International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-2, Issue-8, August 2014

Thermo-Mechanical Analysis of Window Assembly for Traveling Wave Tubes

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***Abstract*— Output window assemblies, derived from coaxial line, are designed for medium to high average RF power propagation in/from traveling-wave tubes (TWTs). During power propagation, thermal load arises due to impedance mismatch and other losses, like, ohmic loss, dielectric loss, etc, causes rise in temperature in the window assembly, hence, demand for proper thermal and structural analysis. This paper presents the thermal and structural analysis of output window assembly for TWTs which includes thermal management, structural deformations and stresses at different joints in ANSYS. Window disc in the assembly plays multiple roles, namely, incorporation of very high vacuum inside TWT that is tolerance of certain stress limits and very good S-parameters or VSWR. Hence, the analysis has also been extended for different window disc materials.**

***Index Terms*— Window assembly, Coaxial Coupler, transmission line, traveling-wave tube, thermal analysis.**

I. INTRODUCTION

Window assemblies, also known as coupler assemblies, are used in traveling-wave tubes (TWTs) for RF power transmission and are comprising of a center conductor, outer conductor and window disc and all are brazed together (Fig. 1) [1]-[3]. The output window assembly in a TWT transports several hundreds of average RF power from the helix slow-wave structure (SWS) [4]-[6]. Electromagnetic design of window assembly is carried out in cold condition for proper transformation of helix characteristic impedance such that S-parameters or cold return loss profile may be obtained less than -15 dB [3]. Under hot condition (due to intercepted beam power) helix deforms and its impedance changes and, also due to heat load, the window assembly is heated up and gets deformed than its cold condition which also changes impedance of the coaxial line. These all together enhances impedance mismatch and deterioration of S-parameters and finally lead to failure of the TWT due to bank and fourth reflection of the signal. Material properties of window disc, such as, dielectric property, strength, loss tangent and thickness of the window disc play an important role sustaining stress limits and in holding leak proof joints [1]-[3], [8]. Hence, thermal and structural analysis of the window assembly is an essential part to design an efficient window assembly if it is to be used for long life application.

In the window assembly (Fig. 1), there are several brazing joints namely, center conductor to window disc, window disc to window cup cup to outer conductor and center conductor to helix, which have to sustain certain stress limit to hold vacuum throughout the life of the TWT. In this paper, analysis of the window assembly has been carried out to study the thermal management of the assembly, dimensional deformation, and stress at different portion. Also, effect of material properties and thickness of the window disc on thermal management and structural integrity (stress) have been studied. The window assembly is thoroughly investigated, developed, taking care of its dimensional deformations under hot condition. The analysis has been carried out using commercially available software package ANSYS [9] and compared with COSMOS [10].

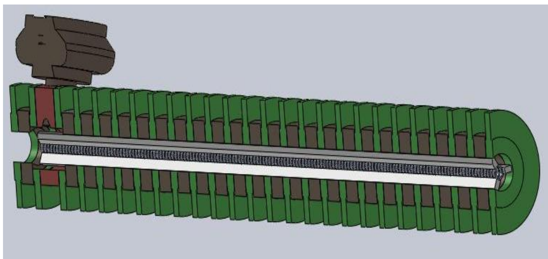

Fig. 1(a)

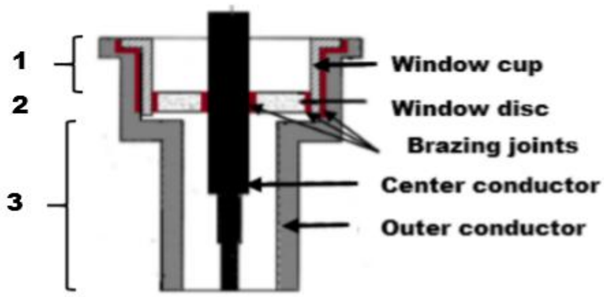

Fig. 1(b)

Fig. 1. **(a)** Three dimensional view of the window assembly with helix SWS in a TWT and **(b)** Schematic view of window assembly.

II. THERMAL ANALYSIS

Thermal model of the coupler assembly (Fig. 1b) consists of three regions: i) the first region (region 1) exposed to ambient condition and heat dissipation from this region takes place through conduction, convection and radiation, ii) in the third region (region 3) heat dissipation takes place only by radiation from center conductor to outer conductor, but due to very high vacuum inside TWT (~ 10^{-9} torr), radiated heat loss

Manuscript received August 20, 2014.

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is very less, iii) the most important region is the second region (region 2) in which upper surface exposed to ambient condition and lower surface is in vacuum and heat dissipation takes place through conduction from center conductor to outer conductor through window disc. In this region (region 2), the conductive path is comprises of series of thermal resistances [5], namely, thermal resistances of center conductor, window disc, window cup and outer conductor and three thermal contact resistances at brazing joints, namely, between center conductor to window disc, window disc to window cup and window cup to outer conductor.

The heat load to the window assembly is the sum of power loss due to impedance mismatch and carry over helix temperature [1]-[3], [5]. For the present TWT operating at 6 kV helix voltage, power loss in helix is equal to 12 W, arises due to 2 mA helix interception current (P= 2 mA × 6 kV = 12 W), which causes ~135^{0}C rise in temperature [5]. Thermal load of the assembly is 1.4 Watt due to impedance mismatch, other losses and carry over temperature from helix, is estimated and used as heat load in simulation. The heat load varies with material property and thickness of window disc, namely, alumina and CVD diamond. This heat load causes rise in temperature at center conductor which is dissipated to outer conductor, which is exposed to ambient condition (20 ^{o}C), through window disc and cup by conduction. Hence, essential boundary conditions required for the simulation are the thermal resistances, heat load and outside ambient temperature. Thus, a temperature gradient among the different parts causes different structural deformations and stress.

The window assembly or the transmission line under study comprises of three section quarter-wave transformers. The ratio of outer conductor (b) to inner conductor (a) radii of three sections, from top to bottom, are 2.2, 3.5 and 6.1, respectively, and corresponding lengths are 9.5 mm, 7.0 mm and 2.0 mm (Fig. 1). Ratio of radii (b/a) and length of each transformer are very sensitive to S-parameters and frequency of operation [2], [3]. Hence, demand for detail analysis such that dimension of different components of the assembly, which were originally envisaged during cold design, are not deviated beyond sensitivity limit. Temperature developed at different points in the coupler has been obtained from ANSYS [9] shown in figure 2 and using same boundary conditions and different material properties [5], results have been compared in COSMOS [10] (Fig. 3) and results agree very closely.

III. RESULTS AND DISCUSSION

Thermal and Structural analysis of the window assembly (Fig. 1), developed for Ku-band space TWT, is carried out with respect to its thermal management in ANSYS (Fig. 2) and compared in COSMOS (Fig. 3). It can be seen that temperature at different regions agree closely in both software packages. It can be seen from figures 2 and 3 that due to heat load, maximum temperature reaches in the center conductor and minimum in the window cup. This temperature gradient is due to different thermal resistances of conductive heat path and brazing joints which are in series.

Temperature distribution at different parts has also been studied using alumina and CVD diamond window disc for different thickness (Table-1), keeping all other dimensions constant. It can be seen from Table-1, that in case of CVD diamond thermal management is improved and this effect deteriorates as the thickness of the disc is reduced to half in both cases (alumina and CVD diamond). Thus, thermal management is better for thicker window disc, however, there is a tradeoff in thermal management and optimum S-parameters. Hence, 0.9 mm alumina disc has been chosen for optimum electromagnetic design and cost effectiveness compared to diamond.

Both axial and radial expansion, arise due to heat load, of the constituent elements have been studied and depicted in Tables 2 and 3, respectively. For CVD diamond, both the effects are less than alumina window disc and these effects further improves if the thickness of the discs are reduced. Thus, it can be seen from the tables that expansions are comparable to wavelength and hence it will affect S-parameters of the window assembly. Hence, during cold design of the window assembly the deformations are necessary to incorporate in cold design of the coupler.

Since window assembly has to hold high vacuum inside the TWT, structural analysis is also an important critical parameter. It can be seen from Tabe-4 that stresses at different parts are considerably less in case of CVD diamond disc than alumina disc. This further improves with the reduction of disc thickness in both cases. This is due to reduction in contact surface area between window disc to cup or center conductor. Diamond being a hard material, stress released by diamond is less.

Thermal and structural analysis of window assembly has been carried out with respect to thermal management, structural deformations and stresses with variable material properties of the window disc. With the increase in disc thickness, thermal management improves, however, with the reduction in thickness, structural deformations and stress improved. However, dielectric property of the disc is also critical parameter in matching character impedances between helix and connector for suitable S-parameters. Thus, to make a tradeoff between electromagnetic design and thermal design, and also for cost effectiveness, 0.9 mm alumina window disc has been chosen. Diamond being a hard material has several advantages over alumina disc but due to cost effectiveness for medium power propagation alumina is also a suitable choice.

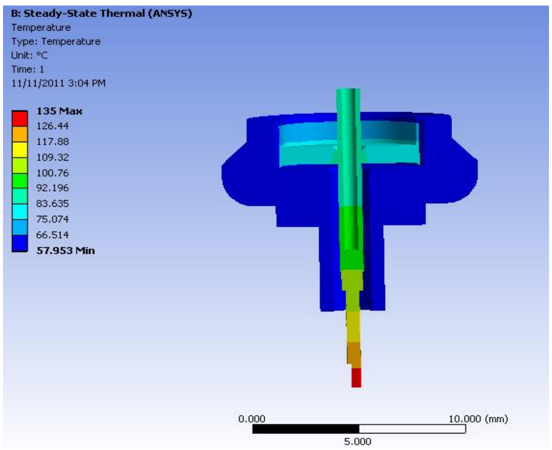

Fig. 2: Temperature distribution of the window assembly for 0.9 mm alumina window disc, obtained from ANSYS (The ratio of outer conductor to inner conductor radii, from top to bottom, are 2.2, 3.5 and 6.1, respectively and corresponding lengths are 9.5 mm, 7.0 mm and 2.0 mm).

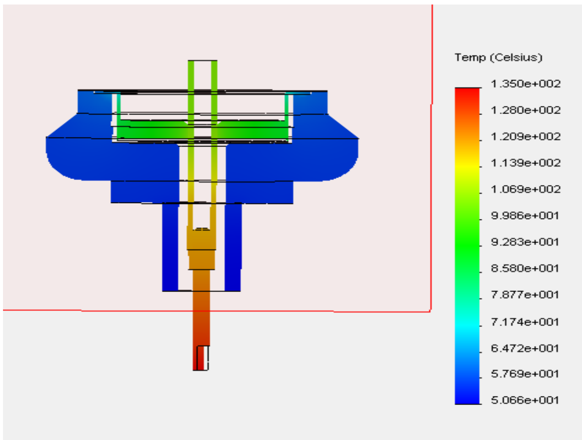

Fig. 3: Temperature distribution of the window assembly obtained from COSMOS (dimensions are depicted in figure 2).

Table-1: Window disc versus temperature (°C) distribution in different parts of the assembly

	Alumina		CVD diamond	
	0.9 mm	**0.5 mm**	**0.9 mm**	**0.5 mm**
Center Pin	134.35	135.26	134.27	134.77
Window Ceramic	115.35	131.1	95.007	102.71
Window Cup	92.51	98.32	94.792	101.48
Outer conductor	63.08	57.33	63.84	58.27

Table- 2: Radial expansion (× 10^{-4} mm) of different parts

	Alumina		CVD diamond	
	0.9 mm	**0.5 mm**	**0.9 mm**	**0.5 mm**
Center Pin	1.43	1.803	1.204	1.90
Window Ceramic	0.128	0.179	0.138	0.189
Window Cup	0.128	0.145	0.150	0.195
Outer conductor	0.195	0.137	0.194	0.199

Table- 3: Axial expansion (× 10^{-4} mm) of different parts

	Alumina		CVD diamond	
	0.9 mm	**0.5 mm**	**0.9 mm**	**0.5 mm**
Center Pin	0.131	0.165	0.168	0.178
Window Ceramic	0.143	0.1140	0.083	0.067
Window Cup	0.209	0.172	0.124	0.116
Outer conductor	0.196	0.180	0.108	0.076

Table- 4: Stress (MPa) at different joints

	Alumina		CVD diamond	
	0.9 mm	**0.5 mm**	**0.9 mm**	**0.5 mm**
Center Pin	0.126	0.199	0.226	0.177
Window Ceramic	32.158	49.26	9.989	17.55
Window Cup	1.167	5.495	1.151	6.062
Center conductor	11.07	4.42	8.59	6.00

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