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Research Article

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Design and Testing of RF Window for a High Power Klystron

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ABSTRACT

This paper describes a simple method to design a symmetrical pill box window used in high power klystrons. Analytical formulation is cross validated and fine tuned using commercial codes CST Microwave studio and HFSS. These results are finally tested by a fabricated cold test model. Low RF power measurement results of the cold test model agrees quite closely with that of analytical and simulation results. A code has also been written based on these analytical formulae. A parametric study has also been conducted by varying different important design parameters. Optimized thermal simulation is also presented in this paper.

Key words: Window, klystron, radio frequency, optimized thermal simulation

INTRODUCTION

As far as nuclear energy is concerned fusion [1] is one of the methods which has gained significant importance for last few decades. There are two promising approaches to carry out the process of fusion. The first one is optically confined fusion and the second one is magnetically confined fusion. The first approach use large powerful lasers or particle beams to illuminate a small target of fusion fuel. Traditional approach is the second one which is known as magnetically confined fusion. Again there are a number of configurations for achieving magnetically confined fusion. One of the most popular processes among these is TOKAMAK [2] system. In TOKAMAK system very heavy amount of RF energy is needed to be coupled to the plasma. In case of LHCD TOKAMAK [3] systems klystron is used as the main source of RF energy. Klystron mainly consists of Gun, RF section, collector and RF window. Like all other microwave wave tubes, R.F Window development is one of the important issues in the design of high power klystron. R.F Window's are fitted in the output section of the klystron. They are used to separate a highly pressurized vacuum environment from normal atmospheric one. Naturally they must be robust to absorb the high pressure difference and also should be transparent to the microwave. Care also should be taken in selecting the dielectric material with low loss tangent, high thermal conductivity, appropriate mechanical strength and also flaw less design to achieve minimum power reflection and maximum power transmission [5]. Most important point in the development of high power window is the dielectric characteristics of the window material [6]. Among pill box type RF windows most common one is symmetric type window. Few literatures are available in the design of symmetric type RF window [7-8]. But detailed analytical design is still missing. Here we present a detailed analytical study of symmetric window with measured results.

ELECTROMAGNETIC FORMULATION

There are mainly three parameters which are very important in the design of symmetric window. These are diameter of the circular waveguide section and length of circular waveguide section in which the ceramic disc is fitted at centre. A schematic diagram of symmetrical window is shown in fig. 1.In this section we describe in detail the design of window diameter and length of the circular waveguide section.

Diameter of the Circular Waveguide Section

We will consider mainly two criterions for determining the diameter of the circular waveguide section.

Mechanical Criterion

Diameter D_c of circular waveguide should at least be equal to the diagonal of the rectangular waveguide and it is given by

$$D_c = (a_r^{\ 2} + b_r^{\ 2})^{1/2} \tag{1}$$

where a_r is the width of the rectangular waveguide and br is the height of the rectangular waveguide. Diameter obtained from this relation is the minimum diameter needed to support the rectangular waveguide.

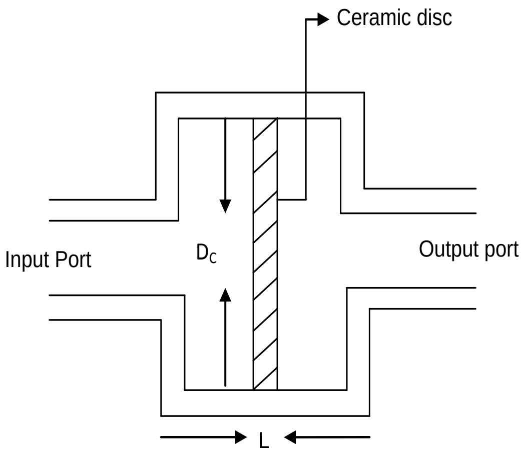

Fig.1 Schematic of RF window

Impedance criterion

In order to have smooth transfer of microwave power from rectangular to circular and then vice-versa for downward transmission, it is required that at the junction, impedance of the rectangular waveguide should match with the impedance of circular waveguide [9-10]. The characteristic impedance for rectangular waveguide Zor and circular waveguide Zoc operating in dominant modes are given by [11]

$$Z_{or} = 377 (\varepsilon_r / \mu_r)^{-1/2} (b_r / a_r) (\lambda_{gr} / \lambda_0) \tag{2}$$

$$Z_{oc} = 377 (\varepsilon_r / \mu_r)^{-1/2} (\lambda_{gc} / \lambda_0) \tag{3}$$

where ε_r and μ_r are respectively, the relative permittivity and relative permeability of the dielectric medium. For non magnetic material μ_r is taken as 1.0, and thus the above equations reduces to

$$Z_{or} = 377 (\varepsilon_r)^{-1/2} (b_r / a_r) (\lambda_{gr} / \lambda_0) \tag{4}$$

$$Z_{oc} = 377 (\varepsilon_r)^{-1/2} (\lambda_{gc} / \lambda_0) \tag{5}$$

λ_{gr} and λ_{gc} are guided wavelengths for rectangular and circular waveguides respectively. Guide wavelengths is given by

$$\lambda_g = \lambda_0 / (\varepsilon_r - (\lambda_0 / \lambda_c)^2)^{\ 1/2} \tag{6}$$

Here λ_0 and λ_c are free space and cutoff wavelengths respectively.

Now from the two equations (5) and (6) it can be easily seen that:

$$Z_{oc} / Z_{or} = (a_r /b_r) (\lambda_{gc} / \lambda_{gr}) \tag{7}$$

The above derivation assumes same dielectric medium (air) in both the waveguides. From equation (7) it is clear that for Z_{oc} to become equal to $Z_{or,}$ one must have

$$\lambda_{gc} / \lambda_{gr} = b_r / a_r \tag{8}$$

But, in this case of pillbox-type window, circular waveguide is partially filled with a dielectric (alumina). This may be treated as equivalent to the circular waveguide filled uniformly with a dielectric having effective relative permittivity (ε_r') which may be obtained as,

$$\varepsilon_r' = 1.0 + (\varepsilon_r - 1.0)\ V_d /V_t \tag{9}$$

where V_d is the volume actually occupied by the ceramic disc in the waveguide and V_t is the total volume of circular waveguide. Then equation (7) becomes,

$$Z_{oc} / Z_{or} = (\lambda_{gc} / \lambda_{gr}) (\varepsilon_r')^{-1/2} (a_r / b_r) \tag{10}$$

For most of the high power pillbox-type windows the value of ε_r' will vary between 1.0 and 2.0. A value of 1.5 is reasonable for ε_r'. Then above equation becomes

$$Z_{oc}/Z_{or} = (\lambda_{gc}/\lambda_{gr})(0.816)(a_r/b_r) \tag{11}$$

Examination of above equation suggests that for impedance matching between rectangular and circular waveguides,

$$\lambda_{gc} / \lambda_{gr} = b_r / (0.816\ a_r) \tag{12}$$

The diameter obtained from this criterion predicts the maximum possible diameter.

For all propagating modes it is necessary to satisfy the following criterion

$$\lambda_c > \lambda_0 / (\varepsilon_r')^{1/2} \tag{13}$$

Hence the minimum possible diameter supporting the TE_{11} mode in circular waveguide with uniform dielectric permittivity ε_r' (which has been taken as 1.5 in this case) is given by

$$1.706\, D_c > \lambda_0 / (\varepsilon_r')^{1/2} \tag{14}$$

The diameter obtained from this relation is the minimum required for smooth transfer of power from rectangular to circular waveguide.

$\lambda_{gc} / \lambda_{gr} = 1$ presents a compromise between maximum and minimum possible diameters and results in an useful design equation. The dominant modes for rectangular circular waveguides are TE_{10} and TE_{11} respectively. The wavelengths for these modes are given by

$$\lambda_{gr} = 2a_r \tag{15}$$

$$\lambda_{gc} = (\pi D_c)/(\chi_{np}') \tag{16}$$

χ_{np}' zeros of the Bessel's function for TE_{np} mode. In this case the dominant mode for the circular wave guide is TE_{11}. Value of χ_{np}' in this case is 1.841 [12].

Equating (15) and (16) we get

$$D_c = 1.1723\, a_r \tag{17}$$

Length of Circular Waveguide Section

Transmission line theory predicts that a half wavelength, or integral multiple of it, sandwiched between lines of equal impedance presents no mismatch and all the available power is delivered down the line [13]. But in case of symmetric window, it consists of a ceramic disc. Hence it results a transmission line with composite dielectric. Equation that has been derived for uniform lines can then be applied if one can replace εr with an effective relative permittivity (εr'), which takes into account the two junctions and the dielectric disc. If the effective relative permittivity of the window structure is correctly known, then λg and hence L can be calculated as

$$\lambda_g = \lambda_0 / \sqrt{\{\varepsilon_r' - (\lambda_0 / \lambda_c)^2\}} \tag{18}$$

$$L = \lambda_g / 2 = \lambda_0 / 2\sqrt{\{\varepsilon_r' - (\lambda_0 / \lambda_c)^2\}} \tag{19}$$

Thermal Losses in the Window

Along with the RF design of the window, it is necessary to simulate the thermal losses for the window. There are several types of losses that can occur due to the window. They are reflection loss due to the mismatch within the line, the dielectric loss due to the imperfect, nonmagnetic dielectric, and the copper loss due to the conductor walls. Dielectric loss and copper loss are given by the following equations.

Copper loss due to TE_{11} mode is:

$$\alpha_c = 0.00423\, [\, (f_c/f)^{1/2} + (1/2.38)\, (f/f_c)^{3/2}\,] \,/\, [\, r^{3/2}\, ((f/f_c)^2 - 1.0)^{1/2}\,] \text{ dB/foot} \tag{20}$$

where r is radius of the guide in inches. f and f_c are the operating and cut-off frequency respectively.

Dielectric loss due to TE_{11} mode is:

$$\alpha_d = [27.3\, (\in_r)^{1/2}\, \tan\delta\,] / [\, \lambda_0\, (1.0 - (f_c/f)^2)^{1/2}\,] \text{ dB/foot} \tag{21}$$

where $\in_r$ is the dielectric constant and tan δ is the loss tangent of the dielectric material, and λ_0 is the free space wave length.

Our interest is with the dielectric loss, which occurs due to the insertion of imperfect and nonmagnetic dielectric material within the waveguide.

PARAMETRIC ANALYSIS

A code has been written depending on these analytical results. With the help of this code together with the simulation tools some parametric analysis has been carried out. Length and diameter of the circular waveguide section and dielectric constant of the disc sandwiched in the circular waveguide section has been varied to observe the shift in frequency. In case of high power klystrons some specific dielectric materials are used in windows [14]. Table 1 show some conventional materials which are used in RF windows. Only these materials were used to observe the shift in frequency. Figure 2 shows the variation of frequency with the variation of window length, figure 3 shows the variation of frequency with the variation of window radius. Figure 4 shows the variation of frequency with the variation of dielectric constant.

Table - 1 Conventional Materials which are used in RF Windows

Material	Purity	Specific gravity	ε	tanδ
Alumina ceramic	99.0	3.9	9.81	9.4
Alumina ceramic	99.7	3.95	9.95	4.2
Alumina ceramic	99.9	3.91	9.67	13.3
Sapphire	100	3.98	10.16	2.3
Aluminium Nitride	99.5	3.26	8.35	420

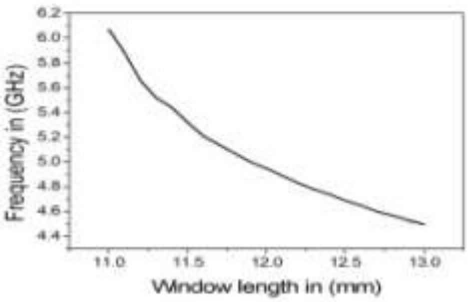

Fig. 2 Variation of freq. with window length

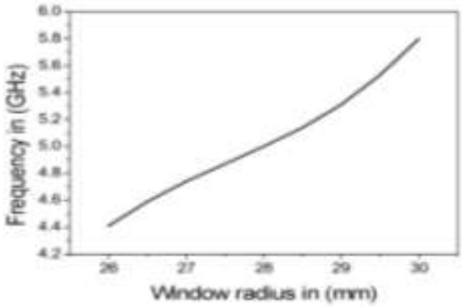

Fig. 3 Variation of freq. with window radius

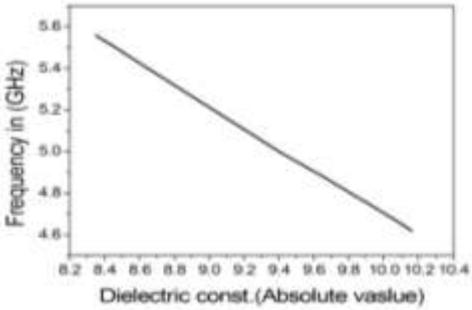

Fig. 4 Variation of freq. with dielectric constant variation

ANALYTICAL AND SIMULATION RESULTS

Based on the above analytical results we have designed a window which is to be fitted with a C band klystron. Frequency of operation is 5 GHz. Rectangular waveguide used is WR 187. With the approximate dimensions (Obtained from analytical model), window was simulated in commercial codes CST MICROWAVE STUDIO and HFSS. Finally it is optimized using these codes which has got a little bit variation then that calculated through analytical formulae. A comparison of simulated results using CST and HFSS is shown in fig. 5. A comparison of Calculated (obtained from analytical formulae) and simulated parameters of the window are tabulated in Table 2.

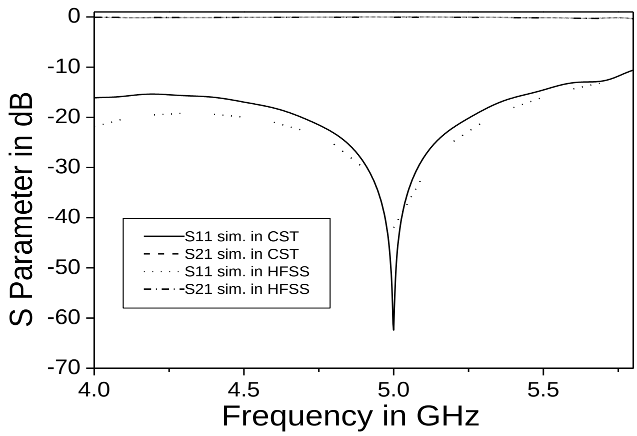

Fig. 5 Plot of S_{11} and S_{21} using CST and HFSS

Table - 2 Comparison of Calculated (Obtained from Analytical Formulae) and Simulated Parameters of the Window

Type of data	Operating frequency	Circular WG length	Circular WG diameter	Dielectric constant
Analytical	5.0	22.08	55.74	9.4
Simulated	5.0	23.8	56.0	9.4

As in case of electromagnetic simulation thermal simulation has also been carried out. Figure 6 shows the results after running a thermal analysis for this RF window using ANSYS [15], considering a water flow rate of 5 liters/minute for cooling while taking the loss tangent value of 0.0012 for the ceramic disc. The temperature distribution on the ceramic and copper surfaces due to losses in the window is shown here and the maximum surface temperature is found to be about 390C and it is at the centre of the ceramic disc.

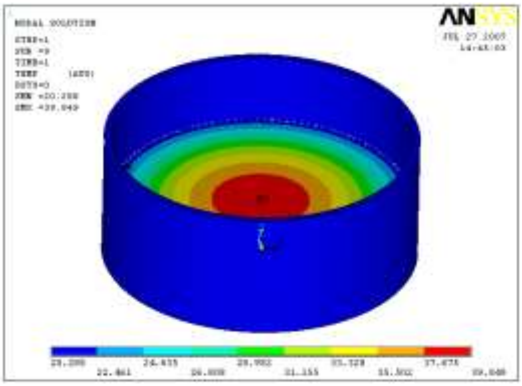

Fig. 6 Thermal simulation of the RF window

FABRICATION AND COLDTEST RESULTS

Based on the optimized parameters we fabricated two prototypes of the window. The diagram of which is shown in fig. 7. This window is made with OFHC Copper having its material purity 99.99%. An Alumina disc is fitted exactly at the centre of the window. Dielectric constant of the Alumina disc is 9.4 Schematic of the measurement set up of the window is shown in fig 8.

Fabricated C band window is measured using a modern V.N.A. Model no of the V.N.A is E8364B. It was calibrated using E cal kit having model no N4692-60001. Standard coaxial to waveguide adapter was used. A screen shot of the measurement set up along with the screen shot of the V.N.A is shown in fig. 9 and fig. 10

Fig. 7 Fabricated C band window

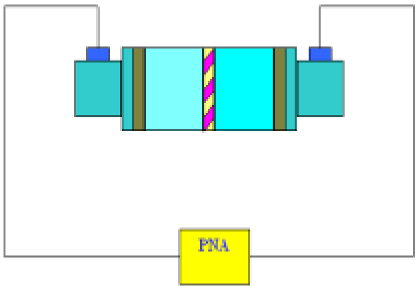

Fig. 8 Schematic of measurement setup of C band window

Fig. 9 C band window in test bench

Fig. 10 Screen shot of PNA with C band window attached

Table - 3 Comparison of the Simulated and Measured Results

Observation	S_{11}(dB)	S_{21}(dB)	S_{12}(dB)	S_{22}(dB)
Simulated result (CST)	-60.54	-0.007	-0.007	-60.54
Simulated result (HFSS)	-43.5	-0.033	-0.033	-43.5
Measured result	-50.36	-0.038	-0.032	-35.04

DISCUSSION

Parameters obtained from the analytical model and that optimized from the simulation shows a close match between them. From the parametric study it is very much clear that as the window length is increased frequency reduces while as the diameter of the window is increased, frequency increases. In case of variation of dielectric constant we can say as the dielectric constant is increased frequency drops down. Circular waveguide diameter calculated from analytical model is 55.74 mm against the optimized dimension of 56mm. The total length of the circular waveguide section calculated analytically is 22.08mm while the optimized dimension is 23mm. Hence we can see there are deviations of 0.4% in case of the diameter and a deviation of 7.56% in case of circular waveguide length. In case of thermal simulation it is very much clear that the centre portion of the ceramic disc is hottest compared to the other peripheral parts of the disc. With the specified flow rate the window works satisfactorily.

CONCLUSION

A methodology has been developed to design a high power window supposed to be used in high power klystron. Two cold test models have been developed. Analytical and optimized dimensions are quite close to each other. Window developed using this methodology achieved an appreciable insertion loss and return loss. From parametric analysis one can predict the approximate frequency with the variation of window length, window diameter and dielectric constant of the material placed exactly at the middle of the circular waveguide.

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