Invited Paper

Experimental research on interaction of gyrotron traveling wave tube with inner mode converter in w-band TE_{02} mode

Efeng Wang *, Xu Zeng, An Li and Shang Gao
National Key Laboratory of Science and Technology on Vacuum Electronics,
Beijing Vacuum Electronics Research Institute,
Post Box 749-41, 100015, Beijing, China
* Email: zhuwang9428@sina.com

(Received September 2021)

Abstract: This paper explicates the experimental research of W-band TE_{02} mode gyrotron traveling wave tube interaction, explores the reasons for adopting TE_{02} mode as the working mode, the existing competitive modes, the high-frequency structure adopted, the simulation of the interaction, and the design of the inner mode converter. Finally, the test results are given.

Keywords: W-band Gyro-TWT, TE_{02} mode, Periodic dielectric loaded, Electron flow rate, Inner mode converter

doi:

1. Introduction

In the millimeter wave band, compared with traveling wave tubes [1-5], the gyrotron traveling wave tube has the characteristics of high power and wide bandwidth. In the W-band, the output power of the traveling wave tube is generally less than $200W$. The gyrotron traveling wave tube can generate output power of more than hundreds of kilowatts, with a bandwidth of more than 5%. Literature [5] reported the parameters of w-band gyrotron traveling wave tube: TE_{01} mode, electron voltage $68kV$, electron beam current $7A$, magnetic field 3.4 *Tesla*, maximum peak output power of 135 *kilowatts*, $3dB$ bandwidth $4.1GHz$. In the experiment, electron was found to bombard the high-frequency cut-off section. As the duty increased, the bombarding electrons seriously damaged the cut-off section structure. The copper bombarded by the electrons evaporated to the input window, causing the reflection of the input window to increase. The signal could not be injected, and the entire tube was damaged, as shown in Figure 1, Figure 2.

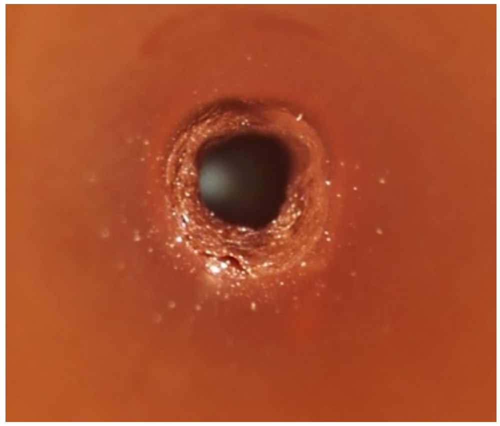

Fig. 1 Cut-off section damaged by electron bombardment

Fig. 2 The input window covered by the evaporated copper after electron bombardment

We have analyzed the reasons for electron bombardment to the high-frequency cut-off section:

1) In The W-band, gyrotron traveling wave tube frequency is high, and the interaction magnetic field in the uniform zone is required to reach 3.4*T*, while the magnetic field in the cathode zone is about 1500-3000 *Gauss*, which causes the length of adiabatic compression zone of the electron gun to be too long.

2) In The W-band, when gyrotron traveling wave tube is working in TE_{01} mode, the high-frequency interaction size is small, and the cut-off radius is smaller at this time.

3) In the experiment, when the Gyro-TWT tube was put into the superconducting magnet, it cannot be guaranteed that the axis of the initial tube body and the axis of the magnetic field are completely coaxial.

Due to the above three reasons, the Z axis along which the electrons were spiraling and the magnetic field axis are different, leading the electron beam to bombard the cut-off section, causing the evaporation of copper, therefore, polluting the window and the interaction section.

In order to improve the power capacity of the whole tube, the TE_{02} mode is selected as the working mode of the W-band Gyro-TWT, which increases the size of the interaction, improves the flow rate of the electron beam, and avoids electron bombardment to the cut-off section. This paper analyzes the testing process.

2. Theoretical analysis

1) *Determination of structural parameters of high frequency interaction:*

Generally, the working voltage of the Gyro-TWT ranges from 60*kV*-70*kV*. We adopted 65*kV* and the working mode is TE_{02}. The operating point of weak relativity devices is generally selected near the cut-off frequency. Combining the working frequency and working mode, the waveguide radius is fixed at R=3.8*cm*, which is much larger than that of TE_{01} mode.

In gyro-TWT, the amplification is achieved by using a cyclotron electron beam to interact with the transmitted microwave, which can be described by the following dispersion equations

$$k_z^2 = k^2 - k_c^2 \tag{1}$$

$$\omega = k_z + s\Omega \tag{2}$$

where S is the harmonic number, Ω is the angular frequency of the electron transverse circular motion, k_z, k and k_c are the axial wave number of the wave, the wave number in the free space and the cutoff wave number in the waveguide, respectively, and ω is the circular frequency of the wave. For general gyrotron devices, the magnitude of the applied DC magnetic field can be determined according to the above two synchronization conditions and working frequency:

$$B_0 \approx \frac{\omega m_0 \gamma}{es} \tag{3}$$

Get the working magnetic field Bo=3.5*T*.

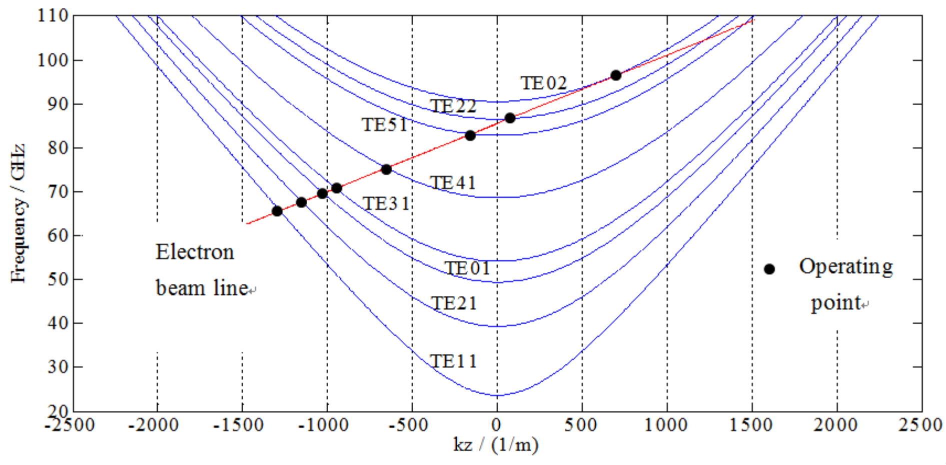

Fig. 3 Dispersion curve of TE_{02} mode gyro-TWT

Basing on the above equation, the dispersion curve of TE_{02} mode gyro amplifier is obtained. As shown in Figure3: Working mode TE_{02}, competitive mode E_{22}, TE_{51}, TE_{41}, TE_{31}, TE_{01}, TE_{21} and TE_{11}, the frequencies are 86.5*GHz*, 83.3*GHz*, 76.2*GHz*, 72*GHz*, 70.9*GHz*, 69.2*GHz* and 67*GHz*, respectively. Therefore, how to suppress the competitive mode is the key to design TE_{02} mode gyro amplifier.

2) ***Determination of guiding center radius***

Fig.4 shows the relationship between the coupling coefficient of TE_{02} mode and competition mode and the guiding center radius [6]. It can be seen from Figure 4 that for TE_{02} mode, when the coupling coefficient is the largest, the guiding center radius is 0.26 *times* the interaction radius.

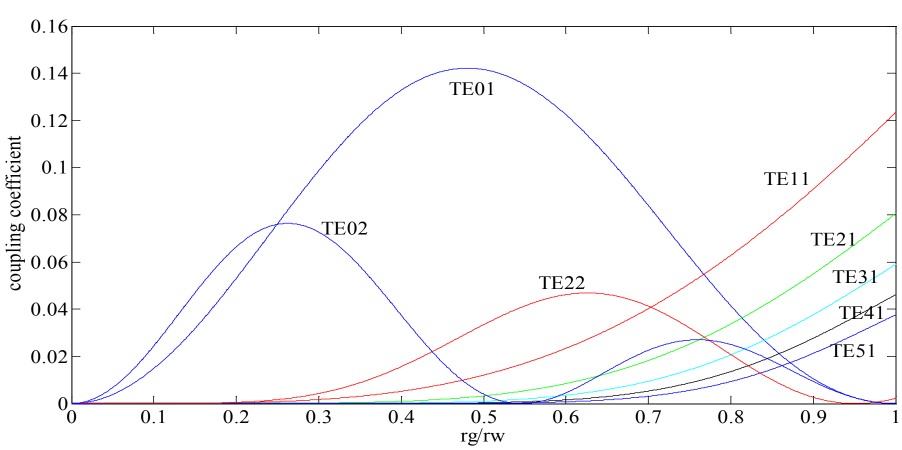

Fig. 4 The dependence of the coupling coefficient on guiding-center radius for TE_{02} mode and possible competing modes

r_g is the guiding center radius, and r_w is the waveguide radius. It can also be seen from Fig. 4 that for TE_{02} mode, when the guiding center radius of the electron beam is 0.26 rw, the guiding center radius of other competition modes at the point of maximum coupling coefficient is far away from 0.26 rw, which helps suppress mode competition.

3) *Determination of high frequency interaction structure*:

The periodic dielectric loaded circular waveguide is used as the high frequency interaction system [7]. As shown in Figure 5, the conductor and the dielectric are interlaced and loaded by adjusting the proportion of the conductor and the dielectric and adjusting the radial thickness of the dielectric. This structure can well suppress the absolute instability and backward wave oscillation.

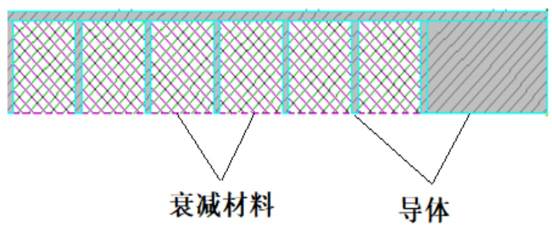

Fig. 5 Periodic medium loading structure.

3. Simulation results

Based on the above discussion, the data given in Table 1 are obtained:

Tab. 1 Interaction structure parameters

Waveguide radius	3.8*mm*	Relative permittivity of dielectric	13
Guide center radius	1*mm*	Loss tangent of dielectric	0.27
Magnetic field	3.4*T*	Medium length in cycle	15*mm*
Voltage	65*Kv*	Periodic conductor length	2*mm*
Electric current	10*A*	Conductor length	40*mm*

After optimized simulation, Fig. 6 shows that the electron beam produces stable pre-modulation when periodic medium loading, and the working mode enlarges when unloading. Fig. 7 shows the field distribution in the interaction system, from which it is clear that a stable TE_{02} mode is obtained in the amplification section of the interaction.

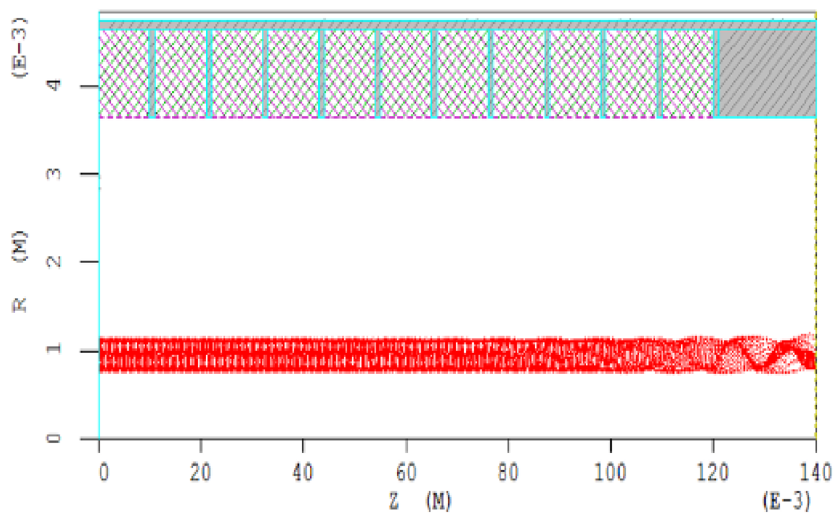

Fig.6 The electron beam trajectory obtained from simulation

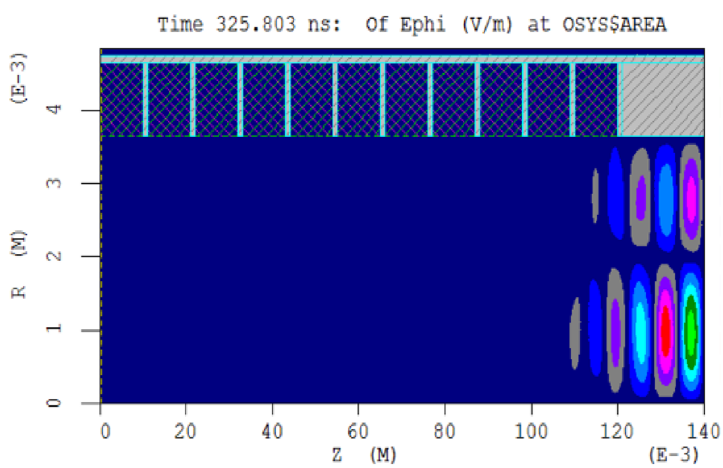

Fig. 7 The field distribution diagram obtained from simulation

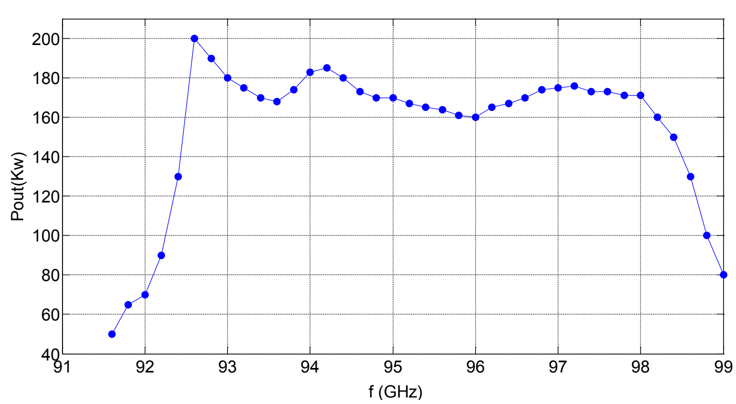

Fig. 8 Interaction power varying with frequency

Fig. 8 shows the dependence of the output power on the frequency for the W-band TE_{02} mode gyro-TWT. When the frequency is 92.6*GHz*, the output power reaches 200*kW* and the 3*dB* bandwidth 6*GHz*.

4. Experiment results

1) *The design of the mode converter*

Through calculation and experimental verification, after the beam-wave interaction, the electron beam falls into the collector region, and the corresponding magnetic field ranges from 2000 *Gauss* to1000 *Gauss*, as shown in the Figure 9. The distance of this area is 130*mm*, and the corresponding distance from the port of the gradual output section to 2000 *Gauss* is 308*mm*.Therefore, this space can be used to place the TE_{02}-TE_{01} mode converter at the position of the collector to convert the working mode of the Gyro-TWT from TE_{02} mode to TE_{01}mode. In this way, the Gyro-TWT can output the TE_{01} mode, which can effectively shorten the size of the millimeter wave transmission system. This requires the TE_{02}-TE_{01} mode converter built in the tube body to have the characteristics of compact and efficient conversion.

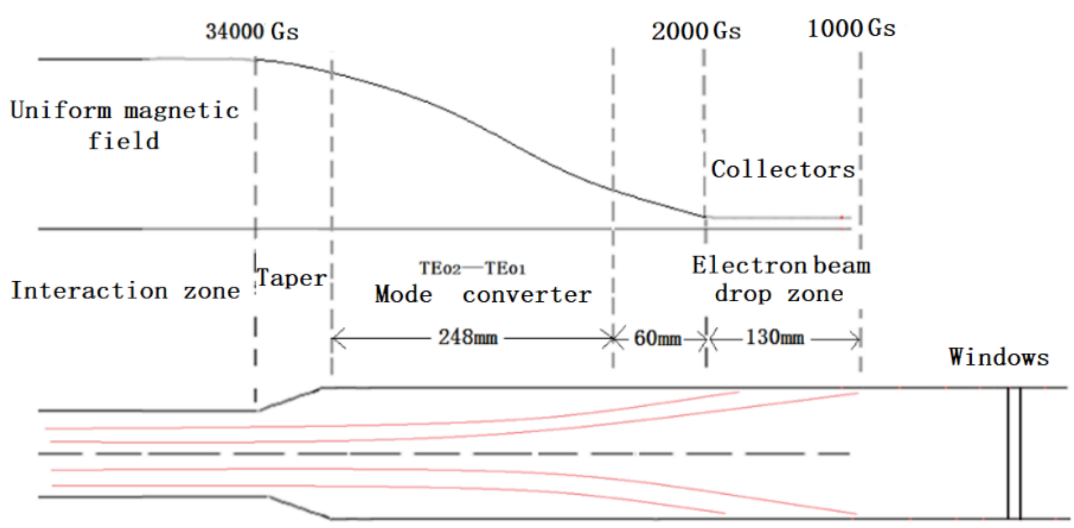

Fig. 9 collector magnetic field and electron beam trajectory diagram

In order to ensure the completion of the TE_{02}-TE_{01} converter within the length of 250*mm*, the waveguide radius is 9*mm* .

Fig. 10 TE_{02}-TE_{01} mode converter

The bandwidth of the mode converter is 215.8*mm*. Figure 10 shows the mode converter. The bandwidth is 5.9*GHz* when the conversion efficiency is 90%.

2) ***Test results***

The test is carried out under the conditions of working voltage 65*kV*, current 10*A* and magnetic field 3.4 *Tesla*. Figure 11 is the voltage, current, input signal, and output signal shown on oscilloscope during the test. The frequency-output power curve obtained from the test in Figure 12 shows a peak output power of 120*kW* at a frequency of 92.4*GHz* and a 3*dB* bandwidth of 4.5*GHz*. In the test, when the duty is increased to the cut-off section when the electron beam bombardment occurs when TE_{01} mode is used as the working mode, there is no electron bombardment to the cut-off section. After that, the duty continued to be increased, and the Gyro-TWT worked normally.

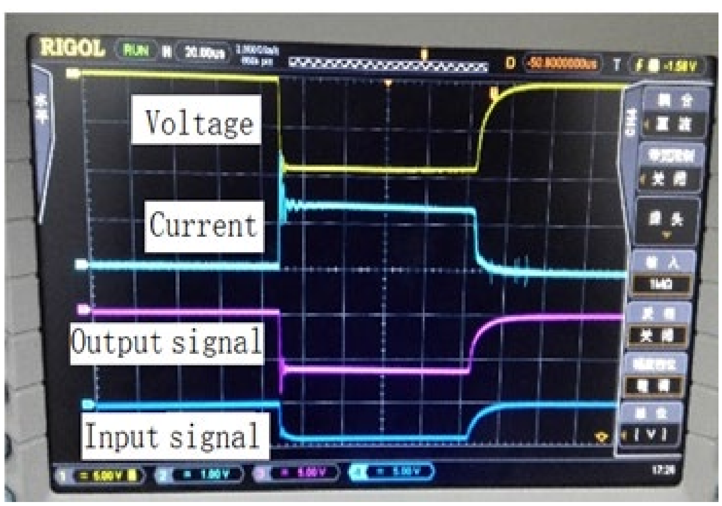

Fig. 11 Signal waveform diagram during test

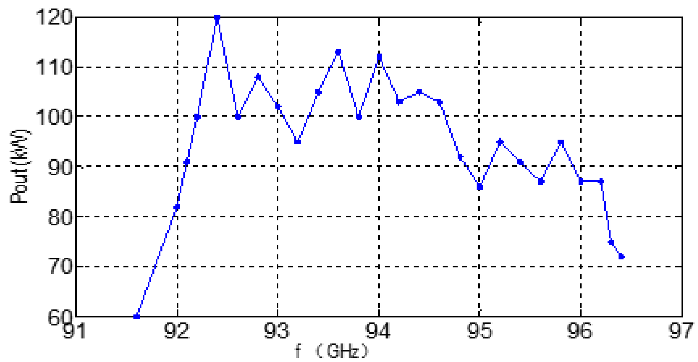

Fig. 12 Power-frequency relationship diagram during test

Comparing the simulation results with the actual test results, the test results are much smaller in terms of power and bandwidth than the simulation results. The reason is that the velocity dispersion of the electron beam is not considered in the simulation, and the velocity dispersion of the electron gun in the is designed to be 5.6%. After the actual assembly, the velocity dispersion of the electronic beam is much larger than the design value, which causes the test result to be much smaller than the simulation result.

5. Conclusions

For the W-band gyrotron traveling wave, the magnetic field is high, adiabatic compression zone of the electron gun is long, and the interaction radius is small. When TE_{01} mode is used, it is easy to cause the electron beam to bombard the cut-off section. Therefore, the TE_{02} mode is used to increase the interaction radius and improve the electron flow rate. In the experiment, the high-frequency structure adopts the periodic dielectric loading structure, which solves the problem of electron bombardment to the cut-off section, and obtains $120kW$ peak power, $3dB$ bandwidth $4.5GHz$, The mode converter placed in the collector converts the working mode TE_{02} into TE_{01} output.

References

[1] Blank M, Danly B, and Levush B. "Experimental demonstration of W-band gyroklystron amplifiers with improved gain and efficiency". *IEEE Transactions On Plasma Science*, 28, 3, 706-712 (2000)

[2] Chu K R, LIN A T. “Gain and bandwidth of the gyro-TWT and CARM amplifiers”. *IEEE Transactions on Plasma Science*, 16(2):90-104 (1988)

[3] Wang, E.F., Zeng, X., Liu, B.T. et al. “Experimental study of high-frequency and high-gain Ka-band gyrotron-traveling wave-tube”. 14th IEEE International Vacuum Electronic Conference, Paris, France (2013)

[4] EFeng Wang, An Li, Xu Zeng et al. “Preliminary experiment research on the W-band gyrotron traveling wave tube”. 16th IEEE International Vacuum Electronic Conference, Beijing (2015)

[5] Wang, E.F., Zeng, X., An Li, et al. “Experimental study on w-band Gyro-TWT”. The 12th annual conference of Vacuum Electronics Branch of Chinese Electronics Society, 2016:150.

[6] Xu Zeng, Efeng Wang, and JinJun Feng. “A Study of W-band TE02 mode Gyro-TWT”. *Terahertz Science & Technology*, 2016,9(4):141

[7] Efeng Wang, and Xu Zeng. “Experimental Study of High-Power Gyrotron Traveling-Wave Tube With Periodic Lossy Material Loading”. *EEE Trans. Plasma Sci*. 40, 7, 1846-1853 (2012)

[8] Niu XinJian，Gu Ling，Yu Sheng. et.al. “Corruagted waveguide mode conversion for 94GHz second-harmonic gyrotron”. *Journal of Infrared and Millimeter Waves*, 26, 2, 117 (2007)