Spectral measurements of gyrotron oscillator with ferroelectric electron gun

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Since the discovery of the ferroelectric electron-emission effect, its implementation in microwave tubes has been impeded by various reasons and in particular by its relatively wide energy spread. Recently, a 1.5 kW microwave output from a gyrotron based on repetitive ferroelectric electron gun has been reported. This letter presents measurements of the spectral variations of the gyrotron output, and relates them to the electron-gun energy spread and to other inherent line-widening causes, such as the pulse length. The result shows that the contribution of the electron energy spread to the spectral content is not significantly larger than the other causes of line broadening. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1499993]

Ferroelectric cathodes have been investigated as a cold electron source in the last decade.[1] A demonstration of microwave generation by ferroelectric cathode was reported by Drori *et al.*[2] A power of ~1 W was obtained, but the interaction mechanism was not identified. In following reports, ~25 W microwave signals were obtained in clear interaction mechanism of cyclotron resonance maser (CRM) oscillations.[3] Improvement of the ferroelectric electron gun led to the successful demonstration of a CRM amplifier,[4] which requires more coherent electron beam. Nevertheless, all these devises were operated in a single-shot mode. Since the strong ferroelectric emission involves plasma,[1] the undesired occurrence of voltage breakdowns limits the pulse repetition rate. Recently, the plasma expansion has been limited in an advanced gun using a control grid, and a high repetition rate gyrotron was operated[5] reaching 3 MHz and ~50% duty cycle. In this electron gun the electron velocity spread was reduced, and consequently 1.5 kW microwave-signal power were measured with a 12% interaction efficiency.

A significant parameter for a proper microwave tube operation is the velocity spread of the electron beam. This parameter influences the tube performance in crucial aspects such as the maximal out-power, efficiency, noise content, signal coherency, bandwidth, and gain. A wide electron-velocity spread reduces these figures-of-merit of the microwave tube, and may result in its insufficient performance level. Since the ferroelectric strong emission involves plasma, the natural velocity spread in the emission process is relatively large. Therefore, in order to properly integrate the ferroelectric cathode into a microwave tube, a reduction of its electron velocity spread is essential.

In this study, the spectral content of the microwave signals is measured. The contribution of the electron velocity spread to the spectral widening of the gyrotron signal is evaluated, and is compared to the other widening elements including the gun pulse width and its stability.

The experimental setup is presented in Figs. 1(a)–1(c).

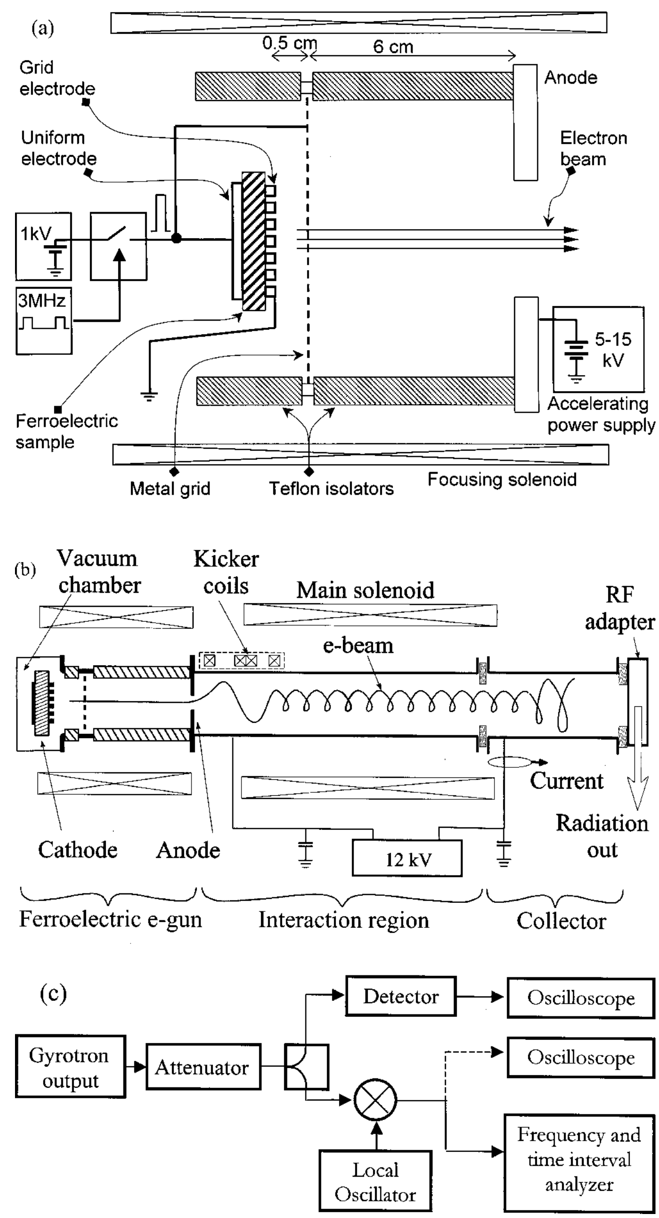

FIG. 1. The experimental setup: (a) The ferroelectric electron gun. (b) The gyrotron oscillator scheme. (c) The diagnostic setup.

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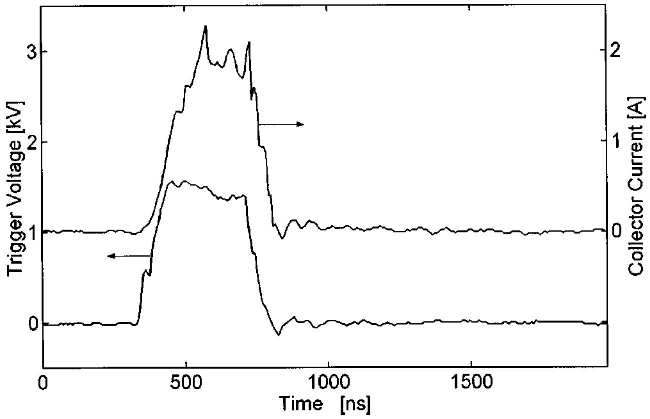

FIG. 2. The exciting trigger voltage and the corresponding collector current.

The electron gun [Fig. 1(a)] is based on a ferroelectric cathode made of a $10\times10\times1\ mm^3$ lead–lanthanum–zirconium–titanate (PLZT) 12/65/35 ceramic plate. The rear (nonemitting) electrode is made of uniform $7\times7\ mm^2$ silver paint. The front (emitting) electrode consists of a $7\times7\ mm^2$ stainless-steel grid, attached to the ceramic plate. Another stainless steel grid is placed 0.5 cm in front of the cathode, and the anode is distant 6 cm from the grid. The front electrode is grounded while the rear electrode is electrically connected to the grid and applied with ~1 kV pulses of $\sim0.2\ \mu s$ duration. These pulses induce electric field on the cathode and ignite the surface plasma from which electrons are attracted by the grid. The electrons pass the grid and are then accelerated by the anode, which is connected to a dc accelerating voltage (~12 kV). A focusing solenoid guides the electron to a hole in the anode center, from where they are delivered to the interaction region of the tube [Fig. 1(b)]. The magnetic field also suppresses the plasma expansion and allows pulse repetition rates of up to 3 MHz.[5] The electrons enter the interaction region and obtain a transverse velocity component by the kicker magnetic field. The main solenoid produces an axial magnetic field that is needed for the CRM interaction and guides the electrons through the interaction region in cycling trajectories. After the interaction, the electrons are collected in the collector section where the electron beam current is measured. More parameters on this section are detailed in Ref. 5.

The microwave radiation is coupled-out through the collector section, and is delivered to the diagnostic setup [Fig. 1(c)]. The microwave signal is attenuated and split to two channels in which its spectral widening is measured by two different means. In one channel the signal envelope is detected, and in the other channel heterodyne measurements are made by a mixer and a local oscillator (LO). An intermediate frequency (IF) in the range of 50–1000 MHz is obtained. An HP5364A microwave mixer detector is employed in this setup. The IF signal is observed either directly by an oscilloscope (for IF signals up to 200 MHz) or by a frequency and time interval analyzer (HP-5372A).

A typical trigger voltage pulse applied on the cathode rear side and the corresponding electron beam current measured at the collector are shown in Fig. 2. The detected signal

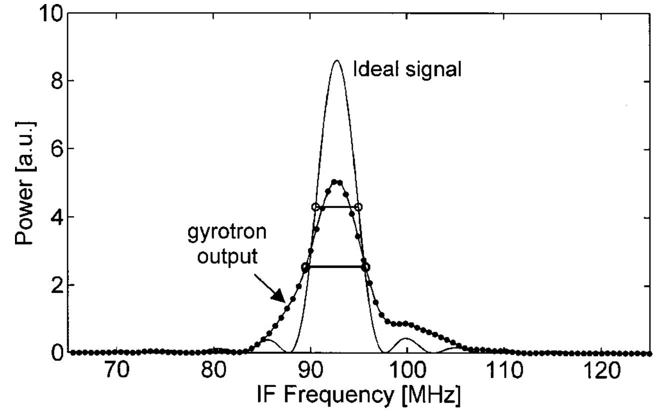

FIG. 4. Fourier transform of the measured IF signal (dotted) compared to an ideal 0.2 μs IF pulse (solid).

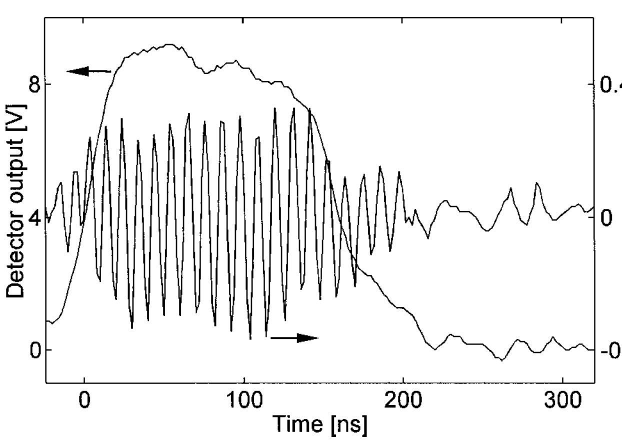

FIG. 3. The detected gyrotron output signal, and the IF signal at the mixer output.

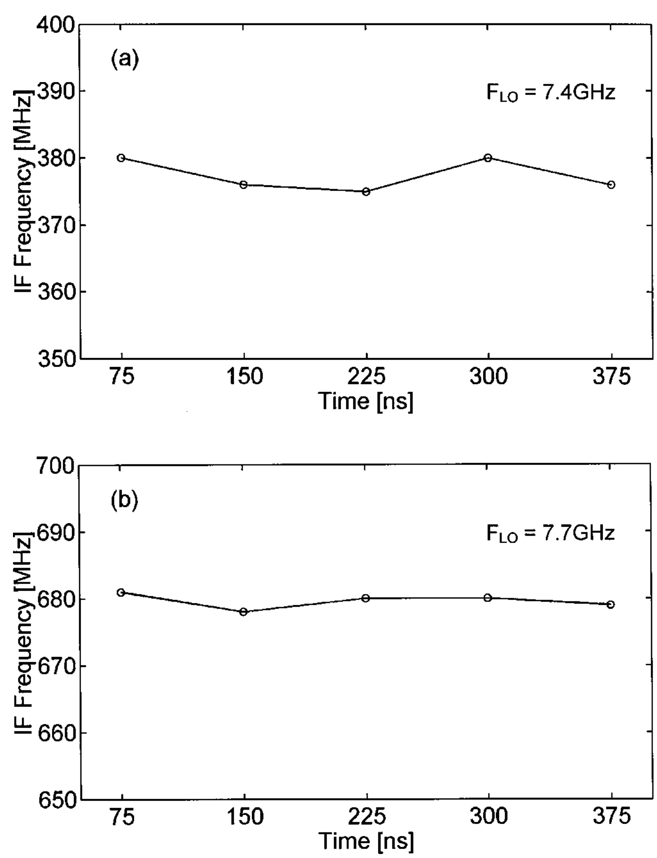

FIG. 5. IF frequency measurements for LO frequencies of 7.4 (a) and 7.7 GHz (b).

envelop and the IF signal of a typical microwave pulse is shown in Fig. 3. In this measurement the LO frequency is 7.1 GHz, and the microwave signal frequency is verified to be around 7.0 GHz. The Fourier transform of the measured IF signal is compared to the Fourier transform of a 97.2 MHz ideal sine wave multiplied by a 0.2 μs square pulse with the same energy. Figure 4 shows for comparison the power spectrum of the two wave forms. The full width at half maximum (FWHM) of the ideal signal is 4.4 MHz while the FWHM of the measured gyrotron output signal is widened to 6.2 MHz.

An independent evaluation of the gyrotron spectral content is obtained by the frequency-and-time interval-analyzer (HP-5372A) measurements. Figures 5(a) and 5(b) show two examples of the frequency variation during the pulse. The LO frequencies are 7.4 and 7.7 GHz, and the measured IF frequencies are 0.38 and 0.68 GHz, respectively. Accordingly, the microwave signal frequency is verified as 7.02 GHz (a similar result was obtained in tens of shots in different LO frequencies). In these measurements the signal zero crossings are counted in intervals of 75 ns and the average frequency value is obtained for each period. IF frequency variations within 5 MHz are measured during the pulse, in accordance with the Fourier transform result.

Another factor that contributes to the spectral widening of the gyrotron output signal in this setup is the instability of the accelerating voltage during the pulse. The high voltage variation during the pulse is $\sim$0.16 kV (out of 12 kV) which corresponds to a $\sim$2.5 MHz variation in the CRM resonance frequency.

The results show that the main spectral widening is attributed to the finite pulse width, which is inherent to the ferroelectric electron-gun pulsed operation. The contribution of the electron energy spread caused by the ferroelectric electron gun itself to the spectral widening is a considerable but not a dominant factor. It appears to have a secondary contribution to the spectral widening, since the ferroelectric gun is inherently operated in pulse mode.

These results indicate also that the remedy for the electron energy spread employed in this electron gun, namely the separation of the electrons from the plasma by a grid[4–6] in a two-stage scheme, satisfies the requirements of gyrotrons in the microwave regime. Beside gyrotrons,[5,7] these results encourage the use of ferroelectric electron guns in other free-electron microwave tubes in pulsed mode, such as high power free electron lasers,[8] and traveling-wave tubes.[2,9] The ferroelectric electron gun can be used as a source of high current electron beam with versatile shapes.[10] It can also be shaped to obtain a multielectron-beam device.[11] Using the same design approach (two-stage gun with a grid), such arrays may produce high total current with a sufficient quality for multibeam microwave-tube arrays.

The authors are indebted to the anonymous reviewer of Ref. 5 who proposed to measure and evaluate the significance of the velocity-spread to the ferroelectric-gun gyrotron spectral widening.

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