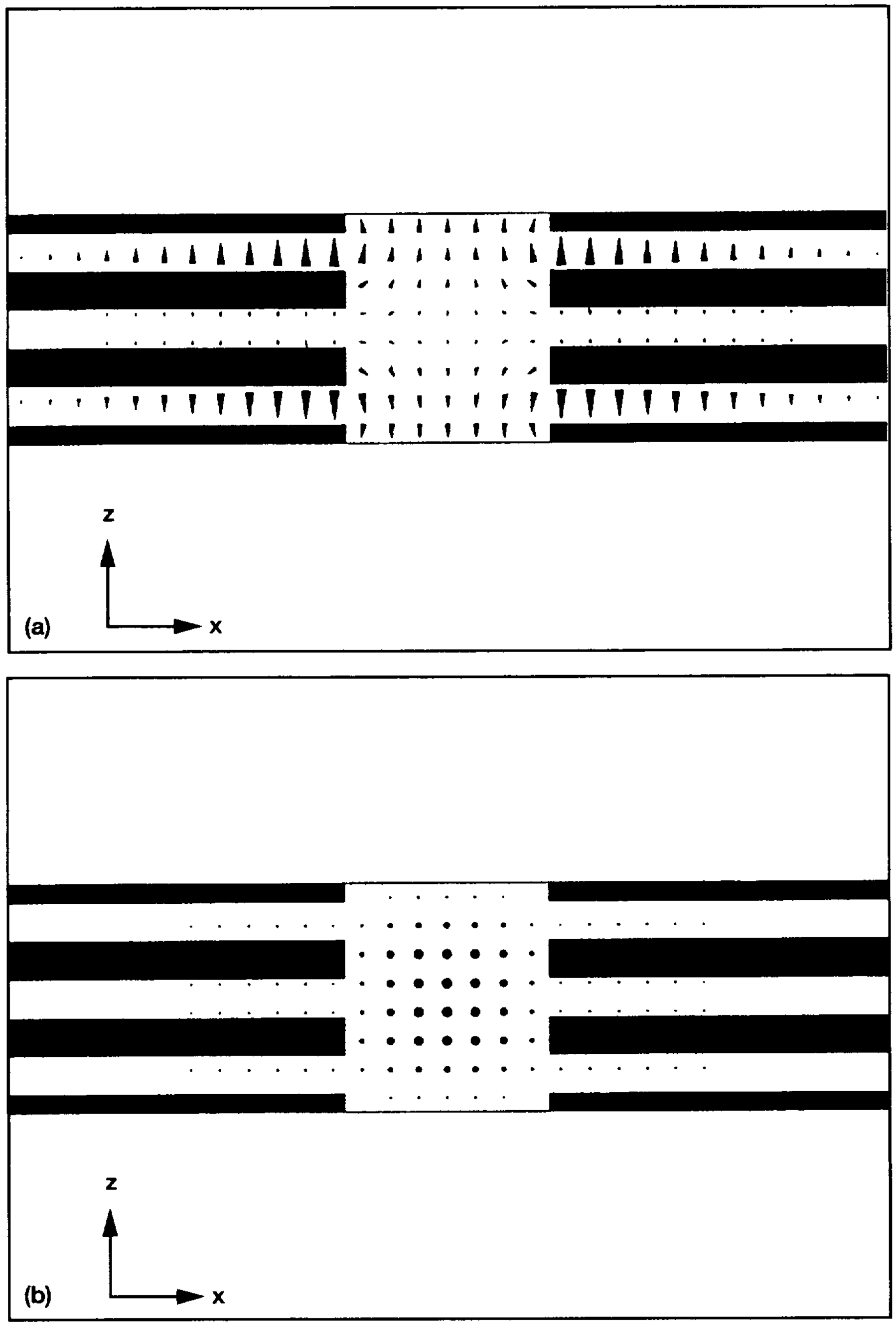

Figure 5.—MAFIA electric field for the TunneLadder slow-wave circuit axial plane at about 2.9 GHz. (a) Symmetric ladder mode. (b) Antisymmetric ladder mode.

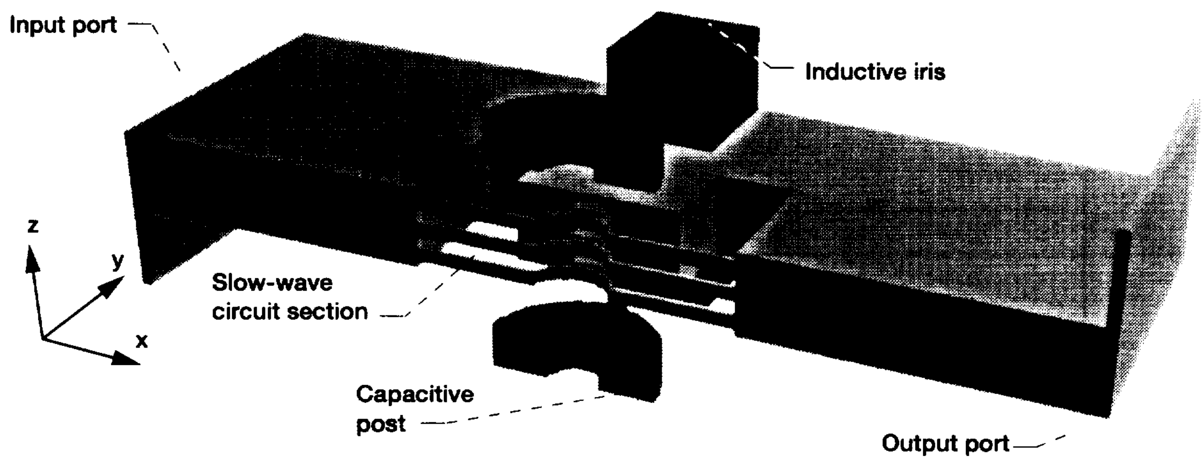

Figure 6.—MAFIA geometry of TunneLadder slow-wave circuit to waveguide transition.

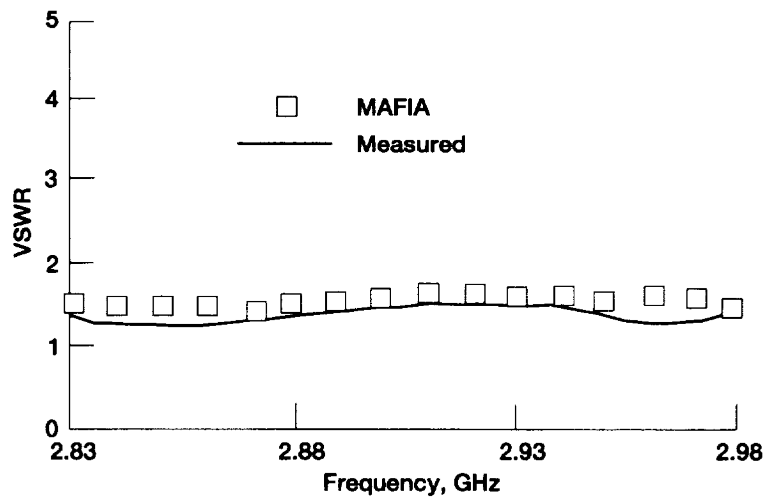

Figure 7.—MAFIA and experimental VSWR data for TunneLadder slow-wave circuit to waveguide transition.

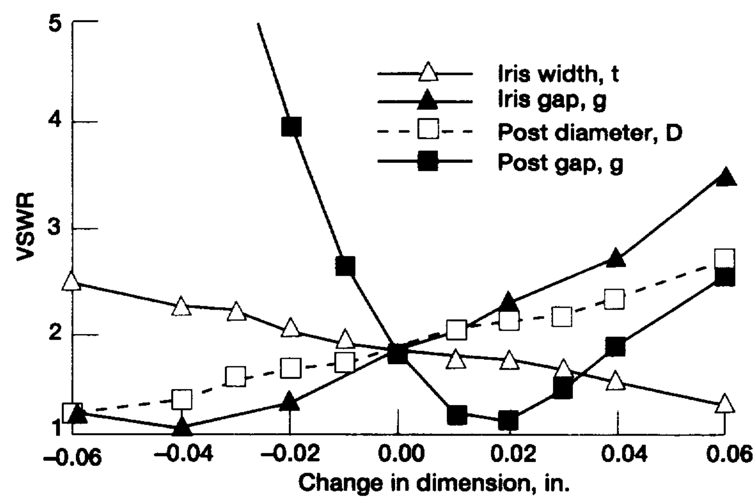

Figure 8.—VSWR as a function of dimensional variations on original iris width t, iris aperture a, capacitive post outer diameter D and capacitive post gap g (for the 10X scale model).

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13. ABSTRACT ***(Maximum 200 words)***

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