Abstract: In order to develop wide-band low-loss windows for W-band vacuum electronic devices and easily fabricate them, symmetric and asymmetric pillbox windows are investigated and reported in this paper. A symmetric pillbox window and an asymmetric pillow-box window were designed, simulation optimized, fabricated, and tested. The initial parameters for the two pillbox windows were designed by equivalent circuit theory. Computer simulation technology (CST) three-dimensional (3D) electromagnetic simulation software was used to verify and optimize the design. Because of the uncontrollability of welding during the experiment, this article provides two solutions. One is to measure and reprocess the symmetrical pillbox window with the dielectric sheet welded to reduce the influence of welding on the measurement results; the other is an asymmetrical box window which is designed to avoid the error caused by the welding of the box window. The best experimental results for the symmetric pillbox window were $|S_{21}|$ close to 1 dB and reflection parameter $|S_{11}|$ close to 10 dB in the frequency range of 77–110 GHz. The experimental results for the asymmetric pillbox window were $|S_{21}| < 1$ dB nearly in the frequency range of 76–109.5 GHz. The experimental results show that both solutions efficiently complete the design of broadband pillbox windows and would potentially be operated in the gigahertz millimeter-wave region.

Keywords: pillbox window; wide-band; W-band; low loss

1. Introduction

Microwave vacuum tubes, such as traveling wave tubes (TWTs), klystrons, magnetrons, and gyrotrons, are important electronic devices. As high-power microwave radiation sources, vacuum tubes are widely used in microwave applications, including wireless communication, high-resolution radar and imaging [1], and industrial heating. In the research of microwave vacuum tubes, the window system is used to isolate the vacuum and atmosphere, which is an indispensable component. Diverse window configurations have been reported, such as the single-disc [2], multi-disc [3], and pillbox [4–7] configurations. Compared with other types of window systems, the pillbox window system has the advantages of being wideband and easy to braze, having large power capacity, and so on. It has been widely used in window design [8–10].

In the research of W-band microwave vacuum windows, great achievements have been made. Table 1 lists the results of microwave windows that have been experimentally tested in recent years.
It can be seen from Table 1 that the pillbox window can be applied to various frequency bands of microwaves and millimeter waves. In W-band, the working frequency bands in most of the measured results for pillbox windows were concentrated within 90–100 GHz [6]. Bandwidth is one of the most important indicators of a microwave window and directly affects the performance of vacuum devices. This paper extends the working band of pillbox windows to 76–110 GHz, which is suitable for microwave devices in the full W-band.

Table 1. Some achievements in vacuum microwave windows.

| Institution                        | Design Bandwidth       | Measured Bandwidth       | Window Type                   |
|------------------------------------|------------------------|--------------------------|-------------------------------|
| University of Strathclyde [6]      | 10 GHz (90–100 GHz)    | 10 GHz (90–100 GHz)      | Pillbox window                |
| Seoul National University [8]      | 9 GHz (93–102 GHz)     | 8 GHz (93.2–101.2 GHz)   | Pillbox window                |
| Vacuum Electronics National Laboratory [11] | 20 GHz (82–102 GHz)   | 10 GHz (92–102 GHz)      | Rectangular waveguide window  |
| China Academy of Engineering Physics [12] | 20 GHz (130–150 GHz) | 13 GHz (132–145 GHz)    | Pillbox window                |
| Tsinghua University [13]          | 10 GHz (215–225 GHz)   | 10 GHz (215–225 GHz)     | Pillbox window                |

The traditional pillbox window system consists of three distinct parts: two symmetrical rectangular waveguides, a straight cylindrical waveguide, and a cylindrical waveguide filled with dielectric. The dielectric window is brazed in a straight circular waveguide. At low working frequency, this type of pillbox window has many advantages and is applied in many products. However, when the operation frequency is up to the sub-millimeter-wave and millimeter-wave region, the yield and reliability of this pillbox window are very low in fabrication and assembly. To improve the success rate of the pillbox window, the traditional window is tested and analyzed in this paper. The reasons for low assembly efficiency are as follows: (1) With increasing operation frequency, the structural parameters of the pillbox window decrease. In the sub-millimeter-wave and millimeter-wave region, it is hard to ensure that the dielectric window is centered and vertical in the straight circular waveguide; thus, it is easy to simulate spurious modes, reducing the bandwidth. (2) Symmetrical pillbox windows cannot be tested before they are brazed. If the test results are not satisfactory, the window is scrapped. To solve these problems, this paper provides two solutions. One is to measure and process the symmetrical pillbox window with the dielectric sheet welded to avoid the influence of welding on the measurement results; the other is an asymmetric pillbox window that was investigated (these results have been published in another paper [14]), the structure of which is shown in Figure 1b. In comparison to the conventional symmetric pillow-box window which is shown in Figure 1a, we see that the diameter of the two sections of the cylindrical waveguide is different in the asymmetric pillow-box window. This system can nicely restrain the variations caused by the brazing process and ensure consistency between the experimental results and design. It can also be roughly tested before brazing to correct the structural parameters.

This paper is organized as follows. Section 2 introduces the selection of the window dielectric material, equivalent circuit theory of the symmetrical pillbox window, simulation results, and structural parameters of the two kinds of pillbox window. Section 3 is devoted to experiments, analysis of experiment results, and improvement of the symmetrical pillbox window and the experimental result of the asymmetrical pillbox window. Section 4 concludes the paper.
2. Model Design and Simulation

In the design of the pillbox window, the first step is the determination of the material of the window piece. Sapphire was finally selected in this investigation; its reference factors include high strength and small electric loss tangent (<1 × 10⁻⁴), and the metalized technology is mature. Strictly speaking, the relative permittivity values in the horizontal and vertical directions of sapphire are different. Under the condition of TE (Transverse electric) mode transmission, the difference in the dielectric constant of sapphire has little effect on the transmission of the pillbox window [13]. The relative permittivity of the transmission is 9.2, according to material reports.

There are some calculation methods used in the design of symmetrical traditional box windows, including the impedance matching approach [6], the method of moments [13], and the equivalent circuit method [7,13,15,16]. In this paper, the equivalent circuit method was used. The transmission modes in the pillbox window are the TE₁₀ mode of the rectangular waveguide and the TE₁₁ mode of the cylindrical waveguide. An equivalent circuit diagram of the pillbox window system is shown in Figure 2. The transfer matrix of the window system is divided into nine parts, under the condition of single-mode transmission [13]. In the following theoretical calculation part, we discuss the calculation process of the symmetric window.

In Figure 2, \( L \) is the length of the rectangular waveguide; \( Bc \) is the equivalent susceptance of the transition from the rectangular waveguide to the circular waveguide; \( L₀, L₁, \) and \( L₁^* \) are the length of the cylindrical waveguide; \( \beta \) is the propagation constant of the TE₁₀ mode in the rectangular waveguide; \( Z \) is the characteristic impedance of the rectangular waveguide; \( \beta₁ \) is the propagation constant of the TE₁₁ mode in the cylindrical waveguide; \( Z₁ \) and \( Z₁^* \) are the characteristic impedance of the cylindrical waveguide; \( \beta₀ \) is the propagation constant of the TE₁₁ mode in a dielectric circular waveguide; \( Z₀ \) is the characteristic impedance of the dielectric waveguide; and \( M \) is the matrix of each waveguide and the connection part.

The transfer matrix of the window system can be obtained by multiplying the nine parts of the transfer matrix, shown as

\[
\begin{align*}
T = M₁ M₂ M₃ M₄ M₅ M₆ M₇ M₈ M₉.
\end{align*}
\]
\[
M = M_1 \cdot M_2 \cdot M_3 \cdot M_4 \cdot M_5 \cdot M_6^* \cdot M_7^* \cdot M_8 \cdot M_1
\]  

(1)

Substituting the transfer matrix of each part into Equation (1), the transfer matrix can be written as \[16–19\]

\[
M = \begin{bmatrix}
\cos(\beta_1 L) & -jZ_1 \sin(\beta_1 L) \\
-jZ_1 \sin(\beta_1 L) & \cos(\beta_1 L)
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix} \\
\begin{bmatrix}
\cos(\beta_1 L_1) & -jZ_1 \sin(\beta_1 L_1) \\
-jZ_1 \sin(\beta_1 L_1) & \cos(\beta_1 L_1)
\end{bmatrix} \begin{bmatrix}
R_0 / R_1 & 0 \\
0 & R_1 / R_0
\end{bmatrix} \\
\begin{bmatrix}
\cos(\beta_1 L_2) & -jZ_1 \sin(\beta_1 L_2) \\
-jZ_1 \sin(\beta_1 L_2) & \cos(\beta_1 L_2)
\end{bmatrix} \\
\begin{bmatrix}
\cos(\beta_1 L_3) & -jZ_1 \sin(\beta_1 L_3) \\
-jZ_1 \sin(\beta_1 L_3) & \cos(\beta_1 L_3)
\end{bmatrix}
\]  

(2)

where \( B_c \) can be written as \[18,19\]

\[
B_c = \frac{\pi b}{2n} \left( 2 \ln \frac{R_0^2 - b^2}{4R_1 b} + \frac{R_0 + R_1}{R_1} + 2 \sum_{n=1}^{\infty} \frac{\sin^2 \frac{\pi b}{n R_1}}{n^2 \pi^2} \right)
\]  

(3)

where \( b \) is the short side length of a rectangular waveguide, and \( B_c = B_c^* \).

In the window system, the length of the rectangular waveguides at both sides only influences the phase of the transfer matrix, \( L \) is set to zero, and \( R_0 = R_1 = R_2 \). The transfer matrix of the symmetric window system can be written as

\[
M = M_2 \cdot M_3 \cdot M_5 \cdot M_6^* \cdot M_2
\]  

(4)

According to the relation between the transmission matrix and scattering matrix, the scattering matrix \( S \) could be written as

\[
S = \begin{bmatrix}
M_{22} + M_{21} - M_{22} M_{11} & \frac{2}{M_{11} + M_{22} + M_{12} + M_{21}} \\
\frac{2}{M_{11} + M_{22} + M_{12} + M_{21}} & M_{11} + M_{12} - M_{11} M_{12}
\end{bmatrix}
\]  

(5)

The S-parameter ideal design goal of the symmetric window is \( S_{12} = S_{21} \), \( S_{11} = S_{22} = 0 \); thus, the structural parameters satisfy the equations

\[
\begin{align*}
\tan \beta_1 L_1 &= A/B \pm \sqrt{(A/B)^2 - C/B} \\
(A/B)^2 &- C/B \geq 0 \\
A &= (-\frac{Z_0^2}{Z_1} + \frac{Z_0^2}{Z_2} + \frac{Z_0^2}{Z_3}) \cos \beta_0 L_0 + (\frac{Z_0^2}{Z_1^2} B_2^2 + \frac{Z_0^2}{Z_2^2} B_3) \sin \beta_0 L_0 \\
B &= -2 B_c \cos \beta_0 L_0 + (\frac{Z_0^2}{Z_1^2} B_2^2 - \frac{Z_0^2}{Z_2^2} Z_0) \sin \beta_0 L_0 \\
C &= 2 B_c \cos \beta_0 L_0 + (\frac{Z_0^2}{Z_1^2} - \frac{Z_0^2}{Z_2^2} B_2^2 - \frac{Z_0^2}{Z_3}) \sin \beta_0 L_0
\end{align*}
\]  

(6)

According to the frequency of the pillbox window, the WR-10 (Waveguide name of EIA standard) standard rectangular window was selected. The three structural parameters of the symmetrical pillbox window, \( L_0, L_1 \), and \( R_0 \), need to satisfy Equation (6). When the center frequency of the design band is 92.5 GHz, the three parameters have infinitely many solutions that satisfy the equation. To obtain the ideal parameter structure, the values of the three structural parameters need to be limited. Considering the sealing and mechanical strength of the window, the dielectric sheet needs to have a larger thickness,
and considering the matching of the window system, the window sheet needs to be thinner. Based on the above reasoning, \( L_0 \) is between one-half of the waveguide wavelength (0.55 mm) and one-quarter of the waveguide wavelength (0.275 mm) (0.275 mm \( \leq \) \( L_0 \) \( \leq \) 0.55 mm). The diameter of the circular waveguide is too large, the high-order mode cannot be cut off, and the diameter of the window is too small, which will narrow the matching bandwidth. The diameter of the general box-shaped window is taken from the diagonal of the rectangular waveguide 

\[
D = \sqrt{a^2 + b^2}.
\]

Based on the bandwidth requirements of the pillbox window in this paper, the diameter of the window can be slightly larger than \( D \), and the scanning range can be set as \( L_0 \leq L_1 \leq 1 \) mm. The value ranges of the three parameters were combined to find the solution set that satisfies Equation (6). The transmission and reflections of each set of structural parameter values can be obtained by Equation (5); the parameter group with a larger bandwidth and reflection less than \(-10 \) dB was selected as shown in Table 2.

### Table 2. Structural parameters of the pillbox windows.

| Equivalent Circuit | Simulation—Symmetric | Simulation—Asymmetric |
|-------------------|----------------------|-----------------------|
| **Rectangular waveguide** | WR-10 | WR-10 | WR-10 |
| Thickness of circular waveguide | 0.49 mm \((L_1)\) | 0.48 mm \((L_1)\) | 0.48 mm \((L_1)\) |
| | 0.49 mm \((L_2)\) | 0.48 mm \((L_2)\) | 0.48 mm \((L_2)\) |
| Radius of circular waveguide | 1.9 mm \((R_1)\) | 1.8 mm \((R_1)\) | 1.8 mm \((R_1)\) |
| | 1.9 mm \((R_2)\) | 1.8 mm \((R_2)\) | 1.75 mm \((R_2)\) |
| Radius of sapphire dielectric | 1.9 mm \((R_0)\) | 1.8 mm \((R_0)\) | 1.8 mm \((R_0)\) |
| Thickness of sapphire dielectric | 0.31 mm \((L_0)\) | 0.34 mm \((L_0)\) | 0.33 mm \((L_0)\) |

The reflection value by the equivalent circuit theory and the transmission characteristics in CST are shown in Figure 3. Except for the frequency deviation of 4 GHz, the two reflection curves have good consistency. This shows that the equivalent circuit theory is reasonable as a preliminary design tool. The equivalent circuit theory is not a very accurate mathematical model, and further optimization should rely on CST three-dimensional (3D) electromagnetic simulation software. The structural parameters were simulated and optimized with the goal of wider transmission bandwidth and smaller transmission loss. The structural parameters of the asymmetric pillbox window were optimized based on the parameters of the symmetrical-type window. Considering the machining accuracy and assembly difficulty, the diameter difference of the two circular waveguides was taken as 0.1 mm. The structural parameters are shown in Table 2.

![Figure 3](image-url)

**Figure 3.** The optimized (a) \( S_{11} \) values of pillbox windows and (b) \( S_{21} \) values of pillbox windows.

The simulation-optimized structural model is shown in Figure 4. For input mode \( \text{TE}_{10} \), the transmission characteristics are shown in Figure 3. In the frequency range of 78–110 GHz,
the $S_{21}$ values of the two designs were greater than $-0.5$ dB; the maximum transmission loss of the symmetric pillbox window was $-0.23$ dB, while that of the asymmetric type was $-0.47$ dB.

![Figure 4](image-url) Simulation model of the (a) symmetrical pillbox window and (b) asymmetrical pillbox window.

3. Experiment Results

According to the optimized structural parameters (Table 2), two box-type windows were processed and assembled, as shown in Figure 5. The testing process in the vector network analyzer (CEYAER AV3672C) is shown in Figure 6.

![Figure 5](image-url) The pillbox windows after brazing assembly: (a) symmetric pillbox window and (b) asymmetric pillbox window.

![Figure 6](image-url) Experimental testing of the pillbox windows.

The experimental results of the symmetrical box window in the early stage were not ideal. The error analysis method in the literature [6] was used to analyze the experimental results. Based on the analysis results, the experimental program was revised. Because the value of $S_{11}$ was small and its
influence on the change of the structural parameters of the window system was not obvious enough, the more sensitive $S_{21}$ was selected as the optimization target, and the random error was the structural parameter of the window. Some of the analysis results are shown in Figure 7, and the calculated tolerance of the window is shown in Table 3.

![Figure 7](image-url) Measurement results and simulation analysis of the symmetric window: (a) $S_{11}$ values of the pillbox window; (b) $S_{21}$ values of the pillbox window.

| Variable Name | $L_0$ | $L_1$ | $L_2$ | $R_0$ | $R_1$ | $R_2$ |
|---------------|-------|-------|-------|-------|-------|-------|
| Figure 7      | 0.013 mm $^1$ | 0.06 mm | -0.08 mm | 0 mm | 0.02 mm | 0.02 mm |
| Figure 9      | 0.02 mm | -0.02 mm | -0.05 mm | -0.04 mm | 0.01 mm | 0.01 mm |

$^1$ A negative sign indicates that the experimental size estimated by the simulation was smaller than the design size.

Figure 8. The test flow chart for the symmetric pillbox window.

As shown in Figure 7, the errors of $R_1$, $R_2$, and $L_0$ made lesser contributions to the deviation of the measurement result and the design value, which is mainly caused by the tolerance of $L_1$ and $L_2$. The main reason is that the position of the dielectric sheet shifted during the welding process. This shift is random due to the purely manual operation of welding fixture assembly and solder filling. The test results of multiple rounds of modification of the welding fixture and assembly scheme showed that this randomness is inevitable. To reduce the influence of welding on the test process, the test plan was modified. After the windows were welded to the circular waveguide, the circular waveguides on both sides were measured and reprocessed to ensure that the values of $L_1$ and $L_2$ were within the tolerance range. The test process is shown in Figure 8. This method can effectively reduce the influence of welding on $L_1$ and $L_2$. The final test result is shown in Figure 9. By error simulation analysis of the test results, the calculation tolerance of each structural parameter was obtained, shown in Table 3. The transmission parameter $|S_{21}|$ was close to 1 dB and the reflection parameter $|S_{11}|$ was close to 10 dB in the frequency range of 77–110 GHz.
The frequency band of the unwelded pill window with a transmission parameter close to 0.5 dB covers 76–109.5 GHz, except for two frequency points at 87.99 GHz and 103.15 GHz. At the frequency of 87.99 GHz, both $S_{21}$ are decreased, which may be caused by spurious modes. Compared to the test results of the unwelded pill window, the measurement results add a spurious mode point at 107.4 GHz. The two test results have a similar frequency offset—about 2 GHz—compared to the calculation results.

Figure 9. The measurement results of the symmetric pillbox window: (a) $S_{11}$ values of the pillbox window; (b) $S_{21}$ values of the pillbox window.

The asymmetric pillbox window can avoid the problems of the symmetric pillbox window in the testing. In asymmetric pillbox window testing, the window can be roughly tested before brazing to reduce the error of structural parameters. The test process of the asymmetric window is shown in Figure 10. A comparison between the two measured results and the simulation is shown in Figure 11. The frequency band of the unwelded pill window with a transmission parameter close to 0.5 dB covers 76–109.5 GHz, except for two frequency points at 87.99 GHz and 103.15 GHz. At the frequency of 87.99 GHz, $S_{21}$ is decreased when $S_{11}$ is increased due to reflection. At the frequency of 103.15 GHz, both $S_{11}$ and $S_{21}$ are decreased, which may be caused by spurious modes. Compared to the test results of the unwelded pill window, the measurement results add a spurious mode point at 107.4 GHz. The two test results have a similar frequency offset—about 2 GHz—compared to the calculation results.

Figure 10. The test flow chart for the asymmetric pillbox window.
4. Summary

In this paper, we report the design, manufacture, and testing of two kinds of wide-band low-loss pillbox windows for W-band vacuum electronic devices. After the experiments, analysis, and improvement, the final results for the symmetrical window were transmission parameter $|S_{21}|$ close to 1 dB and reflection parameter $|S_{11}|$ close to 10 dB in the frequency range of 77–110 GHz. Based on the experimental testing of the symmetrical-type window and the analysis of the experimental results, the asymmetrical pillbox window can reduce the errors caused by the welding process and the assembly process by using an asymmetric circular waveguide to fix the sapphire medium. The test results showed that the transmission parameter $|S_{21}|$ was <1 dB in the frequency range of 76–109.5 GHz, covering the W-band. Our test data and simulation results show that systematic tuning of the asymmetric window after fabrication can achieve broadband transmission close to the ideal design.

Both design methods can reduce the errors caused by welding and experimental processing, and both have successfully produced low-loss, wide-band box windows. The experimental methods in these two testing processes can be applied to the production of box-shaped windows in the terahertz band.

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