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ELSEVIER

Carbon-fiber emitter in a cyclotron-resonance maser experiment

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Abstract

A compact cyclotron-resonance oscillator which employs a carbon-fiber electron-gun is presented in this paper. The maser oscillates at ~3 GHz frequency near the electron cyclotron-resonance. The 2 mm diameter carbon-fiber cathode emits ~1 A current at ~1 kV voltage. The electron beam tends to be unstable. Clear bursts of RF oscillations are observed in this experiment.

1. Introduction

This paper presents a compact cyclotron-resonance maser (CRM) oscillator which employs a carbon-fiber emitter operating at low voltage (~1 kV). Clear radiation bursts are observed at ~3 GHz frequency in this experiment. The carbon-fiber CRM experiment combines two other previous experiments conducted in our laboratory. One is the carbon-fiber cathode experiment presented by Korol et al. in Ref. [1]. The other experiment is the CRM oscillator in a non-dispersive waveguide conducted with a thermionic cathode by Shahadi et al. [2].

Carbon fibers have been studied as electron emitters by various researchers since the early 70s [3–9]. They may operate in a much lower voltage compared to other field-emission cold cathodes. However, they tend to be relatively unstable. In our early experiment [1], a 3 mm diameter carbon fiber "brush" emitted ~1 A current at 1 kV voltage in a 1 ms pulse. The simplicity of the carbon fiber emitter makes it a favorable cathode for compact low-cost FEM and CRM experiments operating at low voltage in our laboratory [10].

The CRM oscillator experiment in a non-dispersive co-planar waveguide [2] has shown a considerable emission of radiation at the first and the second harmonics [11] of the cyclotron frequency, in the frequency range 2–8 GHz. The cyclotron-resonance interaction with free-space (TEM) modes has been studied theoretically and experimentally [12–18], mainly in quasioptical devices with open resonators. It is known to be weaker than cyclotron interactions with other waveguide modes, except for a large initial rotation of the electrons which satisfy the condition

$$V_\perp^2 > 2V_z c\,, \tag{1}$$

where $V_\perp$ and V_z are the electron perpendicular and axial velocity components, and c is the speed of light.

For a cyclotron interaction with a low-energy electron beam, the Doppler shift is negligible and the tuning relation is [2]

$$\omega \sim \omega_c = \frac{e}{\gamma m} B_0\,, \tag{2}$$

where ω is the em wave angular frequency, ω_c is the angular cyclotron frequency, and e, m, γ, and B_0 are the electron charge, mass, relativistic factor, and the axial magnetic field, respectively.

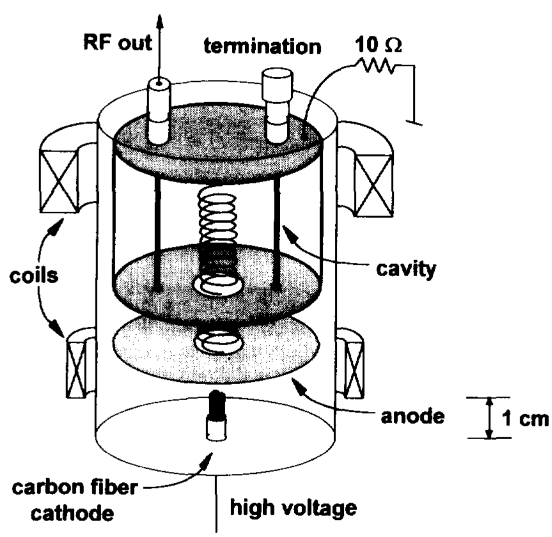

Fig. 1. A schematic of the compact cyclotron maser device with the carbon-fiber emitter.

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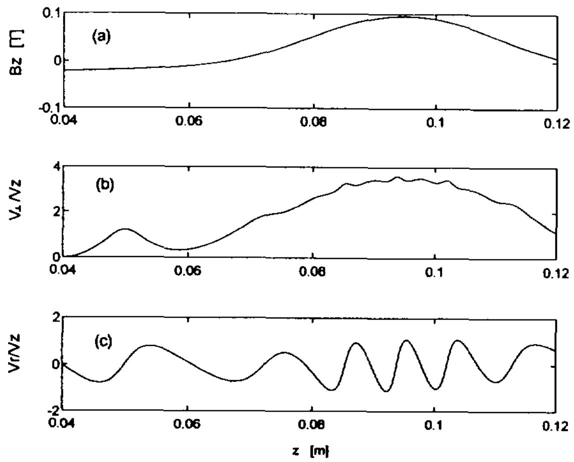

Fig. 2. The axial magnetic field (a), and the electron normalized tangential (b) and radial (c) velocities along the tube.

The next sections describe the compact cyclotron experimental setup and present recent measurements of microwave radiation bursts obtained with a carbon-fiber cold cathode.

2. Experimental setup and results

A schematic of the compact cyclotron oscillator experiment with a cold carbon-fiber cathode is shown in Fig. 1. The device is assembled in a 2.75 in. standard vacuum pipe. It consists of a carbon fiber emitter, a planar anode, and an isolated resonator. The electron current is collected inside the cavity and measured by the voltage drop on a 10 Ω resistor. Two coils around the e-gun and the resonator, respectively, provide the axial magnetic field required for focusing and for the initial rotation of the electrons.

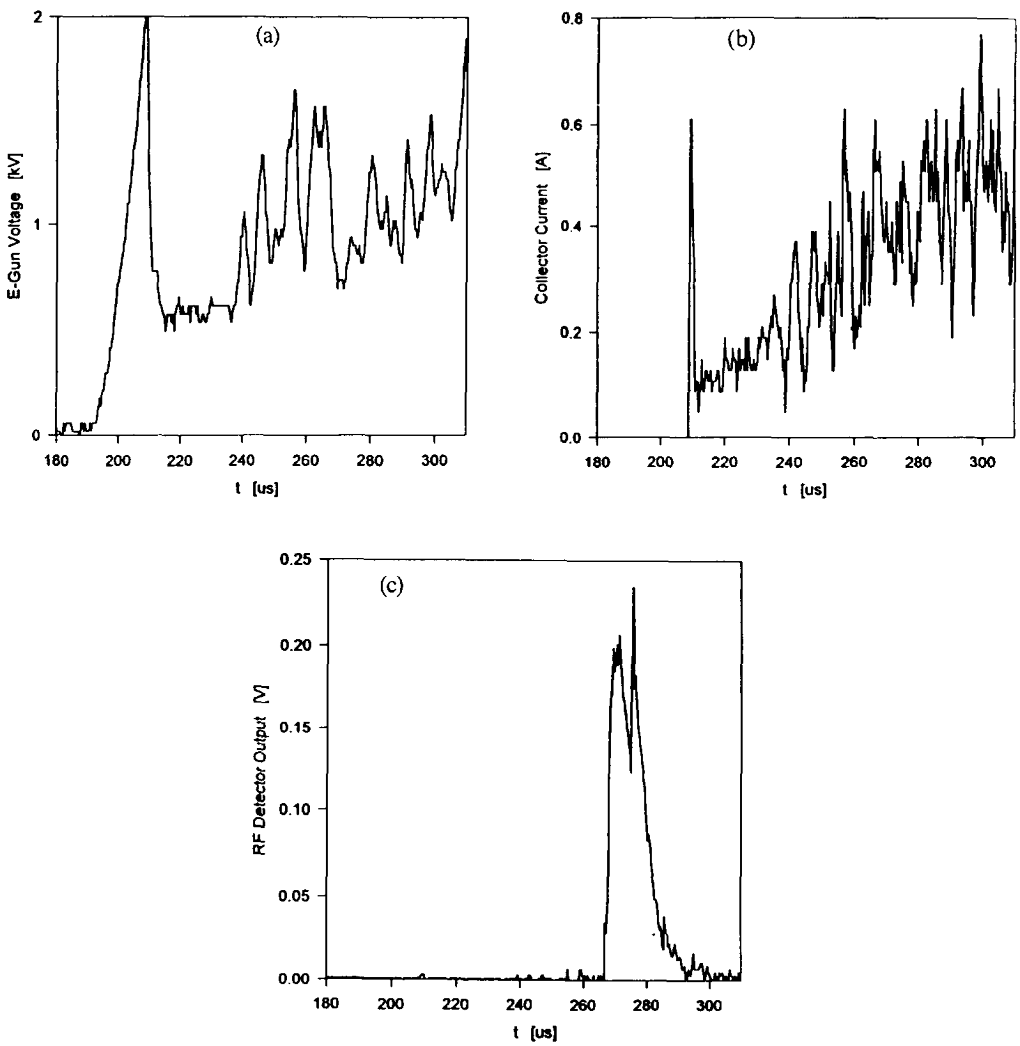

Fig. 3. Typical experimental measurements. (a) The carbon-fiber voltage. (b) The electron current measured in the collector. (c) The detected microwave output power through a 2.8–3.1 GHz bandpass filter.

The cathode consists of a bundle of carbon fibers, 2 mm in diameter. The distance between the fiber tips and the planar anode is 8 mm. The diameter of the hole in the center of the anode is 5 mm. The CRM interaction occurs in a low-Q cylindrical resonator which supports standing TEM waves by two metal wires stretched along it as shown in Fig. 1. The cavity length is 65 mm and the distance between the wires is 12 mm. The resonator is isolated by Macor ceramic holders. The RF signal is detected through internal and external DC blocks, an attenuator, and a 2.8–3.1 GHz bandpass filter. Guard filters in lower and higher frequencies are used to verify the spectral measurement. The input current is measured by a Rogovski coil and compared with the detected output current. The various signals are traced by Tektronix TDS540 and TDS620 digital oscilloscopes. The electron gun voltage and the coil current are supplied by two pulsers with pulse widths of 1 ms and 35 ms, respectively. The cathode voltage and current are slightly stabilized by two 1 kΩ resistors, one in series to the cathode and the other located between the anode and the ground.

The computed distribution of the axial magnetic field along the tube is shown in Fig. 2a. The corresponding normalized electron velocity components in the transverse ($V_\perp/V_z$) and the radial (V_r/V_z) directions are shown in Figs. 2b and 2c, respectively. The initial electron rotation at the entrance to the cavity may satisfy the TEM-CRM interaction condition in Eq. (1).

The compact CRM oscillator with the carbon fiber cathode has been operated recently in our laboratory. Significant bursts of microwave radiation are observed in the range of 2.8–3.1 GHz. Typical results are shown in Figs. 3a–3c. The carbon fiber voltage is shown in Fig. 3a. The voltage in this experiment tends to be periodically unstable. The electron current, as measured by the 10 Ω resistor in the collector, is shown in Fig. 3b. The microwave radiation output, detected through a 2.8–3.1 GHz bandpass filter, is shown in Fig. 3c. Similar results were obtained recently in about one hundred runs.

This experiment shows the feasibility of microwave generation by a CRM oscillator which employs a cold carbon-fiber cathode at low voltage. Though the cathode voltage and the electron current are significantly noisy, clear microwave bursts are obtained.

Future experiments are aimed to stabilize the carbon-fiber voltage and current by appropriate circuits. In these experiments, we will use carbon-fiber emitters in miniature FEM and CRM schemes, in cryogenic super-conducting devices, and in large emitting arrays.

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