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A Low-Voltage, Premodulation Terahertz Oscillator Based on a Carbon Nanotube Cold Cathode

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***Abstract*—To develop miniaturized and compact vacuum electron devices, new approaches to device manufacturing must be embraced. Here, a terahertz oscillator based on carbon nanotube (CNT) cold cathode is investigated through particle-in-cell (PIC) simulations. The studies show that the high-frequency (HF) field excited by the device can modulate the field emission current efficiently, with an output power of 4.6 W at 139.4 GHz obtained at an operating voltage of 2.9 kV and an initial emission current and current density of 15.8 mA and 7.65 A/cm^2, respectively, and the efficiency is 10.0%.**

***Index Terms*—Carbon nanotube (CNT), cold cathode, modulated current, oscillator, terahertz.**

I. Introduction

TERAHERTZ electromagnetic sources have a wider variety of important academic and industrial applications due to their unique position in the electromagnetic spectrum. Terahertz devices have been successfully applied widely in biomedical applications, border control and public safety systems, astronomical observations, and possible next-generation wireless communications [1], [2]. On the whole, the operation of all of these devices, nonetheless, rests on the provision of contextually suitable, high-performance terahertz radiation sources.

Vacuum electron radiation sources (VERSs) have been widely used in international communication, radar technologies, and electronic warfare countermeasures. Unlike solid-state and other competing technologies, VERS remains particularly well suited to the generation of terahertz radiation due to their commensurate high-frequency (HF) and high output power [3], [4]. To date, almost exclusively, commercially available VERS continues to employ thermionic cathodes as the electron emission source. However, thermionic cathode VERS suffers from the need for high-temperature operation, thermal inertia-limited slow reaction times, and large working volumes [5]. Furthermore, when operating in the terahertz frequency band, higher device working voltage and current are required due to the short HF electric field oscillation time. The minimum current density necessary for a notable interaction at a given frequency can be estimated from the following equation:

$$J_{\min} = 1.27 \times 10^{-25} s^2 \omega^2 \frac{T}{\sqrt{V_0}} (\mathrm{A/cm^2}) \tag{1}$$

where ω is the angular frequency of the emergent radiation, T is the temperature of the electron beam, V_0 is the driving voltage, and s is the scale factor, as given in [6]. As shown in (1), the minimum required operating current density of a conventional terahertz VERS system is greater than hundreds of A/cm^2 [7]–[9], which has significantly hampered the development and subsequent adoption of conventional VERS systems.

To develop a new generation VERS, much research into the increased power emission of the electron source is ongoing. Field emission cold cathodes are one of the leading candidates, here, for the replacement of incumbent thermionic electron sources. Cold cathodes can be operated at near-room-temperature and respond almost instantaneously, having much potential for aggressive miniaturization. Across the wide material landscape, carbon nanotubes (CNTs) have proven to be a leading field emission material with high emission current density, impressive chemical and temporal stability, and significant integration potential, making CNTs a prime candidate for the development of a new generation VERS [10]–[17].

In this article, we investigate the use of CNTs in a premodulation terahertz cold-cathode oscillator toward realizing a miniaturized VERS, which can work at ultralow voltages and unexpectedly low current densities. Here, the slow-wave structure (SWS) is integrated with the cathode through a cathode resonator, which can couple the HF field from the

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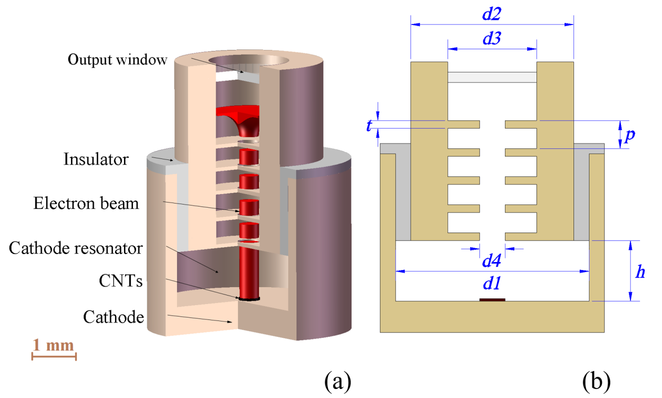

Fig. 1. Schematic depictions of the structure of the proposed CNT cold-cathode-based terahertz oscillator. (a) 3-D structure and the dominant electron beam trajectories are colored red. (b) Cross-sectional structure.

SWS to the cathode surface directly. Direct coupling allows the field emission current to be modulated by the HF field excited in the SWS, and the modulated current beam latterly interacts with the HF field in the SWS, dramatically improving the beam-wave interaction efficiency while also effectively reducing the current density required for device operation, ultimately opening up an exciting avenue to realize a novel VERS structure.

II. Design and Simulation

In this section, we describe the design and operation of a miniaturized terahertz CNT cold-cathodes oscillator using particle-in-cell (PIC) simulation software. The device includes SWS of a disk-loaded waveguide which acts as the anode, a cathode of barrel architecture, and a CNT electron source set at the center of the cathode surface, as shown in Fig. 1. The SWS is mechanically fixed to the cathode through the insulator. Adjusting the gap height h between the cathode and the HF structure, it is possible to accurately control the electric field of the cathode emission surface. By adjusting the inner diameter d_1 of the cathode resonator, the frequency of the resonant cavity can be made matched with that of the SWS.

The experimental model of CNT cold cathode of Yan *et al.* [18] is used. Here, CNTs were synthesized on about 0.1-mm diameter and 0.5-mm length Ni80Cr20 alloy wire substrates, with these electron sources presenting and effective emission area being the region of the upper half of the annulus alloy wire with an included angle of about 160° of about 6.92×10^{-2} mm^2, and a maximum operating emission current and emission current density of 5.3 mA and 7.65 A/cm^2, respectively, at a field of 2.13×10^6 V/m. These experimental parameters indicate that this experimental model is well suited for use in terahertz devices. First, to obtain an accurate depiction of the field emission parameters of the CNT cold cathode, the emission is fitted by the simplified Fowler–Nordheim (FN) equation

$$J = A' E^2 \exp(-B'/E) \tag{2}$$

where A' and B' are the field emission coefficients, which have been estimated by numerical fitting according to the

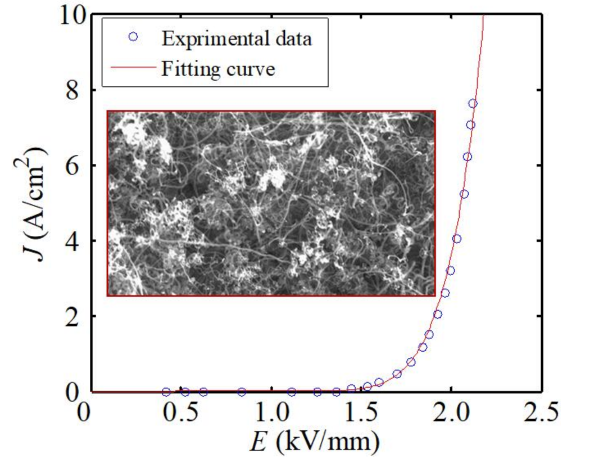

Fig. 2. Fitting and experimental emission current density as a function of the applied electric field. Insets: aerial-view SEM of CNT thin film adapted from [18].

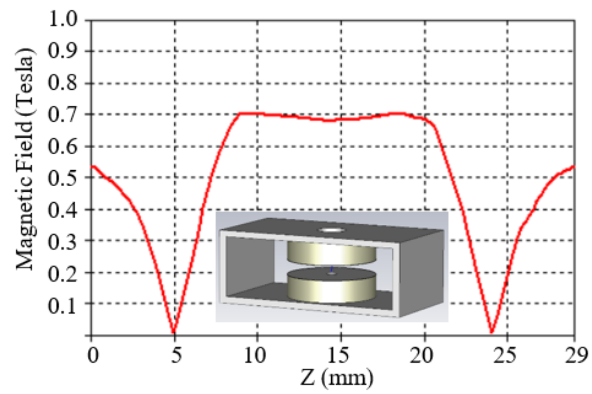

Fig. 3. Magnetic field intensity distribution of the permanent magnetic field on the axis. Inset: simulation model of the permanent magnet.

experimental results in [18]. Here, we find $A' = A\beta^2/\varphi t^2(y) = 2.17 \times 10^{-4}$ A/V^2 and $B' = Bv(y)\varphi^{3/2}/\beta = 2.02 \times 10^7$ V/m, where A and B are the FN constants, φ is the work function, y is the Schottky lowering of the work function barrier, and β is the field enhancement factor. Fig. 2 shows the previous experimental data and the resulting fit emission characteristics in addition to the aerial-view SEM images of the synthesized CNT thin film. When the electric field E includes a variation time-domain component, its time dependence can be modeled as $E(t) = E_0 + E_1(t)$. Here, E_0 is the electrostatic field, and $E_1(t)$ is the HF field. Equation (2) can be translated into

$$\begin{aligned} J(t) &= A' E^2(t) \exp\left[-\frac{B'}{E(t)}\right] \\ &= A'[E_0 + E_1(t)]^2 \exp\left[-\frac{B'}{E_0 + E_1(t)}\right] = \cdots = J_0 + J_1(t). \end{aligned} \tag{3}$$

Field emission beam current has an alternating current component (J_1) [19]–[23].

In the PIC simulations, a permanent magnetic field has been designed. The magnetic material was NdFeB. Simulation results are shown in Fig. 3. The maximum magnetic on-axis field strength was 0.7 T. The HF and cathode resonator are

TABLE I
DIMENSIONS OF TERAHERTZ OSCILLATOR BASED ON CNT COLD CATHODE

Symbols	Parameters	Values and Units
d_1	Cathode resonator inner diameter	3.80mm
h	Cathode resonator length	1.20mm
d_2	Anode external diameter	3.2mm
d_3	Disk outer diameter	1.74mm
t	Disk width	0.08mm
d_4	Disk inner diameter	0.5mm
p	Period length	0.18mm
n	Number of periods	16
B	Magnetic field strength	0.7T

assumed to be machined, with negligible surface roughness, from oxygen-free copper ($\sigma = 5.99E7$ S/m). It is located at the center of the permanent magnetic field (from 15 to 20 mm in Fig. 3). The electrons emit from the surface of the metal wire cathode substrate of a semiannular structure at the bottom of the cathode resonator. In the present design, a semiannular is included on the outer side of the emitting cathode to attenuate common substrate electric field edge effects. In the cathode resonant and SWS, the magnetic field with 0.7 T is along the longitudinal direction of the device and the electrons move forward along the axis. When the electron beam moves out from the SWS, the direction of the magnetic field reverses on the axis. The longitudinal component of the magnetic field tends to zero. The electrons finally impact on the outer wall of the device, as shown in Fig. 4(b). The design parameters of the miniaturized terahertz CNT cold-cathode oscillator are listed in Table I. The SWS is connected to the earth. The cathode is set to a negative direct current (dc) potential of 2.9 kV, resulting in a dc electric field of the cathode surface of 2.13×10^6 V/m, which produces a time-stable field emission current of 15.8 mA, with a corresponding current density of 7.65 A/cm^2. The dc electron beam interacts with the TM_{01} back wave mode in the SWS, and an HF back wave signal is excited. The HF field is coupled to the cathode resonator and oscillates stably through the TM_{02} mode. Thus, the field electron emission excitation process is modulated. As a result, the modulated electron beam exchanges energy with the HF field in the SWS more easily. Furthermore, the modulation depth of field emission is greatly increased.

After oscillation is steadily excited ($t > 80$ ns), the CNT cold-cathode field emission current is 0.1–70 mA, as shown in Fig. 5, and the modulation current pulse width is less than 7 ps. Based on the minimum emission current (0.1 mA) and (2), the amplitude of an HF electric field on the cathode surface is 0.65×10^6 V/m by calculation. We find that the HF back wave field excited in the SWS has been coupled to the cathode resonator and modulated the field emission current efficiently.

The output power of 4.6 W at 139.4 GHz is obtained after 80 ns once a stable operation has been achieved, and the output signal spectrum shows mode purity, with a notable absence of any spurious and unwanted additional modes, as shown in Fig. 4(a) and (b). Compared with Fig. 5, we note an increase in output power as the modulation of the cold cathode emission current increases. The voltage-tunable range is broad, ranging from 2860 to 2990 V; we change the working voltage

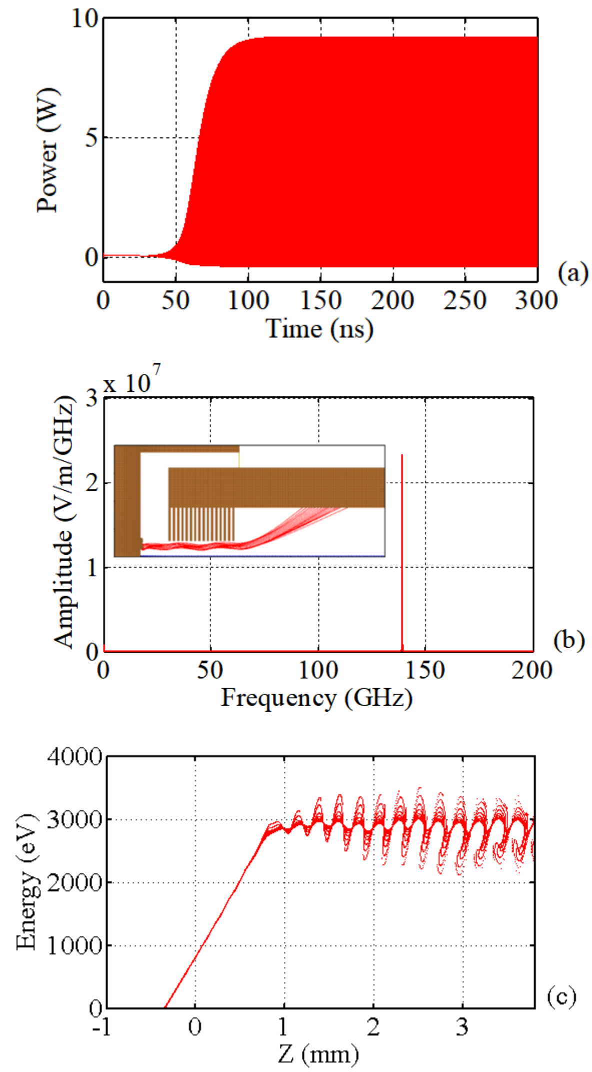

Fig. 4. Simulation results. (a) Signal of power amplitude at the output window. (b) Output signal spectrum. Inset: the state of the electron beam in the simulation. (c) Velocity modulation of electron beam.

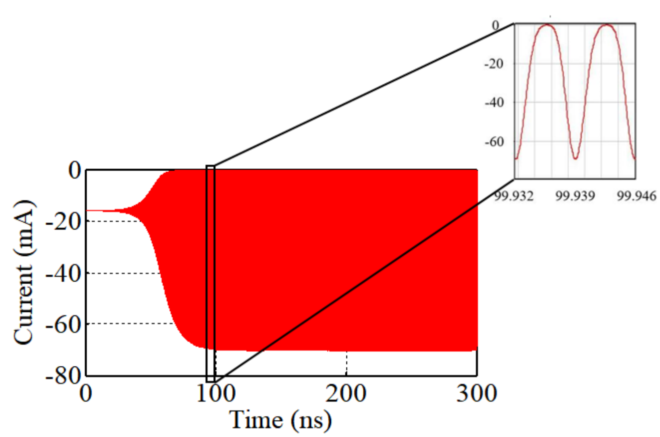

Fig. 5. CNT cold-cathode field emission current modulated by the HF electric field varying with time.

and found that the minimum working voltage is 2860 V, the corresponding frequency is 139.41 GHz, the maximum working voltage is 2990 V, and the corresponding frequency is 139.46 GHz. The frequency-tunable range is found to be approximately 50 MHz.

Fig. 4(c) shows the velocity modulation of the electron beam, which appears similar to the speed modulation in a conventional electric vacuum device. Some distinct differences are, however, worthy of commentary. In conventional devices, the dc electron beam is modulated first by the HF field. The electron speed will change, and the current density modulation is generated only after the most rapid electrons catch up with low-velocity electrons during bunching. These clustered electron beams interact with the HF field to generate the terahertz radiation. Here, both speed and density modulation of the electron beam are concurrently performed in the HF system. Therefore, in conventional devices, a large longitudinal length and high current density are required to produce a significant beam wave interaction. In the present cold-cathode premodulation device, the field emission process is modulated by the HF electric field, as shown in Fig. 5. The time-varying current is generated when the density-modulated electron beam is formed in the cathode resonator. We find that there is only a very modest velocity modulation in the cathode resonator. Thus, the density-modulated electron beam enters the SWS and interacts with the HF field immediately, which greatly reduces the longitudinal length of the device. This also allows for a concurrent reduction in the operating beam voltage and current density during the beam–wave interaction process, which will likely greatly extend the operation lifetime of the device while also reducing material specifications in this less aggressive electron emission environment.

III. Conclusion

A miniaturized and highly integrated terahertz oscillator based on CNT cold cathode has been investigated. We have demonstrated the potential integration of a CNT cold cathode directly with the HF system, thereby greatly reducing the volume and assembly difficulties of the device. At the same time, the HF field in the SWS has been effectively coupled to the surface of CNT cold cathode by the cathode resonator. A modulated electron beam has been obtained and shown to interact with the HF field with an increased efficiency. A miniaturized VERS has been realized which can radiate terahertz waves of 4.6 W at 139.4 GHz operating at only 2.9 kV and current of 15.8 mA. Compared with the traditional VERS radiating at 140 GHz, the present device can operate at an ultralow initial current density, with the longitudinal length of the whole device less than 10 mm, which offers a means to develop a new generation terahertz radiation source based on emerging nanomaterials.

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