Efficiency and stability enhancement of a virtual cathode oscillator*

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A virtual cathode oscillator (VCO) with a resonant cavity is presented and investigated numerically and theoretically, and its efficiency and stability are enhanced. An equivalent circuit method is introduced to analyze the resonant cavity composed of anode foil and feedback annulus, and a theoretical expression for the fundamental mode frequency of the resonant cavity is given. The VCO is investigated in detail with a particle-in-cell method. We obtain the microwave frequencies from simulation, theoretical expression, and relative references, and draw three important conclusions. First, the microwave frequency is a constant when the diode voltage is changed from 588 kV to 717 kV. Second, the fluctuation of the microwave frequency is very small when the AK gap is changed from 1.2 cm to 1.6 cm. Third, the microwave frequency agrees with the theoretical result. The relative error, which is calculated according to the theoretical and simulation frequencies, is only 1.7%.

Keywords: virtual cathode oscillator (VCO), equivalent circuit method, particle-in-cell method

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1. Introduction

A virtual cathode oscillator (VCO) with the general characteristics of simple construction, without magnetic field, broadband frequency, and low impedance, is an important high-power microwave source and a major hotspot in the field of high-power microwave research at present.[1–18] However, because of the mode competition and the frequency instability, the VCO always suffers from low efficiency and operation instability.[1,2,5,6,11]

An axially-extracted VCO with a resonant cavity is an important type of VCO, and it has been investigated in detail in our laboratory.[11–16] In this paper, an equivalent circuit method is introduced to analyze the resonant cavity, and a theoretical expression for the fundamental mode frequency of the resonant cavity is given. Finally, the microwave frequencies obtained from simulation, theoretical expression and relative references are compared, and three important conclusions are given.

2. Theoretical analysis

The configuration of the axially-extracted VCO with a resonant cavity is shown in Fig. 1. The resonant cavity is composed of anode foil and feedback annulus, which is marked with the dashed box. When the beam current exceeds the space-charge-limited current, a virtual cathode will be generated in the resonant cavity. The position of the virtual cathode oscillates axially, shedding charge and behaving like a relaxation oscillator. The motion of the space charge and the potential well of the virtual cathode produce microwave radiation.[19] According to conventional theories, the microwave frequency of the VCO depends on the diode voltage and the A–K gap. However, in the axially-extracted VCO with a resonant cavity, the virtual cathode is formed in the resonant cavity. If the microwave frequency generated by the virtual cathode approaches the fundamental mode frequency of the resonant cavity, the virtual cathode will interact with the cavity mode to oscillate at a frequency tuned to the fundamental mode frequency of the resonant cavity. The interaction of the virtual cathode and the resonant cavity could eliminate mode competition, and the power conversion efficiency and the operation stability are enhanced.[19–21]

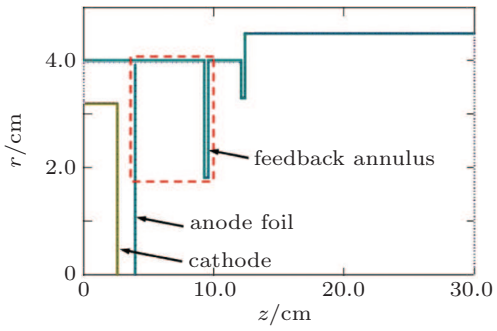


Fig. 1. (color online) Configuration of the axially-extracted VCO with a resonant cavity.

According to the equivalent circuit method, the resonant cavity and its parallel equivalent circuit are shown in Fig. 2, where W, $R_{\rm i}$, and $R_{\rm o}$ are the distance of the anode foil and the feedback annulus, the inner radius, and the outer radius of the feedback annulus, C, G, and L are the equivalent capacitance,

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the equivalent conductance, and the equivalent inductance, respectively. It is well known that the resonance frequency ω_0 of the parallel resonance circuit is given by[22]

$$\omega_0 = \frac{1}{\sqrt{LC}}, \tag{1}$$

where L and C are given by[23,24]

$$L = \frac{\mu_0 W(R_o - R_i)}{4\pi R_o}, \tag{2}$$

$$C = \frac{2\pi\varepsilon_0(R_o^3 + 2R_i^3 - 3R_o R_i^2)}{3W(R_o - R_i)}. \tag{3}$$

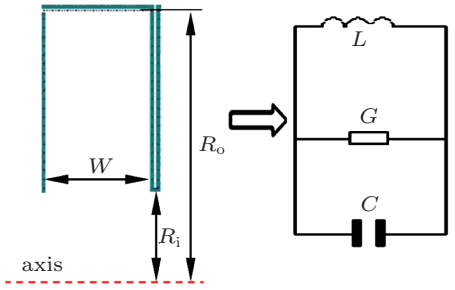


Fig. 2. (color online) Resonant cavity and its parallel equivalent circuit.

3. Comparison and discussion

The axially-extracted VCO with a resonant cavity is investigated in detail with a particle-in-cell method (KARAT code). The optimized VCO has the following parameters: $R_i = 1.6$ cm, $R_o = 4.0$ cm, and $W = 5.3$ cm. In simulation, a high-power microwave is generated with a peak power of 1.87 GW, a microwave frequency of 3.695 GHz, and a peak power conversion efficiency of 14.2%, when the voltage is 717 kV and the current is 18.4 kA. Figures 3 and 4 show the simulation results of the VCO. Figure 3 plots the time history of the average output microwave power at $z = 26.9$ cm. Figure 4 shows the Fourier spectrum of the signal, and the microwave frequency is 3.695 GHz. According to Eqs. (1)–(3), the resonance frequency ω_0 is 3.631 GHz. The relative error, which is calculated according to the theoretical and simulation frequencies, is only 1.7%.

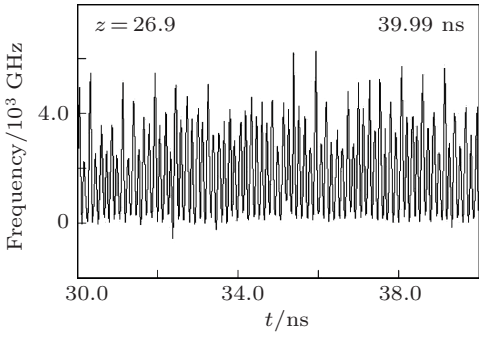


Fig. 3. Output power versus time at $z = 26.9$ cm.

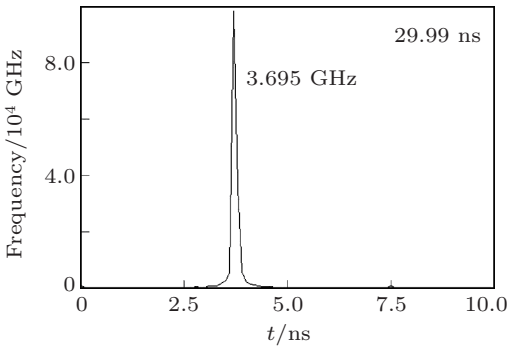


Fig. 4. Fourier spectrum of the signal.

According to conventional theories, the microwave frequency of the VCO depends on the diode voltage and the A–K gap, which has been validated by experimental results. The conventional equations of the microwave frequency of the VCO are given by[19,25–27]

$$f_A = 4.08\sqrt{\frac{J}{\sqrt{\gamma^2 - 1}}}, \tag{4}$$

$$f_B = \frac{4.77\ln(\gamma + \sqrt{\gamma^2 - 1})}{d_{AC}}, \tag{5}$$

$$f_C = \frac{7.5\beta}{d_{AC}}, \tag{6}$$

where f_A, f_B, and f_C are the microwave frequency calculated by the conventional theories, J is the current density, γ is the relativistic factor, and d_{AC} is the A–K gap (in units of cm).

The microwave frequency of the axially-extracted VCO with a resonant cavity is very stable. Simulation results show that the microwave frequency is a constant (3.695 GHz) when the diode voltage changes from 588 kV to 717 kV, and the microwave frequency agrees very well with the theoretical result. However, the microwave frequencies calculated by the conventional theories deviate from the simulation results. The result shows that the conventional theories cannot apply to the axially-extracted VCO with a resonant cavity. Because the VCO oscillations are modulated by the resonant cavity, the stability of the microwave frequency is enhanced. The comparative results are shown in Fig. 5.

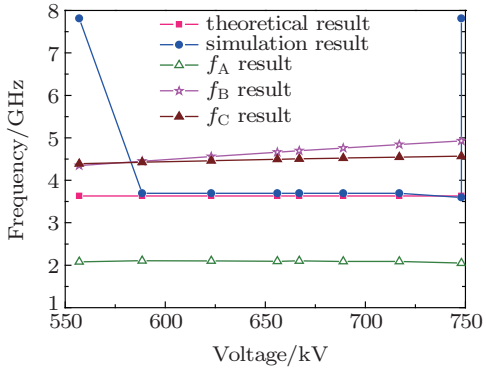


Fig. 5. (color online) Microwave frequency versus the diode voltage.

Figure 6 is a plot of the microwave output power and the power conversion efficiency versus the diode voltage. It can be seen from Fig. 6 that there is an optimal diode voltage for the maximums of the microwave output power and the power conversion efficiency. The optimal diode voltage is 717 kV, and the corresponding microwave output power and the power conversion efficiency are 1.87 GW and 14.2%, respectively.

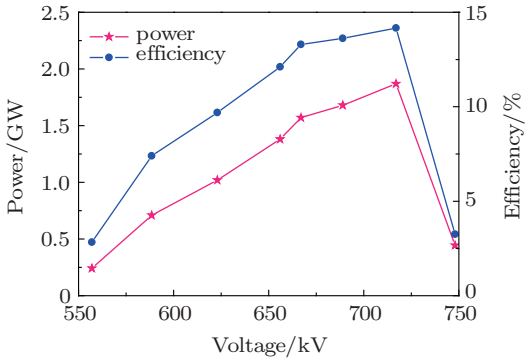


Fig. 6. (color online) Microwave output power and the power conversion efficiency versus the diode voltage.

The microwave frequency obtained by simulation result and Eqs. (1)–(6) versus the A–K gap is shown in Fig. 7. Simulation results show that the microwave frequency is 3.795 GHz when the A–K gap is changed from 1.2 cm to 1.3 cm, and it is 3.695 GHz when the A–K gap is changed from 1.4 cm to 1.6 cm. The fluctuation of the microwave frequency is very small when the A–K gap is changed from 1.2 cm to 1.6 cm. The simulation results agree with the theoretical result. According to conventional theories, the microwave frequency should change in inverse ratio to the A–K gap. However, the microwave frequencies calculated by the conventional theories deviate again from the simulation results. The result shows again that the stability of the microwave frequency is enhanced and the conventional theories cannot apply to the axially-extracted VCO with a resonant cavity.

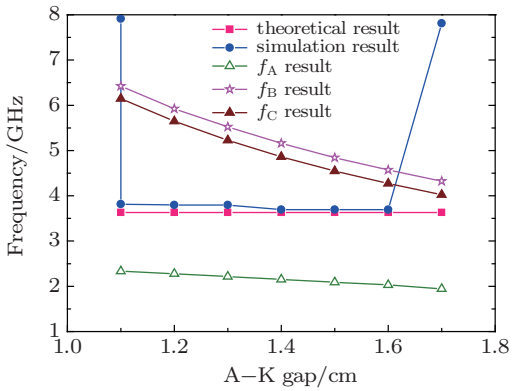


Fig. 7. (color online) Microwave frequency versus the A–K gap

Figure 8 is a plot of the microwave output power and the power conversion efficiency versus the A–K gap. As can be seen in Fig. 8, there is an optimal A–K gap for the maximum of the microwave output power and the power conversion efficiency. Note that the microwave output power and the power conversion efficiency approach the maximum and the microwave frequency is 3.695 GHz, which agrees very well with the resonance frequency of the resonant cavity, when the A–K gap is changed from 1.4 cm to 1.6 cm.

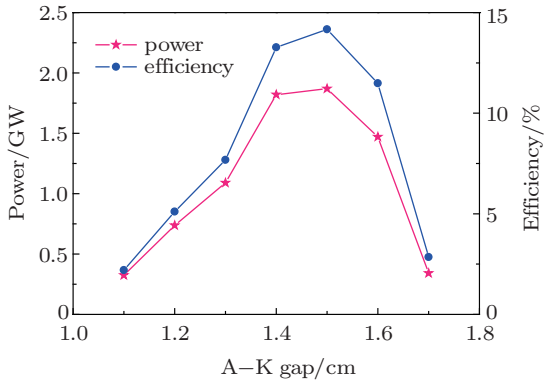


Fig. 8. (color online) Microwave output power and power conversion efficiency versus the A–K gap.

As shown in Figs. 5–8, when the diode voltage and the A–K gap are changed in a moderate range, the microwave frequency generated by the virtual cathode approaches the fundamental mode frequency of the resonant cavity; the virtual cathode will interact with the cavity mode to oscillate at a frequency tuned to the fundamental mode frequency of the resonant cavity, so the output microwave frequency is stable, and the power conversion efficiency and the output power are higher. When the changes of the diode voltage and the A–K gap exceed the moderate range, the microwave frequency generated by the virtual cathode keeps away from the fundamental mode frequency of the resonant cavity, and the interaction of the virtual cathode and the resonant cavity is weakened and even destroyed, which results in the deviation of the output microwave frequency from the fundamental mode frequency of the resonant cavity, and the sharp decline of the power conversion efficiency and the output power.

4. Conclusions

An axially-extracted VCO with a resonant cavity is presented and investigated numerically and theoretically. An equivalent circuit method is introduced to analyze the resonant cavity, and a theoretical expression for the fundamental mode frequency of the resonant cavity is given. Finally, the microwave frequencies obtained from simulation, theoretical expression, and relative references are compared, and three important conclusions are derived. First, the microwave frequency is a constant when the diode voltage is changed from 588 kV to 717 kV. Second, the fluctuation of the microwave frequency is very small when the A–K gap is changed from

1.2 cm to 1.6 cm. Third, the microwave frequency agrees with the theoretical result. The relative error, which is calculated according to the theoretical and simulated frequencies, is only 1.7%. The results show that the VCO oscillations are modulated by the resonant cavity, and so the power conversion efficiency and the operation stability are enhanced.

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