A Study on Instabilities of 220 GHz Confocal Waveguide Gyro-TWT

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Abstract—*Instability problem is one of the most significant limits for high power gyro-TWTs. In this paper, the absolute instabilities and backward wave oscillation (BWO) instabilities of a 220 GHz confocal waveguide gyro-TWT are discussed. The results show that the starting current of absolute instabilities is much higher than the operating current 5A, and the critical interaction length of HE05 mode backward wave oscillation is about 10mm.*

Keywords— instabilities; confocal waveguide;gyro-TWT

Introduction

Gyro-TWT can be wildly applied on radar systems, communications and remote sensing because of its broad bandwidth and high power capacity [1]. However, gyro-TWT often suffers from problems with self-oscillations and instabilities. In THz band, the traditional heavily loaded waveguide is not suitable to be the interaction structure. Therefore, confocal waveguide, due to its mode selectivity, is presented. The EM wave can be filtered out from the open sides through diffraction loss and different mode has different loss, which can suppress the mode competition. There are three kinds of instabilities that are important in a gyro-TWT: absolute instabilities, BWO instabilities and reflected power instabilities. The reflective instabilities is caused by outside feedback, so it is difficult to analyze it in theory [2]. In this paper, based on the dispersion relation derived from kinetic theory, the BWO instabilities and absolute instabilities are analyzed.

Absolute Instabilities

As shown in Fig.1, confocal waveguide consists of two mirrors, which have the same aperture width $2a$ and radius of the curvature R_c, and the distance between two mirrors $L_\perp$ is equal to R_c. When the working current is above the critical threshold for absolute instabilities, the forward wave will couple with backward wave. In addition, the absolute instabilities is a function of the electron beam and EM wave coupling in the gyro-TWT. The absolute instabilities calculation method was well discussed in [3]. The saddle point of the following dispersion equation is the critical condition of absolute instabilities [4].

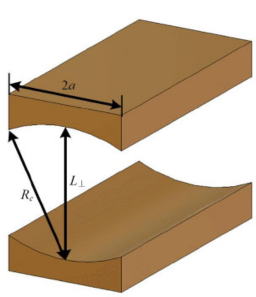

Fig.1 Structure of confocal waveguide

$$D\left(\bar{k}_z,\bar{\omega}\right)=\left(\bar{\omega}^2-\bar{k}_z^2-1\right)\left(\bar{\omega}-\beta_z\bar{k}_z-s\Omega_c/\omega_c\right)^2=-\varepsilon \quad (1)$$

$$D\left(\bar{k}_{zs},\bar{\omega}_{zs}\right)+\varepsilon=0 \quad (2)$$

$$\left.\frac{\partial D\left(\bar{k}_z,\bar{\omega}\right)}{\partial\bar{k}_z}\right|_{(\bar{k}_{zs},\bar{\omega}_{zs})}=0 \quad (3)$$

where $\bar{\omega}=\omega/\omega_c$ and $\bar{k}_z=k_z/k_c$ are the normalized frequency and axial wavenumber, respectively; $\omega_c=k_c c$, k_c is the cutoff number of HE_{mn} mode and c is the light speed. β_z and β_t are the normalized axial and transverse velocity of electron. $R_L=\gamma_0 m_e v_t/eB_0$, $\Omega_c=eB_0/\gamma_0 m_e$, $\gamma_0=1/\left(1-\beta_t^2-\beta_z^2\right)$ are Larmor radius, cyclotron frequency and relativistic factor of electron. When $B=B_g$ (B_g is the external magnetic field meets grazing condition), the starting current for absolute instabilities can be written as:

$$I_c=\frac{27\beta_z^2\bar{k}_{zs}^4k_{mn}^2I_A}{4\beta_t^2\pi}\frac{N_{mn}}{\left\langle\left|F_{mns}\right|^2\right\rangle\left[J_s'\left(k_c r_L\right)\right]^2} \quad (4)$$

where $\bar{\omega}_s=\left\{b+\left[8\beta_z^2\left(1-b^2\right)+64\beta_z^4\right]^{1/2}\right\}/\left(1+8\beta_z^2\right)$ and $\bar{k}_{zs}=\left(\bar{\omega}_s-b\right)/4\beta_z$. And I_A is the Alfven current, $N_{mn}=\int_S\left|\psi\left(x,y\right)\right|^2dS$, $F_{mns}\left(x,y\right)=\left[\frac{1}{k_c}\left(\frac{\partial}{\partial x}+j\frac{\partial}{\partial y}\right)\right]^s\psi\left(x,y\right)$, where $\psi\left(x,y\right)$ is the membrane function of HE_{mn} mode.

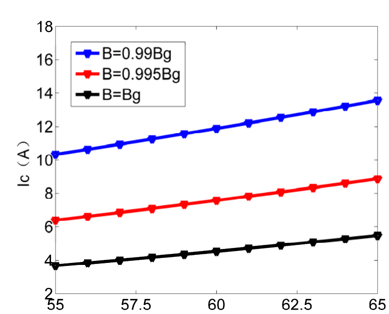

Fig.2 Critical current for absolute instability versus voltage

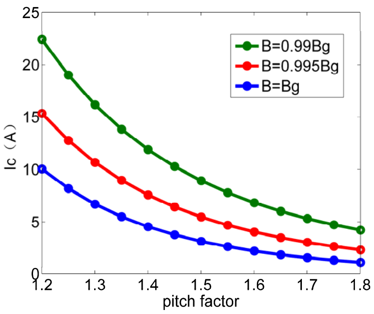

Fig.3 Critical current for absolute instability versus pitch factor

A conclusion can be made from Fig.2 that, increasing the voltage can increase the starting current of absolute instability. As shown in Fig.3, a higher pitch factor can lead to a lower critical current of absolute instability. Moreover, Fig.2 and Fig.3 can indicate that by reducing the magnetic field of the interaction structure, a higher critical current of absolute instability can be reached.

BWO Instabilities

When the cyclotron beam mode synchronous with a backward waveguide mode, the BWO instabilities will occur. By replacing $\bar{\omega}$ with $\bar{\omega}_0+\delta\bar{\omega}$ and $\bar{k}_z$ with $\bar{k}_{z0}+\delta\bar{k}_z$, and $\left|\delta\bar{\omega}/\bar{\omega}\right| \ll 1$, $\left|\delta\bar{k}_z/\bar{k}_{z0}\right| \ll 1$, the dispersion relation can be rewritten as follows[5]:

$$g\left(\delta\bar{\omega}\right)=\delta\bar{\omega}^3-\varepsilon_1\delta\bar{\omega}+\varepsilon_2=0 \qquad (5)$$

where $\varepsilon_1=\frac{27}{4}\left(\frac{\pi}{2L}\right)^2\frac{\beta_z^2\bar{v}_g^2}{\left(\beta_z+\bar{v}_g\right)^2}$, $\varepsilon_2=\frac{27I_cK_m}{8\bar{\omega}_0}\frac{\beta_z\bar{v}_g^2}{\left(\beta_z+\bar{v}_g\right)^3}$,

$\bar{v}_g=-\bar{k}_{z0}/\bar{\omega}_0$ and $K_m=\frac{-4\pi\beta_{t0}^2}{\gamma_0\beta_zI_Ak_c^2}\frac{\left\langle\left|F_{mns}\right|^2\right\rangle}{N_{mn}^2}\left[J_s'\left(k_cr_L\right)\right]^2$.

And the instability occurs when $\varepsilon_1^3=\frac{27}{4}\varepsilon_2^2$, so the critical oscillation start current can be expressed as:

$$I_{st}=2\bar{\omega}_0\left(\frac{\pi}{2L}\right)^3\beta_z^2\bar{v}_g\frac{1}{K_m} \qquad (6)$$

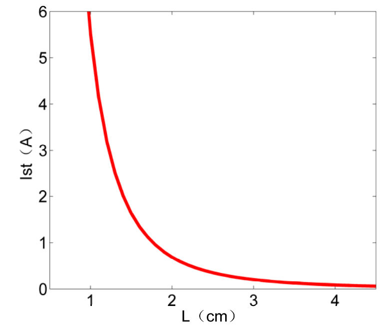

Fig.4 BWO Start current versus interaction length

The start current is proportional to $1/L^3$, where L is the length of interaction length. When the starting current is $5\,\mathrm{A}$, the critical interaction length is 10mm.

Summary

In this paper, the absolute instabilities and BWO instabilities of a 220 GHz confocal waveguide gyro-TWT has been investigated based on kinetic theory. The critical current of absolute instabilities is 10A that is higher than the operating current. In addition, the interaction length should less than 10mm to avoid HE_{05} mode BWO instabilities.

Acknowledgements

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