Interaction Mechanism of a Field Emission Based THz Oscillator

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Abstract—We proposed a vacuum electronic device based on field emission mechanism for the generation of terahertz (THz) waves in a previous work [JVST B 23(2), 849, 2005]. The preliminary simulation results showed that an electronic efficiency up to 4% can be achieved with no external magnetic fields applied. However, the interaction mechanism is not clear. In the present work, the interaction mechanisms are studied. The MAGIC code is used to investigate the interactions between the electrons and the THz waves. To understand the interaction mechanism, the cathode has been trimmed to emit electrons. The simulation results show that the efficiency of the case corresponding to the trimmed cathode is higher than that of the original planar cathode. The interaction regions are located among the gaps between the cathode and the anode. The AC electric fields of the THz waves not only velocity-modulate the electron beam but also cause the density modulation of the field emission current. This pre-bunching effect provides the feedback loop as required by an oscillator.

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1. INTRODUCTION

Terahertz (THz) waves, electromagnetic (EM) radiation in the frequency extending from 0.1 to 10 THz (wavelengths of 3 mm down to 0.03 mm), have been used to characterize the electronic, vibrational and compositional properties of solid, liquid and gas phase materials during the past decade. The millimeter and sub-millimeter gap in the electromagnetic spectrum had been recognized for a long time. The well-known electron cyclotron masers (ECM) provide the solution [1]. In the past four decades, the ECM has undergone a remarkably successful evolution from basic research to device implementation, almost filling the gap. However, degradation of power generation in THz band is still present. Many rotational and vibrational spectra of various liquid and gas molecules lie within the THz frequency band, and their unique resonance lines in the THz wave spectrum allow us to identify their molecular structures. More and more applications in imaging science and technology call for the well development of THz wave sources.

Amplification and generation of a high frequency electromagnetic wave are a common interest of field emission array (FEA) based devices [2]. It is well known that a transition radiation is emitted when an electron passes through an ideally conducting screen in vacuum and a diffraction radiation is emitted when an electron of a constant velocity passes by a metallic structure [3–5]. We proposed a vacuum electronic device based on field emission mechanism for the generation of THz waves in a previous work [6]. The preliminary simulation results showed that an electronic efficiency up to 4% can be achieved with no external magnetic fields applied. However, the interaction mechanism is not clear.

In the present work, a two-dimensional (2D) finite-difference time-domain (FDTD) particle-in-cell (PIC) code MAGIC (developed by ATK Mission Research, VA, US) [7, 8] is used to investigate the interactions between the electrons and the THz waves. To understand the interaction mechanism, the cathode has been trimmed to emit electrons. Three types of cathodes including the untrimmed (original) planar, on-gap trimmed, and off-gap trimmed cathodes are considered for comparisons, as shown in Figure 1. The energy distribution of the electrons throughout the interaction structure has been observed for studying the interaction mechanism involved. The feedback mechanism of an oscillator is also discussed.

2. SIMULATION MODELS AND FIELD EMISSION

2.1. Simulation Models

Figure 1(a) shows the schematic of the field emission based THz wave generator we proposed. The anode consists of six coupled cavities and the cathode is some kind of field emission array. Three
Figure 1: Schematics of the simulation models including (a) the case of the original planar cathode, (b) the case of the on-gap trimmed cathode, and (c) the case of the off-gap trimmed cathode.

Types of cathodes including the untrimmed (original), on-gap trimmed, and off-gap trimmed cathodes are considered for comparisons, respectively, as shown in Figure 1. These trimmed cathodes can be easily fabricated via today’s technologies such as MEMS.

2.2. Field Emission

The field emission is described by the Fowler-Nordheim equation [9–17],

$$J = \frac{AE_s^2}{\phi t(y)^2} \exp\left(-\frac{Bv(y)\phi^{3/2}}{E_s}\right),$$

where $A$ and $B$ are the Fowler-Nordheim constants, and $\phi$ is the effective work function assumed to be a constant allowed dependence on material and surface roughness [18, 19]. The normal electric field at the cathode surface, $E_s$, is computed from the application of Gauss’s law to the half-cell immediately above the emitting surface, or $E_s = (E_c A_c - q/\varepsilon_0)/A_s$. The Nordheim elliptic functions $t(y)$ and $v(y)$, with Nordheim parameter, $y = 3.79 * 10^{-5} E_1^{1/2}/\phi$, can be approximated by $t(y)^2 = 1.1$ and $v(y) = 0.95 - y^2$, respectively [20].

3. SIMULATION RESULTS AND DISCUSSION

The simulation results of MAGIC code for the three cases have been obtained. The last case corresponding to the trimmed cathode off-gap is failed to achieve oscillations. In the following, we discuss only the first two cases, the original planar cathode and the on-gap trimmed cathode. In the simulations, an input voltage $V_{\text{in}}(t) = V_{\text{max}} \times [1 - \exp(-t/T_{\text{rise}})]$, where $V_{\text{max}}$ is 1 kV and $T_{\text{rise}}$ is 0.25 ns, is superposed on the structure between the anode and the cathode for each case. For the field emission, the effective work function is set as $\phi = 0.2$ eV which might be due to the high

Figure 2: (a) Monitored diode voltages, $V_d(t)$ curves, corresponding to the case of the original planar cathode and that of the on-gap trimmed cathode, respectively, with an input voltage 1kV and (b) the corresponding diode current density, $I_d(t)$ curves. $I_d$ stands for the total current divided by the cathode area.
applied electric fields and the local field enhancements [18, 19]. Figure 2(a) shows our monitored time evolution of diode voltages for the two cases. The diode voltages are almost the same. The average of the data is also shown in the figure. Figure 2(b) shows our monitored diode current per cathode area for the two cases. The average current of the case corresponding to the trimmed cathode is smaller than that of the original planar cathode.

![Figure 2](image1)

**Figure 2**: (a) Time evolution of diode voltages for the two cases. The diode voltages are almost the same. The average of the data is also shown in the figure. (b) Diode current per cathode area for the two cases. The average current of the case corresponding to the trimmed cathode is smaller than that of the original planar cathode.

The output power of the devices is also monitored. Figure 3(a) shows our monitored power per cathode area for the two cases. The output power includes low frequency electromagnetic waves as well. It is difficult to separate the component of THz waves from the monitored output power in the time domain, so that the results of the two cases are similar. However, it is easy to analyze the THz waves with the EM power spectrum, as shown in Figure 3(b). The resonant frequency of the case corresponding to the original cathode is about 1.076 THz and that corresponding to the on-gap trimmed cathode is the same. The amplitude of the former case is smaller than that of the latter case. The output peak power of the THz wave for the case corresponding to the original cathode is about 0.055 W/µm² and that for the trimmed cathode is 0.059 W/µm². The estimated values of the corresponding beam power are about 1.600 W/µm² and 1.524 W/µm², respectively. The electronic efficiency of the devices, i.e., the output power divided by the beam power, can be easily estimated to be 3.44% and 3.87%, respectively. The efficiency of the case corresponding to the trimmed cathode is higher than that of the original design. The efficiency of state of the art THz devises based on a quantum cascade laser or free electron laser is less than 2%. In comparison, an efficiency of 3–4% is relatively high and this motivates us to further study the interaction mechanisms.

![Figure 3](image2)

**Figure 3**: (a) Monitored power, \(P_d(t)\) curves, corresponding to the case of the original planar cathode and that of the on-gap trimmed cathode, respectively, and (b) the corresponding radiation power spectra, \(P_d(f)\) curves. The resonant frequency is peaked at 1.076 THz. \(P_d\) stands for the output power divided by the cathode area.

![Figure 4](image3)

**Figure 4**: (a) Phase space diagram of the case of the original planar cathode. The downstream current is oscillating with THz radiation. (b) Phase space diagram of the case of the on-gap trimmed cathode. The “y axis” is designated in the inset of the figure.
From the above simulation results, we can conclude that the interaction regions are located among the gaps between the cathode and the anode. Figure 4(a) and Figure 4(b) show the phase space diagrams of the cases corresponding to the original and trimmed cathodes, respectively. The difference of these two diagrams is the downstream current. There is almost no downstream current in the trimmed case, but the corresponding efficiency is higher than that of the original case shown in Figure 4(a). This indicates that the bunching electrons between the gaps contribute most of the generation of THz waves and the interaction mechanism is strongly related to the gaps. In the gaps, the interactions of the field emission current and the THz waves cause the velocity modulation. As one can see from Figure 4(b), the most of electrons arrive at the anode with the correct phases at which the electrons have lower energy compared to the DC beam energy to lose energy to the THz radiation.

The density modulation of the beam due to the pre-bunching effect can be seen in both Figure 4(a) and Figure 4(b). In Eq. (1), the field emission current can be modulated by the surface electric fields that contain both the DC and AC components of the THz waves. This provides the required feedback loop for the system to be an oscillator. To confirm this, we observe the space-charge density of the system at different phases of the AC electric fields, as shown in Figure 5. As one can see in Figure 5(a) and Figure 5(b), the two bright regions indicated with white arrows in Figure 5(a) are corresponding to the highest negative electric fields and two dark regions indicated with black arrows at the same gaps in Figure 5(b) are corresponding to the highest charge densities. Similarly, in Figure 5(c) and Figure 5(d), after one half period, the fields in the other three gaps become negative and the corresponding charge densities become very large. The process will be continued and repeated. The AC electric fields of the THz waves cause the density modulation of the field emission current. This pre-bunching effect provides the feedback loop as required by an oscillator.

Figure 5: Distributions of the electric field patterns, (a) and (c), and the space-charge densities, (b) and (d). The cases (a) and (b) are observed at the same time step. Similarly with the cases (c) and (d) but with one-half period delay.
4. CONCLUSIONS

We proposed a vacuum electronic device based on field emission mechanism for the generation of THz waves. The interaction mechanisms are studied. The MAGIC code is used to investigate the interactions between the electrons and the THz waves. To understand the interaction mechanism, the cathode has been trimmed to emit electrons. The simulation results show that the interaction regions are located among the gaps between the cathode and the anode. The efficiency of the case corresponding to the trimmed cathode is higher than that of the original planar cathode. In addition, the AC electric fields of the THz waves not only velocity-modulate the electron beam but also cause the density modulation of the field emission current. This pre-bunching effect provides the feedback loop as required by an oscillator.

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