Design and Fabrication of a Novel High Power THz Slow Wave Structure Based on MEMS Technology

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Abstract. With the development of TWT in terahertz band, the size of TWT is greatly reduced and the power gain is also reduced. In order to improve the performance of traveling wave tube (TWT), an E-plane and H-plane tapered folded waveguide slow wave structure operating at 0.34THz is designed. In order to reduce the RF loss, a gradual ridge is added to the E-plane ridge. Compared with other ridge loaded structures, the coupling impedance of this structure has been significantly improved, and it has better dispersion characteristics and higher maximum output power. According to the electromagnetic simulation results, under the condition of 16.8kV, 50mA banded electron beam, the maximum output power of the folded waveguide can reach 65.1w, the power gain can reach 31.8db, the 3dB working bandwidth can reach 12GHz, and the electronic efficiency can reach 7.75%. Finally, a complete DRIE process for processing slow wave structure is explored. The slow wave structure is fabricated by combining silicon with non-silicon.

Keywords: Terahertz Technology; Traveling Wave Tube; Ridge Loaded Folded Waveguide; DRIE Processing Technology.

1. Introduction
Traveling wave tube (TWT) is a kind of common microwave vacuum electron tube. As the core device of microwave power amplifier, TWT has been widely used in communication, radar and electronic countermeasures [1]. TWT is essentially a kind of power amplifier. It makes the electromagnetic wave pass through the slow wave circuit in the form of traveling wave field. At the same time, the electron beam has a speed slightly higher than the phase velocity of the traveling wave field, which makes it move forward synchronously with the electromagnetic wave. In this process, the electron beam interacts with the electromagnetic wave, converting the energy of the electron beam into the energy of the electromagnetic wave, so as to realize the amplification of the electromagnetic wave power [2]. Because the size of slow wave structure in terahertz band is greatly reduced, it is difficult to process. The research on THz slow wave structure mostly stays in the stage of theoretical simulation, so it is very meaningful to explore a set of excellent processing technology. In addition, due to the size reduction, the power gain effect will be greatly reduced [3]. In order to overcome these defects, a ridge loaded folded waveguide slow wave structure working at 0.34THz is designed and fabricated by DRIE process.

2. Design and Simulation
TWT is mainly composed of electron gun system, magnetic focusing system, slow wave structure, input-output device and collector [4]. The slow wave structure is the place where the electron beam interacts with electromagnetic wave. The traditional folded waveguide slow wave structure has the...
problems of low coupling impedance and insufficient power gain. In order to improve the performance of slow wave structures, many scholars have improved the slow wave structures and proposed different ridge loading methods [5-8]. E-plane ridge loading is to add a metal ridge to the narrow edge of the straight waveguide of the folded waveguide. This structure can make the transverse electric field suddenly compressed when the electromagnetic wave is transmitted to the straight waveguide, so as to improve the beam wave interaction of the structure. In addition, H-plane ridge loading is also a method to improve the power gain. A metal ridge is added to the wide side of the slow wave structure to improve the coupling impedance of the structure. Based on the study of H-plane and E-plane ridge loaded folded waveguide slow wave structure, a 0.34THz folded waveguide slow wave structure with gradual loading of E-plane and H-plane is designed and studied in combination with the processing characteristics of dielectric process. In order to enhance the transmission performance of the slow wave structure, a gradual structure is added at the metal ridge of the E-plane to reduce the RF loss and improve the stability (as shown in figure 1).
achieving greater power gain. The calculation expressions of coupling impedance and slow wave structure parameters are as follows [11]:

\[
k_n = \frac{2b}{a} Z_{TE10} \left( 1 + \frac{1}{\beta_n D} \frac{\sin(\beta_n D/2)}{\beta_n D/2} \right)^2
\]

(3)

Where \(Z_{TE10}\) is the characteristic impedance of the waveguide in TE10 mode.

According to the processing characteristics of diode process, a quarter arc tapered ridge is added to the E-plane ridge. Combined with the initial parameters of folded waveguide, a tapered double ridge loaded folded waveguide slow wave structure with center frequency of 0.34THz is designed. The structural parameters are shown in Table 1.

**Table 1.** Design parameters of tapered double ridge loaded folded waveguide slow wave structure.

| DESCRIPTION                                      | DESIGN PARAMETER | VALUE (\(\mu m\)) |
|--------------------------------------------------|------------------|--------------------|
| Wide-edge length                                 | a                | 550                |
| Narrow-edge length                               | b                | 90                 |
| H-Side ridge width length                         | a1               | 450                |
| Length of narrow side of E-plane ridge            | b1               | 60                 |
| H-face ridge length                               | t                | 80                 |
| E-face ridge length                               | L                | 150                |
| Half cycle length                                 | p                | 150                |
| Side length of beam                               | 2w               | 150                |
| Length of straight waveguide                      | h                | 200                |

In this paper, the high frequency performance of folded waveguide is analyzed by CST three-dimensional electromagnetic simulation software. The performances of E-plane ridge loaded, H-plane ridged and graded double ridged folded waveguide slow wave structures are compared and analyzed, and their dispersion characteristics and coupling impedance curves are obtained. The structural parameters of tapered double ridge loaded folded waveguide slow wave structure are shown in Table 1, and some parameters required for H-plane ridge loading and E-plane ridge loading are shown in Table 1. Their dispersion characteristics and coupling impedance curves are obtained.

**Figure 2.** Simulation value of normalized phase velocity of folded waveguide loaded with H-plane ridge, E-plane ridge and graded double ridge.
The coupling impedance and dispersion characteristics of folded waveguide slow wave structures with H-plane ridge loading, E-plane ridge loading and gradual double ridge loading are studied by using three-dimensional electromagnetic simulation software. From the figure 2 it can be seen that with the increase of frequency, the dispersion characteristic curve of the tapered double ridge loading structure is smoother, which means that the structure has a wider working bandwidth and can work in a higher frequency band. It can be seen from figure 3 that under the same size parameters, the tapered double ridge loading structure has higher coupling impedance, which means that the structure has higher beam wave interaction efficiency and greater power gain. The structure has a coupling impedance of 11.97 Ω at the center frequency of 0.34THz.

The pic mode of CST 3D electromagnetic simulation software is used to simulate the beam wave interaction of TWT. Considering the actual processing technology and processing roughness, gold is selected as the background material for simulation, and the conductivity of gold is modified according to expression (4) [12]. Where $\sigma$ is the theoretical conductivity of gold, $\delta$ is the skin depth, and $\Delta$ is the roughness of processing. According to the formula, the corrected conductivity of gold is $1.67 \times 10^7$ s/m.

$$\sigma' = \frac{\sigma}{1 + \exp\left(\frac{\delta}{2\Delta}\right)}$$

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$

**Figure 3.** Simulation value of coupling impedance of folded waveguide loaded with H-plane ridge, E-plane ridge and graded double ridge.

**Figure 4.** Electron cluster diagram of TWT near the output port.
Figure 4 shows the electron beam clustering of slow wave structure near the output port. It can be seen from the figure that the electromagnetic wave modulates the velocity of the electron and the energy of the electron beam changes significantly. And there is a transcendental phenomenon, that is, the positions of the high energy electrons and the low energy electrons are partially coincident.

![Figure 4](image)

**Figure 5.** Electron energy distribution in slow wave structures.

Figure 5 shows the distribution of electron energy along the position in slow wave structure. The initial energy of the electron beam is 16800eV, the maximum energy is 17639.6eV, the energy increase is 839.6eV, the minimum energy is 14793.2eV, the energy decrease is 2006.8eV, and the energy decrease is much more than the energy increase. At the same time, most of the electronic energy is reduced, which means that the energy is transferred to the electromagnetic wave, and the power of the electromagnetic wave signal is amplified.

![Figure 5](image)

**Figure 6.** Time domain signal of input and output port electromagnetic wave.

Figure 6 shows the change of the input and output signals of the tapered double ridge loading structure with time. Among them, green is input signal, blue is output signal. In the simulation, the input power is set to 40 mW. It can be seen from the figure that the output signal tends to be stable after 0.9ns, and the amplitude reaches 7.8sqrt(W), that is, the output power is about 60.84W.
Figure 7. Power gain frequency curve of double ridge loaded folded waveguide.

Figure 8. Output power input curve of double ridge loaded folded waveguide.

The power gain of TWT is obtained by changing its working frequency when the working parameters of TWT are constant. It can be seen from figure 7, the maximum power gain is achieved at 341GHz and the 3dB bandwidth is about 12GHz. Figure 8 shows the output input power curve obtained by changing the input power while keeping the operating frequency of TWT at 0.34THz. From the picture we can see that when the input power is about 60 mW, the maximum output power is 65.1 W, and the electron utilization efficiency is 7.75%.

3. Microfabrication

The traditional slow wave structure machining method is to use micro machining technology (such as micro milling, EDM, etc.) to complete the half structure, and then to form a complete structure by butt welding [13]. However, when the frequency reaches the terahertz level, the size of the device decreases sharply, so it is difficult to meet the accuracy requirements by using the traditional processing methods. The slow wave structure fabricated by UV-LIGA processing technology is all metal, which will make the device easy to bend and damage the structural steepness. Therefore, the silicon and non-silicon processing method is adopted finally. In order to ensure a smooth internal surface of the metal at the same time can have good stiffness.

Deep reactive ion etching (DRIE) was used to fabricate slow wave structures. The slow wave structure is cut symmetrically from the center line, and the half cavity structure is etched on the silicon wafer respectively. Because the depth of electron beam channel, H-plane ridge and S-type channel of slow wave structure are different, it is necessary to carry out multiple engraving (as shown in figure 9).
The first step is to etch a 75 μm deep electron beam channel on the silicon wafer, then to etch a 225 μm deep H-plane ridge after the protection by throwing glue. Finally, the 275 μm deep S-shaped channel is etched by the same process. After etching the complete half cavity structure, a layer of gold is sputtered on the half cavity structure by multiple inclined sputtering, and then two silicon wafers are aligned and bonded to obtain a complete slow wave structure.

Figure 9. Process flow chart of DRIE with slow wave structure.

As shown in figure 10, after the electron beam channel with a depth of 75 μm is protected with photoresist, a 225 μm deep H-plane ridge is etched by dry etching process. It can be seen from the graph that the photoresist is very good for protecting the upper layer structure, and the edge contour of the figure is clear and the error is less than 1 μm, which shows the advanced nature of DRIE technology in processing slow wave structure. Figure 11 shows the fabricated folded waveguide half cavity and the finished product. It can be seen from the figure that the side wall of slow wave structure is steep and straight, and the inner wall roughness is small, which meets the design requirements. In addition, the finished product of slow wave structure is of great significance to the design and research of the whole structure of THz TWT.
Figure 11. SEM of folded waveguide half cavity structure and finished product drawing.

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