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Study of a rectangular coupled cavity extended interaction oscillator in sub-terahertz waves*

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An extended interaction oscillator (EIO) generating 120 GHz wave in sub-terahertz waves is studied by using the three-dimensional electromagnetic simulation software CST and PIC codes. A rectangular reentrant coupled-cavity is proposed as the slow-wave structure of EIO. By CST, the circuit parameters including frequency-phase dispersion, interaction impedance and characteristic impedance are simulated and calculated. The operation mode of EIO is chosen very close to the point where $\beta L = 2\pi$ with corresponding frequency 120 GHz, the beam voltage 12 kV and the dimensions of the cavity with the period 0.5 mm, the height 3 mm and the width 1.4 mm. Simulation results of beam–wave interaction by PIC show that the exciting frequency is 120.85 GHz and output peak power 465 W with 12-period coupled-cavity with the perveance 0.17 μP. Simulation results indicate that the EIO has very wide range of the operation voltage.

Keywords: extended interaction oscillator (EIO), rectangular coupled-cavity, sub-terahertz (Sub-THz) waves, dispersion relation

PACC: 5270G, 4110H

1. Introduction

Coupled-cavity microwave tubes have been used in space communications and modern radar applications since they have broader bandwidths, higher average and peak powers. An extended interaction structure consists of several coupled-cavities that are strongly coupled by slots in the walls. The extended interaction oscillator (EIO) and extended interaction klystron (EIK), based on the extended interaction structure, are often the choice for high power operation.[1−3] EIO is an O-type device[4] and it is available at much higher frequencies up to 280 GHz for sub-terahertz frequency in CPI Inc of Canada.[3] Owing to a demand for advanced radar and communications, EIO with frequencies between 100 and 300 GHz has been employed for the transmitter.[5−8] Another system, in which 120 GHz sub-terahertz wave has been developed for 10-Gbit/s wireless transmission of high-definition television in Japan,[9] attracts interest all around the world.

The slow-wave circuit of EIO is adopted in Hughes type and ladder line structure.[10] As the operating frequencies increase, the circuit structure and fabrication techniques will change in order to make smaller circuits. Due to the complication of Hughes structure, it is difficult to develop higher frequency in the terahertz or sub-terahertz regime. In this paper, a rectangular reentrant coupled cavity is proposed as the slow-wave structure of EIO. As shown in Fig.1 the structure includes two cavities, each adjoining coupled slot of the cavity is staggered. The left of the sketch map is $y-z$ view and the right $x-y$ view in Cartesian coordinates. As an all-metal slow-wave circuit this structure has good heat dissipation, also it can be fabricated from a single copper block with fine machining technique

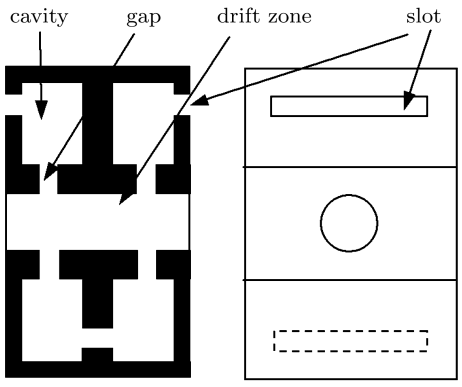


Fig.1. Schematic diagram of a period of the EIO structure.

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such as LIGA fabricating methods.[11] Details on cold test and hot test parameters of the interaction circuit described respectively by CST and PIC are presented. The main goal of this paper is to design an EIO circuit that generates the RF frequency of 120 GHz with a lower operating voltage and a higher efficiency.

2. Properties of the cold circuit

Due to the complexity of the geometrical structure of cavities, the theoretical calculation of cold test characteristic of coupled-cavity always adopts the method of equivalent circuit. However, the equivalent circuit can only be used for qualitative analysis in that the physical model of equivalent circuit is very rough. For a number of years, computer simulation has played an important role in the design process for coupled cavity slow-wave circuits.

2.1. Synchronism between beam and phase velocities

The main goal of designing the interaction circuit is to optimize the dimension of the circuit at the operating frequency of 120 GHz with an operating voltage of 12 kV. Then the velocity of electron beam, u_0, is about 6.5×10^7 m/s. In travelling across the gap, the electron should be in phase with the circuit wave. This means that the phase synchronism requires $v_\mathrm{p} \approx u_0$ in order to maximize the bunching effect and the beam–wave interaction. The periodic length of the circuit, L, from the synchronism condition can be expressed as follows:

$$\beta = \phi/L \approx \beta_\mathrm{e} = \frac{\omega}{u_0}. \tag{1}$$

EIO ordinarily operates very close to the point with $\beta L = m\pi$, where m is an integer. In this paper $\beta L = 2\pi$ is chosen, consequently L is equal to 0.5 mm. As $l/(l+d)$ is in the range between 0.25 and 0.375,[12] where l and d are the length of gap and drift zone, respectively, $l = 0.15$ mm and $d = 0.35$ mm are chosen. The transit angle, $\phi_l(= \beta_m l)$, is $3\pi/5$.

2.2. Dispersion and distribution of electric field of the circuit

Electromagnetic simulation software CST, for solving Maxwell's equations by the finite-integration-algorithm, is a powerful, three-dimensional, electrodynamic code. The frequency-phase dispersion characteristics of the slow-wave circuit can be obtained by CST with the method of setting an electric wall at the axial boundary of a cavity configuration to obtain resonant frequencies in truncated sections of circuit. An electric wall is a boundary condition equivalent to a perfectly conducting plane to which the electric field is perpendicular, while the magnetic field is parallel.

The dispersion of the circuit from 0 to 360 degrees is shown in Fig.2 with the cavity dimension of a height 3 mm and a width 1.4 mm. The dispersion curve is the line of the cavity mode. The other two lines in the figure are the light velocity line and the beam line corresponding to the electron voltage $U = 12$ kV. Figure 2 shows that the synchronism operation point of the beam–wave interaction is very close to 2π point.

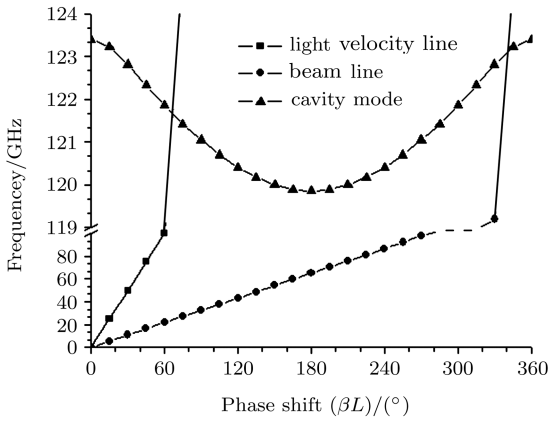


Fig.2. The dispersion of the EIO circuit.

At the same time the distribution of electric field of different mode of this EIO circuit can be simulated by setting different phase shift per cavity. The distribution of the electric field and the contour of its E_z component of the operation point in the dispersion are plotted in Fig.3. The field distribution indicates that the cavity mode is like a TM_{11} mode.

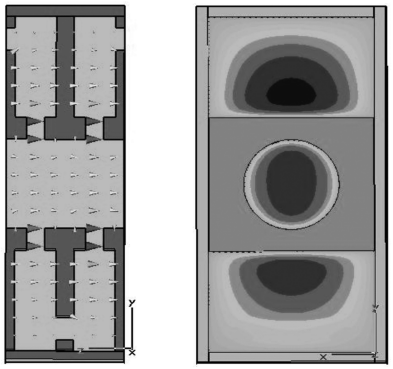


Fig.3. The distribution of the electric field(left) and E_z contour (right) of the operation mode.

2.3. Interaction impedance (K) and characteristic impedance (R/Q)

For each value of phase shift per cavity, the impedance in the cavity for the nth space harmonic is defined by

$$K_n = E_n^2/(2\beta_n^2 P). \tag{2}$$

In Eq.(2), E_n and β_n is respectively the electric field amplitude and the axial phase constant for the nth space harmonic, and P is the total RF power flow.

The electric field amplitude of the desired space harmonic can be obtained from a Fourier analysis of z-direction electric field E_z. The space harmonic amplitude E_n is defined as

$$E_{n,z} = \frac{1}{L}\int_0^L E_z \mathrm{e}^{j\beta_n z}\mathrm{d}z. \tag{3}$$

And the RF power flow is defined as

$$P = W v_\mathrm{g}, \tag{4}$$

where v_g is the group velocity and W is the stored electromagnetic energy per unit length.

Characteristic impedance, R/Q, is defined as

$$\frac{R}{Q} = \frac{V^2}{2\omega W}, \tag{5}$$

where R is the shunt resistance, ω is the angular resonant frequency, V is the equivalent voltage in the cavity. Then R/Q, corresponding to the circuit coupled-impedance, can be expressed as[1]

$$K_n = \frac{|E_n|^2}{2\beta_n^2 P} = \frac{R}{Q}\frac{1}{\phi_n}\frac{v_\mathrm{p}}{v_\mathrm{g}}, \tag{6}$$

where v_g and v_p are the group velocity and phase velocity, respectively.

The coupled impedance and the characteristic impedance varying with the phase shift are shown in Fig.4. The interesting interaction region exists in the forward wave zone of the first space harmonic in the phase shift range between 277.5° and 352.5°. The coupled impedance is varied nonlinearly from 38 to 92 Ω and the corresponding characteristic impedance is varied nonlinearly from 35 to 55 Ω at a point in the gap. The quality factor, Q, is obtained about 800.

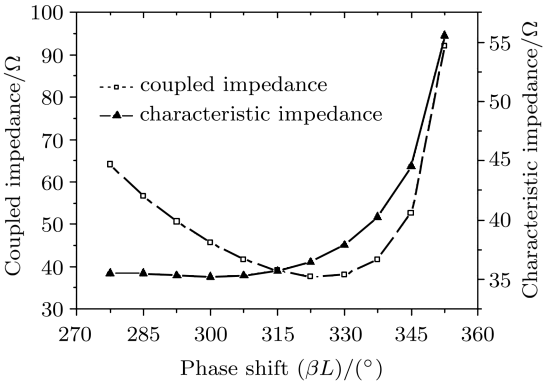


Fig.4. The coupled impedance and the characteristic impedance against the phase shift.

3. Beam–wave interaction simulation

A specialized particle-in-cell (PIC) code in this paper is used to simulate the beam–wave interaction in the EIO. The PIC code is used to numerically solve the Maxwell's equations and Lorentz force equation by adopting the method of time-finite-difference, based on electromagnetic dynamics. We can directly obtain the physical process (evolving in time) of the electromagnetic field, the particle trajectories and the beam–wave interaction. It is an effective simulation method and can accurately predict many performance parameters of the oscillator. During the simulation, we find that the output power is the largest and the starting time is the shortest when the period number is 12 with a transverse output window at the last cavity. The 12-period slow-wave circuit of EIO is chosen to simulate the beam–wave interaction. The perveance of the beam is about $0.17 \times 10^{-6}\,\mathrm{A/V^{3/2}}$ with the current and the voltage of the electron beam being 0.226 A and 12 kV, respectively. Several parameters are shown in Fig.5 under the simulation condition of $B_z = 0.5$ T. The longitudinal coordinates of Fig.5(a), 5(b) and 5(c) are the power, the voltage and the longitudinal momentum, respectively. Figure 5(a) shows the output power evolving in time at the output window; and the output peak power is 465 W. Figure 5(b) shows the RF frequency of E_z at the output window, and the exciting frequency by the beam in this EIO is 120.85 GHz and its bandwidth is 50 MHz. Figures 5(c) and 5(d) show respectively the phase space and the bunching of the beam in the EIO circuit at 60 ns. This EIO can operate with lower voltage and higher

output power.

EIO can operate in a very wide range of the operation voltage. For the different voltages the generated power and the exciting frequency as well as the starting time of EIO are different. Figure 6 shows the variation of excited frequency and the starting time with the voltage of the beam. In the figure both the frequency and the starting time increase with increasing voltage. And the line of the former is nearly straight, while the latter is a curve partly because the coupled impedance decreases with increasing voltage as shown in Fig.4. Figure 7 shows the variation of RF power and transferring efficiency of the EIO with increasing voltage of the beam. Both the power and the efficiency increase nearly linearly with the voltage. Figures 6 and 7 indicate that the EIO can operate in a very wide range of the voltage.

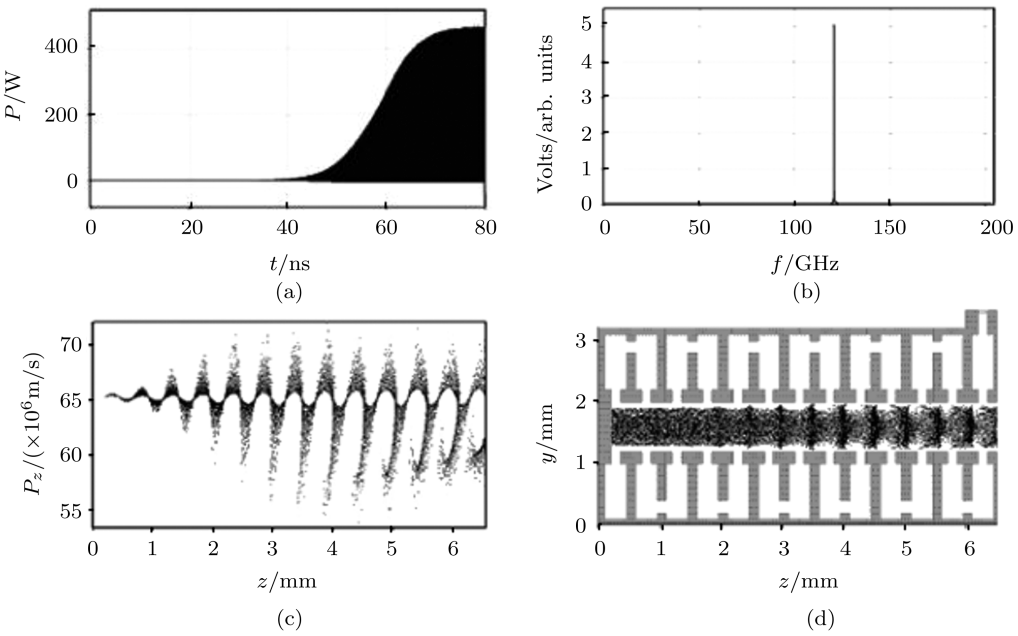


Fig.5. Several hot test parameters of the EIO. (a), (b), (c) and (d) are the power, the frequency, the phase space and the bunching of the beam, respectively.

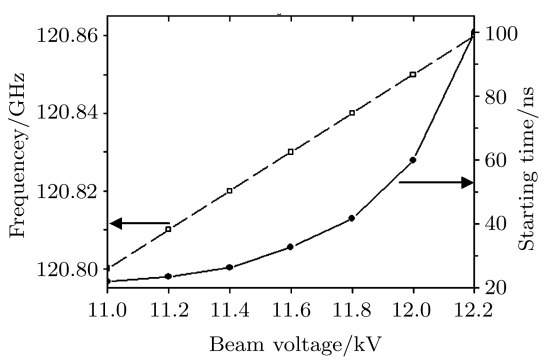


Fig.6. The frequency and the starting time versus the voltage.

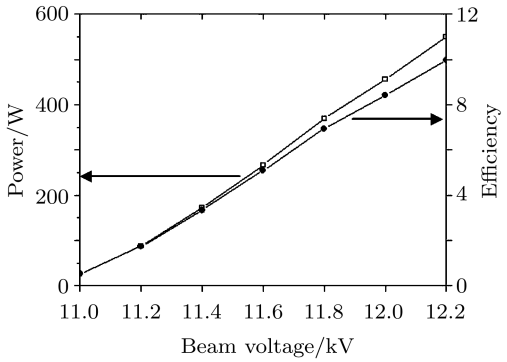


Fig.7. The RF power and the efficiency versus the voltage.

4. Conclusion

A rectangular reentrant coupled-cavity EIO has been simulated by using CST and PIC codes in this paper. The operation mode of EIO is chosen very close to 2π point in the cavity with a period 0.5 mm, a height 3 mm and a width 1.4 mm, and the cavity mode is a TM_{11}-like one. Under these conditions the RF frequency-phase dispersion of the cavity mode is simulated in CST code. Also the coupled impedance

and the characteristic impedance between 277.5° and 352.5° are computed. By PIC code, the exciting frequency obtained is 120.85 GHz for the operation voltage of the beam 12 kV, the perveance 0.17 μP, output peak power 465 W and the efficiency more than 8.6% when the 12-period slow-wave circuit is chosen. The operation of EIO can be conducted in a very wide range of the voltage. This EIO has a merit of low voltage and high efficiency, which is suitable for sub-THz transmitter of sub-THz radar.

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