URSI - RCRS 2022, IIT (Indore), India, 1 - 4 December, 2022

Challenges involved in Design, Development, and Testing of High Power Ka Band WR-51 RF Vacuum Window

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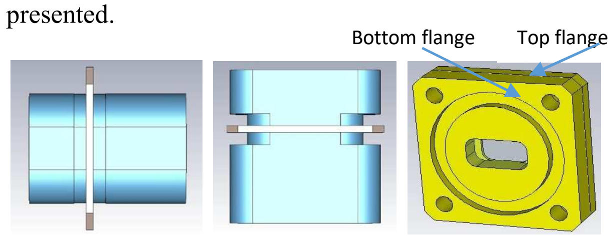
Abstract- This paper presents the design, realization, and testing of Ka-band (WR51), high power vacuum window (VW), which consists of brazed fused quartz substrate and optimized for the frequency band of 17.5-21.5 GHz. The challenges involved at the various stages during the development and testing are mentioned with all corrective measures to manage these challenges to make a better product available in the market. This Vacuum window will be used as an interface at the TVAC chamber for testing high-power passive components of communication payloads such as Diplexer, Omux, filter, OMT, PIMP filter, etc.

Keywords- Multipaction, TVAC, Quartz substrate, DUT.

I. INTRODUCTION

RF vacuum window is used to isolate high vacuum inside TVAC chamber and to act as a transparent medium for RF without much degradation. The vacuum window or co-axial feed through is mounted at TVAC chamber flange for high power test setup to simulate payload passive components like OMUX, Diplexer, Filter, Coupler, HRF, OMT, etc. as in actual space environment. The ideal RF window should have low loss, high transmission, high thermal conductivity, and high mechanical strength, and be capable to hold the desired vacuum level inside the TVAC chamber. A VW is designed and tested at our Lab for multiple units to establish the desired specification. In this paper, we illustrate a VW that has low insertion loss, high transmission, wide bandwidth (4 GHz), and to withstand high power handling and multipactor free without breakdown. **Challenges Involved:** In our case, the designed vacuum window must withstand very high average power as well as peak power threshold without degrading its performance as it will be used for high power handling and multipaction testing of the payload components having higher power requirements. Along with this, it should also handle differential pressure developed during the high vacuum condition inside the TVAC chamber typical 1.0×10^{-6} mbar. Any type of failure in the vacuum Window during the testing can lead to catastrophic damage to the FM component under the test. It is not only enough to make a vacuum window with optimum parameters but also to qualify it by test and measurement for all aspects. There are several windows in the market with different materials that are available at cheaper rates but have not been tested for High Power because of the complexity, cost, and time involved in High power testing. Any test compromise may result in the loss of money and time. Here, a fully tested vacuum window is presented.



(a) Side View (b) Top View (c)

Fig.1: (a) and (b) 3D Model of Vacuum Window, (c) Complete Model assembly of Vacuum window with top and bottom flanges along with fused Quartz substrate.

II. DESIGN OF VACUUM WINDOW

A. Electrical Design

Based on the above requirements, the material choice is very important. Materials like Alumina, Beryllium oxide, sapphire, and Quartz [8]; Alumina and Quartz substrate are used in RF windows frequently. The Electrical Properties of Quartz substrate like dielectric strength, and electrical dissipation far better than other materials. In this paper, the RF window using fused Quartz (dielectric constant = 3.75) substrate is analyzed due to its low dielectric loss, ease of fabrication, and wider bandwidth. The VW is modeled and EM (Electromagnetic) simulation is carried out in CST Microwave studio. The impedance matching is done at the substrate junction using inductive iris to increase bandwidth which in turn increases differential pressure handling capability without compromising power handling compatibility as in the case of the capacitive iris [1]. The electrical design parameter of VW: Quartz substrate thickness (t), Substrate length (l), Substrate Width (W), Iris length ($Iris\_l$), Iris thickness ($Iris\_t$), the dielectric constant of Quartz substrate ($\epsilon_r = 3.75$). The Quartz substrate used has typical properties like thermal conductivity at $25°C$ is 1.38 W/m/K, loss tangent at 100 MHz is 0.0005, and Coefficient of thermal expansion is 0.7 ppm / $°C$. Several iterations were done on design parameters to achieve the best possible scattering parameter in terms of bandwidth, insertion loss, and return loss [3]. The simulation is carried out in CST Microwave Studio. The model of the proposed window is shown in "Fig. 1 (a) and (b)" without a ka band WR-51 flange. The inductive iris used for matching and its parameter iris length ($Iris\_l$) is varied vs frequency as shown in "Fig. 2". Other parameters were also varied [4] in a similar way to achieve desired electrical specifications. After achieving the best parameters, all design parameter is varied to 2% to take care of fabrication tolerances and it does not have much effect on VSWR.

The complete structure of VW with standard WR-51 flange along with top and bottom flange is presented in "Fig. 1 (c)". The cylindrical groove on the bottom flange is for the gasket or O-ring as it is required to take care of any leak from the TVAC chamber directly. The fused quartz substrate is sandwiched between the top and bottom flange.

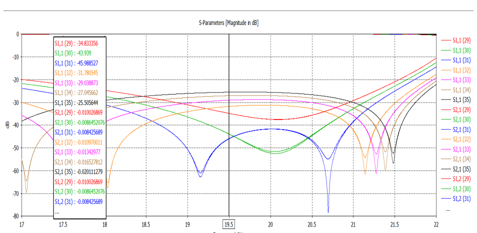


Fig 2: Reflection vs frequency for varying Iris length ($Iris\_l$)

B. Theory

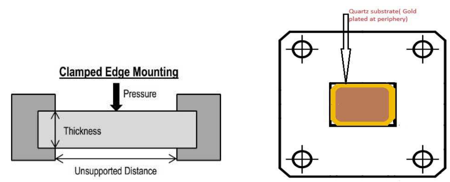
The thickness of quartz substrate is very important in design as on one hand it is the parameter that governs the desired return loss over the frequency band. On other hand, this thickness will decide the differential pressure withstanding capability. It means that the larger the thickness, the more will be its differential pressure handling capability. Consequently, lower the achievable in-band return loss [2]. So the thickness of the quartz substrate will be selected based on the above two factors. In our case, the first thickness will be selected based on differential pressure handling capability with sufficient margin as a prime requirement, and then the selected thickness will be matched in the rectangular waveguide using impedance matching to achieve the desired electrical specifications. For clamped rectangular window as in "Fig. 3 (a)", the thickness of the Quartz substrate can be approximated using the equation [7] given below:

$$t = l.w.\sqrt{\frac{P.K.SF}{2.M.w.(l^2+w^2)}} \qquad (1)$$

Table 1: Ka BAND VACUUM WINDOW DESIGN SPECIFICATIONS

S.No	***Parameters***	***Units***	***Specifications***
1.	Frequency	GHz	19.5
2.	Insertion Loss	dB	< 0.15
3.	Bandwidth	GHz	4
4.	VSWR	-	1.1:1
5.	Leak Rate	atm-cc/s	10^{-8}
6.	Differential Pressure	PSI	35
7.	Input/output Interface	-	WR-51
8.	Power Handling	W	800
9.	Peak Power Handling	W	2000

where, l = unsupported window length, w = unsupported window width P = 14.7 PSI for vacuum window, K = empirical constant (0.75), M= modulus of rupture of quartz substrate, SF = safety factor. A safety factor is a value to encompass the many other factors not included in the design. Its value can be selected based on application. SF = 4 would be considered a moderate value, sufficient for this VW applications.



(a) (b)

Fig. 3: (a) Substrate clamped on rectangular Window, (b) For brazing the substrate on the bottom flange.

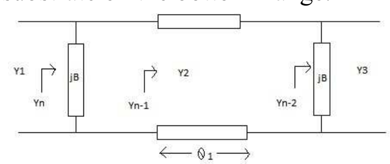


Fig.4: The equivalent circuit representation of the vacuum window.

The input design parameters are : Window material: Fused Quartz, Loss tangent: 0.0005, Dielectric Constant: 3.75, Substrate length (l): 13 mm, Substrate Width (W): 9.5 mm, Substrate thickness (t): 0.38 mm, Iris length ($Iris\_l$): 10 mm, Iris Thickness ($Iris\_t$): 0.7 mm, and Input/Output W/G interface: WR51(a =12.954, b = 6.477) The EM simulation is carried out for this ka band RF W/G VW using CST Microwave Studio software, the frequency domain solver which is based on the Finite element method (FEM). A signal at 19.5 GHz in the dominant TE10 mode is excited through the designed rectangular Ka-band window. The substrate length and width are kept greater than standard WR-51 dimensions. It is required to sandwich the substrate between the top and bottom flange and for brazing the substrate on the bottom flange as depicted in "Fig. 3 (b)". The guided wavelength in a dielectric-filled waveguide is calculated using the following formula:

$$\lambda_{gr} = \frac{\lambda_o}{\sqrt{\mu_r.\epsilon_r - \left(\frac{\lambda_o}{\lambda_c}\right)^2}} \qquad (3)$$

The equivalent reactance of inductive iris as in [7] can be calculated as:

$$\frac{X}{Z_o} = \frac{a}{\lambda_g}\tan^2\left(\frac{\pi . l}{2a}\right)\left\{1+\frac{3}{4}\left[\frac{1}{\sqrt{1-\left(\frac{2a}{3.\lambda}\right)^2}}-1\right]\sin^2\left(\frac{\pi . l}{2a}\right) + \left(\frac{2a}{\lambda}\right)^2 X\left[1-\frac{4E(\alpha)-\beta^2F(\alpha)}{\pi . a^2}.\frac{4E(\beta)-\alpha^2E(\beta)}{\beta^2}\frac{1}{12}\sin^2\left(\frac{\pi . l}{2a}\right)\right]\right\}$$

$$\alpha = \frac{\sin\pi . l}{2a}, \beta = \frac{\cos\pi . l}{2a}$$

$F(\alpha)$ and $E(\alpha)$ are complete elliptic integrals of the first and second kinds, respectively. The equivalent circuit of the 3D model is based on the transmission line as shown in "Fig. 4". The dielectric electrical length is $\theta_1 = \beta l_1$. The admittance at each junction can be calculated using the below equations.

$$Y_n = j\beta + Y_{n-1} \tag{4}$$

$$Y_{n-1} = Y_2\left[\frac{Y_{n-2}+jY_2\tan\theta_1}{Y_2+jY_{n-2}\tan\theta_1}\right] \tag{5}$$

$$Y_{n-2} = Y_o + j\beta \tag{6}$$

The equivalent susceptance of the junction is β and the admittance is Y. The reflection coefficient and VSWR [9] of the circuit can be calculated as:

$$|\Gamma| = \frac{Y_o-Y_n}{Y_o+Y_n} \tag{7}$$

$$|VSWR| = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{8}$$

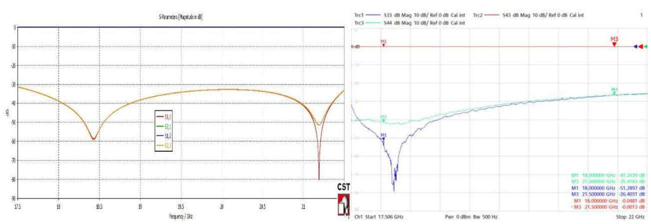
III. SIMULATED AND MEASURED RESULTS

A. *Simulated Results*

The full 3D EM simulation is carried out to achieve the desired specification. The simulated result of S11 and S21 as a function of frequency is depicted in "Fig. 5 (a)". The EM simulated results show that the insertion loss (S21) is around 0.01dB and the return loss (S11) is better than 30 dB. The designed vacuum window should handle very high peak power. To ensure this the field distribution in the rectangular waveguide and on the substrate should be as minimum as possible [4]. The Electric field and Magnetic field distribution of EM simulated VW are presented in "Fig. 6". It corressponds to a 0.5W average power feed at the input of the RF window resulting in a maximum electric field value of 10.419 kV/m on the substrate. On scaling field to the dielectric breakdown of the substrate, the power required for breakdown is more than 40kW.

B. Manufacturing And Measured results

After the mechanical fabrication of the designed vacuum window, the substrate is brazed on the bottom flange and the top part is assembled using mounting screws. The low power measurement of VW is carried out on VNA with waveguide calibration applied at input and output ports.



(a) (b)

Fig. 5: (a) Simulated transmission (dB) and reflection (dB) vs frequency (GHz) plot. (b) Measured transmission (dB) and reflection (dB) vs frequency (GHz) plot.

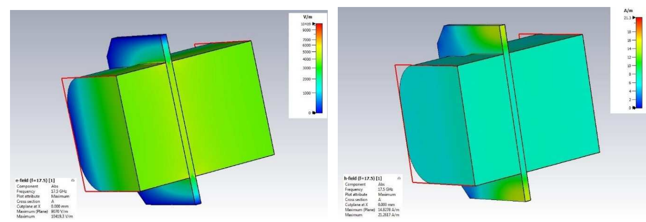
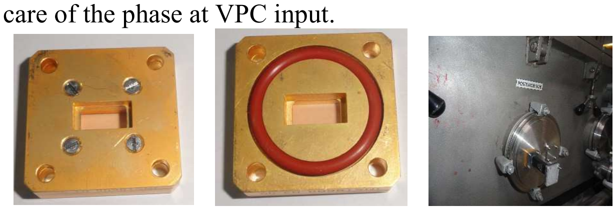


Fig. 6: Simulated Electric field and Magnetic field distribution.

The measured results are presented in "Fig. 5 (b)". The other mechanical parameters such as leak rate, and differential pressure holding capability are practically measured. This vacuum window has a leak rate of 1.3x10-9 atm-cm3/s. After obtaining satisfactory specifications of VW, it is mounted on the TVAC flange as in "Fig. 7 (b)" for vacuum withstand before applying any high power. This was done to gain confidence in the designed VW. This VW withstands differential pressure for several days without any failure.

IV. HIGH POWER ANALYSIS

After low power measurement, VW is subjected to high power testing. For this, it is mounted on the TVAC chamber flange. A Ka-band test bed configuration is established at HPTD Lab (SAC-ISRO) as shown in "Fig. 8". Three multipaction detection methods have been employed [11]: harmonic detection, noise near to carrier, forward and reversed power nulling at the carrier frequency. To have better electron availability, electron seeding source Sr90 is placed near the VW flange inside the TVAC chamber. The TWTA availability for 1kW CW output power is rare at this frequency. Usually, passive communication payload components were tested at 120W CW and 480 W in peak power at the Ka-band. For generating higher power, two TWTA's are combined using a 3dB hybrid to achieve 1kW CW power as in "Fig. 9 (b)". Furthermore, it is difficult to generate 2kW peak power at this frequency. So a Ring resonator test setup was established to get the desired power. The ring resonator setup as in "Fig. 9 (a)" was employed to get the desired peak power for the multipaction testing with the existing TWTA's. For achieving gain, ring resonator length should be integer multiple of the wavelength operating at 18 GHz, and a VPC (variable power coupler) is connected to add unequal power of ring input and power within the ring resonator. In addition to it, a phase shifter is added to take care of the phase at VPC input.



(a) (b)

Fig. 7: (a) Photograph of the fabricated and tested VW, (b) photograph of the mounted VW on TVAC chamber flange

The parameters incorporated during the power handling and multipaction test are: frequency 18 GHz, TVAC vacuum level maintained better than 1.0x10-5 mbar, 25 percent pulse duty cycle with a pulse width of 250 µs, ring resonator maintaining at least 3dB gain for 2 hrs. The VW tested for Power handling at 800W CW without using a ring resonator. The temperature at the flange was monitored continuously for six Hrs. and it does not exceed 63.2°C. After completion of the Power-handling test, a ring resonator setup is employed in the same test setup using a waveguide switch for multipaction testing for two Hrs.

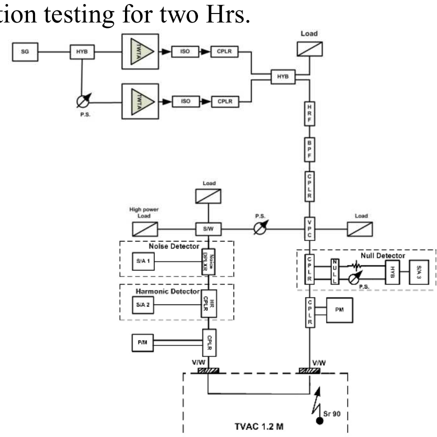
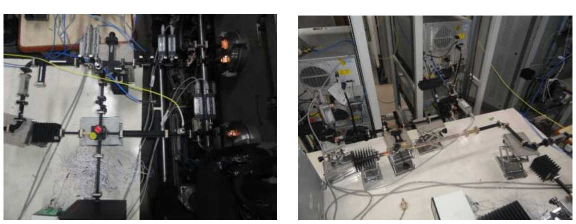


Fig. 8: Schematic of multipactor detector test bed including ring resonator.



(a) (b)

Fig. 9: Photographs of the test setup for power handling and multipaction detection, (a) Ring resonator setup, and (b) TWTA's are combined using a 3dB hybrid to achieve required power levels.

All three detectors were monitored for the complete duration. The High power test results are summarized in Table 2. No discharge and no signature have been observed during the entire testing.

Table 2: High Power test results

Freq (GHz)	Test	Power level	Duration (hrs.)	Temperature (°C)
18	Power handling(CW)	800W	6	63.2
18	Multipactor (Peak power)	2000W	2	50.9

V. CONCLUSION

In this paper, the design of the Ka-Band RF vacuum window is presented keeping in view the criticality in the design w.r.t to multipaction, power handling, insertion loss, and differential pressure handling capability of VW. In addition to it, all the above parameters are practically established using proper tests and measurements. The designed VW is qualified for 800 W CW and 2000W peak power. Although it can be qualified for higher power but existing qualification is at par for current passive communication payload components at this frequency. Using a similar approach other frequency bands of RF vacuum windows like in S, C, X, Ku, etc. can be developed.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the encouragement and helpful suggestion given by HPTD (High power testing division) team in this work

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