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COMPUTATIONS OF VSWR AND MODE CONVERSION FOR COMPLEX CROSS-SECTION WINDOW GEOMETRIES

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ABSTRACT

A computational method is described for determining VSWR and mode conversion for complex gyron window geometries. Assuming symmetric TE_{on} modes propagating in a circular cross-section guide containing the window, one can write the total solution to the wave equation as the sum of an incident wave plus a wave scattered from the dielectric window region. The equations can be reformulated in terms of the scattered wave, resulting in a Helmholtz wave equation with an inhomogeneous driving term corresponding to the polarization current of the dielectric. Solutions are obtained using a suitable modification of the wave equation solver OPWAVE, and reflection coefficients, VSWR's and mode conversion information are then derived from an analysis of the reflected and transmitted power. VSWR computations for typical single- and double-disk windows agree with conventional impedance calculations to within about one percent. Results for more complicated curved-boundary windows which cannot be treated by the standard methods are discussed.

INTRODUCTION

One of the most critical components of a gyron device is its window, the interface through which the microwave energy passes from the vacuum collector region to the laboratory environment. These windows must be able to withstand severe stresses due to the pressure differential, and also to the temperature gradients built up in the dielectric window by absorption of the rf energy. Typically, state-of-the-art gyron windows are constructed using double planar disk windows with associated fluid cooling. However, as gyron technology evolves in the direction of higher power and higher frequency devices, it becomes necessary to improve window design. For example, window elements with appropriately curved dielectric surfaces would presumably have superior mechanical properties under typical operating conditions. Unfortunately,

such complex-geometry windows are extremely difficult to design, particularly in terms of minimizing reflections and the degree of mode conversion introduced by the non-planar geometry.

Motivated by these considerations, and the present need for appropriate design tools, we have developed a computational method for obtaining the VSWR and the mode conversion characteristics of proposed curved-geometry windows which is described briefly in this paper. The technique is limited at the present time to axisymmetric geometries and to TE_{on} modes.

COMPUTATIONAL METHOD

A schematic diagram of a circular cross-section guide containing a dielectric window is shown in Figure 1. With no window in the guide, the TE_{on} electric field solution (assuming an e^{-iωt} time dependence) is

$$E_z = A J_0(k_z r) e^{ik_z z} \quad (1)$$

obtained from

$$\nabla^2 E_z + k_0^2 E_z = 0 \quad (2)$$

with

$$k_0^2 = \omega^2/c^2 \quad (3)$$

and

$$k_z^2 = k_0^2 - k_1^2 \quad (4)$$

Note that for TE_{on} modes it suffices to write the above as scalar equations. If a window is inserted into the guide, the rf electric field intensity E must now be obtained from the more general Helmholtz equation

$$\nabla^2 E + \epsilon_r k_0^2 E = 0 \quad (5)$$

where the relative dielectric coefficient ϵ_r may be an arbitrary function of r and z . The boundary conditions must now correspond to both an incident and reflected wave in the region to the left of the window and a transmitted wave traveling in the positive z -direction on the right. These boundary conditions cannot be implemented with the existing wave equation codes, but we can reformulate the

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problem so that it can be handled by the available programs. To do this, we assume the rf field intensity can be written as

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 \quad (6)$$

where $\mathbf{E}_2$ represents the contribution to the field due to the interaction of the dielectric with the incident wave. Combining Equations 2, 5 and 6, we obtain

$$\nabla^2 \mathbf{E}_2 + \epsilon_r \epsilon_0 \nabla^2 \mathbf{E}_2 = -\epsilon_0 \nabla^2 (\epsilon_r - 1) \mathbf{E}_1 \quad (7)$$

Thus the equation for the dielectric-excited wave $\mathbf{E}_2$ is obtained as the solution of an inhomogeneous Helmholtz equation with a driving term $-\epsilon_0 \nabla^2 (\epsilon_r - 1) \mathbf{E}_1$. The boundary conditions on $\mathbf{E}_2$ correspond to waves traveling in the positive- and negative-z directions away from the dielectric window region, and are conveniently implemented in the wave equation code OPNIAV, an extension of the SUPERFISH code (1).

One can interpret the driving term as follows: The incident rf electric field produces an oscillating electric polarization in the dielectric in accordance with the relation

$$\mathbf{P} = (\epsilon_r - 1) \mathbf{E} = (\epsilon_r - 1) \epsilon_0 (\mathbf{E}_1 + \mathbf{E}_2) \quad (8)$$

The associated polarization current is therefore given by

$$\mathbf{J}_p = \frac{\partial \mathbf{P}}{\partial t} = j\omega (\epsilon_r - 1) \epsilon_0 (\mathbf{E}_1 + \mathbf{E}_2) \quad (9)$$

In the presence of the polarization current, $\mathbf{J}_p$, the Helmholtz equation can be written as

$$\nabla^2 \mathbf{E}_2 + \epsilon_0 \nabla^2 \mathbf{E}_2 = j\omega \mathbf{J}_p \quad (10)$$

which, with Equation 9, is equivalent to Equation 7. Hence the driving term in Equation 7 can be identified as being due to polarization current produced by the incident wave in the dielectric region.

We have used a modified version of the wave equation solver OPNIAV (renamed as OPNIFIL) which, as discussed previously, implements the open boundary conditions required in these problems to solve Equation 7 for the dielectric-excited wave $\mathbf{E}_2$. The total field $\mathbf{E}$ is then computed using

Equation 6, and ultimately, the power P_r reflected from the window, the power P_t transmitted through the window and the power P_i incident on the window can all be obtained. From these quantities, the reflection coefficient

$$\rho = (P_r/P_i)^{1/2} \quad (11)$$

and the effective voltage standing wave ratio

$$VSWR = \frac{1 + |\rho|}{1 - |\rho|} \quad (12)$$

may be determined.

The code also does a Fourier analysis of the transmitted field in order to determine its modal composition. The degree of mode conversion to other TE_{0n} modes can then be ascertained.

COMPUTATIONS

A number of tests have been run to check out the method on simpler planar window geometries of various kinds for which standard computational techniques are already available (2). For example, in Fig. 2, VSWR results obtained using the OPNIFIL code for a model alumina double-disk window with an intermediate cooling region (75-75 coolant) are compared with computations using the standard impedance method. The window was designed for the TE_{02} mode and for a match at 60 GHz. The two sets

of results agree to about one percent. Electric field contour lines (lines of constant magnitude field) for the double-disk window system are shown in Figure 3 obtained at the match frequency. The contour lines both to the left and right of the window are straight (to within the "noise" level) and horizontal, characteristic of a TE_{02} traveling

wave with no sign of reflections from the window, whereas the contours within the window demonstrate the expected standing wave pattern. The results can be compared to the corresponding field contour pattern for this window at 59 GHz, one GHz below the match frequency as shown in Figure 4. Here, we see a TE_{02} standing wave pattern on the left,

indicating clearly that reflections from the window are occurring. The VSWR at 59 GHz was computed as 1.53. The pattern on the right is that of a ~~travelling~~ wave consistent with the imposition of the open boundary condition.

Figure 2. Schematic diagram of non-planar dielectric window in circular cross section waveguide

* A more extensive solver was written by P. K. Kuo for JPL.

Figure 2. Computations of VSWR for 60 GHz TE₀₂ double-disk window

Figure 4. Electric field contour lines for 60 GHz TE₀₂ wave incident from left on double-disk window (VSWR = 1.52)

The method was then used to compute the VSWR and mode conversion characteristics of a curved boundary dielectric window for which no standard computational techniques were available. Figure 5 shows the field contour lines at the best match point for a curved boundary dielectric window. In Figure 6 are shown curves of VSWR and of the percentage of the mode conversion (to all other modes) in the transmitted wave over the range of frequencies from 20 to 150 GHz. Two match points are observed, one slightly below the nominal 60 GHz goal and another at twice the frequency of the first match point, both with relatively high VSWR values of about 1.5. Mode conversion at the lower

Figure 3. Electric field contour lines for 60 GHz TE₀₂ wave incident from left on double-disk window (VSWR = 1.02)

Figure 5. Electric field contour lines for 60 GHz TE₀₂ wave incident from left on curved boundary window (VSWR = 1.55, mode conversion 3.4%)

Figure 6. VSWR and mode conversion for a curved boundary window

Computational
approach

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- (2) S. Ramo, J. R. Whinnery and T. Van Duzer, "Fields and Waves in Communication Electronics", John Wiley and Sons, Inc., 1975, pp 349 - 351.

replace by

- (1) The OPNZAW code was developed by Electron International Inc (formerly Harris, SAI, Inc) 48000 Arbor, Michigan under a contract with the Naval Research Laboratory. For a description of SUPERFISH, see R. Helbach and R. F. Holsinger, "SUPERFISH - A Computer Program ..."

match point was only about 3.4 percent, but builds up rapidly at the higher frequencies. One indeed might expect coupling to other modes to become appreciable as the ratio of window curvature to guide wavelength increases.

SUMMARY AND CONCLUSIONS

A computational technique has been developed for computing the VSWR and mode conversion characteristics of gyrotron windows with non-planar surfaces. The method has been checked out on

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