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EFFECT OF HELICAL SLOW-WAVE CIRCUIT VARIATIONS ON TWT COLD-TEST CHARACTERISTICS

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***Abstract*—Recent advances in the state of the art of computer modeling offer the possibility for the first time to evaluate the effect that slow-wave structure parameter variations, such as manufacturing tolerances, have on the cold-test characteristics of helical traveling wave tubes (TWT's). This will enable manufacturers to determine the cost effectiveness of controlling the dimensions of the component parts of the TWT, which is almost impossible to do experimentally without building a large number of tubes and controlling several parameters simultaneously.**

The computer code MAFIA is used in this analysis to determine the effect on dispersion and on-axis interaction impedance of several helical slow-wave circuit parameter variations, including thickness and relative dielectric constant of the support rods, tape width, and height of the metallized films deposited on the dielectric rods. Previous computer analyses required so many approximations that accurate determinations of the effect of many relevant dimensions on tube performance were practically impossible.

INTRODUCTION

Unfortunately, it is not an uncommon experience that TWT's of the same model, presumably fabricated within manufacturing tolerances, exhibit significant variations in performance. These variations represent a considerable cost to the industry, particularly when they are large enough that completed TWT's do not meet specifications. It would seem likely that these variations are the result of inadequately controlled manufacturing processes, but an accurate investigation of this hypothesis has been impossible until recently. This paper demonstrates the variations that can occur in TWT performance, in terms of dispersion and on-axis interaction impedance, when key parameters of the slow-wave structure vary within and beyond the tolerances typically employed within the industry.

The most common type of TWT slow-wave structure comprises a helical metal wire or tape supported by three or more dielectric rods in a conducting barrel. This commonly manufactured structure cannot be analyzed by conventional mathematical methods because it cannot be described conveniently in any coordinate system. An accurate simulation of this structure has been recently achieved [1, 2] using the computer code MAFIA; consequently, the analysis of the effect of dimensional variations on TWT performance is possible for the first time. MAFIA (Solution of **MA**xwell's equations by the **F**inite-**I**ntegration-**A**lgorithm) is a powerful, electrodynamic code [3, 4], which accepts data directly from standard engineering design software making analyses using the code convenient and efficient.

The particular device analyzed here is the helical slow-wave structure of the Northrop Grumman microwave power module (MPM) TWT [5] shown in Figure 1. The TWT nominally produces 100 Watts of RF output power at midband and operates over a range of frequencies from 6 to 18 GHz. The MPM circuit was chosen for this analysis because it represents most of the elements of a modern slow-wave structure design including a tape helix supported by partially metallized rectangular support rods, and because a complete set of dimensions and experimental data were available from the manufacturer [5]. Several Northrop broadband circuit parameters were varied including the tape width (tapew of Figure 1), the width and relative dielectric constant of the support rods (rodw and ε_r, respectively) and the distance from the helix axis to the metallized films deposited on the dielectric rods (metalr). The dispersion and impedance are compared for each set of variations.

The specific results presented here apply only to the mentioned circuit; however, these results can serve as a general guide for similar devices, and the computational techniques are readily applicable to other TWT's. Based on this kind of information, manufacturers can conduct cost-benefit analyses of their manufacturing tolerances and optimize designs for a wide variety of devices before fabrication.

SIMULATION AND ANALYSIS

Helical Model

The helical tape is generated with the actual width and thickness of the experimental circuit in the cylindrical coordinate system by varying axial and azimuthal coordinates consistent with the formula of a circular helix. Initially, the support rods were modeled using the quasi-rectangular configuration discussed in [1] and [2], where rectangles are approximated by generating radial increments with decreasing rod angles with increasing radius. With this configuration, it is necessary to use ten radial increments for the dielectric support rods to prevent the protrusion of the dielectric material through the metal coating. This increased number of radial increments, compared to six for the typical circuit, complicates the boundary conditions of the problem, and increases the time for the computation to converge. Because of this added complexity and computational time, the rectangular support rods were generated as wedges divided into p sections with graded dielectric constants consistent with the relationship

$$\varepsilon_{rp}' = 1 + (\varepsilon_{rp} - 1)\frac{A_p}{A_p'} \tag{1}$$

where ε_{rp}' and A_p' are the effective dielectric constant and cross-sectional surface area, respectively, of the pth section of the wedges in the MAFIA model, and ε_{rp} and A_p are the actual dielectric constant and cross-sectional surface area, respectively, of the pth section of the actual rectangular rods. It was shown in [2] that there was a significant savings in computational time with negligible change in dispersion and on-axis interaction impedance when using this modeling configuration compared to the quasi-rectangular configuration.

Figure 2 shows the cross-sectional view of the Northrop broadband circuit graded wedge model with p = 4. Figure 3 shows a MAFIA electric field plot of the cross-sectional view of the circuit; the size of the arrows is proportional to the magnitude of the field. It is apparent that the electric fields are concentrated more between the helix and the beginning of the metal film than in the region extending from the film to the barrel. Thus, the section of the support rods extending radially from the helix to the metal radius was divided into three regions, and the section from the metal radius to the barrel was treated as one region. A three-dimensional MAFIA plot of several turns of the Northrop broadband helical slow-wave structure is shown in Figure 4.

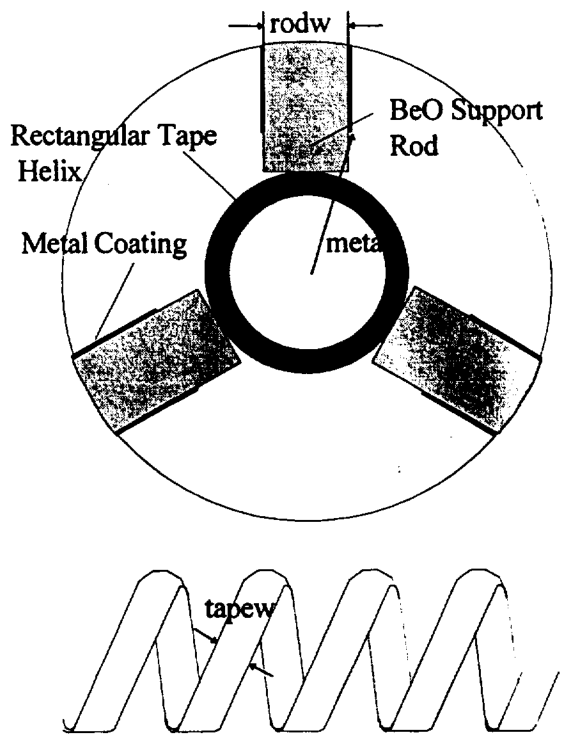

Figure 1 Northrop Grumman broadband MPM TWT helical slow-wave circuit

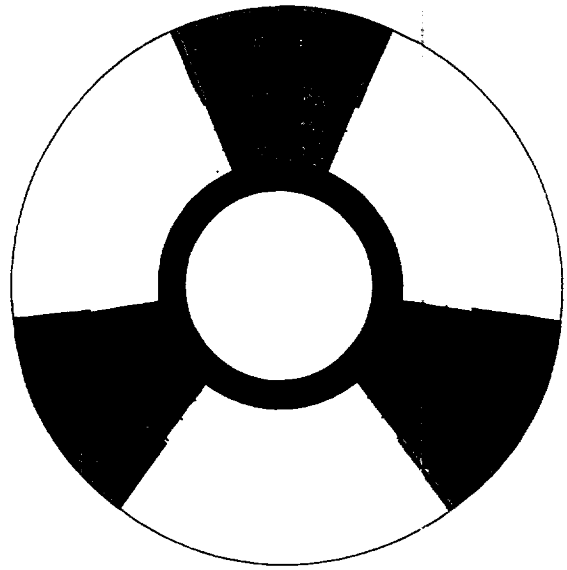

Figure 2 Northrop broadband helical slow-wave circuit model with graded wedge support rods

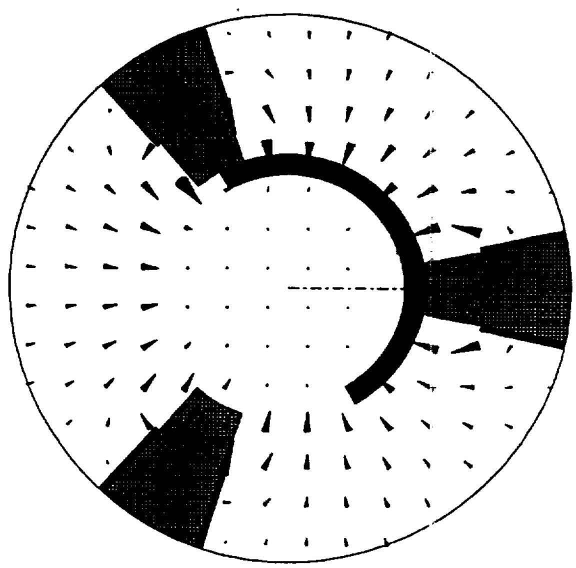

Figure 3 MAFIA electric field plot of cross-section of Northrop broadband helical circuit ($\beta L = 9$ degrees)

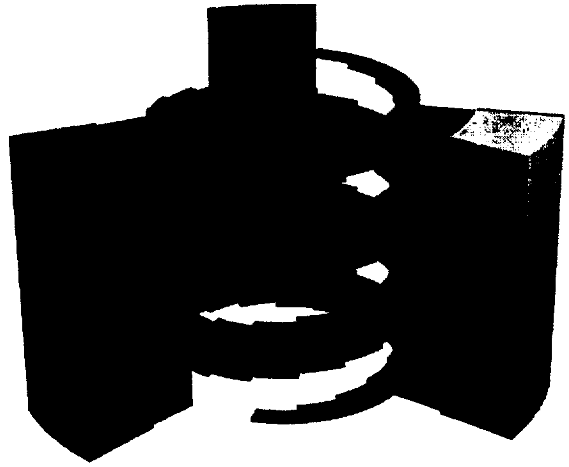

Figure 4 MAFIA three-dimensional plot of several turns of the Northrop broadband helical circuit

Dispersion

The method for calculating the dispersion is similar to experimental methods where frequency-phase characteristics are determined by measuring the resonant frequencies in a section of circuit shorted at both ends. Truncating an infinite circuit at two points with either an electric or magnetic wall with MAFIA corresponds to simulating standing waves with an integral number of half-wavelengths (phase shifts of π) within the isolated circuit section. Although the helix has no symmetry planes at which these boundary conditions are exact, if enough turns are modeled the effects of the fields at the boundaries become small [6]. The results presented here are based on ten helical turns for which the CPU time, using an IBM RISC/6000 Model 590 workstation, is approximately eight hours.

On-axis Interaction Impedance

The same truncation method is also used in the calculation of the on-axis interaction impedance. The on-axis interaction impedance is a measure of the strength of interaction between an RF wave harmonic and the electron beam. In the helix slow-wave circuit, the beam is synchronous with only the fundamental RF space harmonic. For this space harmonic, the interaction impedance on the axis is defined as

$$K_0 = \frac{|E_0|^2}{2\beta_0^2 \, P_{RF}}, \tag{2}$$

where $|E_0|$ is the magnitude of the fundamental space harmonic of the on-axis electric field, β_0 is the axial phase constant and P_{RF} is the RF power flow defined by

$$P_{RF} = w v_g . \tag{3}$$

v_g is the group velocity and w is the stored electromagnetic energy per unit length [7]. These calculations are described in detail in [2]. Refs. [7] and [8] give an excellent description of how dispersion and impedance affect TWT performance, such as gain, efficiency and bandwidth.

SIMULATION RESULTS

The accuracy of the MAFIA model has been validated in [6], where the dispersion and on-axis interaction impedance calculated using MAFIA were compared to experiment. The absolute average differences across the bandwidth were 1.5% and ten Ohms, for the dispersion and impedance, respectively.

Various circuit parameters were varied including tape width, support rod width and effective dielectric constant and metal film radius. The cold-test dispersion and on-axis interaction impedance are compared for each variation. First the dispersion and on-axis interaction impedance were calculated for several variations on the metal film radius (metalr of Figure 1). The dimension was varied within and beyond its manufacturing tolerance of 0.0005 inches. The results are plotted for the dispersion in Figure 5. From this plot it is obvious that as the film approaches the helix, or the loading is increased, the bandwidth is increased. Figure 6, which plots the on-axis interaction impedance for the same variations, shows that this increase in bandwidth is achieved at the expense of a slightly decreased impedance.

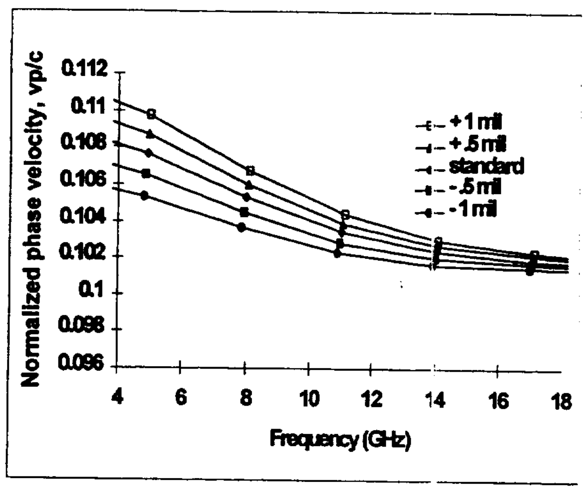

Figure 5 Simulated dispersion for variations on metal film radius, metalr

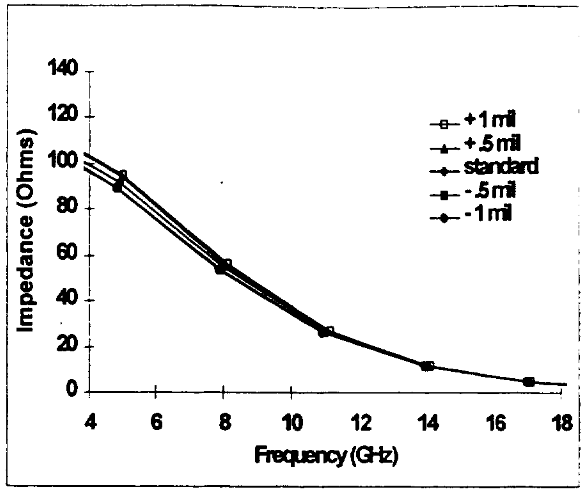

Figure 6 Simulated on-axis interaction impedance for variations on metal film radius, metalr

Next, the dispersion and on-axis interaction impedance were calculated for several variations on the support rod width (rodw of Figure 1). Figure 7 and Figure 8 show the dispersion and on-axis interaction impedance, respectively, for variations within and beyond its manufacturing tolerance of 0.0005 inches. From these plots we see that these variations will not affect bandwidth, but will increase or decrease the phase velocity uniformly across the bandwidth. The impedance is also uniformly increased or decreased across the bandwidth, increasing slightly when the rod is made thinner.

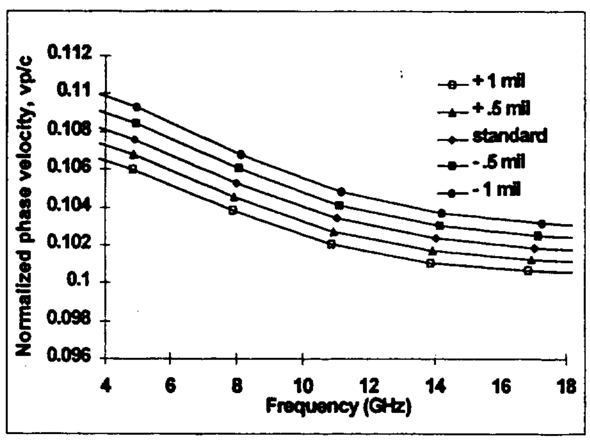

Figure 7 Simulated dispersion for variations on support rod width, rodw

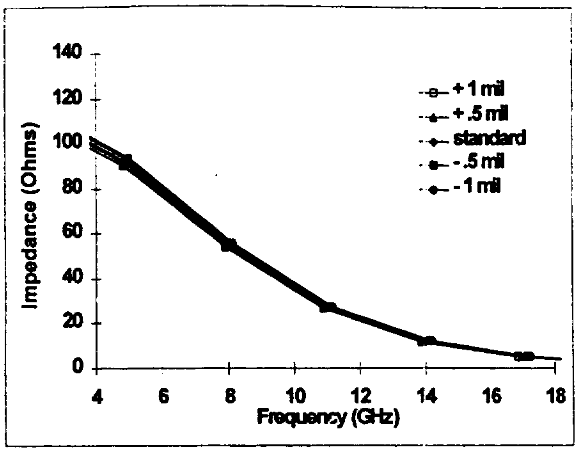

Figure 8 Simulated on-axis interaction impedance for variations on support rod width, rodw

The axial width of the helical tape (tapew) was varied within and beyond its dimensional tolerance of .0005 inches. Figure 9 and Figure 10 show the dispersion and on-axis interaction impedance, respectively. With increased tape width, only a slight decrease in both phase velocity and impedance occurs uniformly across the bandwidth except for the + 1 mil variation, which decreases the phase velocity more significantly. Because a helix fabricated with wider tape width would have improved thermal properties, this result may have valuable engineering significance.

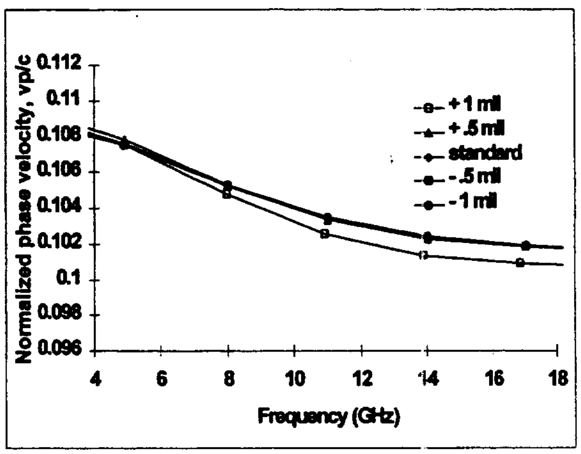

Figure 9 Simulated dispersion for variations on helical tape width, tapew

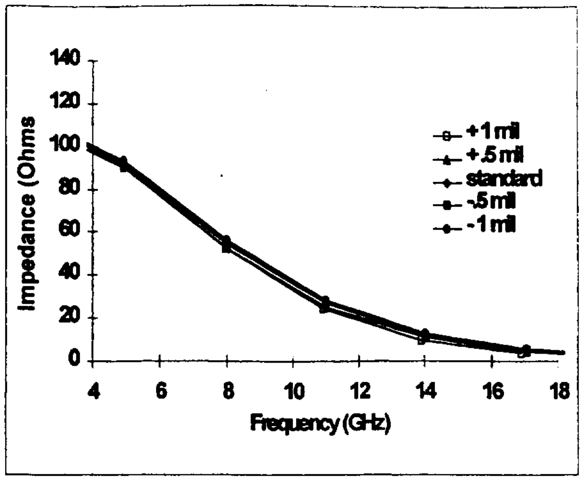

Figure 10 Simulated on-axis interaction impedance for variations on helical tape width, tapew

Lastly, the relative dielectric constant of the support rods was varied. The motivation for this last set of variations was based on citations from various sources that reported the dielectric constant for BeO to be anywhere from 6 to 7.5. As part of another investigation, we have already done some in-house dielectric measurements on anisotropic pyrolytic boron nitride (APBN) where we found variations in the permittivity as high as +/- 10% within the same sample [9]. We intend to also conduct an experimental study of the permittivity of BeO.

Figure 11 and Figure 12 show the dispersion and on-axis interaction impedance, respectively, for variations on the dielectric constant from 6 to 7.5. The difference in the dispersion and impedance is greater than for any of the other dimensional variations, even those beyond the dimensional tolerances. This could be a large contributing factor to why TWT's of the same model, presumably fabricated within manufacturing tolerances, exhibit significant variations in performance. From these results it appears the phase velocity and impedance are uniformly shifted up or down across the bandwidth. With increased permittivity, phase velocity and impedance decrease.

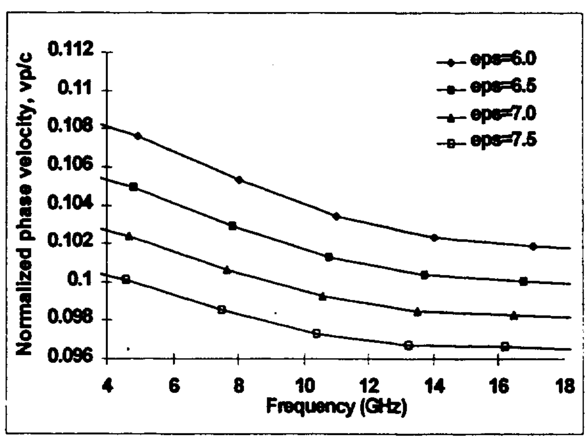

Figure 11 Simulated dispersion for variations on support rod effective dielectric constant, ε_r

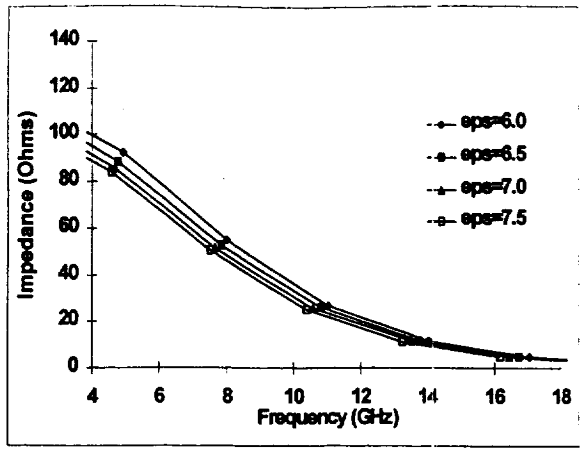

Figure 12 Simulated on-axis interaction impedance for variations on support rod effective dielectric constant, ε_r

CONCLUSIONS

A method has been demonstrated by which the sensitivity of parameter variations can be accurately obtained for helical TWT slow-wave circuits. Several variations were performed with MAFIA on the basic helical circuit parameters. We found the effect on tube performance of the dimensional tolerances on metal vane radius, tape width and support rod width. Most importantly we found that the effect on performance due to variations in the dielectric constant was the most prominent, implying that support rod permittivity is the most sensitive parameter of any of the variations made. This demonstrates the need for more complete information about the material being supplied for tube manufacturing.

With this accurate model for helical slow-wave structures, much potential exists to improve reliability and cost effectiveness in TWT manufacturing. A large amount of time and money can be saved by avoiding experimental measurements by optimizing designs and determining tolerance sensitivity with MAFIA prior to fabrication.

LIST OF FIGURES

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