Design and Analysis of A Waveguide Window for W-Band TWT

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***Abstract*—A waveguide window is designed for W-Band folded waveguide TWT. The window performance is initially designed by the transmission line theory and then optimized by 3D EM simulation code CST MWS, HFSS and MTSS. The results of these codes are in agreement and all show us that the waveguide window has excellent transmission performance from 90GHz to 102GHz with VSWR less than 1.1 and S11 less than -30dB.**

I. INTRODUCTION

As one kind of most important high-frequency and high-power Vacuum Electronic Devices (VEDs), W-band folded waveguide Traveling-Wave Tubes (TWTs) have promising potential in high-resolution imaging applications [1]. In such VEDs, waveguide windows are used to isolate the high vacuum inside of the device from the atmospheric pressure. When the operating frequency moves towards the Millimeter-wave and THz-wave region, the dimension of the window assembly parts decreases proportionally. This makes it more challenging to design a wide-bandwidth window with air-tight brazing.

In reference [2] and [3], the pillbox type window is used for W-band vacuum devices. For the wide bandwidth, high power handling capacity, and compactness, a waveguide window is designed here for the W-band folded-waveguide TWT [1], in which the standard input/output WR10 rectangular waveguide is used. The structure of the window is presented in Fig.1 (a).

According to the transmission line theory, the ceramic window length should be a multiple of half the dielectric guide wavelength for a good match, [3], i.e.

$$\beta_1 t = n\pi \tag{1}$$

$$t = n\lambda_g' / 2 \tag{2}$$

where β_1 and λ_g' are the guide wavenumber and wavelength in dielectric portion of the guide, *t* is the thickness of the ceramic disk. Here, $t = \lambda_g' / 2$ is chosen. The composite diamond with relative dielectric constant of 5.6 is used and the wavelength in dielectric portion can be valued as

$$\lambda_g' = \lambda \Big/ \sqrt{\mu_r \varepsilon_r - (\lambda / 2a)^2} \tag{3}$$

Once the material of the ceramic window and the thickness *t* is decided, the width of the diaphragm *d* and the distance *L* from center of the ceramic window to the diaphragm can be designed by the transmission line theory.

II. THEORY DESIGN

The equivalent circuit model of the waveguide window is shown in Fig.1 (b). The waveguide section with and without ceramic filling are depicted as sections of uniform transmission line with specific characteristic impedance. The diaphragm is embodied as the normalized admittance, which can be estimated as:

$$\frac{B_1}{Y_0} = -\frac{\lambda_{g0}}{a}\cot^2\left(\frac{\pi d}{2a}\right) \tag{4}$$

According to the transmission line theory, the A matrix of the equivalent circuit is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jB_1 & 1 \end{bmatrix} \begin{bmatrix} \cos(\beta L) & j\sin(\beta L) \\ j\sin(\beta L) & \cos(\beta L) \end{bmatrix} \begin{bmatrix} \cos(\beta_1 t) & jg_1 \sin(\beta_1 t) \\ j\frac{1}{g_1}\sin(\beta_1 t) & \cos(\beta_1 t) \end{bmatrix} \begin{bmatrix} \cos(\beta L) & j\sin(\beta L) \\ j\sin(\beta L) & \cos(\beta L) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jB_1 & 1 \end{bmatrix} \tag{5}$$

Where β and λ_g are the guide wavenumber and wavelength. B_1 is the normalized admittance of the diaphragm. g_1 is the characteristic impedance of the waveguide with and without ceramic filling,

$$g_1 = \frac{Z_c}{Z_0} = \frac{\sqrt{1-(\lambda/2a)^2}}{\sqrt{\mu_r \varepsilon_r - (\lambda/2a)^2}} \tag{6}$$

From Equ.(5), we get

$$\begin{aligned} A = D = &\left\{\cos(\beta_1 t) - g_1 B_1 \sin(\beta_1 t)\right\}\cos^2(\beta L) \\ &-\left\{\left(g_1 + \frac{1}{g_1}\right)\sin(\beta_1 t) + 2B_1\cos(\beta_1 t)\right\}\sin(\beta L)\cos(\beta L) \\ &+\left\{\frac{1}{g_1}B_1\sin(\beta_1 t) - \cos(\beta_1 t)\right\}\sin^2(\beta L) \end{aligned} \tag{7}$$

$$B = j\left\{\begin{aligned} &\sin(\beta_1 t)\left(g_1\cos^2(\beta L) - \frac{1}{g_1}\sin^2(\beta L)\right) \\ &+2\cos(\beta_1 t)\sin(\beta L)\cos(\beta L) \end{aligned}\right\} \tag{8}$$

$$\begin{aligned} C = &\,j\left\{2B_1\cos(\beta_1 t) + \left(\frac{1}{g_1} - g_1 B_1^2\right)\sin(\beta_1 t)\right\}\cos^2(\beta L) \\ &+j\left\{2(1-B_1^2)\cos(\beta_1 t) - 2B_1\left(g_1 + \frac{1}{g_1}\right)\sin(\beta_1 t)\right\}\sin(\beta L)\cos(\beta L) \\ &+j\left\{\left(B_1^2\frac{1}{g_1} - g_1\right)\sin(\beta_1 t) - 2B_1\cos(\beta_1 t)\right\}\sin^2(\beta L) \end{aligned} \tag{9}$$

For a lossless reciprocal network, $A = D$ and the power loss ratio becomes

$$P_L = 1 - \frac{1}{4}(B - C)^2 \qquad (10)$$

From $\rho = (1+|\Gamma|)/(1-|\Gamma|)$, $|\Gamma| = (\rho - 1)/(\rho + 1)$ and $P_L = 1/\left(1-|\Gamma|^2\right)$, we get the relationship between voltage standing-wave ratio ρ and the power loss ratio P_L

$$\rho = 2P_L - 1 + 2\sqrt{P_L^2 - P_L} \qquad (11)$$

At the center frequency, we take $t = \lambda_{g1}/2$ and get :

$$B = -2j\sin(\beta_0 L)\cos(\beta_0 L) \qquad (12)$$

$$C = j2\begin{Bmatrix} B_1\left(\sin^2(\beta_0 L) - \cos^2 \beta_0 L\right) \\ -\left(1-B_1^2\right)\sin(\beta_0 L)\cos(\beta_0 L) \end{Bmatrix} \qquad (13)$$

Where β_0 is the waveguide propagation constant at central frequency. To get zero reflection power, B=C is required, that is

$$\sin^2(\beta_0 L) - \cos^2(\beta_0 L) + B_1 \sin(\beta_0 L)\cos(\beta_0 L) = 0 \quad (14)$$

That is

$$\tan^2(\beta_0 L) + B_1 \tan(\beta_0 L) - 1 = 0 \qquad (15)$$

And we get

$$\tan(\beta_0 L) = \frac{-B_1 \pm \sqrt{B_1^2 + 4}}{2} \qquad (16)$$

$$L = \frac{\lambda_{g0}}{2\pi}\left(\pi + \arctan\frac{-B_1 - \sqrt{B_1^2 + 4}}{2}\right) \qquad (17)$$

Based on the transmission line theory, we get the relationship between the normalized admittance B_1 and the length of waveguide section L. Once B1 is obtained by filtering theory or EM simulation, L can be determined. And then the transmission performance can be analyzed or optimized by the transmission line theory or 3D EM simulation codes.

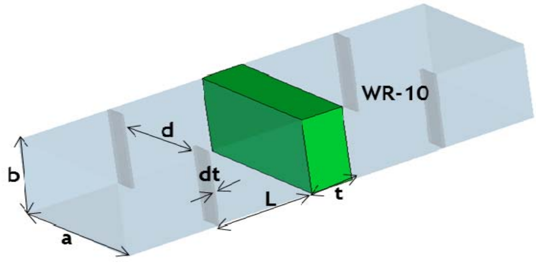
III. Results

With the initial parameters from the equivalent circuit model, CST MWS, HFSS and MTSS are used to optimize the performance. The final geometrical parameters are listed in Table I and the performance is plotted in Fig.1(c) and Fig.1 (d). The window width is half the dielectric guide wavelength (0.7mm), which is much wider than that initially used in the pillbox window of ref [1]. This is very favorable for vacuum sealing and strength guarantee.

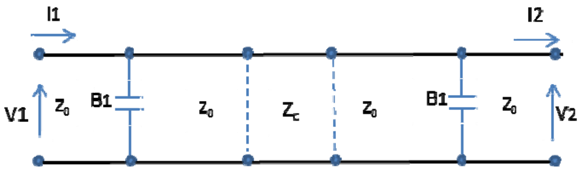
Table I Optimized Parameters of the waveguide window

a	2.54 mm	b	1.27 mm
L	1.60 mm	t	0.70 mm
d	1.84 mm	dt	0.05 mm
Window material		Diamond with relative permittivity of 5.6	

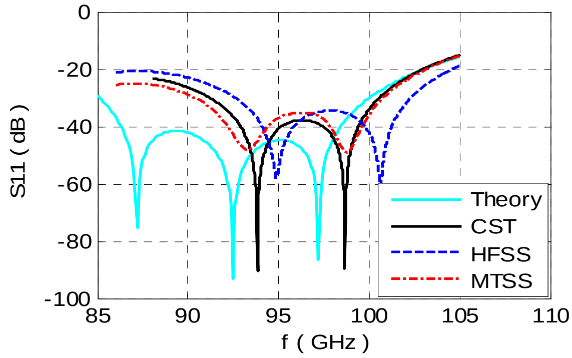
In the theory analysis, the diaphragm is considered to be infinite thin and the effect of the thickness is ignored. This leads to the much better performance of theory evaluation. Although there are some difference between results of HFSS, CST and MTSS, all the simulations have shown excellent transmission performance from 90GHz to 102GHz with S11 less than -30dB and VSWR less than 1.1. This meets our requirement of the waveguide window of the W band TWT.



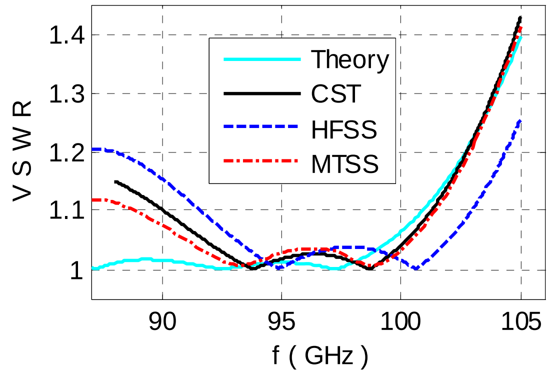
(a)



(b)



(c)



(d)

Fig.1 (a) Illustration of waveguide window, and (b) the equivalent circuit model, (c) S11 and (d) VSWR performance of the waveguide window in W band with CST, HFSS and MTSS.

References

[1] Jinjun Feng, Jun Cai, Yinfu Hu, et al., "Development of W-band Folded Waveguide Pulsed TWTs," *IEEE Trans. On Electron Devices,* vol. 61, No.6, pp. 1721-1725, June, 2014.

[2] A.Srivastava, O.J. Kwon, M.Sattorov, et al., "Broadband THz Vacuum Window Using Impedance Matching Approach," *Proc. IVEC 2012,* Monterey, USA, May. 18-20, 2010.

[3] M.E.Hill, R.S.Collin, and D.H.Whittum, "High-Power Vacuum Window in WR10," *IEEE Trans on Microwave Theory and Techniques,* Vol.49, No.5, pp.994-995, 2001.