High-repetition-rate ferroelectric-cathode gyrotron

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The intensive research on ferroelectric electron-emission mechanisms in the last decade has resulted in a wide understanding of the physics and characteristics of this plasma-assisted electron source. Nevertheless, practical devices employing this cathode were hardly introduced. In this experimental study, a high-repetition-rate microwave oscillator based on a ferroelectric electron gun has been developed. The device operates as a cyclotron-resonance maser in the gyrotron mode. Microwave pulses exceeding 1.5 kW at ~7 GHz are measured in repetition rates above 3 MHz and duty cycles of ~50%. These experimental results encourage the implementation of ferroelectric cathodes in practical high-power microwave tubes. © *2001 American Institute of Physics.*
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Ferroelectric cathodes have been investigated intensively during the last decade as high-current electron emitters.[1,2] Many characteristics of the cathode were investigated such as the emission physics, turn-on time, brightness, cathode lifetime, material compositions, velocity spread, pulse duration, maximal density and current, and perveance.[2–7] Since the demonstration of ferroelectric strong electron emission,[1] the desire to implement ferroelectric cathodes in practical devices, and specifically in microwave tubes, has been brought up.[1,2,6,8]

The demonstration of microwave emission by a ferroelectric based tube was reported in Ref. 9. In a successive report,[10] we have shown the experimental feasibility of a cyclotron-resonance maser (CRM) based on a ferroelectric cathode. This preliminary device has produced 25 W of ~7 GHz microwave radiation, but it was limited to a single-shot operation only, with an electronic efficiency of ~1%. Nevertheless, a repetitive operation in a large duty cycle of the ferroelectric-based tube has not been demonstrated. Since the ferroelectric emission is a plasma-assisted effect,[2] the electron emission is inherently pulsed with limited repetition frequency, pulse duration, and duty cycle.

In this experimental work, a repetitive operation of a CRM oscillator with a ferroelectric electron gun is accomplished in repetition rates of up to 3 MHz, with a duty cycle of up to 50%. The microwave power exceeds 1.5 kW. Variable pulse durations, repetition frequencies, and spectral content are also measured. This demonstration of a high-pulse-repetition-rate CRM operation promotes the implementation of ferroelectric-cathode-based electron guns in high-power microwave tubes.

The CRM oscillator experimental device is shown in Fig. 1. It consists of three sections, the ferroelectric electron gun, the interaction region, and a collector section. The electron gun is based on a ferroelectric cathode, made of a $10\times10\times1\ \mathrm{mm}^3$ lead–lanthanum–zirconium–titanate (PLZT) 12/65/35 ceramic plate. The rear (nonemitting) electrode is made of uniform $7\times7\ \mathrm{mm}^2$ silver paint. The front (emitting) electrode consists of a $7\times7\ \mathrm{mm}^2$ stainless-steel grid, attached to the ceramic plate. The electron gun is activated by application of the positive pulse (~1 kV) to the rear electrode, while the front electrode is grounded. The device operates in the modest vacuum condition of 10^{-4}–10^{-5} Torr.

The ferroelectric electron gun is designed to minimize the relatively wide electron energy spread related to the ferroelectric plasma emission, and to overcome breakdowns caused by the plasma expansion and subsequent shortening. It has two acceleration stages. At the first stage the electrons are extracted out of the ferroelectric surface plasma by a relatively low-voltage pulse (~1 kV) applied on a stainless-steel grid electrode, placed 5 mm in front of the cathode. This electrode is connected to the rear electrode. At the second stage, a dc accelerating voltage of ~12 kV is applied to the anode, which is distanced 60 mm from the cathode.

While operating the electron gun, any breakdown between the cathode and the anode is avoided by the immediate grounding of the first grid electrode after the pulse, and by the large anode–cathode spacing that prevents a gap closure. The energy spread of the electrons is bound by the extracting voltage from the cathode itself. Hence, the two-stage accelerator enables us to extract the electrons at a low voltage, and therefore, with a low-energy spread (determined by the first stage). The accelerated electrons are focused by a solenoid, operated continuously. It applies an axial magnetic field of ~400 G guiding the electron beam throughout the relatively long electron-gun section.

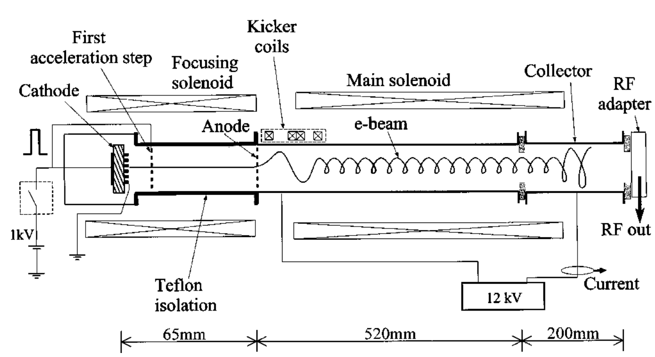

FIG. 1. Experimental setup of the ferroelectric cathode gyrotron.

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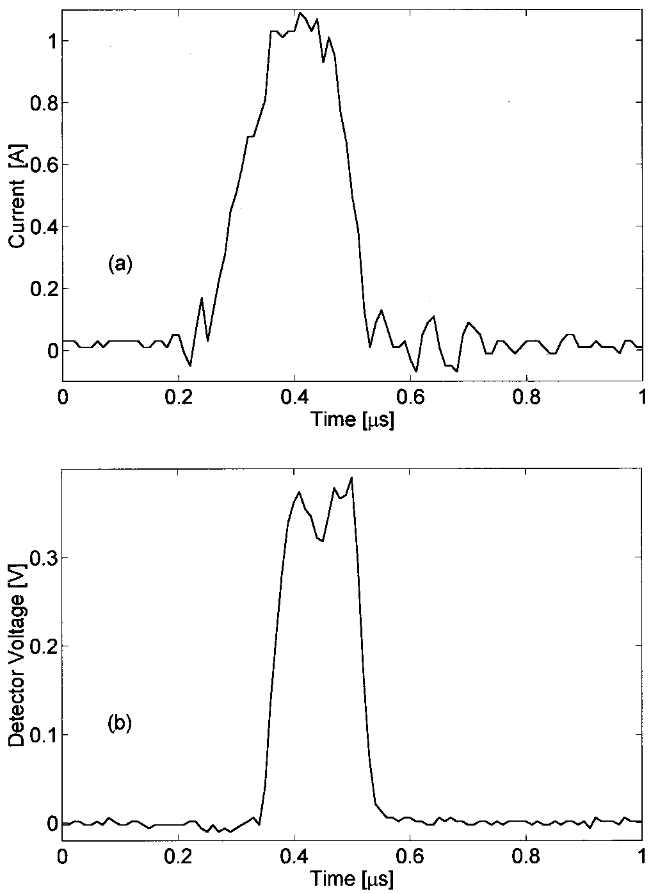

FIG. 2. Typical experimental run of ferroelectric cathode gyrotron: (a) Current pulse measured at the collector. (b) Generated microwave output pulse.

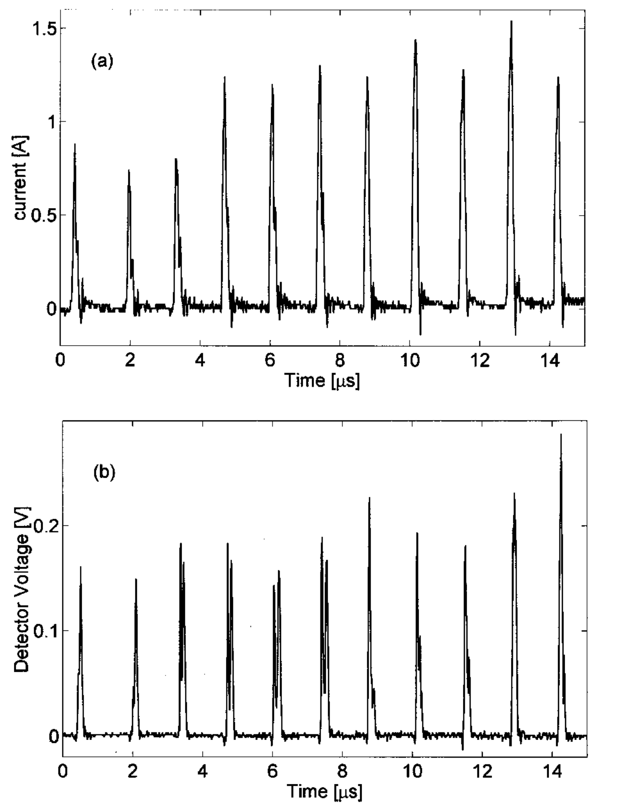

FIG. 3. Typical 1 MHz PRF pulse train of ferroelectric cathode gyrotron: (a) Current pulses measured at the collector. (b) Generated microwave output pulses.

The CRM interaction section is made of a copper rectangular waveguide (WR90) with a cutoff frequency of ~6.6 GHz. The waveguide is connected to the high dc voltage, which accelerates the electrons at the entrance to the tube. The collector section is separately connected to the waveguide potential, whereas a Rogowski coil measures the collected electron current (Fig. 1). The microwave output is fed through a dc block to microwave attenuators and diagnostic elements.

A solenoid generates the axial magnetic field (~2.4 kG). The electron transverse velocity component is induced by a kicker made of a pair of magnets, either fixed or rectangular current loops, placed above the entrance of the interaction region[11,12] (Fig. 1). The kicker position, size, and current determine the electron-beam pitch ratio. According to electron optics simulations $V_{\perp}/V_{\parallel}\simeq 2$, where $V_{\perp}$ and $V_{\parallel}$ are the transverse and axial velocity components, respectively.

The system is operated in a semirepetitive mode. Pulse generators determine the synchronization between the electron gun, solenoid, and kicker pulses. The magnetic-field pulse duration is ~40 ms, repeated every ~1 s. The 1 kV pulses supplied to the electron gun are driven by a solid-state switch (Behlke, HTS 80-PGSM) gated by 5 V pulses. The electron-gun pulse duration is ~200 ns, hence, during the electron-gun pulses, the magnetic field is relatively constant. For each magnetic-field pulse, a train of a few tens of pulses is applied on the electron gun, at a repetition rate of ~1 MHz. Therefore, the device operates in a two-time-scale mode. A train of tens of pulses at ~1 MHz pulse repetition frequency (PRF) is obtained in each period of ~1 s.

The experimental results of the ferroelectric-cathode CRM oscillator are presented in Figs. 2–5. A typical electron-current pulse measured at the collector section is shown in Fig. 2(a). The electron-beam transmission is 0.9 (i.e., only 10% of the electrons are lost before reaching the collector section). The corresponding microwave signal at the detector output is presented in Fig. 2(b). These pulses are a part of a train of pulses presented in Figs. 3(a) and 3(b). The current pulse train is shown in Fig. 3(a). Each train contains several tens of pulses, repeated every ~1 s. Every pulse has a ~0.2 μs duration and the PRF is ~0.8 MHz. The experiment has been operated in this manner for more than 100 h, continuously. The corresponding microwave signal is shown in Fig. 3(b). Each current pulse generates a microwave pulse. The microwave output power exceeds 1.5 kW, and the measured frequency is in the range 6.8–7.5 GHz. The latter depends mainly on the axial magnetic field. The microwave spectral content measured by a heterodyne setup shows a spectral bandwidth of ~5 MHz within each ~0.4 μs pulse, and a frequency variation of ~40 MHz along a 20 pulse train.

Variable pulse duration and repetition frequency were used for the assessment of the device capabilities. The shortest pulse duration applicable by this setup was ~150 ns, due to the electronic switch limitations (shorter electron-beam pulses were measured in other schemes[2]). For this pulse duration, the PRF obtained exceeds 3 MHz, and the duty cycle is as high as ~50% [Figs. 4(a) and 4(b)]. The longest pulse

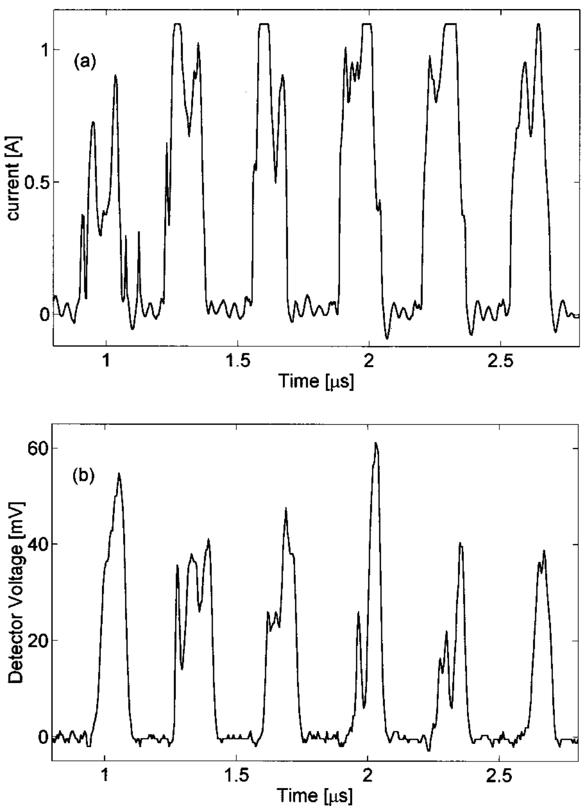

FIG. 4. 3.1 MHz PRF gyrotron operation: (a) 150 ns 50% duty-cycle current pulses measured at the collector. (b) Generated microwave output pulses.

duration obtained was ~2 μs [Fig. 5]. The maximal PRF in this mode is reduced to ~20 kHz.

In this work, a high-PRF CRM based on a ferroelectric electron gun is demonstrated. The unique design of this ferroelectric electron gun separates the electron acceleration stage from the plasma region. The electron beam delivered to the microwave cavity is acceptably uniform, retaining a sufficiently low electron velocity spread, suitable for the cyclotron radiation mechanism in the near-cutoff gyrotron mode. The beam uniformity and the alleviation of breakdowns are achieved by several means in the electron-gun design. The electron emission is triggered by low-voltage pulses (~1 kV), therefore, the electron emission energy spread is limited. The acceleration by a dc voltage enables us to decrease the variations in the electron energies and to establish steady parameters for the interaction. A large spacing between the two accelerating stages ensures the prevention of gap closure and breakdowns.

The separation of the electrons from the ions in the generated plasma is achieved by the first accelerating stage. Electrons are extracted from the plasma, which becomes positive and more confined. The ions are repelled back to the ferroelectric-plate surface, increasing the ferroelectric-plate surface regeneration. This assumption is reinforced by the long lifetime of the cathode in this experiment. The pulse repetition mode was operated for more than 100 h using the same cathode. Therefore, $\sim 10^7$ pulses were obtained without destruction of the cathode. This outcome is 20–100 times

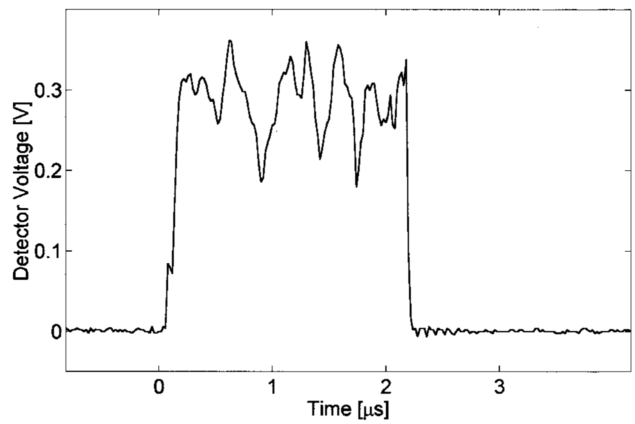

FIG. 5. Maximal 2 μs pulse-width gyrotron operation (PRF=20 kHz).

larger than that obtained in a lifetime measurement of a PZT ferroelectric cathode in a conventional setup.[4,5] Furthermore, no measurable degradation of the cathode performance has occurred (this cathode still operates properly). No visible change of color, erosion, or any wear in the cathode surface is observed.

The presented experimental device demonstrates the feasibility of high PRF microwave generation based on a ferroelectric electron source. The maximal PRF exceeds 3 MHz in a ~50% duty cycle. The maximal microwave power obtained exceeds 1.5 kW, and the electronic efficiency obtained is over 12%. The spectral bandwidth (~5 MHz) is reasonable. These results encourage the implementation of the ferroelectric cathode in practical high-power microwave tubes, utilizing the benefits of the ferroelectric cathode, such as high current, room-temperature operation, modest vacuum conditions, simple handling, and low cost. This study leads to further research and development of ferroelectric cathodes for various microwave sources, and to the development of microwave-tube schemes according to the unique characteristics of this cathode.

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