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X-ray high frequency pulse emission characteristic and application of CNT cold cathode x-ray source cathode x-ray source

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Abstract

Carbon nanotube (CNT) field-emission x-ray source has great potential in x-ray communication (XCOM) because of its controllable emission and instantaneous response. A novel voltage loading mode was proposed in this work to achieve high-frequency pulse x-ray emission. The characteristics of cathode current and pulse x-ray versus voltage, frequency, and pulse amplitude were studied, and XCOM data transmission experiment was carried out. Results showed that the CNT cold cathode x-ray source, as a communication signal source, could work in 1.05 MHz pulse emission frequency. When the grid voltage was higher than 470 V, the pulse x-ray waveform amplitude achieved peak, and the shape exhibited a pseudo square wave. The duty cycle of the x-ray waveform exceeded 50%, reaching 56% when the pulse frequency reached 1 MHz. In the XCOM data transmission experiment, the pulsed x-ray waveform was well consistent with the loading data signal voltage waveform under different pulse-emission frequencies. This work realized the x-ray high-frequency pulse emission of CNT cold cathode x-ray source and lays a foundation for the development and application of CNT cold cathode x-ray source in XCOM.

Keywords: x-ray communication, carbon nanotube x-ray source, high-frequency electron emission, pulse source

(Some figures may appear in colour only in the online journal)

1. Introduction

X-ray communication (XCOM) is a kind of communication technology that uses x-ray as a communication carrier to realize information transmission [1, 2]. It was first proposed by Dr Keith Gendreau of NASA in 2007, and the communication experiment was carried out. X-rays can not transmit too far in the atmospheric environment due to severe physical attenuation. However, the penetration rate of x-ray can almost reach 100% when the energy of x-ray is higher than 10 keV and the atmospheric pressure is lower than 0.1 Pa, which means that x-ray can propagate without attenuation in vacuum environment [3]. Therefore, XCOM is especially suitable for deep space communication or interstellar communication. Wang *et al* [4] theoretically calculated the feasibility of XCOM in thousands of kilometers communication. The x-ray energy suitable for XCOM is below 50 keV and the signal direction angle is generally required to be in the order of milliradian according to the current research on XCOM. The safety of x-ray for application is generally not considered due to the particular application environment of XCOM. XCOM has the advantages of high penetration, strong anti-interference ability, and wide transmission band, and the theoretical maximum transmission rate could reach 40 000 Tbps

[5]. Given these distinctive advantages, XCOM is expected to solve the communication problems in blackout region, deep-space communication, and other fields [6]. According to the current x-ray source technology and XCOM's application environment, the x-ray source must be compact and consume low power, such as hot cathode x-ray source and photo-cathode x-ray source [7–9]. However, the hot cathode x-ray source has some shortcomings of heating and uncontrolled emission [10, 11], while the photocathode x-ray source has low quantum efficiency and short life, thus limiting their application in XCOM. Carbon nanotube (CNT) cold cathode x-ray source has many unique advantages, such as controllable emission, low power consumption, good switching characteristics, large current density, easily integrated array, and small and compact structure [12–15], and hence its great potential in XCOM. Therefore, the research of CNT cold cathode x-ray source is of great importance to the development and application of XCOM technology.

X-ray source is one of the core components of the XCOM system. It requires an x-ray source to be able to emit x-rays in pulse. Some researchers have studied cold cathode pulse emission. Zhang *et al* [16] studied the electron emission and structural stability of CNT cold cathode driven by millisecond pulse voltage and found that the electron emission of CNTs was stable under this voltage. Leberl *et al* [17] researched the electron emission characteristics of CNTs under 200 μs pulse voltage and found an electron emission attenuation effect. Lei *et al* [18] studied the electron emission characteristics under pulse voltage with 50 ms duty cycle and obtained the current emission density of 8 A cm^{-2}. Chen *et al* [19] studied the electron emission performance of CNT cathode under pulse and constant voltage. However, the previous studies on CNT cold cathode pulse emission are still at a relatively low frequency. Furthermore, XCOM requires that CNT cold cathode x-ray source could emit x-rays with arbitrary, modulated, and information characteristics instead of repetition frequency x-rays. Previous studies on CNT cold cathode x-ray source could not meet the requirement for XCOM, because CNT cold cathode electron emission is demanding [20, 21]. The realization of high-frequency pulse electron emission from CNT cold cathode still needs to be broken through and researched. Therefore, employing a novel pulse-emission mode to achieve high-frequency pulse electron emission of CNT cold cathode is necessary. Meanwhile, the amplitude frequency characteristic, amplitude voltage characteristic, and data transmission verification of CNT cold cathode x-ray source for XCOM require further research.

In this work, CNT cold cathode was prepared by screen printing method, and its triode measure structure was built in dynamic vacuum system. A cathode-grid bipolar voltage coupling mode to realize electron high-frequency pulse emission was proposed. The characteristic of pulse x-ray versus influence factor was studied. This work lays a foundation for the development and application of CNT cold cathode pulsed x-ray sources.

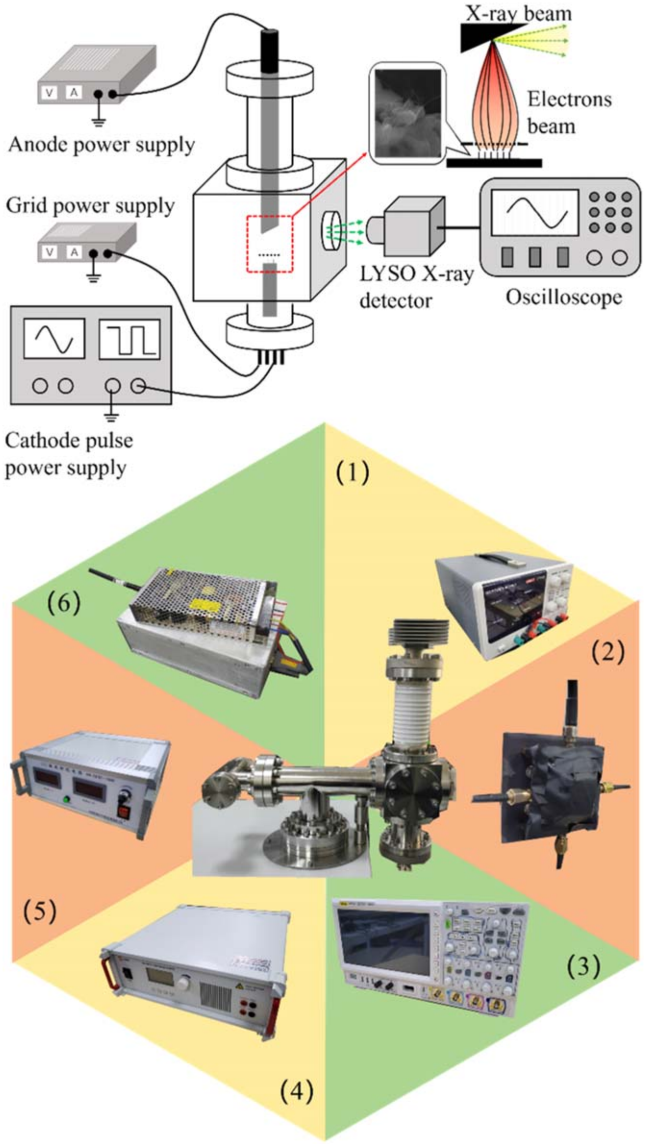

Figure 1. Measure circuit structure of CNT cold cathode in dynamic vacuum system and experimental devices: (1) conventional power supply of x-ray detector; (2) self-made lutetium–yttrium oxyortho-silicate (LYSO) scintillator coupled with silicon photomultiplier (SiPM) high-frequency sensitive photodetector; (3) oscilloscope (ROGIL MSO7024); (4) cathode pulse power supply (ATA 2022H, Xi'an Aigtek Electronic Technology Co., Ltd); (5) conventional DC power supply; and (6) anode high voltage power supply (XRW50P50B, Wisman High Voltage Power Supply, Ltd).

2. Experimental process

A triode structure was built in the self-made dynamic vacuum system platform to study the electron emission characteristic of the CNT cold cathode in pulse or constant mode, as shown in figure 1.

The diameter of CNT cold cathode was approximately 5 mm, the distance of cathode-grid was 200 μm, and the anode was inclined to 15°. Each component was connected to an external device through electrode flange. The vacuum level of the system was maintained at roughly 10^{-6} Pa during the experiment. Conventional technical methods, where the cathode is connected to the ground and the grid is connected to high voltage, could not be used to realize the high-frequency pulse electron emission of CNT cold cathode. Due to the limitation of high-voltage pulse power supply performance at present, it could not meet the requirements of high frequency and high voltage. Therefore, a cathode-grid bipolar voltage coupling method was proposed in this work to realize cathode electron high-frequency pulse emission. This method refers to one pole with constant voltage and the other pole with pulse voltage. The constant voltage maintained the electric field intensity between cathode and grid in the state of critical or few emission of electrons. The low amplitude negative pulse voltage further enhanced the electric field intensity between the cathode and grid, and therefore a large number of electrons emited from cathode surface. This method could solve the limitation of high-voltage pulse power supply performance at present and achieved electron high-frequency pulse emission of cold cathode. The grid with constant voltage and the cathode with pulse voltage were adopted in this work.

The CNT cold cathode used (purchased from Nanjing NorthTech Co., Ltd) in this study was prepared via screen printing method, using molybdenum as cathode substrate. The mass ratio of CNTs and organic solvent is 1:19, and the organic solvents are terpineol (solvent) and ethyl cellulose (binder). The CNT cold cathode was prepared by printing uniformly on an on-screen printing table, with a diameter of 5 mm, and then heated in muffle furnace at different temperature ranges for 3 h. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to characterize the CNT cold cathode, as shown in figure 2.

The CNT filaments were firmly adhered to the surface, and most of the filaments were gathered in the surface bulge, and some CNTs were cross-twisting together. The direction of CNTs was arbitrary, which is the characteristic of screen printing. Most CNTs were creeping on the substrate surface, and only a small part extended out of the surface, which is the key part for electron emission. The diameter of multi-walled CNT was approximately 10 nm, as shown in figure 2(b).

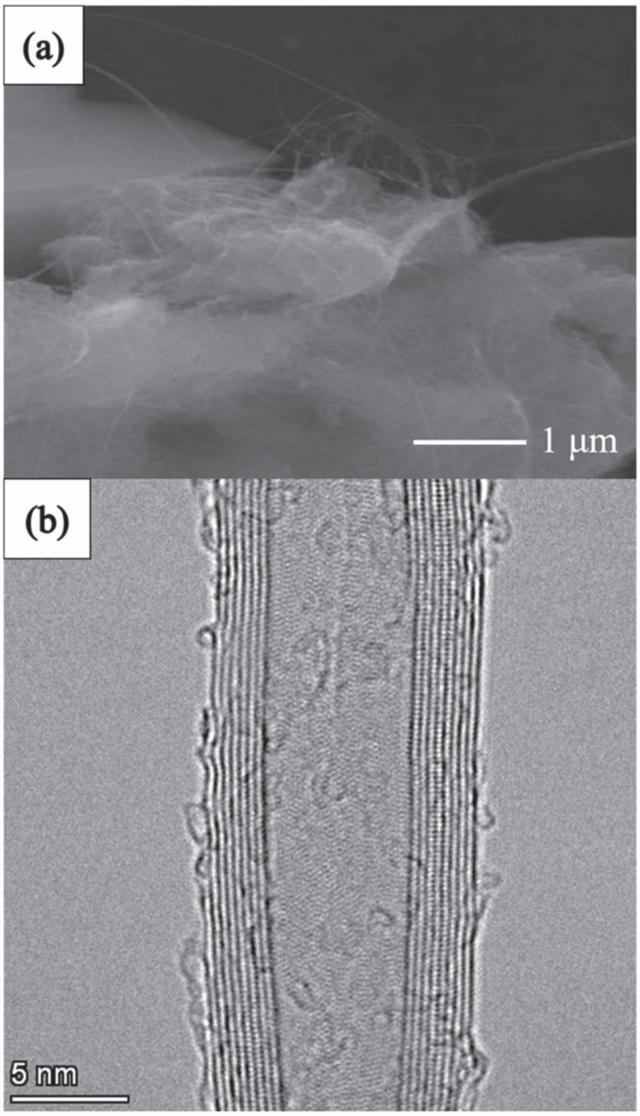

Figure 2. Characterization of CNT cold cathode, (a) SEM scale in 1 μm; (b) TEM scale in 5 nm.

3. Results and discussion

3.1. Electron emission characteristics

A triode measure structure, in which cathode, grid, and anode were connected to the ground, constant voltage, and high voltage, respectively, was employed to measure the *I–V* characteristics to obtain the electron emission characteristic of the CNT cathode. The grid voltage range was 350–1030 V, and a constant high voltage of 2.5 kV was added to the anode to prevent electron backflow bombarding the CNT cold cathode. The cathode emission current and grid voltage showed an exponential growth trend, as shown in figure 3(a). At approximately 500 V, an emission current of 0.1 mA was obtained, and the corresponding turn-on electric field was 2.5 V μm^{-1}. With the increase in grid voltage, the cathode emission current increased exponentially. The threshold voltage was roughly 760 V, with 1 mA emission current, and the threshold electric field intensity was 3.8 V μm^{-1}.

According to the F–N formula:

$$J = \frac{AE^2}{\phi}\exp\left(-\frac{B\phi^{\frac{3}{2}}}{E}\right). \tag{1}$$

After transformation

$$\ln\left(\frac{J}{E^2}\right) = -B\phi^{\frac{3}{2}}\frac{1}{E} + \ln\left(\frac{A}{\phi}\right), \tag{2}$$

where J is the current density, E is the cathode electric field strength, and ϕ is the work function of CNT; here, $\phi = 5$ eV [22, 23], A and B are constants. Formula (2) shows that $\mathrm{In}(J/E^2)$ and $1/E$ have a linear relationship. The linear relationship of *I–V* obtained from the experimental and transformed by the F–N formula is excellent, indicating that the cathode electron emission belongs to field emission type.

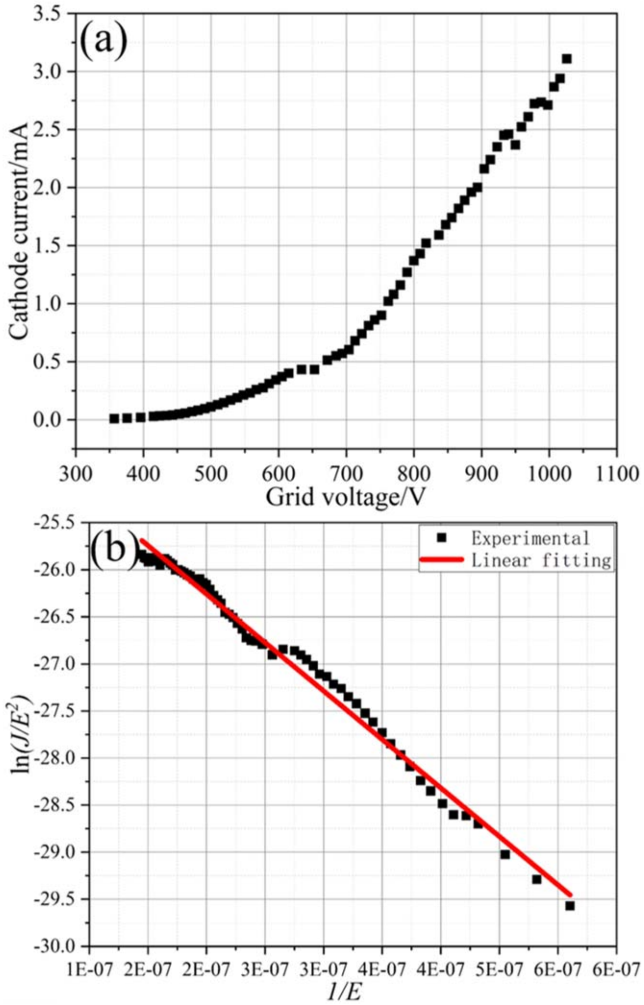

Figure 3. Electron emission characteristics of CNT cold cathode, (a): *I–V* curve; (b) Fowler–Nordheim (F–N) theoretical verification.

3.2. X-ray pulse-emission characteristic

A triode measure structure, where the cathode and the grid were connected to a pulse power supply source and a constant voltage power supply, respectively, and the anode was connected to a constant of 26 kV, was employed to explore the pulse-emission characteristic of CNT cold cathode x-ray source, as shown in figure 1. The x-ray detector used in this study was a self-made lutetium–yttrium oxyorthosilicate (LYSO) scintillator coupled with silicon photomultiplier (SiPM) high-frequency-sensitive photodetector [24].

Figure 4 shows the amplitude frequency characteristic of the CNT cold cathode x-ray source and a part of measure result diagrams. The amplitude frequency characteristic curve was used to evaluate the pulse-emission frequency limitation of a signal source in communication technology, and it generally adopts a sine signal for measurement [25]. Therefore, a sine voltage signal with an amplitude ranging from −50 to 50 V and a constant voltage of 650 V was loaded in the cathode and the grid, respectively. In accordance with the 3 dB bandwidth theory, the normalized amplitude of x-ray waveform was calculated by $20\text{In}(A/B)$ where A and B are the corresponding x-ray amplitude, and the pulse frequency range of the cathode voltage was from 10 kHz to 1.6 MHz.

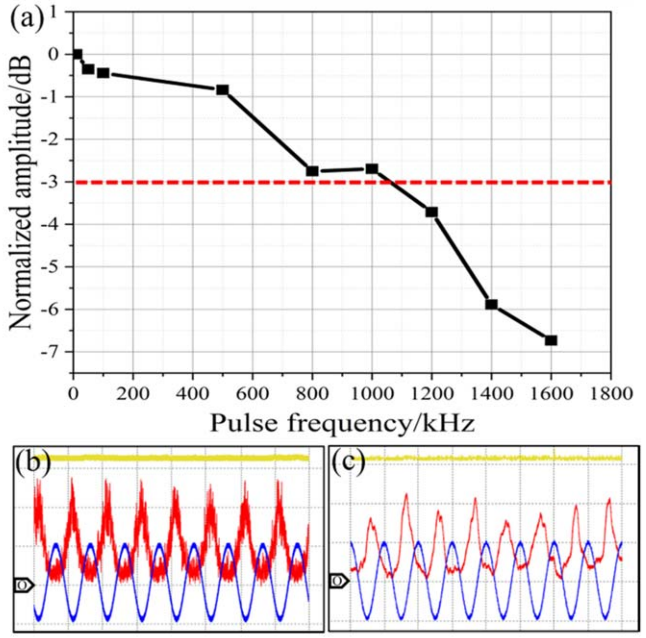

Figure 4. Pulse emission performance of CNT cold cathode x-ray source, (a): amplitude frequency characteristic. A part of measure result diagrams: (b) 10 kHz pulse and (c) 500 kHz. The yellow line refers to the voltage waveform of the grid, the blue line refers to the voltage waveform of the cathode, the red line is the x-ray waveform. Longitudinal scales of yellow line, blue line, and red line are 200 V, 50 V, and 1 V in (b) and (c), respectively.

With the increase in pulse frequency, the normalized amplitude of x-ray waveform decreased gradually, and the same phenomenon of x-ray waveform amplitude decline was observed when the pulse frequency of the cathode voltage was increased from 10 to 500 kHz, as shown in figures 4(b) and (c). On the basis of 3 dB bandwidth, the pulse emission frequency limitation of this CNT cold cathode x-ray source was 1.05 MHz, as shown in figure 4(a). This finding indicates that the bandwidth of CNT cold cathode x-ray source as a communication signal transmitter is 1.05 MHz under the existing conditions.

In the actual communication experiment, the square wave signal was adopted to transmit information. Thus, carrying out the research of x-ray waveform characteristics under different square wave grid voltage amplitudes was necessary. In the following experimental results, the bottom of the pulse voltage waveform corresponded to the top of the x-ray waveform. A large number of x-ray would emit when the pulse voltage waveform was at the bottom. In contrary, there was no x-ray or a small amount of x-ray emission when the voltage waveform was at the top. During the pulse experiment, the pulse frequency of cathode voltage had a serious influence on the x-ray waveform peak amplitude. When the pulse frequency of cathode voltage reached 1 MHz, the x-ray waveform was terrible, and the peak amplitude was uneven, as shown in figure 5.

If the x-ray waveform amplitude is non-uniform, it produces error in actual communication. Thus, improving the

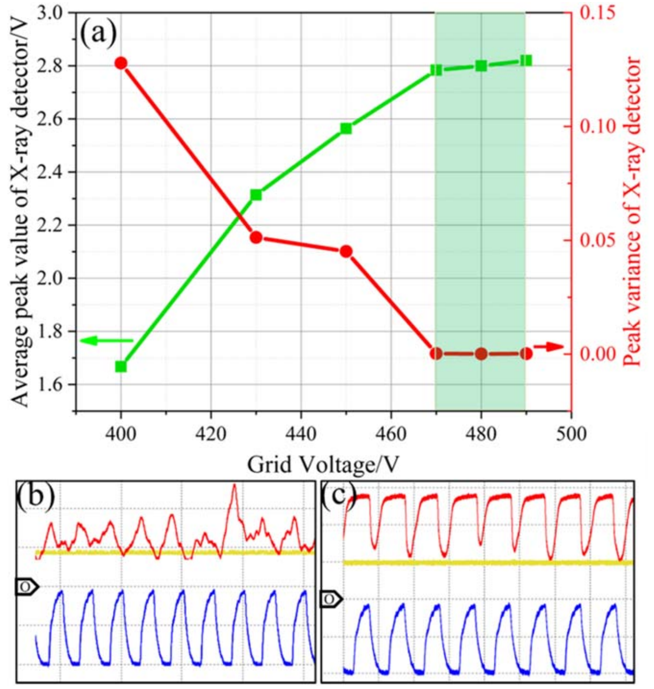

Figure 5. Relationship of x-ray waveform characteristic and grid voltage amplitude in 1 MHz of cathode voltage. (a) X-ray waveform characteristic versus grid voltage: grid voltages of (b) 400 V and (c) 490 V. The yellow line refers to the voltage waveform of the grid, the blue line is the voltage waveform of the cathode, and the red line denotes the x-ray waveform. The anode voltage is maintained at 26 kV. Longitudinal scales of yellow line, blue line, and red line are 500 V, 50 V, and 1 V in (b) and (c), respectively.

x-ray waveform is important. During the experiment, increasing the grid voltage amplitude was shown to be an effective method to improve the x-ray waveform under the same pulse voltage amplitude loading in the cathode. The results are illustrated in figure 5. With the increase in grid voltage, the average peak value of x-ray increased remarkably. Meanwhile, the peak variance of the x-ray waveform decreased evidently. The reason is that with the increase in grid voltage, more electrons are generated in a single pulse. Thus, more x-rays are detected by the detector. The finding indicated that the x-ray waveform became uniform, and the amplitude increased, as shown in figures 5(b) and (c). When the grid voltage was higher than 470 V, the average peak and variance of the x-ray waveform were 2.8 V and 0, respectively. When the grid voltage was low, the electron emission from CNTs was few under the same pulse voltage amplitude of the cathode. Therefore, the x-ray yield from the anode target was relatively small. Upon increasing the grid voltage, more electron emissions from the CNT yielded more x-ray, and the x-ray waveform became saturated.

During the pulse emission experiment, the duty cycle of pulse voltage was set to 50%. However, the duty cycle of the x-ray waveform was more than 50%, reaching approxiamtely 56%, but the whole cycles of the pulse voltage and x-ray waveform were still 1 μs, as shown in figure 6. The reason is because the distortion of the cathode pulse-voltage waveform caused the x-ray waveform duty cycle to broaden and exceed 50%.

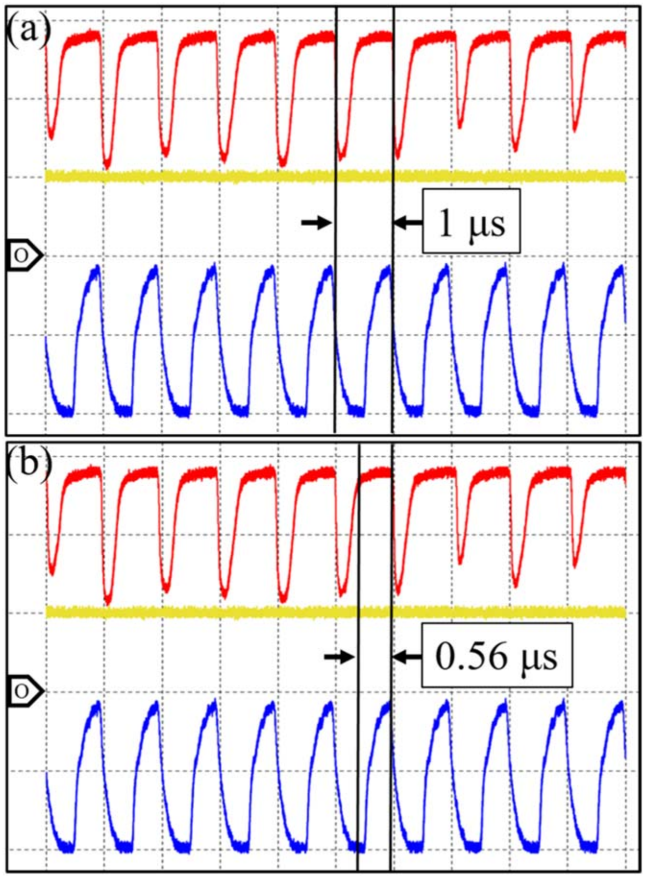

Figure 6. The yellow line is the grid voltage, the blue line refers to the cathode voltage, and the red line represents the x-ray waveform. The anode voltage is 26 kV, the grid constant voltage is 500 V, and the pulse voltage frequency is 1 MHz. (a) The x-ray waveform cycle is consistent with the period of cathode pulse voltage; (b) the duty cycle of the x-ray waveform exceeds 50%, reaching 56%. Longitudinal scales of yellow line, blue line, and red line are 200 V, 50 V, and 1 V in (a) and (b), respectively.

3.3. XCOM data transmission experiment

XCOM data transmission experiment was carried out to research the XCOM signal transmission characteristic. The partial results are shown in figure 7. The data signal voltage was loaded to the cathode, and the grid voltage was kept to 400 V. The shapes of the loading data signal voltage waveform and the x-ray waveform were the opposite. The low level of data signal voltage was denoted as '1,' and the high level was denoted as '0' in binary, as shown in the blue waveform in figure 7. Thus, the conventional x-ray waveform with high level was '1' and with low level was '0', as shown in the red waveform in figure 7.

As shown in figure 7(a), a data sequence that the partial data sequence was '11101101110010011' in binary was transmitted and loaded to the cathode voltage in 10 kHz frequency. The x-ray waveform was well consistent with the data signal voltage waveform, and the x-ray amplitude was obvious. Other data sequences, in which the data sequence were '10010110000100000', '1111001011100111000', '1011000101111010' in binary, were transmitted in 100 kHz, 500 kHz, and 1 MHz loading frequency, respectively, as shown in figures 7(b)–(d).

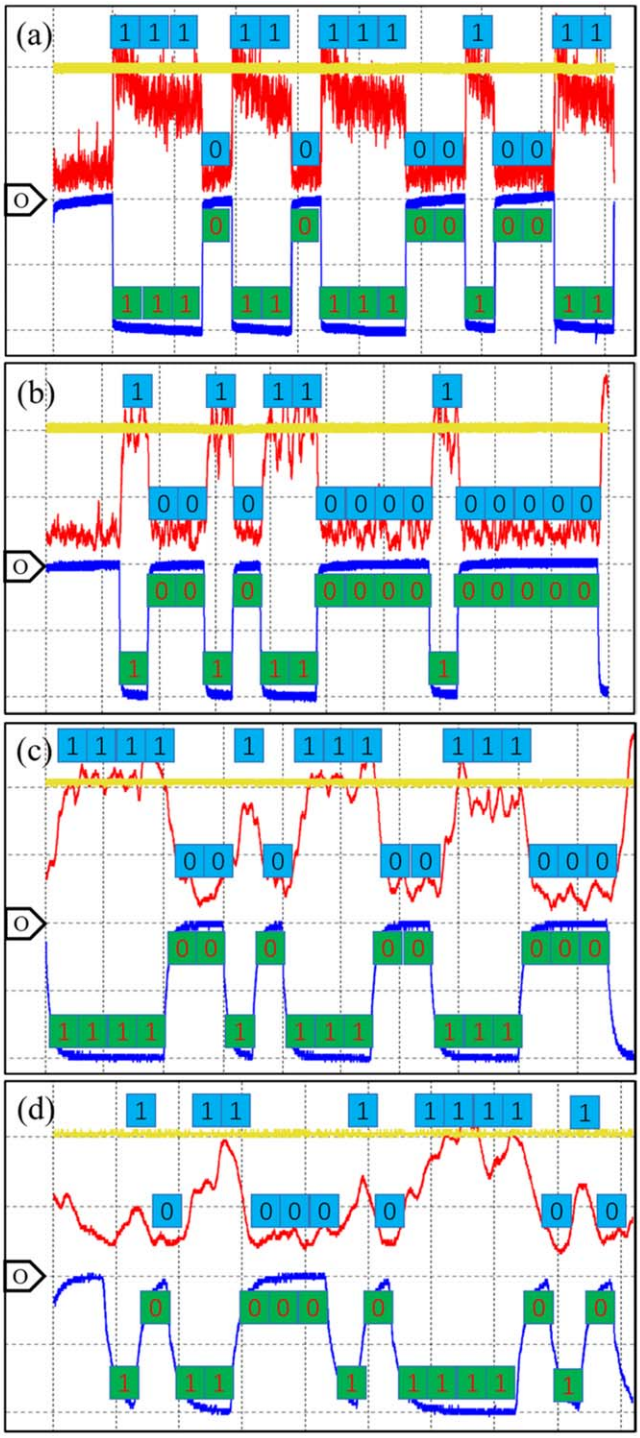

Figure 7. XCOM data transmission experiment. Data signal loading frequency in (a) 10 kHz; (b) 100 kHz; (c) 500 kHz; (d) 1 MHz. The yellow line denotes the voltage waveform of the grid at 400 V, the blue line refers to the data signal voltage waveform loading in the cathode, and the red line is the x-ray waveform. The anode voltage is kept at 26 kV. Longitudinal scales of yellow line, blue line, and red line are 200 V, 50 V, and 1 V in (a)–(d), respectively.

As the grid voltage was 400 V, the generated electrons were relatively few in a short time. Thus, the amplitude of the x-ray waveform was low. However, it could also evidently generated the high and low levels. Given that the level amplitude in 1 MHz is relatively low, an error data waveform may exist when transmitting much data. Therefore, improving the grid voltage amplitude or developing an algorithm for waveform discrimination may be a means to improve signal reading. The XCOM data transmission experiment verified that the CNT cold cathode x-ray source can be used as a communication signal source to produce x-ray signal, and the pulsed x-ray waveform is well consistent with the loading voltage signal.

4. Conclusion

In accordance with the current level of pulse power supply technology, a cathode-grid bipolar voltage coupling mode to realize high-frequency pulse electron emission of CNT cold cathode was proposed in this paper, and then the pulse x-ray was obtained. First, the CNT cold cathode with a diameter of 5 mm was prepared by screen printing method. The electron emission characteristic of this cathode was measured using the triode structure, in which the distance of the cathode-grid was 200 μm. The turn-on electric field of the cathode was 0.1 mA@2.5 V μm^{-1}, and the threshold electric field was 1 mA@3.81 V μm^{-1}. The linear relationship in F–N theoretical verification is excellent, which indicated that the electron emission belongs to field emission type. Furthermore, the pulse emission x-ray characteristic versus pulse voltage amplitude and frequency of CNT cold cathode x-ray source was studied. The results showe that the bandwidth of CNT cold cathode x-ray source as a communication signal source was 1.05 MHz under the existing conditions. The grid voltage amplitude showed a significant effect on the x-ray waveform. With the increase in grid voltage, the x-ray waveform amplitude and shape were enhanced. The higher the pulse frequency was, the more obvious the duty cycle broadening effect. Finally, the CNT cold cathode x-ray source could be used as a communication signal source to realize XCOM. The communication quality was affected by pulse frequency, voltage amplitude, and waveform shape. In this work, cathode-grid bipolar voltage coupling mode to realize XCOM was proposed, laying a foundation for the technology and application of CNT cold cathode high-frequency pulse x-ray source.

Breaking through the pulse-emission frequency limitation of CNT cold cathode is necessary in the future. The CNT cold cathode has easily integrated array. Thus, it can be carried out study on the array cathode x-ray source, laying a foundation for the development and application of CNTs cold cathode x-ray source in high-speed XCOM technology in the future.

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Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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