Theoretical research on electron beam modulation in a field-emission cold cathode electron gun*

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In order to develop miniaturized and integrated electron vacuum devices, the electron beam modulation in a field-emission (FE) electron gun based on carbon nanotubes is researched. By feeding a high-frequency field between the cathode and the anode, the steady FE electron beam can be modulated in the electron gun. The optimal structure of the electron gun is discovered using 3D electromagnetism simulation software, and the FE electron gun is simulated by PIC simulation software. The results show that a broadband (74–114 GHz) modulation can be achieved by the electron gun with a rhombus channel, and the modulation amplitude of the beam current increases with the increases in the input power and the electrostatic field.

Keywords: carbon nanotubes, cold cathode, field emission, electron gun

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1. Introduction

Vacuum electron emitters are widely used in radar, communication systems, broadcasting devices, accelerators, and other electron systems due to their high output power and strong anti-interference.[1] But the use of a thermionic cathode has brought many limitations, such as large volume, high power consumption, and slow reaction, which causes great inconvenience. Solid emitter devices have been paid increasing attention and have been developed quickly because of their advantages of miniaturization, low working voltage, ability to work at room temperature, and integration. They have substituted the vacuum device in many fields. However, these solid devices cannot solve problems such as bad anti-interference and low output power. Vacuum microelectronics (VME)[2] devices are a combination of vacuum electron devices and solid devices, so they have inherited advantages from both, including good anti-interference, high operation frequency, small volume, low power consumption, and integration.

At present, metal field emission arrays (FEAs) fabricated with micro-electromechanical system (MEMS) technology have the advantages of room-temperature operation, instant opening, high current density, and so on. However their applications are limited by high cost and difficult processing. In contrast, carbon nanotubes (CNTs) as the electron source of field emission have been the focus of international research in the field of VME[3–5] because of their sufficient emission current density, good chemical stability, high mechanical strength, and long-term stability.[6–8]

Due to the small size of the VME devices, the electron vacuum devices cannot provide adequate space for the interaction of the electron beam and high-frequency field. The high-frequency field cannot obtain sufficient energy from the electrons, which influences the efficiency of the device, and could even make the device non-operational. The research results in traditional vacuum devices show that if the high-frequency field interacts with a modulated electron beam, then the beam–wave interaction space can be greatly reduced. In Refs. [2] and [9], the density modulation of electron beams by the field emission from a cathode is shown to be possible. Therefore, the problems of the beam–wave interaction space can be solved in VME devices.

Kenneth *et al.* studied the characteristics of a carbon-nanotube microwave diode operating at 1.5 GHz,[10] and Legagneux *et al.* conducted a modulation investigation in a 32 GHz triode.[11] In their investigations, the field-emission (FE) electric field was only provided by the high-frequency field, so a very high-power field was demanded to produce the FE. Their devices also worked at a point frequency. In this paper, a broadband modulated method is proposed. In this method, both the electrostatic field and the high-frequency field act on the cathode at the same time, and a modulated electron beam is then obtained. Due to the electrostatic field, the modulated electron beam can still be generated even if the input power is very weak.

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2. The modulation theory of field emission

Under a high electric field, the surface barrier would be lower and thinner, and the FE is produced by the tunnel effect.[12] The emission current density is

$$J = \frac{A}{\varphi t^2(y)} E^2 \exp\left(-\frac{Bv(y)\varphi^{3/2}}{E}\right), \tag{1}$$

where A and B are the the Fowler–Nordheim constants, φ is the work function, E is the electric field between the cathode and the anode, $t(y)$ and $v(y)$ are Nordheim's elliptic functions, and $y = 3.79 \times 10^{-5}\sqrt{E}/\varphi$.

When the electric field E includes a time-domain variation component

$$E(t) = E_0 + E_1(t), \tag{2}$$

where E_0 is the electrostatic field, and $E_1(t)$ is the time-domain variation component, Eq. (1) can be translated into

$$\begin{aligned} J(t) &= \frac{A}{\varphi t^2(y)} E^2(t) \exp\left[-\frac{Bv(y)\varphi^{3/2}}{E(t)}\right] \\ &= \frac{A}{\varphi t^2(y)} [E_0 + E_1(t)]^2 \exp\left[-\frac{Bv(y)\varphi^{3/2}}{E_0 + E_1(t)}\right] \\ &= J_0 + J_1(t). \end{aligned} \tag{3}$$

As shown in Eq. (3), the electron beam is modulated because of the time-domain variation component, and when the direction of the high-frequency electric field is parallel with that of the electrostatic field, the amplitude modulation has the maximum value. As Fig. 1 shows, when there is a high-frequency field $E_1(t)$, there will be a modulated current density $J(t)$. According to this, we calculate the FE current density of the CNT cathode in Ref. [13]. The electrostatic field is 5 V/μm and the high-frequency field $E_1(t)$ paralleling the electrostatic field fed in at $t = 0.02$ ns is

$$E_1(t) = \Delta E \cdot \sin(\omega t). \tag{4}$$

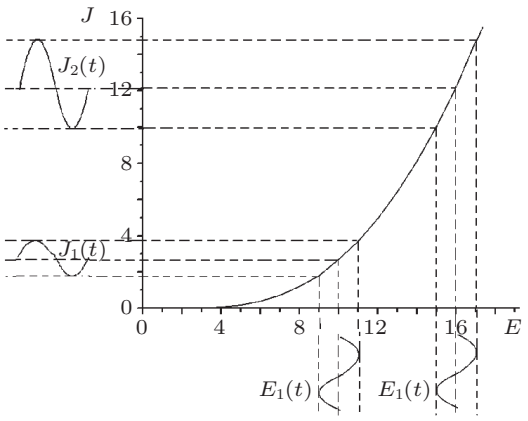


Fig. 1. Field-emission current density as a function of the electric field.

The calculation result of the FE current density with $|\Delta E|/|E_0| = 0.1$ is shown in Fig. 2. When $t < 0.02$ ns, there is only the electrostatic field, and the stable electron beam current density J_0 is 1.5 A/cm^2. When $t > 0.02$ ns, the high-frequency field is also applied between the cathode and the anode, and a modulated current density with a maximum $J_{\max}$ of 1.828 A/cm^2 and minimum $J_{\min}$ of 1.216 A/cm^2 is obtained.

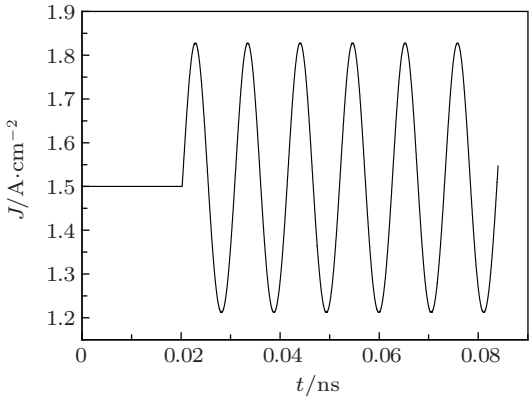


Fig. 2. The modulated current density of the electron beam.

3. Electron gun structure

In order to obtain the modulated electron beam, the first important problem is how to input the high-frequency field and make its direction parallel to that of the electrostatic field. To solve this problem, parallel plates are used to transmit quasi-TEM waves. The parallel plates are selected as the cathode and the anode of the electron gun. A high-frequency field is fed into the parallel plates by a rectangular waveguide. To ensure that the electron beam can be generated effectively and the electric field is as uniform as possible, a grid mesh is designed in the anode, which is fixed above the CNT cathode. The circular CNTs are grown on the cathode. The anode is then fixed on the cathode using a medium. Figure 3 shows the structure of the electron gun. In this structure, the waveguide broad side a is 2.54 mm, and the waveguide narrow side b is 1.27 mm. The distance between the cathode and the anode, d, is 0.1 mm. The width of the anode, W, is 0.57 mm, and the radius of the CNT cathode, r, is 0.25 mm.

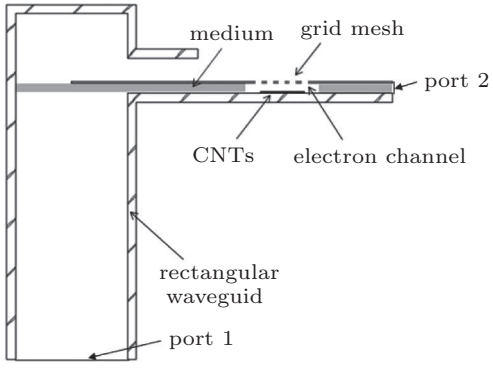


Fig. 3. The structure of the electron gun.

The structure is similar to a waveguide-to-microstrip transition. The high-frequency field is input from the waveguide port (port 1), and output from the microstrip (port 2). The electron channel and the grid mesh will be some influence. However, the grid is small enough, so only the electron channel is investigated. To obtain the best transmission effect (a relatively high $|S_{21}|$), the cylinder, cone, rhombus column, and square column shapes of the electron channel are analyzed in the paper. The cylindrical radius is 0.3 mm, the bottom radius of the cone is 0.3 mm, and the top radius is 0.35 mm. The short-side diagonal of the rhombus is 0.6 mm and the long-side diagonal is 1.2 mm. The side length of the square is 0.6 mm. Figure 4 shows the S parameters with different electron channels within the frequency range of 74 GHz to 114 GHz.

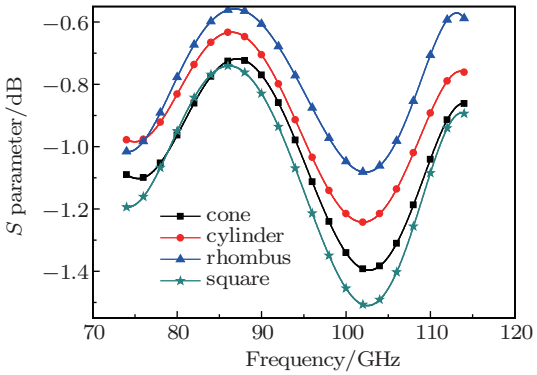


Fig. 4. (color online) The S parameter of the high-frequency field with different electron channels in CST.

In Fig. 4, it is obvious that the transmittance of the electron gun with the rhombus column electronic channel is the best. Therefore, in the following research, the rhombus column electron channel is applied.

4. Simulation result and analysis of the electron gun

Because there are some differences between the metal cathode and the CNT cathode, the simulation model of the CNT cathode is firstly developed in this section. However, in some particle-in-cell (PIC) electromagnetism simulation software, such as CHIPIC and CST Particle Studio, the field-emission model is based on the metal F–N formula

$$J = AE^2 \exp\left(-\frac{B}{E}\right), \tag{5}$$

where A and B are adjustable parameters. In Ref. [14], the A and B of the CNT cathode were successfully obtained according to the experimental results. In Ref. [13], the emission current density of the CNT cathode was 1.5 A/cm^2 in their experiment. When the adjustable parameters of the CNT cathode are $A = 1.05 \times 10^{-9}$ and $B = 4.9 \times 10^7$, the same emission current density can be obtained in the PIC simulation software.

Based on the above research, the electron gun based on the CNT cathode is simulated by CST Particle Studio. In the simulation, the distance between the cathode and the anode is 0.1 mm, and an electron collector is placed 0.5 mm away from the anode. The voltages applied on the cathode, the anode, and the electron collector are 0 V, 500 V, and 550 V, respectively. A high-frequency field of 94 GHz and 20 W power is fed into the rectangular waveguide. The electron trajectories are shown in Fig. 5. The electrons are emitted from the CNT cathode and go through the grid mesh, eventually being collected by the collector. In Fig. 5(b), the electron beam is contracted because of the electrostatic field, which is shown in Fig. 6. The mean current emitted from the CNT cathode is 2.27 mA, the intercepted mean current by the grid mesh is 0.85 mA, and the mean current collected by the collector is 1.42 mA.

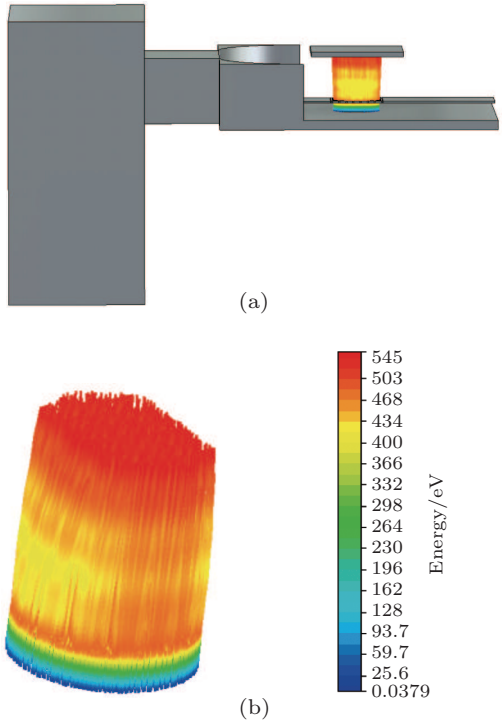


Fig. 5. (color online) The electron trajectories of the field emission in the simulation.

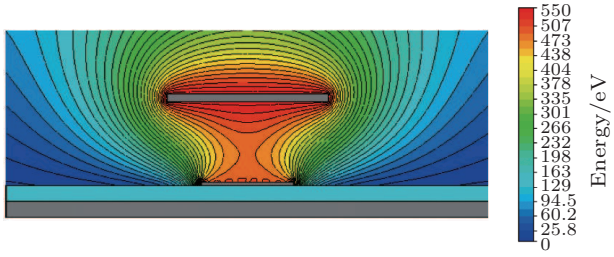


Fig. 6. (color online) The equipotential lines.

In order to identify the broadband modulation, the electron beam is modulated by 74 GHz, 94 GHz, and 114 GHz high-frequency fields (20 W), respectively, which are input

from the waveguide port. The influences of the modulation depth with different electrostatic fields are also investigated. The electrostatic field strength $|E_0|$ is 4 V/μm, 6 V/μm, and 8 V/μm, respectively. As shown in Fig. 7, at $t = 0$, the electrostatic field acts on the surface of the CNTs instantaneously, while the high-frequency field is input through port 1, and then there is only the electrostatic field, so the emission current is stable. About 0.02 ns later, both the electrostatic field and the high-frequency field act on the CNTs, so the electron beam begins to be modulated. From 0.02 ns to 0.05 ns, the high-frequency field is unstable, so the modulated amplitude is changed. In Fig. 7, the modulated cycle times in three conditions are 0.0135 ns, 0.0106 ns, and 0.0088 ns, respectively. The corresponding frequencies are in accordance with the frequencies of the input high-frequency fields.

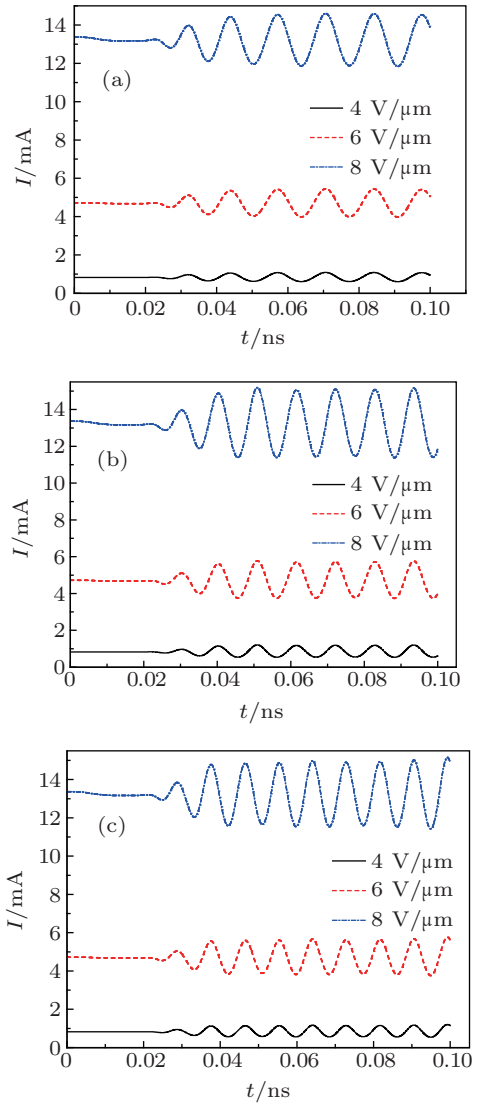


Fig. 7. (color online) The field-emission electron beam currents modulated by high-frequency fields of different frequencies in the simulation: (a) 74 GHz, (b) 94 GHz, (c) 114 GHz.

Based on Fig. 1, when the input power is equivalent, the higher the electrostatic field, the larger the modulated amplitude. As shown in Fig. 7, when the electrostatic field is 4 V/μm, the electron beam average current emitted from the CNT cathode is $I_0 = 0.82$ mA and the modulated amplitude is $\Delta I = 0.59$ mA ($\Delta I = I_{\max} - I_{\min}$). When $|E_0| = 6$ V/μm, $I_0 = 4.68$ mA and $\Delta I = 1.8$ mA. And when $|E_0| = 8$ V/μm, $I_0 = 13.25$ mA and $\Delta I = 3.32$ mA.

In Fig. 8, the high-frequency fields with different powers (1 W, 5 W, 10 W, 20 W, 50 W) are fed into the rectangular waveguide, and the electrostatic fields of 4 V/μm, 6 V/μm, 8 V/μm, 10 V/μm are adopted between the cathode and the anode. Figure 8 shows that under the same electrostatic field, ΔI increases with the input power increasing. Higher input powers generate stronger high-frequency electric fields, which increases the modulation. This phenomenon becomes more obvious with the increase in the electrostatic field. In addition, under the same input power, ΔI increases with the increase in the electrostatic field. Thus, the high electrostatic field in the electron gun should be as high as possible when safety is ensured.

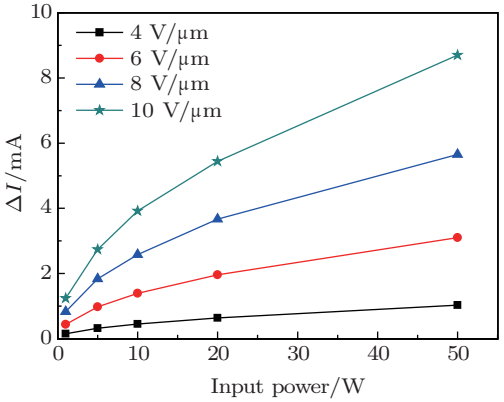


Fig. 8. (color online) The modulated amplitudes of the FE electron beam with different input powers and different electrostatic fields in the simulation.

5. Conclusion

In this paper, parallel plates are used as the cathode and the anode of a CNT cold cathode electron gun. A high-frequency field is fed between the cathode and the anode by a rectangular waveguide. The 3D electromagnetism simulation results show that the rhombus column electronic channel has a better transmission effect. In the PIC simulation, the high-frequency electric field and the electrostatic field act on the surface of the cathode at the same time. Thus a high-frequency modulated electron beam is obtained in the simulation, and the modulation frequency is the same as the input high frequency. The broadband modulation can reach a distance of 0.1 mm in the electron gun. When the input fields have the same frequency and power, the electron beam average currents and modulated amplifiers increase with the increase in the electrostatic field. Compared to Kenneth's and Legagneux's point frequency research results, the gun in this paper can be used for broadband modulation. In their works, only a

high-frequency electric field was used to achieve the goal of generating the strong electric field needed for the field emission, so they had to use a high-frequency electric field of very high power. While in this paper, because of the electrostatic field, the power of the high-frequency field does not need to be so high. In addition, the current density can be changed by the electrostatic field, and the modulation depth can be controlled by the high-frequency field in this gun. This gun opens up the possibility of light, compact, and highly efficient devices, which is significant for the development of microminiaturized and integrated electrical vacuum devices.

References

[1] Sun L M, Yuan X S, Zhang Y, Li X Y, Yang H and Yan Y 2013 *J. Infrared Millim. Waves* **32** 400

[2] Wei Z 2001 *Vacuum Microelectronics* (New York: John Wiley & Sons) pp. 13–30

[3] Wang Y Y, Li Y A, Xu J S and Gu G R 2012 *Chin. Phys. B* **21** 087902

[4] Legagneux P, Sech N L, Guiset P, Gangloff L, Cojocaru C, Schnell J P, Pribat D, Teo K B K, Robertson J, Milne W I, Andre F, Rozier Y and Dieumegard D 2009 *Vacuum Electronics Conference IVEC '09. IEEE International*, April 28–30, 2009 Rome, Italy, p. 80

[5] Li Z H and Wang M 2001 *Acta Phys. Sin.* **50** 790 (in Chinese)

[6] Zhang Y, Deng S Z, Duan C Y, Chen J and Xu N S 2008 *J. Vac. Sci. Technol. B* **26** 106

[7] Guo P S, Chen T, Cao Z Y, Zhang Z J, Chen Y W and Sun Z 2007 *Acta Phys. Sin.* **56** 6705 (in Chinese)

[8] Zhao X Y, Liu W M, Hou S M, Zhao X Y, Shi Z J, Gu Z N, Liu W M and Xue Z Q 2001 *Acta Phys. Sin.* **50** 1805 (in Chinese)

[9] Liao F J 2008 *Vacuum Electronics* (2nd edn.) (Beijing: National Defence Industry Press) p. 193 (in Chinese)

[10] Teo K B K, Minoux E, Hudanski L, Peauger F, Schnell J P, Gangloff L, Legagneux P, Dieumegard D, Amaratunga G A J and Milne W I 2005 *Nature* **437** 968

[11] Xu N S and Huq S E 2005 *Materials Science and Engineering R Reports* **48** 47

[12] Chen H and Jiang J P 1986 *Cathode Electronics* (Xi'an: Xidian University Publishing House) pp. 90–104 (in Chinese)

[13] Li C, Zhang Y, Mann M, Hasko D, Lei W, Wang B P, Chu D P, Pribat D, Amaratunga G A J and Milne W I 2010 *Appl. Phys. Lett.* **97** 113107

[14] Yuan X S, Zhang Y, Sun L M, Li X Y, Deng S Z, Xu N S and Yan Y 2012 *Acta Phys. Sin.* **61** 216101 (in Chinese)