Invited Paper

A Study of W-band TE_{02}mode gyro-TWT

Xu Zeng [*], Efeng Wang, Jinjun Feng
National Key Laboratory of Science and Technology on Vacuum Electronics,
Beijing Vacuum Electronics Research Institute,
Post Box 749-41, 100015, Beijing, China,
[*] Email: zengxu1108@163.com

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Abstract: In order to increase the electron beam transmission, a W-band TE_{02} mode gyro-TWT with a periodic dielectric loaded interaction circuit has been studied and the main parameters have been presented in the paper. The simulation results show that the W-band TE_{02} mode gyro-TWT is predicted to yield a peak output power of above 160*kW* with the bandwidth of 8*GHz*, and saturated gain above 49 *dB* at the interaction efficiency above 20%.

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

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1. Introduction

Gyrotron traveling wave tubes (Gyro-TWTs) are main broadband sources for generation of power as the millimeter and sub-millimeter wave radiation, which are suitable as the microwave sources of the radars, telecommunication and other applications, especially in W-band, the high-power, high-resolution radar plays an important role in the applications of satellite imaging and deep space detection. A Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) has been developed in the United States, in which a W-band gyro-TWT has been used as the final amplifier [1].

Worldwide progresses made on the gyro-TWT have been well documented in Ref. 2. In China, the research of the gyro-TWTs is getting more and more attention. The main units such as BVERI (Beijing Vacuum Electronics Research Institute), UESTC (University of Electronic Science and

Technology of China) and IECAS (Institute of Electronics, Chinese Academy of Sciences) have done a lot for achieving better performances of the tubes. Status of the gyro-TWT developments in these institutions [3-11] is listed in Table 1.

Tab. 1 The development status of the gyro-TWTs in China

Institution	Frequency band	Peak power (*kW*)	Efficiency (%)	Gain (*dB*)	Bandwidth (*GHz*)
BVERI	Ka	330	37	70	2.8
	Q	160	35	50	3
	W	110	27	39	5
UESTC	Ku	420	23	35	1.6
	Ka	185	23	45	2
	Q	158	22.6	47	3
	W	112	23.3	69.7	4
IECAS	Ka	110	15.7	34	1.8

In our previous work, W-band gyro-TWTs have been designed to operate at fundamental harmonic of TE_{01} mode, which has yielded output power of 110 *kW*, 3 *dB* bandwidth of 5 *GHz* [6]. However, in the recent experiment, an inner groove on the tube wall which is caused by bombardment of the electrons had been observed, which is shown in Fig. 1.The phenomenon indicates that a poor electron beam transmission restricts the performance of the tube seriously. In order to solving this problem by increasing the electron flow rate, a W-band TE_{02} mode gyro-TWT operating at fundamental harmonic has been designed due to larger interaction cavity radius and smaller guiding-center radius.

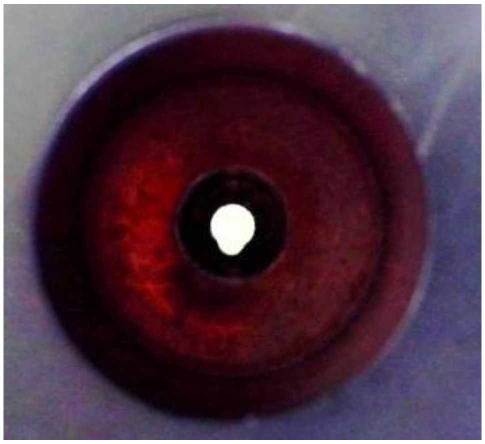

Fig. 1 The photo of an inner groove on the tube wall caused by bombardment of the electrons

2. Theoretical analysis

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

$$\omega = k_{\mathrm{z}} v_{\mathrm{z}} + s\Omega \tag{1}$$

$$\omega^2 - k_{\mathrm{z}}^2 c^2 - \omega_{\mathrm{c}}^2 = 0 \tag{2}$$

Here, ω and ω_{c} is the operating angle frequency and cut-off angle frequency respectively, k_{z} is the axial wave number, s is the cyclotron harmonic number, v_{z} is the axial velocity and $\Omega = \mathrm{e}B/(\gamma m_0)$ is the relativistic cyclotron frequency.

The interaction cavity radius can be determined by

$$r_w = c\chi_{mn}/\omega \tag{3}$$

In the above, χ_{mn} is the n^{th} root of the derivative with respect to x of $J_m(x)$, the m^{th} order Bessel function of the first kind. Because the χ_{mn} of TE$_{02}$ mode is 7.016, which is roughly two times larger than the χ_{mn} of TE$_{01}$ mode, the interaction cavity radius will be increased significantly at the same operating frequency, but the number of the competing modes will also increases (shown in Fig. 2). The Fig. 2 shows that the possible competing modes will be TE$_{22}$, TE$_{51}$, TE$_{41}$, TE$_{31}$, TE$_{01}$, TE$_{21}$ and TE$_{11}$ mode; meanwhile, they will oscillate at frequency of 86.5*GHz*, 83.3*GHz*, 76.2*GHz*, 72*GHz*, 70.9*GHz*, 69.2*GHz* and 67*GHz*, respectively. Therefore, a method to suppress these competing modes is critical in the design.

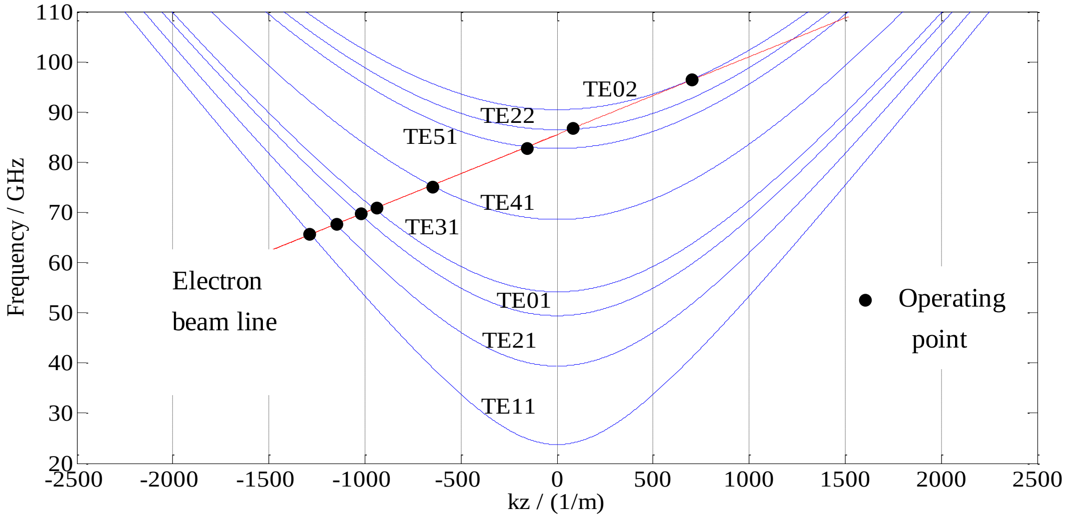

Fig. 2 The dispersion diagram of TE$_{02}$ mode and the possible oscillating modes (64*kV*, α=1.0, $B/B_g = 1.02$ r_w=3.7*mm*)

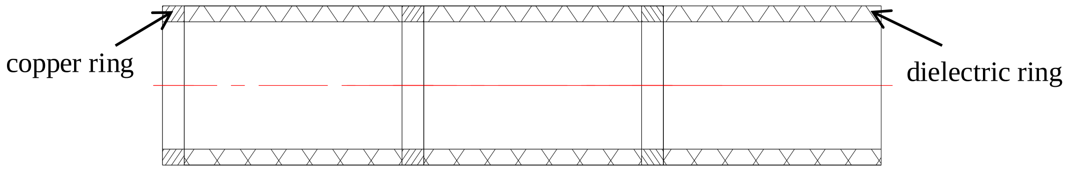

Fig. 3 The schematic of the periodic dielectric loaded circuit

According to the experience of the previous experiment for W-band TE_{01} mode gyro-TWT, in order to suppress these competing modes, a periodic dielectric loaded circuit (shown in Fig. 3) has been applied, in which the relative permittivity and the loss tangent of the dielectric, the periodicity and the dimension of the circuit have been optimized for the highest efficiency.

Meanwhile, the harmonic coupling coefficient that represents the interaction strength is defined as [12]

$$H_{sm}(r_g, r_L) = J_{s-m}^2(x_{mn} r_g/r_w) J'^2_s(x_{mn} r_L/r_w) \qquad (4)$$

Here, r_L,r_g and r_w are the Larmor radius, the guiding-center radius of the electrons and the interaction cavity radius, respectively. Fig. 4 is the dependence of the coupling coefficient on guiding-center radius for TE_{02} mode and the possible competing modes. In this figure, the coupling coefficient peaks at $r_g/r_w = 0.26$ for the TE_{02} operating mode, although it is smaller than the coupling coefficient of TE_{01} mode, the smaller guiding-center radius contributes to the increase of the electron flow rate. In addition, the coupling coefficients of the other possible competing modes are very small at the value of $r_g/r_w$is 0.26, which indicates the oscillations of these modes have less influence on the performance of the tube.

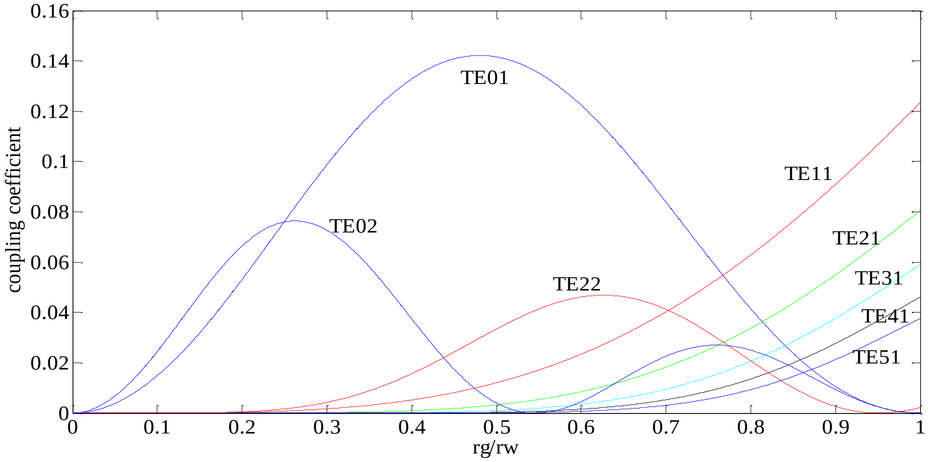

Fig. 4 The dependence of the coupling coefficient on guiding-center radius for TE_{02} mode and possible competing modes

3. Design and simulation results

According to the above theoretical analysis, the design of the W-band TE_{02} mode gyro-TWT has been carried out. The main parameters have listed in Table 2, meanwhile, the performance of the tube has been simulated by PIC code.

Tab. 2 The main parameters of the W-band TE_{02} mode gyro-TWT

Electron voltage	64 *kV*
Electron beam current	13 *A*
Velocity ratio	1.0
Operating mode	TE_{02}
Cyclotron harmonic	1
Magnetic field	3.35 Tesla
Interaction cavity radius	3.7 *mm*
Guiding-center radius	0.96 *mm*
Relative permittivity of dielectric	15
Loss tangent of dielectric	0.08
Circuit length	23 *cm*

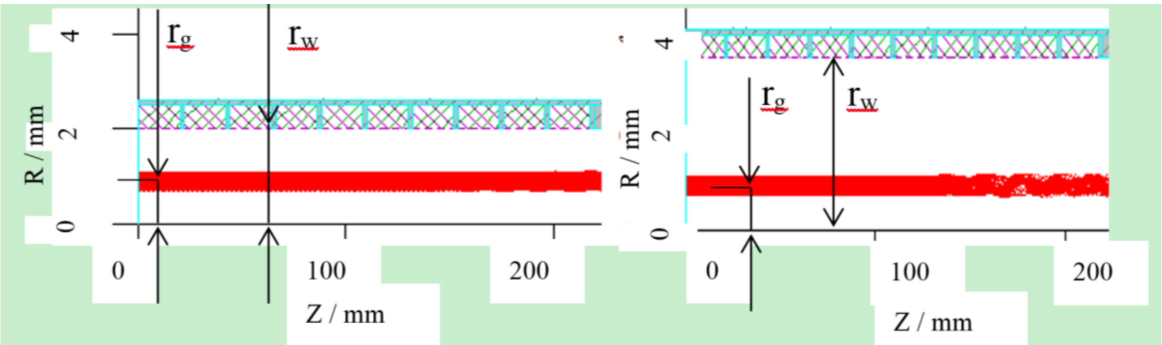

Fig. 5 The comparison of the electron beam track of the W-band TE_{01} mode (left) and TE_{02} mode (right) gyro-TWT

Fig.5 shows a comparison of the electron beam track of the W-band gyro-TWT between TE_{01} mode and TE_{02} mode. In this figure, it is obviously found that the interaction cavity radius of TE_{02} mode is 3.7*mm*, which is larger than the interaction cavity radius of 2*mm* for TE_{01} mode. In addition, the guiding-center radius of TE_{02} mode is 0.962*mm*, which is roughly same with the guiding-center radius of 0.96*mm* for TE_{01} mode. In conclusion, choosing TE_{02} mode as the operating mode for

W-band gyro-TWT can significantly increase the electron flow rate; and the risk of the bombardment on the tube wall of the electrons can be decreased greatly; furthermore, the performance of the tube will be ensured effectively.

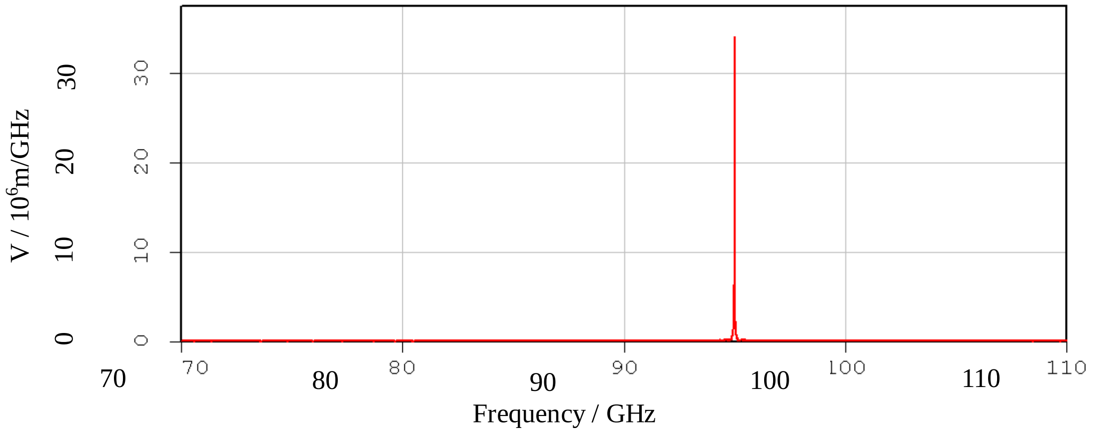

Fig. 6 The simulation results of the frequency spectrum of the W-band TE_{02} mode gyro-TWT

Fig.6 indicates the design of the periodic dielectric loaded circuit can suppress the oscillations of the possible competing modes availably. Furthermore, the performance of the gyro-TWT can be improved by optimizing the profile of the output taper section to achieve the minimum refection.

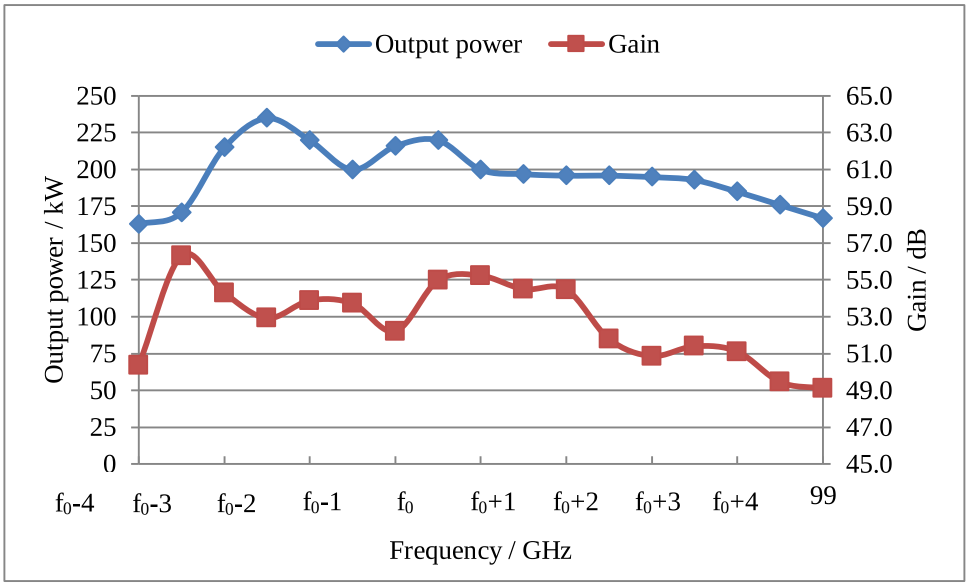

Fig. 7 The simulation results of the output power and gain of the W-band TE_{02} mode gyro-TWT

Fig.7 shows the dependence of the output power and gain on the frequency for the W-band

TE_{02} mode gyro-TWT. The peak output power above 160*kW* in the bandwidth of 8*GHz*, corresponding to the saturated gain above 49*dB* at the interaction efficiency above 20%.

4. Conclusions

In previous experiment of the W-band TE_{01} mode gyro-TWT, a phenomenon of bombardment on the tube wall of the electrons has been observed, which restricts the performance of the tube seriously. In order to increase the electron flow rate, TE_{02} mode has been chosen as the operating mode due to larger interaction cavity radius and smaller guiding-center radius. A W-band TE_{02} mode gyro-TWT with a periodic dielectric loaded circuit has been designed and the performance has been simulated. The results indicate that the electron transmission can be improved in this design and the peak output power above 160*kW* in the bandwidth of 8*GHz*, corresponding to the saturated gain above 49*dB* at the interaction efficiency above 20%.

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