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Self-consistent nonlinear analysis of a frequency-quadrupling terahertz gyroklystron*

Liu Di-Wei(刘頓威)†, Yuan Xue-Song(袁学松), Yan Yang(鄢 扬), and Liu Sheng-Gang(刘盛纲)

THz Research Center, Research Institute of High Energy Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China

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This paper analyses a three-cavity frequency-quadrupling terahertz gyroklystron with successive frequency-doubling in each cavity with self-consistent nonlinear theory. The beam–wave interaction efficiency and the electron bunching process are studied. The variation of output efficiency with the length of drift tubes and output power and the variation of Ohmic loss with the length of output cavity are considered. Numerical simulations predict an optimal output efficiency of 1.8%, a power output of more than 2 kW and a gain of 33 dB after taking into account Ohmic losses when the frequency-quadrupling gyroklystron, driven by a 40-kV, 3-A electron beam and 1 Watt input power, operates at 225 GHz.

Keywords: frequency-quadrupling gyroklystron, terahertz, self-consistent nonlinear analysis
PACC: 7640, 4110H, 5270G

1. Introduction

As the most powerful source of radiation in the submillimetre wave and THz region, THz gyrodevices are one of the most attractive topics in recent years;[1−3] for example, 1 THz gyrotrons are experimentally studied in Fukui University[4] and the IAP of Russia,[5] respectively. In order to reduce the magnetic fields required for producing coherent radiation in this frequency region, a three-cavity frequency-quadrupling gyroklystron with successive frequency-doubling in each cavity was proposed.[3] In Refs.[3] and [6], a point-gap model was used to analyse the interaction between the electron beam and electromagnetic waves of the frequency-quadrupling gyroklystron. In this article, we will use self-consistent nonlinear theory to calculate the interaction efficiency and analyse the electron bunching process; meanwhile, the effects of drift tube length on the output efficiency, output power and Ohmic loss variation with the length of output cavity will be considered. A brief self-consistent nonlinear theory model is presented in Section 2, and a numerical simulation and conclusion are presented in Sections 3 and 4, respectively.

2. Self-consistent nonlinear theory

The electron orbits on the cross sectional plane of the gyroklystron are shown in Fig.1. For a weakly relativistic annular electron beam, when space-charge effects are neglected, from the Lorentz force equation,

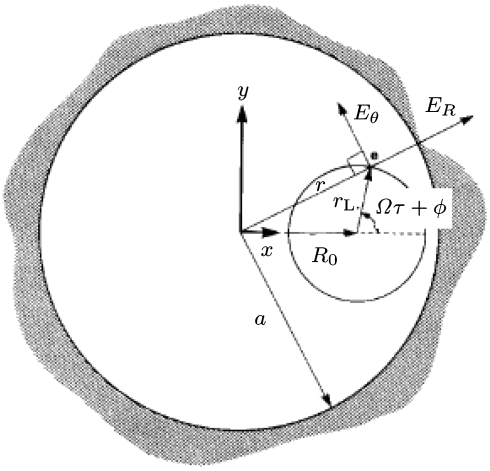


Fig.1. Electron orbits on the cross sectional plane of the gyroklystron.

we can obtain[7]

$$\frac{\mathrm{d}P}{\mathrm{d}z}+\frac{j}{u_z}\left(\frac{\gamma\Omega}{c}-\frac{\eta B_0}{c}\right)P = -\frac{\gamma\eta}{2u_z}c^{l-3}k_{mn}C_{mn}J_{m-l}\left(k_{mn}R_0\right)f \times\left(\frac{1}{(l-1)!}\right)\left(\frac{k_{mn}}{2\eta B_0}\right)^{l-1}\left(P^*\right)^{l-1}. \quad (1)$$

Here, $P=u_t\exp\left(-j\Lambda\right)$ describes the transverse component of the electron momentum, u_t and u_z are the transverse and axial components of the normalized momentum respectively. $\Lambda=\left(\omega/l-\Omega\right)\tau-\phi+\omega t_0/l$

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†Corresponding author. E-mail: dwliu212220@163.com

is the slow time scale phase variable, l is the number of cyclotron harmonics, Ω is the cyclotron angular frequency, η is the ratio of charge to the rest mass for an electron, B_0 is the static axial magnetic field, γ and c are the relativistic factor and light velocity, respectively. f is the complex field profile function, R_0 is the electron guiding central radius. For the cylindrical cavity the normalization constant C_{mn} is given by

$$C_{mn} = 1/\sqrt{\pi(k_{mn}^2 R_W^2 - m^2) J_m^2(k_{mn} R_W)} \quad (2)$$

and the transverse wave number $k_{mn} = \mu_{mn}/R_W$, where μ_{mn} is the n-th root of $J'_m(x) = 0$ and R_W is the radius of the cavity.

From Maxwell's equation, we can obtain the following equation for the field profile function

$$\begin{aligned}&\left(\frac{\mathrm{d}^2}{\mathrm{d}z^2} + \frac{\omega^2}{c^2} - k_{mn}^2\right) f \\ &= -\mathrm{j}\mu\omega I_0 k_{mn} C_{mn} J_{m-l}(k_{mn} R_0) \\ &\quad \times \frac{1}{2\overline{u}_z}\left(\frac{1}{(l-1)!}\right)\left(\frac{ck_{mn}}{2\eta B_0}\right)^{l-1} \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\Lambda_0 (P)^l,\end{aligned} \quad (3)$$

where I_0 is the beam current, μ is the permeability, ω is the operating angular frequency, Λ_0 is the initial phases of electrons.

The initial conditions on the radio frequency (RF) fields are completely specified by the initial profile function f and the operating frequency ω. The condition on the profile function at the entrance and the exit of the drift tubes which is cut off for the operating mode is

$$f(z_{\mathrm{in}}) = f(z_{\mathrm{out}}) = 0. \quad (4)$$

At the exit of the output cavity, the output RF boundary condition is an outgoing travelling wave, the profile function satisfies

$$\left.\frac{\mathrm{d}f}{\mathrm{d}z}\right|_{z_{\mathrm{out}}} = -jk(z_{\mathrm{out}}) f(z_{\mathrm{out}}), \quad (5)$$

where

$$k(z_{\mathrm{out}}) = \left[\frac{\omega^2}{c^2} - k_{mn}^2(z_{\mathrm{out}})\right]^{1/2}. \quad (6)$$

In the drift tubes, the operating modes are cut off and the RF fields can be neglected. The phase change when the electrons pass through the drift tubes can be expressed as follows:

$$\Delta\Lambda = \left(\frac{\gamma}{c}\Omega - \frac{\Omega_0}{c}\right)\frac{L}{u_z}, \quad (7)$$

where L is the length of the drift tubes, $\Omega_0 = \gamma_0\Omega$. The electron efficiency η_{e}, which can be calculated from the average energy loss of electrons, is

$$\eta_{\mathrm{e}} = \frac{\gamma_0 - \langle\gamma\rangle}{\gamma_0 - 1}. \quad (8)$$

where γ_0 is the initial relativistic factor, $\langle\cdots\rangle$ denotes an average value for all electrons. When the gyrotron works in the submillimetre wave and THz region, the Ohmic loss cannot be neglected. The output efficiency η_{out} are related as[2]

$$\eta_{\mathrm{out}} = \left(1 - \frac{Q_{\mathrm{d}}}{Q_{\mathrm{d}} + Q_{\mathrm{ohm}}}\right)\eta_{\mathrm{e}}, \quad (9)$$

where Q_{d} and Q_{ohm} are the diffractive quality factor and Ohmic quality factor, respectively. With Eqs.(1), (3), (9) and the initial condition Eqs.(4), (5), the beam–wave interaction of the frequency-quadrupling three-cavity gyroklystron can be analysed.

3. Numerical simulation

In this section, we will use the theoretical method discussed above to analyse the beam–wave interaction of the 225 GHz frequency-quadrupling gyroklystron.[8] A schematic diagram of the frequency-quadrupling gyroklystron is shown in Fig.2. The circuit parameters and system parameters are shown in Tables 1 and 2, respectively.

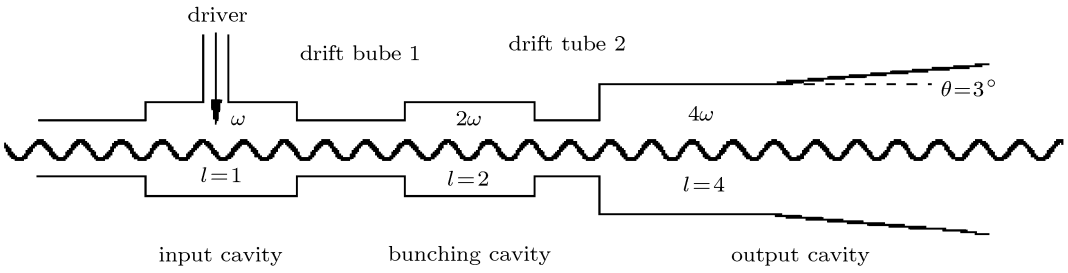


Fig.2. Schematic diagram of the frequency-quadrupling gyroklystron.

Table 1. Circuit parameters.

	length/mm	radius/mm	cyclotron harmonic	operating mode
input cavity	10	1.63	l=1	TE_{11}
bunching cavity	9	1.31	l=2	TE_{21}
output cavity	11	2.69	l=4	TE_{43}
drift tube 1	35	1	–	–
drift tube 2	6	1	–	–

Table 2. System parameters.

parameters	value
beam voltage	40 kV
beam current	3 A
velocity ratio	1.5
guiding centre radius	0.28 mm
driver frequency	56.2 GHz

Figure 3 shows the phase bunching of electrons at the outlets of the input cavity, bunching cavity, output cavity and drift tubes. The longitudinal field distribution and output efficiency in the output cavity are shown in Fig.4. From Fig.4 we can see that when the output cavity of the frequency-quadrupling gyroklystron operates at the 4$^{\text{th}}$ cyclotron harmonic, the output efficiency is about 1.8%, and the corresponding output power and gain are about 2 kW and 33 dB, respectively.

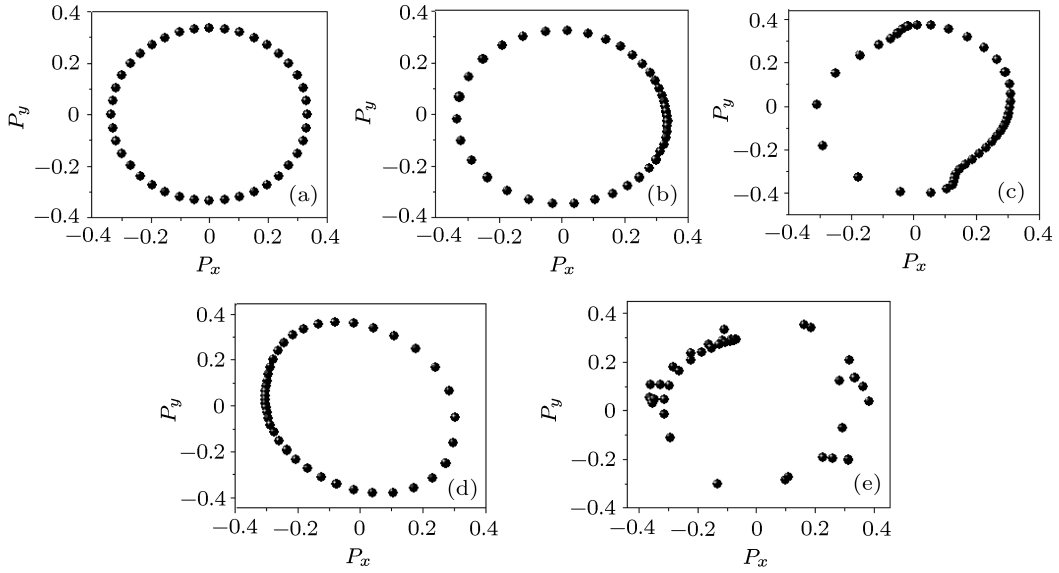


Fig.3. Phase bunching of electrons. Figures (a), (b), (c), (d), (e) present the phase bunching at the outlets of the input cavity, drift tube 1, bunching cavity, drift tube 2, and output cavity respectively.

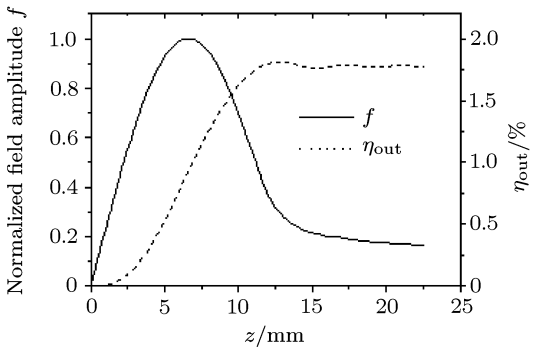


Fig.4. Longitudinal field distribution and output efficiency in the output cavity.

The output efficiency variation with drift tube length is shown in Fig.5. Here, L_1 and L_2 are the lengths of drift tube 1 and drift tube 2, respectively. From Fig.5, we can find that output efficiency varies greatly with the drift tube lengths L_1 and L_2. When drift tube 1 is short, a higher output efficiency can be obtained with a long drift tube 2; otherwise, when drift tube 2 is short, a higher output efficiency can be obtained with a long drift tube 1; namely, output efficiency is higher when the bunching cavity is close to the input cavity or the output cavity, and the output efficiency is maximal when the bunching cavity is close to the output cavity.

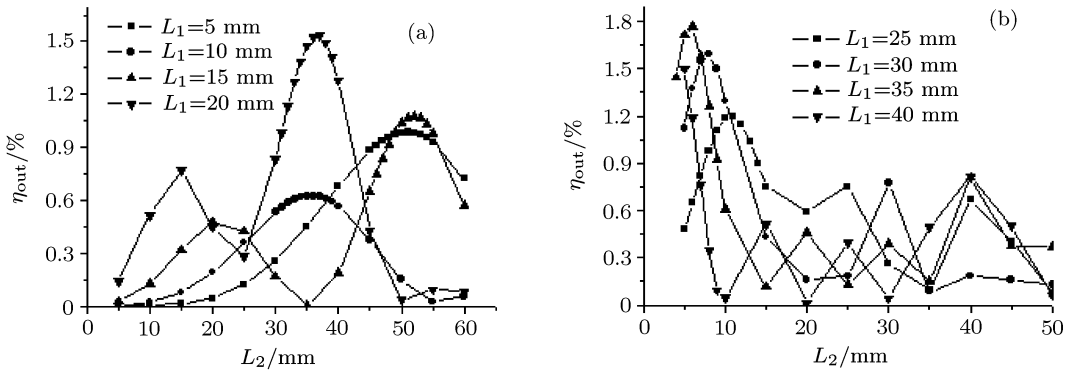


Fig.5. Output efficiency vs. drift tube length.

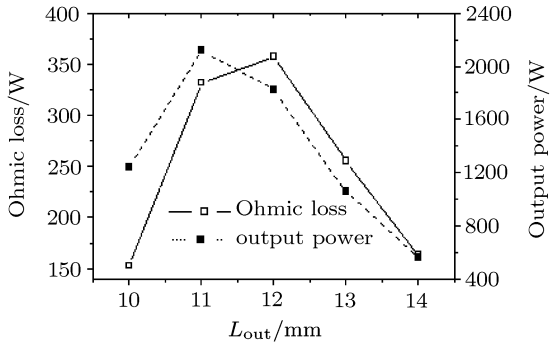


Fig.6. Output power and Ohmic loss vs. output cavity length.

The output power and Ohmic loss variation with the length of the output cavity is shown in Fig.6, which shows that the length of the output cavity has a great effect on the output power and Ohmic loss. When the output power is maximal, the Ohmic loss is about 1/6 of the output power.

4. Conclusion

In this article, applying self-consistent nonlinear theory, the interaction between the electron beam and electromagnetic field of the 225 GHz three-cavity frequency-quadrupling gyroklystron is analysed. The output efficiency of the frequency-quadrupling gyroklystron varies greatly with the length of drift tubes. A higher output efficiency can be obtained when the bunching cavity is close to the input cavity or output cavity, and the output efficiency is maximal when the bunching cavity is close to the output cavity; meanwhile, the length of the output cavity has a great effect on the output power and Ohmic loss. Ohmic loss cannot be neglected when the device works in the submillimetre and terahertz region. When the three-cavity frequency-quadrupling gyroklystron is driven by a 40-kV, 3-A electron beam, and 1 Watt input power, the optimal output efficiency is about 1.8%, the corresponding output power is about 2.1 kW and the gain is about 33 dB after taking into account Ohmic losses.

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