Nonlinear Analysis of Gyro-TWT Amplifier with Helical Interaction Waveguide

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***Abstract*—Operation of a gyro-TWT amplifier with helical interaction waveguide is investigated by means of nonlinear self-consistent code. Simulation results are in good agreement with reported experimental observation. Reduced sensitivity to the electrons' velocity spread and broad bandwidth of this type of gyro-device are demonstrated.**

I. INTRODUCTION

DURING the last decade, growing attention has been paid to the gyro-TWT amplifiers with helical interaction waveguide[1-4]. This kind of gyro-devices has potential capability of broad bandwidth and high efficiency. Therefore, it is considered as a promising source of radar and communications. Both experimental and theoretical investigations have been devoted since the appearance of the novel idea, which showed the advantages of reduced sensitivity to the electrons' velocity spread. An approximated nonlinear calculation has ever been employed to predict its performance. In this paper nonlinear analysis of the beam-wave interaction in the gyro-TWT with helically corrugated waveguide is carried out in detail. The simulation results are in good agreement with the reported experimental observation.

II. THEORETICAL MODEL

The profile of a helical interaction waveguide is represented in cylindrical coordinates as follows:

$$a = a_0 + a_1 \cos(m_B \varphi - k_B z)\,, \qquad (1)$$

where a_0 is the mean radius of the waveguide, a_1, m_B, k_B are respectively the amplitude, azimuthal, and axial numbers of the corrugation. The beam-wave interaction differential equations can be expressed as [1, 2]

$$\frac{d}{dz} b - i(k_{zl} - k_B) b = \frac{i}{k_{zl}} \kappa f \qquad (2)$$

$$\frac{d^2}{dz^2} f + k_{zj}^2 f = -2\kappa b + i2\omega\mu I \left\langle \frac{\vec{v}_n \cdot \overline{E^*}}{v_{zn} \cdot f^*} \right\rangle_n \qquad (3)$$

where

$$\kappa = \frac{1}{2} \frac{\chi_j^2 \chi_l^2 - m_j m_l a_0^2 (k_{cl}^2 + k_B k_{zl})}{\sqrt{(\chi_j^2 - m_j^2)}\sqrt{(\chi_l^2 - m_l^2)}} \frac{a_1}{a_0^3} \qquad (4)$$

is the coupling coefficient, b and f are partial waves' amplitudes. Here subscripts j and l respectively represent the higher and lower modes, $\overline{E}$ is the electronic field of higher mode and $\overline{E^*}$ is its complex conjugate, χ and m are the eigenvalue and azimuthal mode index of each mode, and $\langle \cdots \rangle_n$ represents an average over the ensemble of n electrons.

As the helical waveguide is connected with the smooth cylindrical waveguide at each side, f should satisfy the boundary conditions:

$$\frac{df}{dz}\Big|_{z=z_{in}} = -ik_{zj} f, \qquad \frac{df}{dz}\Big|_{z=z_{out}} = ik_{zj} f \qquad (5)$$

Equations (2),(3) and (5) together with the motion equations of electrons constitute a set of nonlinear, coupled equations for gyro-TWT amplifier with helical interaction waveguide.

To reduce simulation error, the consistency check should be carried out by the principle of the conservation of energy

$$p_l + p_j = \eta P_{beam} \qquad (6)$$

with

$$p_l = \frac{k_{zl}}{2\omega\mu} |b|^2 \qquad (7)$$

$$p_j = \frac{1}{2\omega\mu} \left(f_r \frac{df_i}{dz} - f_i \frac{df_r}{dz}\right) \qquad (8)$$

where p_l and p_j are the time averaged power flow of the partial modes, f_r and f_i are the real and imaginary parts of f, respectively.

From the mathematical point of view, this is the two-point boundary value problem. To solve it, f at $z=z_0$, which is regarded as a free parameter, must be determined by repeated integration of the equations from the beginning to the end of the helical waveguide until it satisfies the output boundary condition. Based on this model, a code was developed to study the gyro-TWT amplifier with helical waveguide.

III. SIMULATION RESULTS

Our simulations are carried out for a set of parameters in a Gyro-TWT amplifier experiment [3], where the waveguide employed had a length of 40 cm, a mean radius of 14.5 mm, and helical corrugations with amplitude of 1.5 mm and period of 37.5 mm. In that device a 200-kev, 25-A electron beam with initial transverse velocity is 0.55c (c being the light speed in vacuum) was used, the operating magnetic field was 0.22 T, the first spatial harmonic of the operation mode TE_{11} at frequency of 9.4 GHz was coupled with counter-rotating TE_{21} mode, and the input power of TE_{11} was 5.5 kW.

Figure 1 shows the field amplitude profile along the axial position z. It can be found that the partial wave satisfies the boundary conditions. As the operating frequency is below the cutoff frequency of TE_{21}, it is an evanescent wave at both sides.

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Fig 2 indicates the evolvement of the two partial modes' power flow in the interaction region. The power flow of the higher partial wave *f* is far less than the lower partial wave *b*. It demonstrates that *f*, which draws energy from the electron beam, transfers its electromagnetic energy to the lower mode *b*.

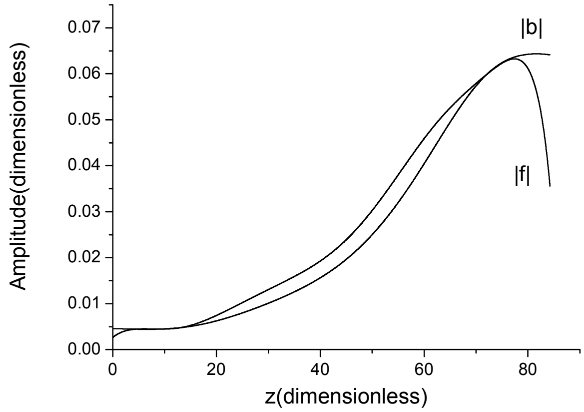

Fig.1The field profile of two coupled modes along z-axis

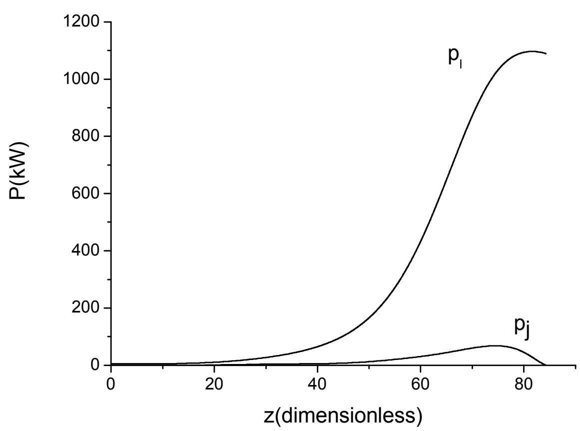

Fig.2 Evolvement of two coupled modes' power flow along z-axis

In Fig. 3 it appears that efficiency resulting from the beam-wave interaction is no longer sensitive to the axial velocity spread of the electron beam (here the axial velocity spread being RMS value). The electronic efficiency has a slight decrease from 24.6% to 21.7% as the axial velocity spread is 10%.

With an axial velocity spread of 10%, the efficiency was calculated as a function of frequency, shown in Fig. 4. It can be found that minimum efficiency corresponding to a frequency bandwidth of 3 dB at the central frequency of 9.5 GHz is about 13.8%.

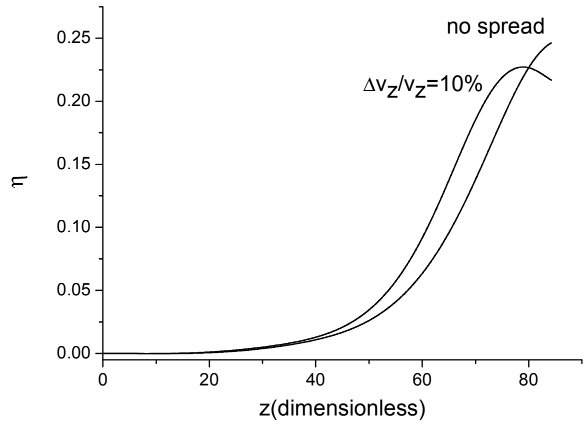

Fig.3 The influence of the axial velocity spread on efficiency

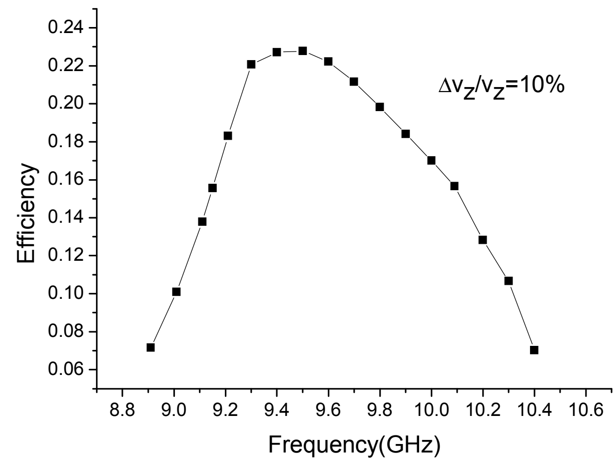

Fig. 4 Efficiency as a function of frequency

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